# DIESEL GENERATOR HANDBOOK

L L J MAHON

ELSEVIER

# Diesel Generator Handbook

L L J Mahon
CEng, FIEE, FBIM, FIOA, CDipAF

ELSEVIER
BUTTERWORTH HEINEMANN

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# Contents

# Preface

I fir~t got involved with diesel generators in the Middle East, in the mid 1950s. As a young engineer, without any previous experience or knowledge of diesel engines, I was responsible for the operation and maintenance of a number of small power stations employing medium- and slow-speed engines. Fortunately, as an ex-BTH trainee, I had a reasonable grounding in electrical machines, switchgear, and controlgear. Two years later, I was engaged in preparing estimates and submitting proposals for turnkey diesel generator power projects, to meet consultants' specifications. Over the next 30 years, I was to be involved with the design, development, manufacture, installation and commissioning of both stationary and highly-specialised mobile plants for a variety of applications. When I was starting out in this career, I needed a book which would have given me a single-source reference on the practical design and application of diesel generating plant. There wasn't one. I resolved to fill the gap one day.

This then is that book, conceived 35 years ago, the writing of which was deferred some 28 years. During the 'gestation' period, I accumulated an extensive collection of learned papers and articles on the topics covered. Many of these are included in the references and bibliographies given at the end of the chapters. These lists are not only an acknowledgement of my sources of information but also serve to augment the text which can, at best, provide only a general outline, for so large a subject, in the space of a single volume.

The book is intended to serve as an engineering guide to all those who may be concerned with the selection, specification, testing, commissioning, operation and maintenance of diesel generator plant. It should therefore be valuable to: the plant or services engineer; to non-specialist engineers and users; and to young techniCians and engineers (especially in industrially developing countries) who are embarking on a career in the supply industry.

The starting point is the prime mover - in its compression ignition and spark ignition forms. An explanation follows of the significant terms relating to engine power; and the accepted methods of specifying ratings. The general features and the performance characteristics of synchronous generators are then discussed in some detail. The techniques used in load assessment, and the most suitable ways of combining and operating multiple generators are examined. Those loads which have a direct bearing on the sizing of plant, and on the quality of supply, are reviewed in Chapter 5. The next three chapters consider the principles used in the control of engines and generators - in both single-running and parallel-running modes; and describe proprietary governors and excitation control systems. Chapter 9 outlines the principles affecting the choice and application of switchgear and controlgear; and Chapter 10 examines the protection that needs to be applied to engines and generators. The many forms of emergency and standby power available to the user, who has need for an alternative or additional electrical power source to that which is normally obtained from a public utility, are delineated in Chapter 11. The relevance, to engine performance, of certain key properties in fuels and lubricating oils are examined in Chapter 12. The last three chapters then deal with the important aspects of power plant installation and commissioning; noise reduction; and plant operation and maintenance.

It is quite possible that some of the products described may have been modified, or even superseded, in the time that it has taken from composition to publication of a book of this size. Every effort has been made to ensure that information on national and international standards is as up-to-date as possible, at the time of going to press. The practice of designating standards by reference to their numbers only (and not always by date) has been largely adopted. Extracts from British Standards are reproduced with the permission of BSI. Complete copies of the standards can be obtained, by post, from BSI Sales, Linford Wood, Milton Keynes MK14 6LE (Fax 0908 320856).

I am greatly indebted to those manufacturers, publishers and learned bodies who have provided

me with information and assistance; and whose material help is acknowledged beneath the illustrations concerned. I also have to thank the following individuals for their advice, constructive criticism, and invaluable help on points of detail.

Derek Jones (Dorman Diesels), John Yarrow (Hawker Siddeley Group); Colin Hudson, Tony Montriou and Brian Beech (GEC Alsthom Group); Arthur Allen (P & B Engineering); Michael Webb (Woodward Governor (UK»; Derrick Barber (Petbow); Ben Hicks (T Mat Engineering); and Leslie Minikin (Briiel & Kjrer (UK».

*L. L. J. Mahon*
*Yelvertoft*

# 1 Reciprocating internal combustion engines

**Contents**

## 1.1 Introduction

The purpose of this chapter is to give the reader an introduction to the subject of reciprocating internal combustion engines. It discusses the various ways used to classify engines. In describing the working principles, and the salient features, of both the engine itself and its principal auxiliary equipments, the meanings of terms and phrases in common usage are explained. The factors affecting choice of primary and ancillary systems are discussed and the major decision areas are examined. Finally, basic information is given on the increasingly important subject of co-generation, in the context of total energy conversion systems.

## 1.2 Classification of engines

There are several ways of classifying reciprocating internal combustion (RIC) engines. The more usual are:

1. by use;
2. by speed;
3. by design; and
4. by size.

*1. By use*

Here, engines are categorized by their application. For example:

(a) marine for ship propulsion and auxiliaries;
(b) industrial for generators, compressors, pumps, etc.;
(c) automotive for land transport, both on and off highways; and
(d) traction for locomotives and rail cars.

Rigid groupings of this kind can be too restrictive. In America, with its strong tradition of automotive and locomotive diesel engines, users have found it advantageous to adapt engines of these types to industrial use, rather than seek purpose-built units. On an international scale, RIC engines for power generation will continue to be adaptations from the high production manufacturers of automotive, traction, and marine engines [1].

*2. By speed:*

Because speed of crankshaft rotation basically determines the weight and size of an engine in relation to its output power, this type of classification is the one most widely adopted. The weight of an engine is a good guide to its first cost and its life. First cost is roughly proportional to weight; and life is proportional to the ratio of weight to power output [2].

Industrial engines are generally accepted as being divided into three speed classes:

| | |
|---|---|
| (a) High speed | over 1000 rev/min |
| (b) Medium speed | 400---1000 rev/min |
| (c) Low speed | up to 400 rev/min |

In the context of alternating current, generating sets are constructed to operate at one of the appropriate synchronous speeds governed by the expression:

$$n = f.60/p$$

Where $n$ is the speed of the generator shaft, in rpm
$f$ is the frequency of the generated supply, in Hz (or cycles/second), and
$P$ is the number of (field) pole pairs on the generator.

Typical synchronous speeds (rpm) for 50 Hz and 60 Hz applications are:

| 50 Hz | 60 Hz |
|---|---|
| 3000 | 3600 |
| 1500 | 1800 |
| 1000 | 1200 |
| 750 | 900 |
| 600 | 720 |
| 500 | 600 |
| 428 | 514 |
| 300 | 360 |

See Sub-section 4.2.2 of Chapter 4 for a fuller treatment of the speed-frequency relationship.

The choice between low, medium or high speed engines must be related to evaluation of power supply security against operational economy. Security is essentially a function of the availability of engines; and the number of units and spare capacity installed, in relation to the average load demand [3].

*3. By design:*

Engines may be sub-classified with respect to their design features. These would include:

(a) working cycle (four-stroke or two-stroke);
(b) piston action and/or piston connection;
(c) cylinder arrangement;
(d) type of fuel used (e.g. liquid, gaseous, dual fuel, etc.);
and
(e) the manner in which air is fed into the cylinders (either at ambient pressure or with overpressure) .

*4. By size:*

This is perhaps the most contentious of the classification methods since 'size' interrelates with many different factors such as: cylinder dimensions; the number of cylinders; speed; and mean effective pressure (see Chapter 2). In acknowledging this, Kates and Luck [4] have attempted to give some idea of size by using horsepower per cylinder, at rated speed, to arrive at the following rough definitions. The figures in parentheses are the corresponding values in kilowatts mechanical ($kW_m$).

| | |
|---|---|
| Small size | below 25 hp/cyl (19) |
| Medium size | 25 to 200 hp/cyl (19-149) |
| Large size | above 200 hp/cyl (149) |

Most manufacturers have 'type series' of engines. This means that they limit their production to a series of types, each using various numbers of cylinders of similar dimensions. The output of a multi-cylinder engine, of a given type, is then the output of the single-cylinder model multiplied by the number of cylinders of that engine. Engines may be applied to a wide range of power requirements by simply changing the number of cylinders, and engine operating speed. The manufacturer's aim throughout, is to maximize the number of common parts used within a type series. This, in turn, calls for rationalization of as many items of the engine as possible; and also for maximum utilization of tooling for the economic manufacture of the engines. This philosophy certainly applies to all manufacturers of small- and medium-size units.

The user who intends purchasing generating sets of various capacities would be well advised to choose engines from a type series wherever possible. This is beneficial both in servicing and in spare parts stocking. See Chapter 15.

## 1.3 Working cycles

RIC engines may be of the self ignition (compression ignition, c.i.) or of the indirect ignition (spark ignition, s.i.) type. The salient differences between their combustion processes are explained later.

Compression ignition and spark ignition engines can be arranged to run in one of two operating cycles. These are diagrammatically represented in Figures 1.1 and 1.2; together with the appropriate indicator diagrams, which portray the events within the engine cylinder during each cycle.

In the *four-stroke* (or two-revolution) cycle, fuel ignition takes place in every other revolution of the crankshaft. An engine using this cycle gets work from its fuel during one stroke in four (Figure 1.1), i.e. its working stroke occurs once in every two revolutions. In contrast, *two-stroke* (or one-revolution cycle) engines have a working stroke in each revolution of the crankshaft (Figure 1.2).

While two-stroke engines are generally lighter and smaller in size than four-stroke engines of the same output, it does not follow that, because the two-stroke engine has twice as many power strokes

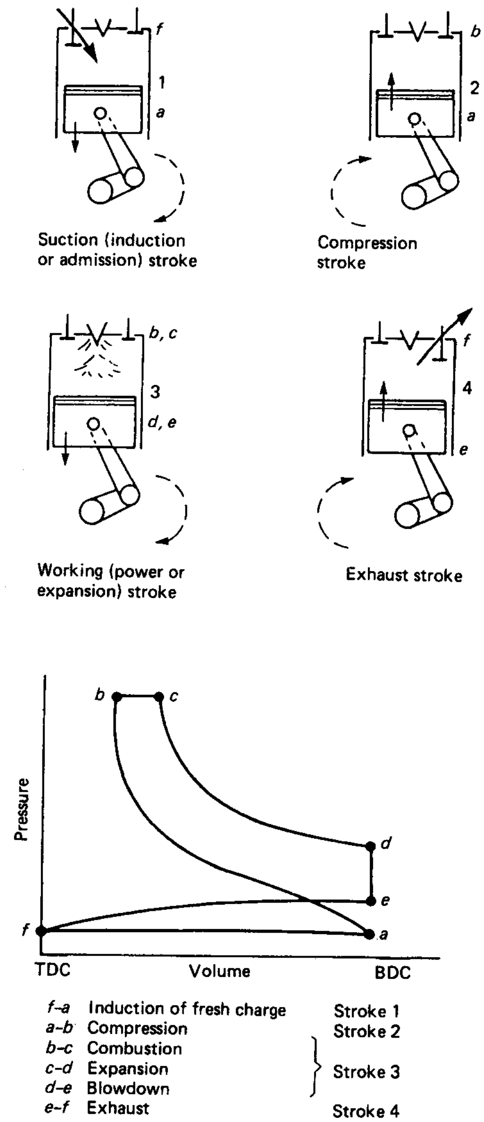
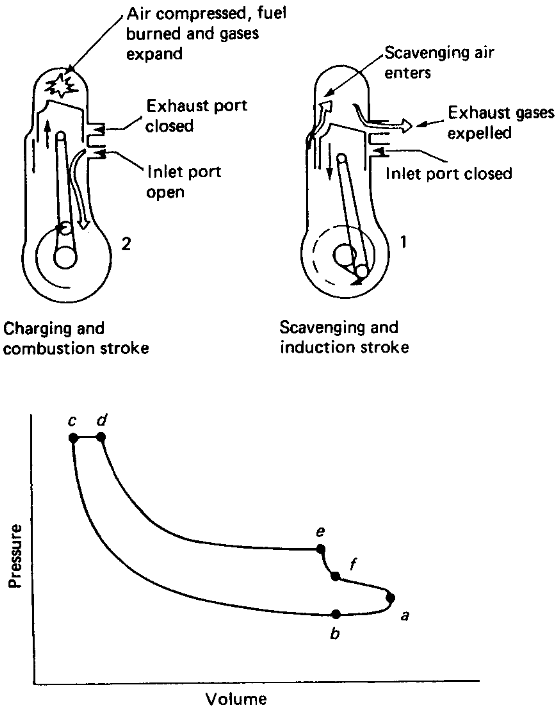



**Figure 1.1** Four-stroke cycle

as the four-cycle engine, it will produce twice the power.

The down stroke of the two-cycle engine combines both power and exhaust strokes. As the intake and exhaust ports are cleared by the piston, some mixing of fresh air charge and burned gases takes place (scavenging). Not all the burned gases are exhausted; which prevents a larger fresh charge of air being induced into the cylinder. The resulting power stroke therefore has less thrust.

In the four-stroke engine, nearly all the burned gases are forced out of the combustion chamber by the up-stroking piston. This allows almost a full air/fuel mixture to enter the cylinder; since a com-




*a–b* Scavenging and induction } Stroke 1
*b–c* Compression
*c–d* Combustion
*d–e* Expansion } Stroke 2
*e–f* Exhaust blowdown
*f–a* Exhaust and scavenging

**Figure 1.2** Two-stroke cycle (valveless form)

plete piston stroke is devoted to induction of the mixture. The power stroke, therefore, produces relatively more power than its two-cycle counterpart [3].

One important advantage of the four-stroke engine is that its lubricating system is simple and reliable, making it the better choice for unattended or partially-manned generator installations.

The theoretical air standard cycle on which modern c.i. engines work is represented by the diagram of Figure 1.3. It is known as the dual-combustion, mixed, or composite cycle and is a combination of the constant volume (Otto) and the constant pressure (diesel) combustion cycles. It is useful for comparison with actual diesel cycles operating in their mid-to-full load range [5]. The area of the diagram, to a suitable scale, represents the work done on the piston during one cycle.

Fuel may be injected at two points only: either at B or at C (Figure 1.3). Starting at point A, the events in the cycle are as follows:

1. adiabatic compression of air takes place between A and B;

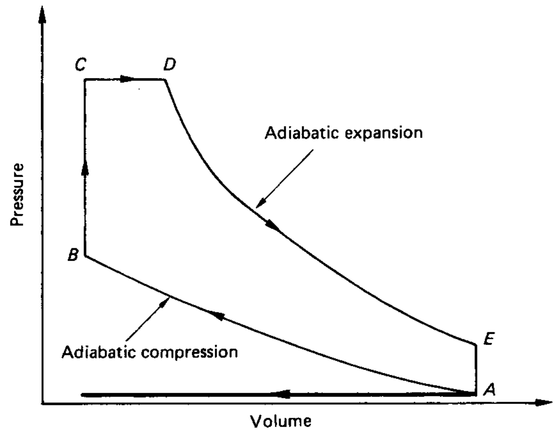



**Figure 1.3** The theoretical (mixed) air standard cycle for the diesel engine

2. heat is then added, partly at constant volume (B-C) and partly at constant pressure (C-D);
3. adiabatic expansion then occurs from D to E;
4. the cycle is closed at constant volume (E-A), and heat is rejected to exhaust.

This theoretical cycle does not represent what actually happe.ns in the cylinder. For example, the compression and expansion strokes are not truly adiabatic since there is heat loss to the cylinder walls. In practice, the diagrams for actual diesel cycles approach those illustrated in Figures 1.1 and 1.2.

For high speed engines it is more usual to use an indicator diagram based on crank angle. A typical graphical representation of the combustion process would then be as shown in Figure 1.4. It is possible to derive a stroke-based indicator diagram from this, by transposition [6].

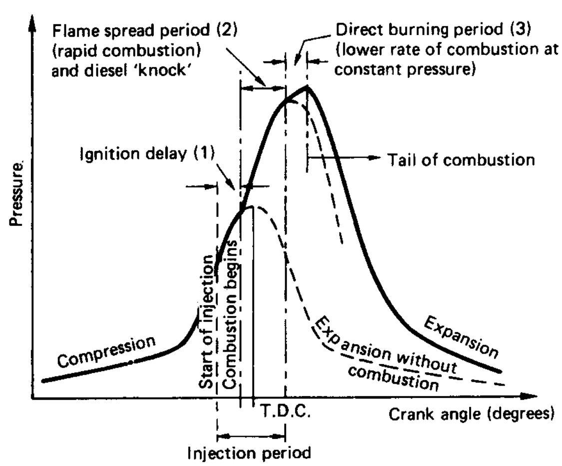



**Figure 1.4** Pressure–time diagram of injection and combustion periods in a c.i. engine

The combustion process in a high speed engine may be described as taking place in several stages. Firstly, there is a very short delay period (the 'injection lag') between the commencement of delivery by the fuel pump and the start of fuel entry into the combustion space. This is followed by an 'ignition delay' period (phase 1) during which the fuel does not ignite instantaneously, because it must first be heated to its spontaneous ignition temperature. The speed with which this happens depends upon a number of factors [7]:

1. the ignition quality of the fuel;
2. the fineness of atomization; and
3. the rate of heat transfer from air to fuel.

The last of these factors is affected by: the difference in temperature between the air and the fuel; the air density; and the relative movement of fuel and air.

When ignition occurs it takes place at several points. After combustion has commenced, there is a 'flame-spread' period (phase. 2), during which the combustion spreads rapidly throughout the chamber volume. This results in a very rapid liberation of heat, and a rapid increase in pressure. As the piston is almost stationary at this point in the cycle, a sudden shock load may be imposed on the working parts of the engine, resulting in very rough running. Also, a phenomenon known as *'diesel knock'* or *'fuel knock'* (because of the sharp knocking sounds it produces) results from the sudden increase in pressure caused by the rapid burning of fuel - which has accumulated during the ignition delay period (phase 1). Diesel knock is worse at high speeds; at low compression ratios (see Chapter 2); at low ambient temperatures; and with fuels resistant to ignition. Cure is effected by either reducing the delay period or reducing the rate of injection during that period [8].

Improving the ignition quality of the fuel (by using a fuel with a higher cetane number - see Chapter 12) results in earlier ignition and reduces the delay period. The shorter the delay period, the less the quantity of accumulated fuel; and, consequently, the less fuel available to burn rapidly and cause diesel knock [4].

The third phase in the combustion process is one in which a lower rate of combustion occurs. It is the period during which fresh fuel is being delivered into the combustion chamber, to mix with a highly-heated and burning mass of accumulated fuel. The fresh fuel is therefore immediately ignited as it leaves the injector nozzle.

After fuel injection has been completed, the rate of combustion tails off. A high rate of heat transfer, by radiation, occurs during this and the previous stage [8].

### 1.3.1 The four-stroke cycle

In the four-stroke cycle, air is drawn into the cylinder through an inlet valve(s) as the piston moves down in its *suction* stroke (diagram 1 of Figure 1.1). The inlet valve then closes and the piston moves upwards to compress the air in the cylinder. This is the *compression* stroke (diagram 2). At or near the end of this stroke, fuel is sprayed into the cylinder. The pressure to which the air is compressed ensures that a sufficiently high temperature is attained in the cylinder to give rapid spontaneous ignition of the injected fuel. As combustion spreads, cylinder pressure rises rapidly to force the piston down on its *working* stroke (diagram 3). While the piston moves up on the *exhaust* stroke, the exhaust valve opens, allowing the burnt gases to be pushed out of the cylinder (diagram 4). At the end of the stroke the exhaust valve closes, the inlet valve opens, and the four-stroke cycle is repeated.

### 1.3.2 The two-stroke cycle

Two-stroke engines may employ valves (in *unitlow* engines) or they may use ports in the cylinder walls. A cylinder of the latter type is shown diagrammatically in Figure 1.2. The downward movement of the piston in the working stroke, uncovers both the exhaust and inlet ports (diagram 1). This allows *scavenging* air, which has previously been admitted tG the lower side of the piston via the inlet port, to expel the exhaust gases through the exhaust port. The rising piston (in the *charging* and *combustion* stroke - diagram 2) covers both ports. The air is compressed and quickly heated; and fuel is injected, as in the four-stroke cycle. The working stroke then begins. Note, that some fresh fuel is lost with the spent gases; and that some of the gases remain in the cylinder, to contaminate a subsequent fresh fuel charge.

Two-stroke engines may be subdivided into those types which employ:

1. crankcase scavenging (i.e. using the underside of the piston and the crankcase as an air compressor); or
2. pump, or blower, scavenging (i.e. using discrete pumps or blowers to provide the scavenging air).

## 1.4 Piston action and piston connection

Piston action is classified as:

I. single-acting;
2. double-acting; or
3. opposed piston.

Single-acting engines use only one end of the cylinder and one face of the piston to develop power; whereas double-acting engines use both ends of the cylinder and both faces of the piston (on the up-stroke and on the downstroke). Engines of the latter type are mechanically complex in construction. They are confined to very large, low speed units that were primarily designed for marine propulsion duties, but have also been applied to land-based generating plant.

The opposed-piston engine uses two pistons in each cylinder - the combustion space being in the middle of the cylinder. There is no cylinder head; and each piston is single-acting [4]. The commonest arrangement employs two crankshafts connected together (typically through bevel gears and flexibly coupled pinion shafts, as in the American Fairbanks-Morse two-stroke 38TD8V2 engine series). The upper pistons drive one crankshaft, and the lower pistons the other (see Figure 1.5). Other configurations using a single crankshaft have either cross-connected rod link systems, or lever connections, or they may employ three cranks per cylinder. A classic example of the last-mentioned type was the very low speed Doxford J-type engine described by Wallace [5]; and now out of production. It was capable of developing about 20 $MW_m$.

One of two methods may be used to connect a piston to the upper end of the connecting rod. In the *trunk-piston* arrangement, the connecting rod acts directly on the piston. The geometry is such that the piston exerts side thrust against the cylinder wall. Most of the wear caused by this thrust is near the middle of the stroke. Making the piston skirt (i.e. the lower section of the piston) relatively long, has the effect of spreading the side thrust over a greater area; so reducing the unit pressure [5].

In the alternative arrangement (see Figure 1.6), the piston is indirectly connected to the connecting rod through a *crosshead,* which slides up and down in guides. The big advantage of this system is that it removes piston side thrust; and therefore reduces cylinder and liner wear. This is offset by greater complexity, added engine height and weight, and the need for careful adjustment. Crosshead construction is generally used only when it cannot be avoided; such as on double-acting engines [5].

Examples of very large slow-speed, single-acting, two-stroke engines, which also use the crosshead principle are given in [6].

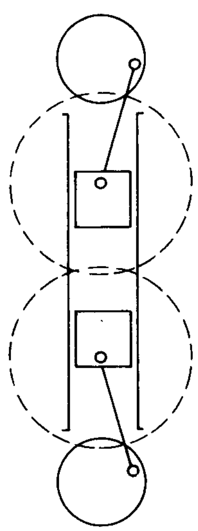


**Figure 1.5** Twin crankshaft opposed-piston configuration

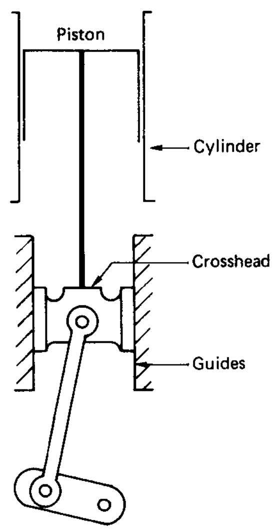



**Figure 1.6** The crosshead-piston principle

## 1.5 Cylinder arrangements

The RIC engine may have its cylinders arranged in one of several ways. In the context of generating plants, the most commonly used engines are those in which the cylinder axes are either perpendicular (vertical) and in-line; or are arranged in a vee-form.

The general definition of the single bank, or in-line engine, is one 'having a number of working cylinders all located on one side of the crankshaft, and in which all the cylinder centre lines lie in one and the same plane, which usually contains the crankshaft' (BS5673:1979/ISO 1205-1972). This form of construction may be used for engines of up to 9 cylinders. The opposed-piston engine described in Section 1.4 would be classified as an in-line engine.

Above a total of 9 cylinders, it becomes difficult to make a sufficiently rigid frame and crankshaft for an in-line arrangement. Also, the engine becomes quite long and takes up considerable space [6]. For this reason, it is usual for medium- and high-speed engines to employ a vee-form arrangement, where there are more than 10 cylinders. By using two identical connecting rods running on each crankpin (in a 'side-by-side' arrangement), a stiff crankshaft is obtained; and the frame is much more rigid. The overall length of the engine is just over one-half that of an equivalent in-line engine. This makes it compact, easy to install, and suitable for trailer-mounted and transportable generator plants. The included angle of the vee between the banks of cylinders may range from about 30° to 120°. Incidentally, a flat engine (also referred to as a horizontally opposed or vis-a-vis engine) is a vee-engine whose angle between banks has been increased to 180°. It should not be confused with an opposed-piston engine.

Another form of multi-bank engine is the double bank (twin bank) unit, which has its cylinders grouped in two vertical banks; each with its own crankshaft. Gear wheels, of suitable step-up ratio, are fitted on the crankshafts and drive a common output shaft. Engines of this type, manufactured in Europe by Sulzer and Lister-Blackstone in the 1950s and 1960s, found wide application in locomotives; and were successfully employed on stationary generator duties.

The international convention for the numbering and identification of the banks of cylinders, of various engineforms, is given in ISO 1205 (BS 5673). This specifies the method of designating the cylinders of RIC engines for marine, locomotive and stationary use.

The 'position of the observer', in relation to an engine, is defined in the standard as being: 'in an extension of the axis of the shaft which provides the driving extremity, the observer directing his view towards this shaft extremity'. The *position* equally applies to single-bank and multi-bank engines; and to those units, such as the twin-bank engine, which have an integral gear. If the engine has more than one driving shaft, the manufacturer must state which shaft extremity is used as the datum when designating the cylinders.

The terms *primary driving end* and *free* (or secondary) *driving end* were in use before the withdrawal of BS 1599 in 1979, and may still be found in some engine specifications. The primary end was defined as the end connected to the principal power take-off (e.g. the generator), and the free end as that opposite to it. Note, that the numbering system of ISO 1205 is the reverse of that previously applied in BS 1599.

The direction of an engine's rotation (clockwise or counter-clockwise) is described from the position of the observer - i.e. the end of the engine associated with the driven unit.

The designation of each cylinder in an RIC engine is effected by either a number alone, or by a combination of a capital letter and a number. On single-bank engines, including those of the opposed-piston variety, the cylinders are designated by number; starting with 1 at the cylinder nearest the observer.

Combinations of letters and numbers are used for the cylinders of multi-bank engines. Letters are assigned to the banks, which are defined as groups of cylinders arranged in a common plane parallel to the axis of the crankshaft. BS 5673 uses the concept of an imaginary semi-plane P, centred upon the axis of the driving crankshaft. This semi-plane is assumed to be rotating in a clockwise direction; and the crankshaft in a horizontal position. The starting point on the semi-plane is in its 9 o'clock position- as seen by the observer (see Figure 1.7). The bank **at** this point on the semi-plane, or the first bank through which the semi-plane moves, is given the capital letter A. The following bank is assigned the letter B; and so on. Each individual cylinder il} the engine is given an alpha-numeric symbol: AI, B8, etc.

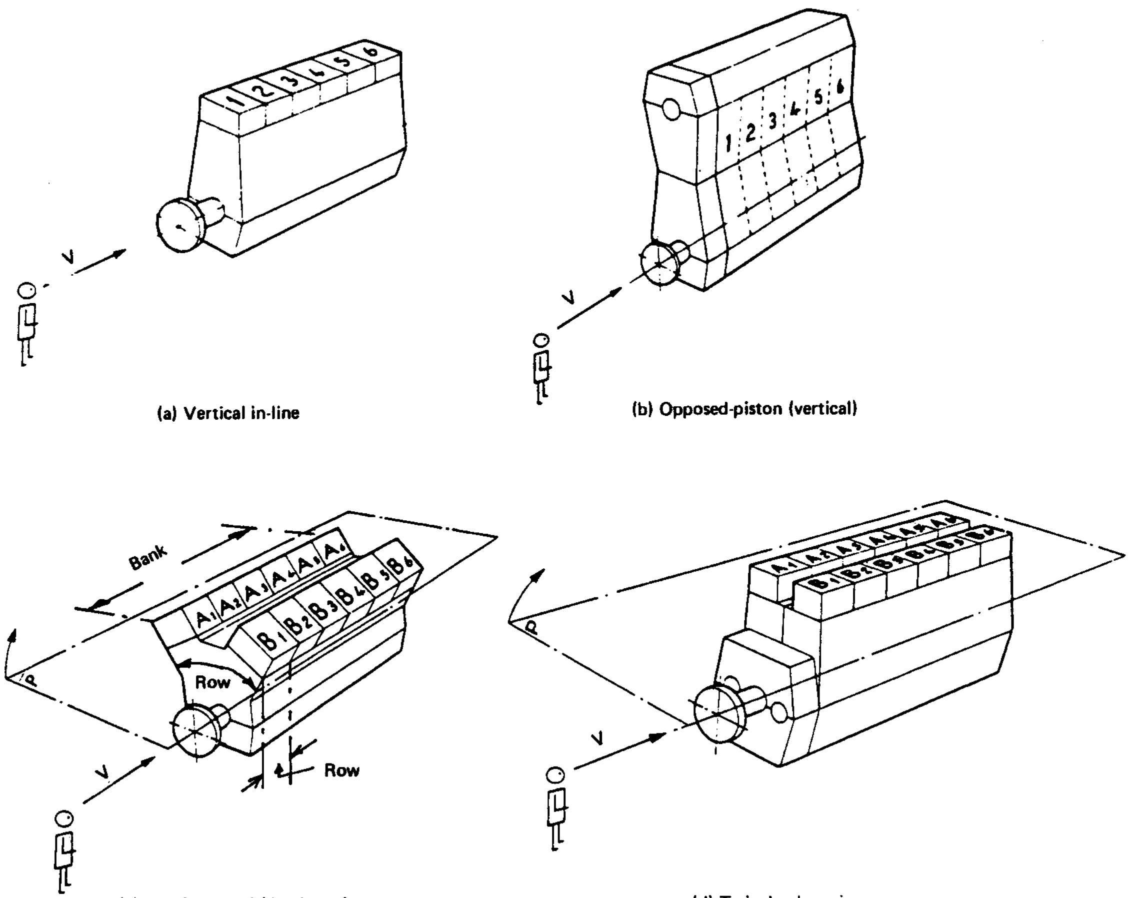
The cylinders in each row of the bank are numbered in the same way as for a single-bank engine, i.e. starting with 1, from the row nearest the observer. A row is defined as a group of cylinders arranged in a common plane at right angles to the axis of the crankshaft; so that cylinders having similar numbers form a row. For example, A 1 and B 1 are in one row, and A 6 and B 6 are in another (see Figure 1.7). In the case of the twin-bank engine, the axis of rotation of the semi-plane is the central line between the two crankshafts (the line coinciding with the arrow V in Figure 1.7).

The direction of crankshaft rotation does not affect the cylinder designations. Cylinders should be marked with their letters and numbers.

Single-bank engines are also said to be *'handed'*. Handing is determined by the location of the exhaust pipes on the side of an engine - referred to the observer's position. Thus, a right-hand, single-bank engine would be one whose exhaust pipes are located to the right of the plane which contains the cylinder centres, as viewed from the observer's position. See the illustrations in Figure 1.8, reproduced from the related British Standard BS 5675: 1979 (ISO 2276: 1972). Note, that the handing definitions only apply where the location of the exhaust pipes is on one side of the engine.

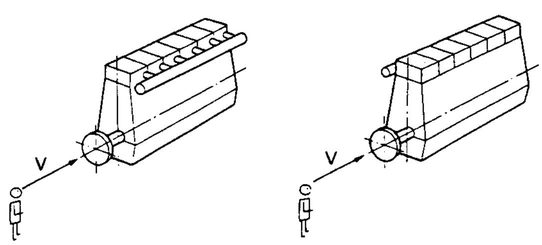
## 1.6 Fuels and operating modes

In its compression-ignition (c.i.) form, using fuel injection equipment, the RIC engine may be run either as a straight diesel or as a dual-fuel engine.




(a) Vertical in-line
(b) Opposed-piston (vertical)
(c) Vee form multi-bank engine
(d) Twin-bank engine

**Figure 1.7** Cylinder designation to BS 5673 (ISO 1205)
[Courtesy: British Standards Institution]




Right-hand single bank engine
Left-hand single bank engine

**Figure 1.8** The handing of engines to BS 5675 (ISO 2276)
[Courtesy: British Standards Institution]

Choice of fuel, in the first mode of operation, depends on:

1. engine design;
2. the fuels selected in development; and
3. engine usage.

Liquid fuels range from a distillate (gas oil) through to heavy residual oils. See Chapter 12. High speed engines traditionally operated on gas oil. Medium speed engines are designed to accept the heavier distillate fuels; and some can run on blends of distillate and residual fuels. Those that have any history of marine use also run satisfactorily on heavy residual oils [9].

In terms of usage, a low speed engine, required to operate in a remote area, may run quite economically on a distillate fuel. This avoids the costs of specially heated storage and of delivery vehicles for heavy residual fuel. Also, it would be advantageous if medium speed engines, driving marine auxiliary generators, were capable of operating on the heavy residual fuel used in the ship's main propulsion engines [9].

Engines operating in the dual-fuel mode use a mixture of gas and air which is ignited in the cylinders by the injection of a small pilot charge of liquid distillate fuel. Pilot fuel consumption is between 5 and 10% of the normal full-load quantity required for straight diesel operation. It remains fairly constant throughout the load range; unless there is a gas shortage, in which case, any input energy shortfall is made up by an increase in the liquid fuel injected. Should the gas supply fail at any time, or become inadequate for the load demanded, the engine automatically reverts to the straight diesel mode. Because of the need to modulate both oil and gas flows, the control and protection system is more complex than that for straight diesel or gas engines. The engine may be switched, at any load, from dual-fuel to liquid fuel operation; and vice versa. The same output rating must therefore be selected for both modes of operation [3].

In its spark-ignition (s.i.) form, the RIC engine, which is generally a 'converted' diesel engine, may operate on a wide variety of gaseous fuels. These may include well-head gas, natural gas, as distributed by National Utilities, bio-gas produced in digesters at sewage works and landfill sites, and the paraffin series gases, such as propane. See Chapter 12.

The largest petrol engines, which can be converted to gas operation, have a capacity below 1 litre per cylinder swept volume. It is for this reason that gas engines, above that capacity, are based on diesel engines converted from the c.i. cycle [10]. The gross continuous output of such engines is about 60% of that which would be available from them in their compression-ignition form.

Compression ratios (see Chapter 2) may range from 7.5 to 12.5, depending upon the fuel quality. High-voltage ignition systems are employed, using robust, shielded, 'industrial' type spark plugs placed in the cylinder heads - normally where the fuel oil nozzles would be sited for c.i. operation. A feature of these plugs is that they have a number of ground electrodes. As erosion takes place, more metal can wear away before the spark gap becomes excessive. This gives them a life of about 1600 hours [10].

Air flow control is more important on s.i. engines, since an electric spark is not as good an 'ignitor' as a spray of burning oil. Various forms of gas/air proportioning are employed to keep the mixture ratio within close limits. They may range from single mixing valves to individual air-throttling valves on each cylinder. Perhaps the simplest device used on high-speed engines is the carburettor.

*(Note:* the term *stoichiometric mixture* is used to define the, theoretically, correct air-to-fuel ratio. It is that mixture which yields, on reaction, a stoichiometric compound. For example: two molecules of hydrogen and one of oxygen, yield two molecules of water on combustion [11])

Speed control is then achieved by a governor operating on the butterfly within the carburettor; and affecting control of the gas/air mixture admitted to the cylinders. Governor choice depends upon the degree of control required; and upon the generator's application. See Sub-section 1.7.2.

Because the carburettor's butterfly is at the inlet to the air induction manifold (which is usually large enough to hold a sufficient mixture for two revolutions of the engine crankshaft), there is an inherent delay in governor response [10]. Generally speaking, response characteristics on gas engines are not as good as those on diesel engines, given the same governor system.

RIC engines may be designed to incorporate both c.i. and s.i. systems to give operation on either liquid or gaseous fuels. They are known as *alternative-fuel* engines. More often than not, change to either type of fuel requires engine stoppage. Conversion operations may take several hours. Some engines, however, have link mechanisms, which disconnect the liquid fuel pump drive and close the air intake; whilst, simultaneously, energizing the electrical ignition and turning on the gas input. Changeover is then possible with the engine running - much as in the dual-fuel mode described earlier. Again, it must be appreciated that output rating will vary with the type of fuel used; it will be lower for gas operation.

The fuel gas composition and a complete analysis of the constituents of any gas proposed for either dual-fuel, straight gas, or alternative-fuel operation is mandatory for checking its suitability for use. A fuel analysis also allows the engine manufacturer to evaluate the performance of his engine. For example, the presence of inert gases in the fuel will have the effect of reducing the power output rating of the engine [10].

## 1.7 Engine features

It is not intended to describe the technicalities of engine construction in any detail. The conventional principles are to be found in the many textbooks that specialize in the subject. Some of these are listed in the references and bibliography at the end of this chapter. In any event, construction detail varies from one engine type to the next and manufacturers' instruction manuals must be the appropriate source for information.

Instead, we shall only consider certain distinguishing features. The intention, in so doing, is to give the reader a clear picture of the terms used; and the criteria for selection of equipment to match needs.

### 1.7.1 Primary systems

#### *Fuel injection*

Most modern RIC engines have a mechanical or airless fuel injection system embodying *jerk pumps.* Low and medium speed engines tend to use individual camshaft-actuated pumps for each cylinder. Higher speed engines employ distribution type, *block pumps* (within which all the jerk pump elements are incorporated) driven from a self-contained camshaft. This, in turn, is coupled to an auxiliary drive from the engine.

Certain two-stroke engines use the *common rail system,* wherein fuel is maintained at a constant pressure by a pump and a hydraulic accumulator. A fuel valve at each cylinder, driven and timed from the main camshaft, then delivers the fuel to the engme.

The *injector,* the device which delivers the fuel (by finely divided spray) into the combustion space, is in essence a spring-loaded needle valve, whose tip covers the injector *nozzle* hole(s). The number of holes, their angles, and the angle of spray are largely dependent upon the shape of the combustion chamber. Since fuel systems must have small passages and nozzle holes, it is very important that the fuel within them is well filtered.

## *Combustion chambers*

These are basically of two types: those designed for *indirect injection;* and those for *direct injection.*

The former employ *pre-combustion* chambers in the cylinder head, into which a relatively coarse, low pressure fuel spray is injected. Subdivided chambers of this type include the so-called *antechamber,* the *swirl* and *turbulence* chamber, and the *air cell* chamber. They are favoured by European and American engine manufacturers and have the advantage of being able to successfully handle a wide range of fuels. When required to operate over a broad band of environmental conditions, they compare 4nfavourably with direct-injection chambers, on fuel consumption. Also, since heat loss from the pre-combustion chamber is high, cold starting can be difficult without prolonged cranking, or without recourse to some form of external heating.

In direct-injection systems the underside of the cylinder head is usually flat; and the clearance volume (see Chapter 2) on compression is mainly contained within the piston crown. Crown depressions are so shaped as to effectively induce swirled air turbulence as the piston rises on its compression stroke. Fuel is then injected in the same direction as this flow of swirling air. Many different bowl shapes have been employed. The most popular now appear to be the simple toroidal shape (for high-swirl engines); and the wider and shallower *quiescent chamber* for low-swirl engines. As the latter's description implies, it is one in which there is the minimum air motion. Reliance is then placed on multi-hole nozzles to give fuel distribution. The quiescent chamber is particularly well suited to cooling by undercrown oil jets; and by oil galleries in the piston crown [12]. The direct-injection principle is almost universally employed in modern medium speed and high-speed engines.

Small-bore engines tend to have lower thermal efficiencies (see Chapter 2) because their high 'surface-area/cylinder-volume' ratios give larger heat losses. Again, the greater heat losses from the larger exposed surfaces of indirect-injection systems means that they give lower thermal efficiencies than direct-injection ones. For these reasons, small indirect-injection engines may have thermal efficiencies as low as 28 %; whilst larger engines, particularly those using direct-injection techniques, may have efficiencies as high as 43 %.

## *Induction*

The induction system of an engine is designed to provide the air required for fuel combustion. Also, air must be available for scavenging spent gases from the cylinders of two-stroke engines. The system should be designed to supply clean air to the engine at, or as near, ambient temperature as is possible and with the minimum of restriction. The quantity of air supplied has a direct bearing upon an engine's output and its fuel consumption.

Engine makers stipulate the maximum permissible total restriction at induction manifold or turbocharger inlet. The induction system's total restriction is made up of that due to:

- air filtration restriction;
- the resistance to air flow due to intake pipe friction;
- the velocity effects.

Intake pipework should be as short and as straight as possible. Any bends in the system should be kept to a minimum and should have long sweeps. The objective must be to minimize the resistance to air flow. Also, reliable sealing must be provided in the piping and associated fittings.

While the velocity effects may be relatively low for naturally-aspirated engines, they can be substantial in the case of turbocharged engines. A higher total inlet restriction is therefore normally allowed for turbocharged engines, but this does not affect the restriction allowable across the air filter [13]. Turbochargers tend to 'pull' oil on high air intake depressions.

Filtration of intake air is necessary in dusty environments because solid particles have an abrasive effect on internal surfaces (such as piston rings and cylinders) and shorten the service life of an engine. Choice of filter depends upon the installed plant's environment and the service life required. Engine maker's recommendations should be sought and observed.

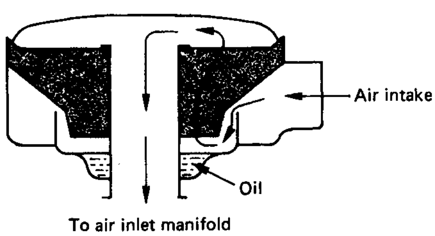
Duty categories in which the various types of filters may be applied are as follows:

1. Normal duty for plant installed in sheltered and low dust-concentration conditions: either oil bath or dry type filters - both without pre-cleaner stages.
2. Medium duty for installations in temperate, relatively dry, and moderately dusty conditions:

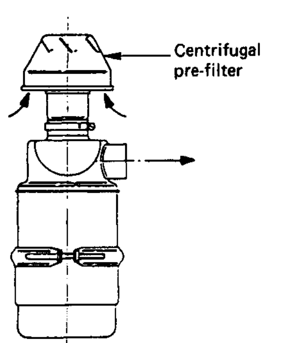
oil bath or dry element filters with centrifugal pre-cleaner stages, and with greater dust holding capacity than those in (1).
3. Heavy duty for severe dust-concentration applications, or where regular maintenance is not possible: heavy duty, dry element filters, with highly efficient (90--95%) centrifugal pre-cleaner stages; and, preferably, with self-emptying or dust unloading arrangements. Filters of this type may include safety elements as an optional feature. Their purpose is to protect the engine in the event of main element perforation, or to act as temporary substitutes when the main elements are being serviced.

A normal duty oil bath air filter consists of a steel wool packing within a sheet metal housing, which also contains an oil bath in its base (see Figure 1.9). The fast-moving intake air is first drawn across the oil bath. Any heavy impurities in the air are removed by the oil, which is usually of the same grade and viscosity as the engine lubricant. Final cleaning of the now oil-laden air takes place within the steel wool mesh, which is always covered with a fine oil mist.

Medium duty units work in much the same way, but have a larger stack of steel wool; and are usually




(a) Normal (light) duty type — engine mounted




(b) Medium duty type — remote mounted

**Figure 1.9** Oil bath air filters

of the remote-mounting type. They are fitted with centrifugal pre-filters, which eject the larger dust particles from the air before it is passed down a central tube to the oil bath. See Figure t.9(b).

Oil bath filters are matched to suit engine type and operating speed. Incorrect matching will give poor filtration efficiency, and/or oil *carry-over (pull-over)* from the filter into the engine. Carry-over limits (to about 15°) the angle of inclination at which the filter can be operated.

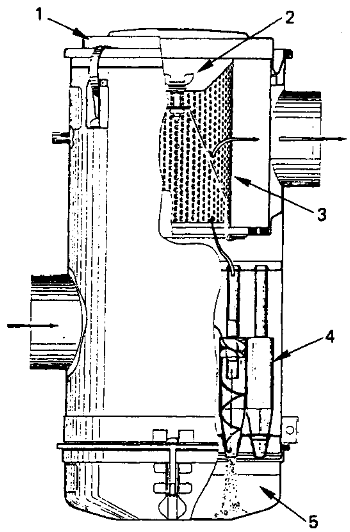
Dry type filters clean the intake air by passing it through a fibrous element. Modern paper elements must have a sufficiently large area to ensure that the pressure drop across them does not exceed permitted values. They must also have sufficient space for a large number of dust particles in order to remain active for prolonged periods. Kates and Luck [4] have computed that the dust entering a 300 bhp, two-stroke, crankcase-scavenged engine, running 9 hours a day for 250 days in an air environment which has 1.2 grains of dust per 28.3 $m^3$ (1000 cu ft), would be 12.35 kg (27 Ib). Haggh [14] suggests that the element area should be at least 0.5 $m^2$ for each cubic metre of air per minute passing through the filter. On this basis, he calculates that a 257 kW turbocharged engine drawing 21 $m^3$ of air per minute would require a filter with an area of at least 0.04 $m^2$ per kW.

Medium and heavy duty filters usually employ pre-cleaners as primary filters, in a two-stage operation. In particularly dusty environments, filter capacity may be increased by automatic dust evacuation. Proprietary units are shown in Figure 1.10.

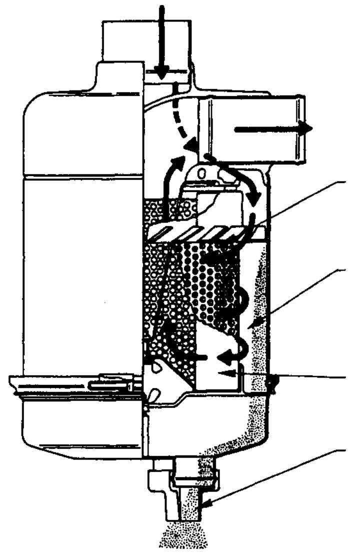
In the Donaldson *Donae/one* filter (Figure 1.lO(a)) air enters the cleaner body at the centrifuge assembly (4); and the heavier dust particles are deposited in the bowl (5). The air then passes up the centrifuge tube bores to the inside of the filter element (3); and through the element to the engine. The level of dust in the bowl must never be nearer than 25 mm to the bottom of the centrifuge tubes.

The Cooper/Donaldson *Cye/opac* (Figure 1.lO(b)) is also of the two-stage type; and uses a centrifugal type pre-filter. The dust bowl may be emptied by means of an automatic valve. It is a rubber valve (called a *vactuator)* which is operated by the pulsating, induced air flow.

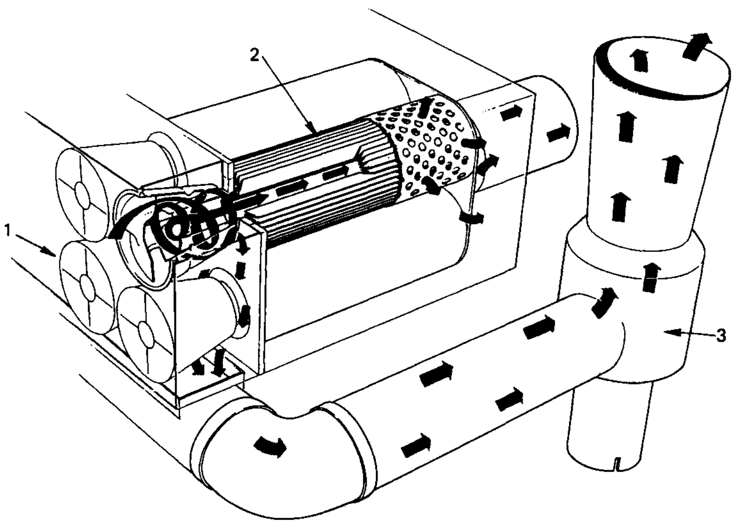
The Farr *Rotopamic* air cleaner of Figure 1.1O(c) uses an exhaust-assisted arrangement to evacuate dust from the pre-filter stage. The casing contains a number of paper filter cartridges (2) sealed to a pvc face plate. The cartridge assembly is retained by a pre-cleaner panel (1) clamped to the casing. The inner face of this pre-cleaner is perforated with fixed fan-type deflectors, each of which is concentric with a filter cartridge. Air entering the pre-cleaner spins the deflectors so that the dust is centrifuged to the walls of the primary tube. About 10% of the air and




(a) The Donaldson 'Donaclone' two-stage filter




(b) The Donaldson 'Cyclopac' two-stage filter




(c) The Farr 'Rotopanic' two-stage air cleaner

**Figure 1.10** Examples of medium and heavy duty dry type air filters (Courtesy: Donaldson Filter Components Ltd. and Farr Filtration Ltd.)

90 % of the dust enters the self-cleaning bin which is connected, by metal hose, to an aspirator (3) installed at the engine's exhaust system outlet. The remainder (90 %) of the air passes through the filter cartridges to the engine. The aspirator, which produces a drop in pressure by venturi effect, assists in the efficient evacuation of dust from the pre-cleaner stage.

It is good practice to fit air restriction (pressure drop) indicators to all dry type filters, to warn when the elements have reached a preset limit of fouling. They are connected to the 'clean air' side of the filter and are therefore sensitive to the restriction caused by its element(s). They contain optical signal devices (such as red sleeves) to alert attendant staff when a predetermined pressure drop has been exceeded.

*Lubrication*

The lubricant in an engine performs many tasks. Among the more important are:

1. the reduction of friction, and therefore wear, in all rotating and rubbing surfaces within the engine;
2. the provision of cooling - either undercrown and/or in piston ring areas;
3. the cleaning and flushing of impurities;
4. the absorption of shock and impacts between bearings and other engine parts; and
5. piston cooling - using oil chambers, galleries or ducts under the crown.

Also, it affords a seal between piston rings and cylinder walls to reduce the seepage of gas that passes from the combustion chamber into the crankcase. The chief properties of lubricating oils are discussed in Chapter 12.

Most engines use a pressurized (or force-fed) system to circulate the lubricant from an external drain tank or from a sump in the base of the crankcase. The main components of any system are:

1. the circulating pump, which may be of the gear or the multi-lobed rotor type;
2. a pressure relief valve, to maintain constant pressure in the system;
3. oil filter(s), in combinations of full-flow and partial-flow types; and
4. a heat exchanger fitted between the feed pump and the filters.

Deliverr pressure is normally in the range 0.5 to 2 kg/cm , but it may be as much as 5 kg/cm$^2$ in high speed engines.

Two pumps are employed in the so-called *dry sump* system. Oil that has circulated through the engine oilways returns by gravity to the crankcase pan. The task of the first (scavenger) pump is to transfer this oil from the pan to a reservoir tank external to the engine. The second (pressure) pump draws oil from this tank and delivers it through the heat exchanger and filters to the bearings, etc.

The arrangement, mainly used on higher speed engines, in which the crankcase oil pan is in itself the reservoir is known as a *wet sump* system. See Figure 1.11.

A *semi-wet sump* system, combining the basic elements of both wet and dry sump schemes, is sometimes used on engines for marine and off-shore applications, where generators are required to operate in an emergency at specified angles of roll and pitch. It is important that the oil suction inlet always remains submerged under these conditions. This is done by providing a deep pannier at one end

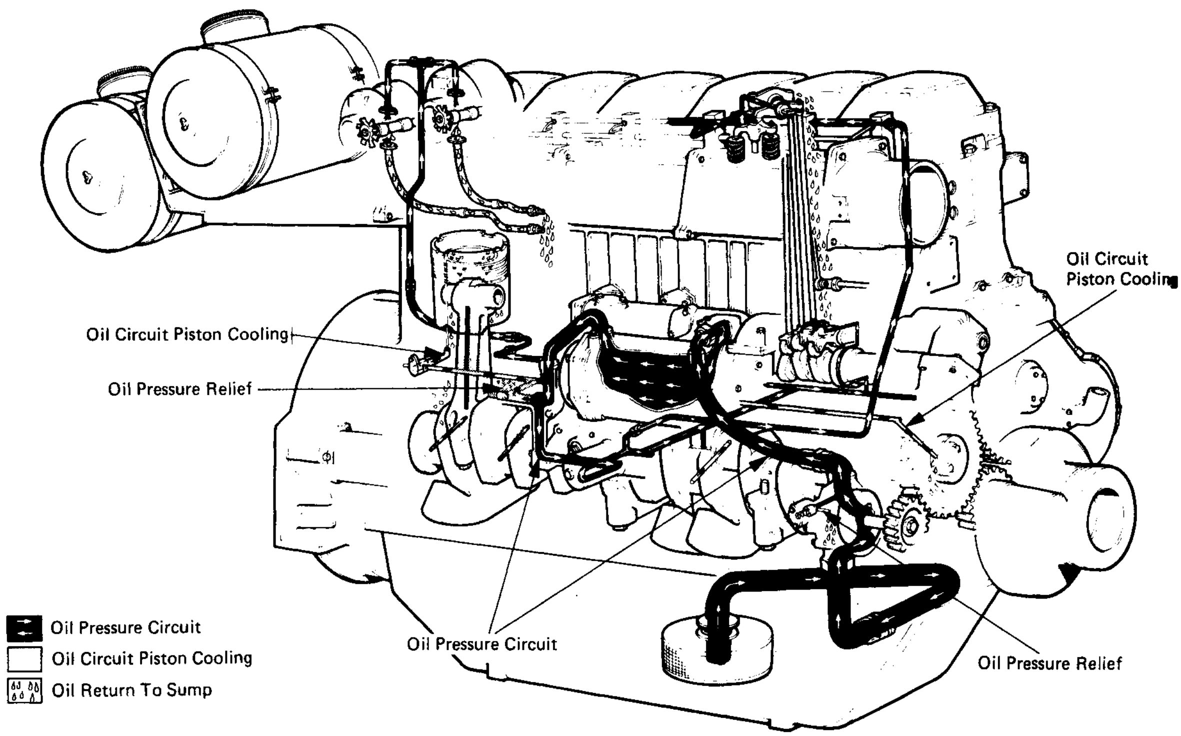



**Figure 1.11** Lubricating oil diagram for a 6-cylinder, turbocharged, charge cooled, high speed engine [Courtesy: Dorman Diesels Ltd.]

of the sump, from which the pressure pump supply is drawn. The scavenge pump, driven in tandem with the pressure pump, draws its oil from the shallow end of the sump pan and discharges it into the panmer.

Probably the most severe cylinder wear conditions occur just after an engine has started, and when piston lubrication is at its poorest. For this reason, pre-priming systems are incorporated into low-speed engines, and higher-rated medium-speed engines.

It is also advisable to use periodic priming of lubricant on the larger high-speed engines, when these are operating in an automatic standby mode. Oil, fed from a separate electric-motor-driven pump, is circulated at periodic intervals through the oilways to flush the liners and generally wet the engine moving parts in readiness for an automatic start. Periodic priming also has the advantage of reducing the severe wear that can occur on cylinders as a result of condensed combustion products, when an engine is at standstill.

## *Cooling*

Between one-third and one-half of the heat energy provided by the fuel burned in an engine is converted into mechanical energy. The rest is expended in:

1. exhaust gases;
2. friction in the rubbing surfaces of the engine parts; and
3. the combustion chambers, the cylinder assemblies and the pistons.

The cooling system's function is to remove the unwanted heat from these parts, in order to prevent [3]:

1. overheating and subsequent breakdown of lubricant films;
2. overheating and loss of material strength; and
3. excessive stresses within or between engine parts, due to unequal temperatures.

Engines may be either *air-cooled* or *water-cooled.* Piston cooling is by oil. Various methods are used. The simplest form employs an oil jet, from the small-end bearing in the connecting rod, splashed against the underside of the piston. Another method is to provide an oil gallery or duct under the piston crown. Whilst very low output engines may not require separate oil-to-air lubricating oil heat exchangers, they are standard features on larger engines.

Air-cooling is satisfactorily applied to high speed engines up to 400 $kW_m$. Air is drawn into an impeller (which may be secured to the engine flywheel, or vee-belt driven from the crankshaft) and discharged through shrouding across the finned external surfaces of the cylinder and cylinder heads. The design of air-cooled engines is largely determined by their 'unit cylinder' construction. The rest of the engine design follows from this [15].

Good installation of air-cooled engines is critical, especially in high ambient conditions and in confined spaces. Care must be taken with the design and application of air intake, and hot air outlet ducting, to avoid the possibility of hot discharged air being re-circulated within the generator housing. See also Chapter 13.

In water-cooled engines, the liquid coolant is circulated through jackets around the cylinder walls, and through passages in the cylinder heads. Systems may be classified as being either of the *open* type or of the *closed* type. In the open system, water leaving the engine is not returned to it or, if it is, it is exposed to atmospheric air before being re-circulated. Typical arrangements are shown diagrammatically in Figure 1.12.

Where direct water cooling is used (Figure 1.12(a», the quality of the water has an important bearing on the life of the engine. Most natural water, such as that from rivers, lakes, reservoirs, and ponds, carries scale-forming impurities. At the high temperatures obtaining in cylinder jackets, the dissolved minerals separate out in solid form and coat the metal surfaces. These scale deposits reduce the rate of heat transfer from the combustion space into the jackets. The result is that the metals are subjected to higher temperatures and local overheating may cause cracks and failures [4].

Where sea water is used for direct cooling, salts are deposited in the engine waterways if the water temperature is raised above 55°C. The penalty for operating at this temperature (engines normally run at twice this level) is likely to be increased liner and ring wear due to condensation of the acid products

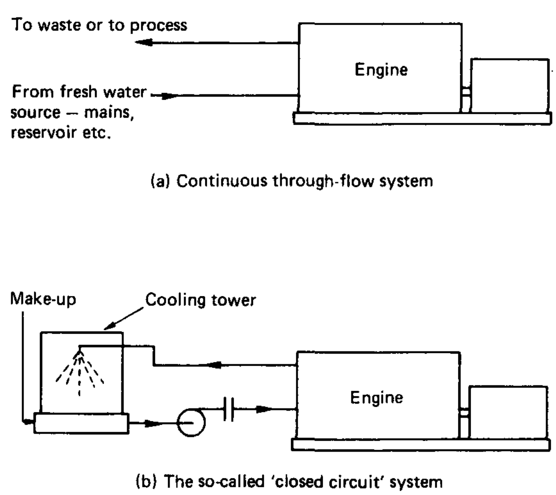



**Figure 1.12** Alternative open-cooling systems

of combustion, and perhaps a small increase in fuel consumption as a result of thicker oil on the cylinder liners [16].

The problems associated with scaling due to water impurity also exist with the cooling tower (or spray pond) scheme shown in Figure 1.12(b). This is because the make-up water required to replace losses due to evaporation brings additional impurities with it. Since the vapour in the tower does not carry away the impurities, these concentrate and may eventually deposit more scale than if the water had been run to waste [4]. See Figure 1.12(a). Open systems may only be safely used where there is an ample water supply of exceptional purity.

Where engines are required to run continuously for long periods, the better method is to use treated water circulating in *closed* circuit, and to transfer the engine heat to a heat exchanger. This means that the engine coolant is never exposed to air and remains in the system indefinitely. Several schemes may be used. Some are shown in Figure 1.13. Thermostatic elements are incorporated within the closed circuit to by-pass the 'heat exchanger' when starting from cold, so as to allow the engine to attain its operating temperature more quickly.

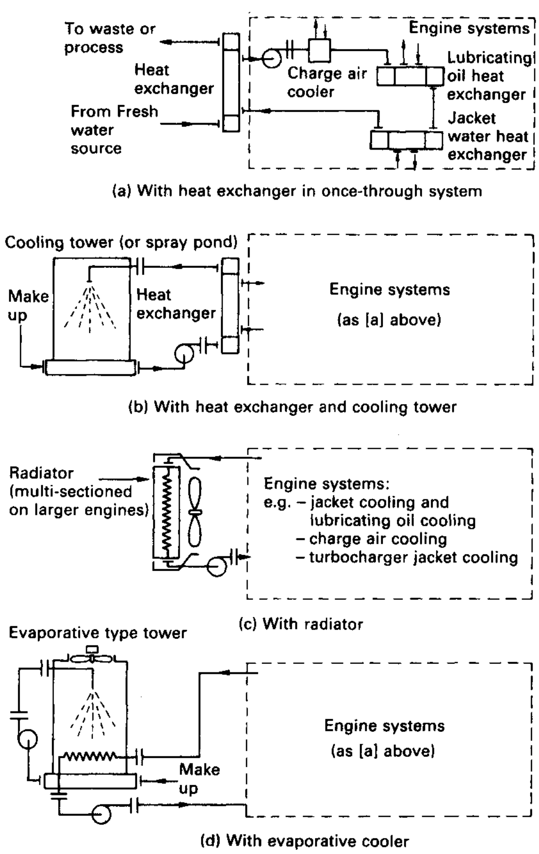


**Figure 1.13** Typical closed-circuit cooling arrangements

The water-to-water heat exchangers used in the first two schemes are of the shell-and-tube type. Where an unlimited supply is available, the so-called *raw* water may be passed through the tubes of the heat exchanger to waste; or to some process from which it is not returned (Figure 1.13(a)). This is known as a *'once-through'* system. Heat exchangers are not as seriously affected by scale deposits as are engine waterways. The raw water should be passed through the tubes of the heat exchanger, because the inside of the tube can be cleaned more easily than the outside [4]. Pre-knowledge of the character and quality of the water is necessary to ensure correct selection of materials for the tubes.

The system most often employed is that shown in Figure 1.13(c), which uses a fan-cooled radiator. The radiator may either be mounted on the same baseframe as its engine-generator assembly, or it may be remote-mounted. Set-mounted types usually have engine-driven cooling fans, whilst remote units incorporate single or multiple fans driven by electric motors. Single- or double-sectioned radiators are employed, on small- or medium-sized engines. Multi-sectioned units may be used on larger engines, to provide separate circuits for engine (and turbocharger) jacket water, lubricating oil, and charge air cooling.

The cooler (or wet-type tower) of Figure 1.13(d) uses evaporative cooling. Its coils, which form a water-to-water heat exchanger for the engine's closed circuit, have a large surface area. Evaporation of the secondary cooling water is then achieved by either producing water droplets (by spray), or by forming thin films. A motor driven fan pulls the air through the top of the tower, or forces it from the bottom. The draught so created removes the evaporated water molecules. Because there will be roughly 2% loss of water through evaporation, make-up facilities must be provided. Special precautions are necessary in order to reduce the risk of legionellae (Legionnaires' disease). See Sub-section 15.4.4 of Chapter 15.

Since most modern medium- and high-speed engines are designed for high-temperature coolant conditions, they employ pressurized closed circuit cooling systems. System pressures may vary from 0.3-0.7 $kg/cm^2$. These equate to water boiling points at sea level of 107°C and 115°C, respectively. Engine makers would then design for corresponding operating temperatures at engine outlet of 80°C and 90°C.

Whatever the system, it is always advisable to use a high rate of jacket circulation, with a small temperature difference between engine inlet and outlet, rather than a slow circulation and a large temperature rise.

It is perhaps more appropriate to use the term 'coolant' rather than water, when describing the cooling medium in water-cooled engines. This is because engine makers specify formulations of clean fresh water and approved rust and corrosion inhibitors. They do not recommend the use of plain tap, well, distilled or deionized water as engine coolants. The inhibitors are gradually consumed in service. If the pH value of the coolant should fall outside a specified range, it is necessary to add inhibitor(s) - to the same specification as those already in use. Likewise, coolant for topping-up purposes must be to the same formulation and strength as that in the engine.

### *Pressure charging*

We shall establish, in later discussions (see Chapter 2), that the density of the air entering the cylinders has a significant bearing upon the power that can be developed by an engine. This is because the air's density regulates the amount of fuel that can be burned within the cylinder during the power stroke.

The working cylinder in a *naturally-aspirated* engine is charged (not fully) with fresh air at atmospheric temperature and pressure, at the end of its induction stroke. In practice, when the piston sucks in air a partial vacuum is created so that not even atmospheric pressure obtains in the cylinder. Also, the incoming air is diluted and warmed by residual exhaust gases in the cylinder. At high altitudes, where air pressure is low, and at locations with high ambient temperatures, the engine's power rating must be reduced to compensate for atmospheric variations (see Chapter 2).

If a compressor is employed to supply the engine with intake air at a pressure higher than atmospheric, the engine's mean effective pressure (and therefore its power output) may be increased without altering crankshaft speed or cylinder volume. This, effectively, is what pressure charging does. *[Note:* mean effective pressure is defined in Subsection 2.3.4 of Chapter 2.]

There are two basic ways of pressure charging an engine. They are distinguished by the method used to drive the compressor:

1. supercharging: where the compressor is mechanically driven from the crankshaft, either by chain or by gearing; or
2. turbocharging: where the compressor is driven by a gas turbine which, in turn, is driven by the exhaust gases from the engine.

Most of the compressors used in supercharging are of the 'positive displacement' rotary type. Those of the *Roots* type employ two impellers (or rotors), whose shafts are in parallel; and rotate in opposite directions within the compressor housing. Each impeller has two or three vanes (or lobes) which mesh with those on the other impeller - in much the same way as gear teeth. The action of the 'compressor' is then similar to that of a gear pump. In truth, it is not a compressor, but simply an 'air displacer'. Nowadays, supercharging is confined to small high speed engines of the type used in cars and passenger vehicles, but, even in that market, turbocharging is being developed to meet the demands for more rapid boost response and better boost levels at low speed [17].

Turbocharging makes use of energy already available in the exhaust gases (about 35 % of the total heat energy in the fuel is wasted in these gases); whereas supercharging deprives the engine of a portion of its shaft output.

.The t~rbocharger basically consists of a gas turbme, dnven by the exhaust gas flow, mounted on a common spindle with a *blower* or compressor; and placed in the air intake path. The power generated in the turbine must be equal to that required by the compressor. Figure 1.14 illustrates, in schematic form, the application of the turbocharger to a four-stroke engine.

Turbocharger designs vary from the simple types used on high speed engines to those employed on large medium- and slow-speed engines. The former types employ single-stage radial flow centrifugal compressors and radial flow turbines mounted on a common shaft with an inboard bearing system, (see Figure 1.15). Designs for the latter types vary considerably from one manufacturer to another. Typically, they include single-stage radial flow compressors, which may be of two-piece construction, and water-cooled axial flow turbines.

There has been a trend towards non-cooled (or air cooled) turbines, as a means of promoting higher gas exit temperatures for waste heat recovery systems [6]. Lubrication is self-contained and separate oil supplies are used for turbocharger and engine bearing systems [18].

Two turbocharging arrangements are generally used on engines for electrical power generation:

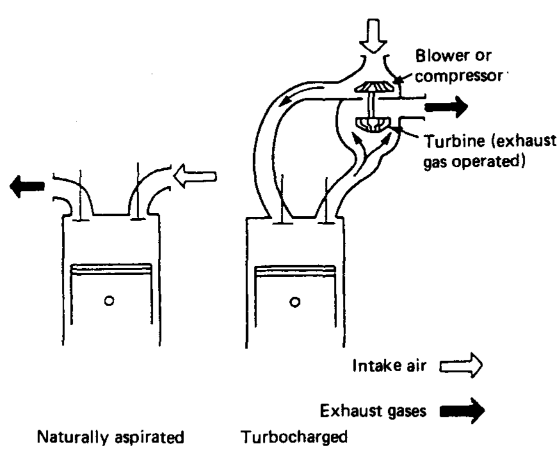
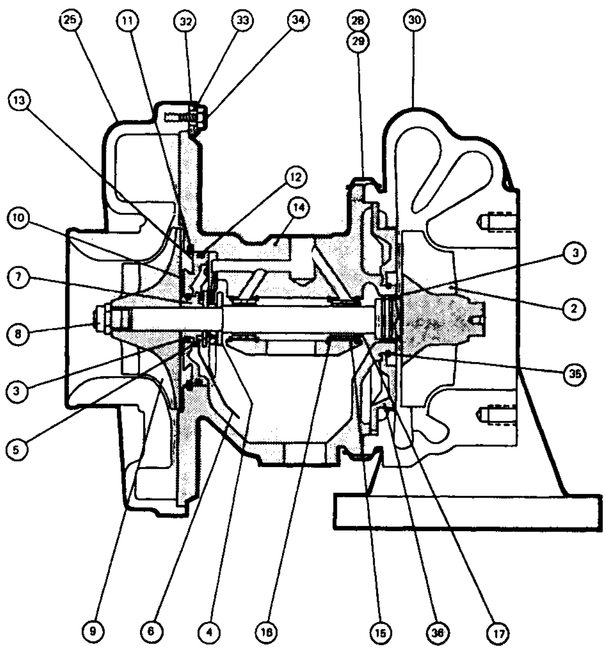



**Figure 1.14** Four-stroke engine with exhaust gas-operated turbocharger




| Item no. | Name of part |
|---|---|
| 1 | Core assembly |
| 2 | Shaft and turbo wheel assembly |
| 3 | Piston ring |
| 4 | Thrust ring |
| 5 | Spacer |
| 6 | Oil deflector |
| 7 | Finger sleeve |
| 8 | Lock nut |
| 9 | Compressor wheel |
| 10 | Insert |
| 11 | Retaining ring |
| 12 | '0' ring (insert) |
| 13 | Thrust bearing |
| 14 | 8earing housing assembly |
| 15 | Bearing |
| 16 | Snap ring |
| 17 | Oil control sleeve |
| 18 | Oil inlet gasket |
| 19 | Oil drain gasket |
| 20 | Serial nameplate |
| 21 | Self tapping screw |
| 22 | Warning tag - oil |
| 25 | Compressor cover |
| 28 | Locknut ('V' clamp) |
| 29 | 'V' clamp |
| 30 | Turbine housing |
| 31 | Turbine inlet gasket |
| 32 | Washer |
| 33 | Lockwasher |
| 34 | Setscrew |
| 35 | Retaining ring |
| 36 | Turbine back plate |

**Figure 1.15** Sectional view of Holset 4LEV turbocharger (Courtesy: Holset Engineering Ltd.)

1. the *pulse* (or Buchi) system; and
2. the *constant pressure* system.

*Pulse turbocharging* The pulse system was the first to be developed and the majority of engines use it today in one or other form - derived from the original 'pure impulse' concept [6]. It makes direct use of the high velocity of gas surging from each cylinder when its exhaust valves open. These pulsating gases flow through carefully-designed manifold pipes to the exhaust turbine of the turbocharger. Two (or more) separate exhaust manifolds are used on multi-cylinder engines to prevent the exhaust pulse of one cylinder blowing back into another which is being 'exhausted'. Two or three cylinders are usually arranged to exhaust into each manifold.

The turbine has several inlet openings. Each is connected to corresponding nozzle ring segments which deflect the exhaust gases into the turbine wheel. It is important that there is significant overlap between the opening times of inlet and exhaust valves, after pulse decay. This requirement is vital for the efficient scavenging of two-stroke engines [6]. The pulse system is the most effective arrangement for standby generator applications where rapid run-up to operating speed and minimum speed variations on load-step changes are required [121.

*Constant pressure turbocharging* In the constant pressure system, all the engine's cylinders exhaust into one large manifold in order to minimize the pressure pulses and absorb their energy. Near steady-state and constant pressure conditions then obtain at the turbine wheel. Engines rated above 14 bar bmep (brake mean effective pressure) now use this system for power generation, and high load demand [19]. Its main advantages are:

1. it eliminates the complication of the multiple exhaust pipe arrangements of the pulse system;
2. it permits greater flexiblity in positioning the turbocharger relative to the engine; and
3. it leads to higher turbine efficiencies and hence improved specific fuel consumptions.

Militating against these advantages is the relatively poor performance of the system at part load conditions and during large load-step changes [6].

Two-stroke engines usually employ constant pressure turbocharging. Because it is difficult to obtain a self-sustained air supply to the engine over its whole speed range, some supplementary assistance is required [6]. One method is to use the engine's scavenging pump (or blower) in series, or in parallel, with the turbocharger. Atmospheric air drawn into, and compressed by, the scavenging pump is passed to the turbocharger, where it is pressurized.

Thus, at light loads, where there is insufficient energy in the exhaust gases to drive the turbocharger at the speed required for the necessary air flow, the scavenging pump alone puts air into the cylinders. Then, as engine load increases, the pump is unloaded and the turbocharger provides both scavenging and pressure-charged air to the cylinders.

Another scheme makes use of a separate compressed air supply - such as that which is provided for engine starting. Compressed air is fed, on starting, to the turbocharger to get it going. The jets of air may be fed either to the gas turbine or to the compressor wheel. In the latter case, the air passes into the engine cylinders and directly assists the scavenging process. This system is known as *jet air starting [4].*

*Charge air cooling* The full potential of the increase in air inlet density by pressure charging is marginally offset by an increase in air temperature arising from adiabatic compression in the turboblower. This loss is recoverable by the use of charge air coolers *(intercoolers)* placed downstream of the turboblower, which have the effect of increasing the charge air density. This allows more fuel to be injected into the cylinder, so raising the engine's power output. The lower air intake temperature has the further effect of reducing not only the maximum cylinder pressure but also the exhaust temperature, and with it, the engine's thermal loading. Another spin-off is a reduction in nitrogen oxide (NOx) emissions. Increase in engine power over a straight turbocharged model is usually of the order 20 to 25 %, and thermal efficiencies (see Section 2.3.2 of Chapter 2) of over 40 % are obtainable.

Charge air coolers are heat exchangers in which the heat transfer medium may be either water or air. Some typical schemes are shown in Figure 1.16.

Air-to-water systems may use the engine's jacket water (the commonest form of intercooler - Figure 1.16(a», or a separate source of water. The first method offers the simplest installation but cooling is limited by the high water temperature. Where a separate water supply is used, one has the choice of:

1. raw water - given that adequate quantities, at an acceptable temperature, are available, e.g. for marine applications (Figure 1.16(b»; or
2. a closed circuit with its own water-to-air section incorporated within the radiator, which cools the engine's jacket water (Figure 1.16(c».

Figure 1.16(d) shows an air-to-air charge cooling system, which may be used where a satisfactory raw water supply is not available and where high ambient temperatures make the alternative scheme of Figure 1.16(c) unacceptable. The air-to-air charge cooler is then one element of a radiator, whose other sections are used for cooling the engine's jacket water and, possibly, the lubricating oil as

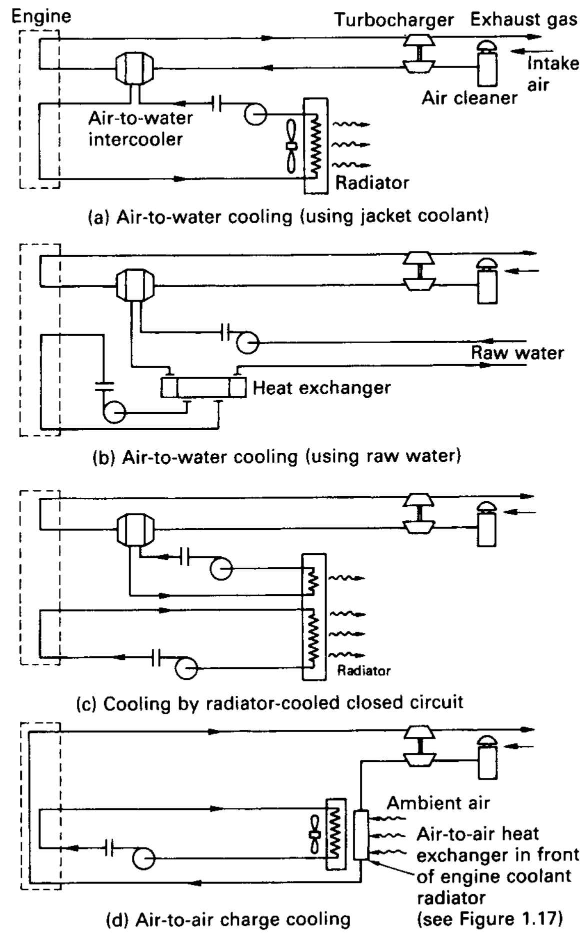



**Figure 1.16** Charge air cooling systems

well. The intercooler section is placed in front (air-side) of the other elements (see Figure 1.17) in order to maximize the cooling effect of the incoming air flow to the radiator. This arrangement gives very efficient intercooling. Its major disadvantage is the cost of the large radiator.

Exhaust gas turbocharged and intercooled engines can deliver as much as twice the continuous power available from an equivalent naturally-aspirated engine of similar speed and cylinder volume. Also, appreciable reductions in specific fuel consumption rates are achieved at all load levels. Less arduous working conditions at the cylinders give increased engine reliability and reduced maintenance. On the debit side, it is impractical to expect a turbocharged engine to accept full load in one step from an initial start-up condition. See Section 2.5 of Chapter 2.

*High pressure two-stage turbocharging* Some manufacturers employ four-stage (or twin) turbocharging on medium speed, 4-stroke engines, to give higher air intake densities. This boosts power

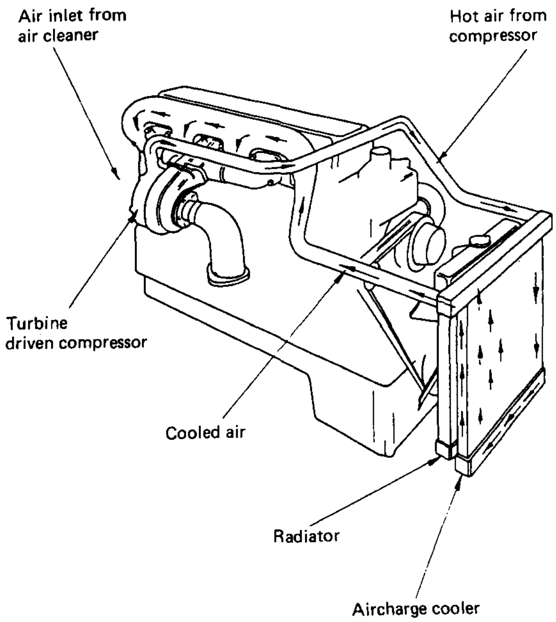



**Figure 1.17** Arrangement of air-to-air charge cooler (Courtesy: Perkins Engines Ltd.)

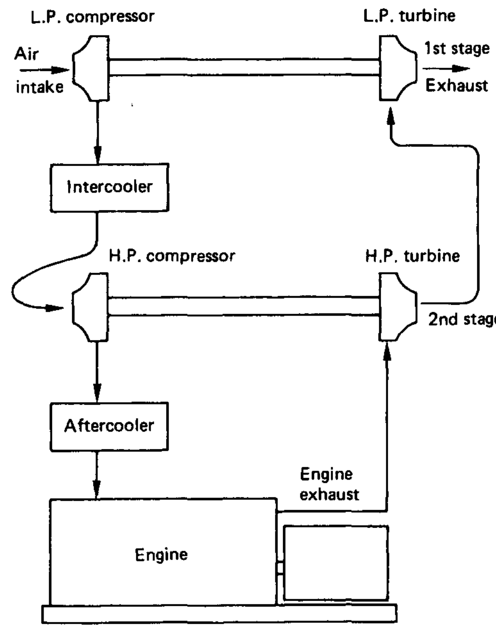



**Figure 1.18** Schematic of typical two-stage turbocharging system

beyond the limits imposed by the flow characteristics of conventional single-stage compressors. The system uses two turbochargers operating in series. A typical arrangement is shown in Figure 1.18. The engine exhausts into the HP turbine where the gas partially expands before it passes to the LP turbine, in which expansion is completed. Amospheric air first enters the LP compressor and then passes (via an intercooler) to the HP compressor. Here, it is compressed still further before passing through an aftercooler to the engine. The engine power gain offsets the cost of the second turbocharger. By dividing the compressor work into two stages, one also obtains the higher working pressures required - without exceeding the flow range of either compressor, or the efficient operating range of either turbine [5]. The load-acceptance capability of the engine is considerably enhanced.

### 1.7.2 **Ancillary** systems

#### *Starting equipment*

The simplest method of starting engines is by manual cranking. It is practicable only with the smallest units. A decompression device (preferably automatic) is required on the engine. See the later sub-section on 'starting aids'.

*Hydraulic starting systems* Hydraulic energy starting systems are often used on high speed engines. They may employ motors with pinion engagement on the engine flywheel starter ring; or they may use a rack and pinion arrangement on the front of the engine crankshaft. The Lucas Bryce *'Handraulic'* system, shown schematically in Figure 1.19, is an example of the latter type. Known as an *impulse action* system it provides a high torque to the engine crankshaft for one revolution, during which the reciprocating and rotating masses of the engine (and its connected generator) are accelerated to speeds above the minimum starting speed of the engine [20]. It is successfully applied to generating sets of up to 250 kW rating. It uses a starter unit (3) in which two hydraulically-driven racks are meshed to a helical pinion (4), which engages with the engine crankshaft through a serrated face-type coupling. The two hydraulic rams in the starter unit are each attached to a toothed rack. Lateral movement of the racks (in opposed directions) causes the helical pinion and, consequently, the crankshaft to rotate.

Hydraulic energy is stored in the piston-type accumulator (6), which is pre-charged with nitrogen (at about 195 $kg/cm^2$) in the sealed volume above the piston. The hydraulic fluid is contained in the space below the piston. A pressure of 300-350 $kg/cm^2$ is normally required for starting purposes. The hand pump (2) is used to transfer hydraulic fluid from the reservoir (1) to the lower space in the accumulator. This has the effect of raising the piston and compressing the nitrogen in the top portion of the accumulator. Hydraulic fluid is limited by a relief valve.

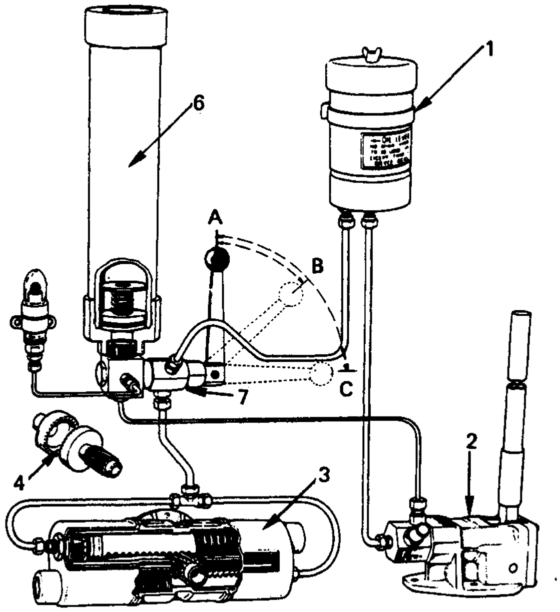



**Figure 1.19** Lucas Bryce 'Handraulic' starting system (Courtesy: Lucas Automotive Ltd.)

A two-stage start relay valve attaGhed to the base of the accumulator is controlled by a lever (7). The valve may be solenoid operated for remote start applications. Initial movement of the start lever from position A to position B admits limited hydraulic pressure to the starter unit (3). This allows the two rams within the starter to move their racks slowly across the helical pinion (4), which then travels axially rearwards to engage with the engine cran~shaft (through the face coupling). Further movement of the start lever (7), to position C, admits full hydraulic pressure to the rams which, in turn, apply a rapid turning impulse to the crankshaft through the racks and pinion. The crankshaft is rotated at well above the minimum cranking speed required.

When the engine has fired, the helical pinion is disengaged from the crankshaft by the serrated-face coupling (4) and moves forward until it is retained in the starter unit by a spring-loaded catch. Once the start lever is released, the starter unit is isolated from the accumulator. The rams are vented to the reservoir (1); and are spring-returned to their original pre-start positions.

The start cycle may be repeated as often as is required - provided there is sufficient charge within the hydraulic accumulator. Automatic recharging is possible, using an optional auto-charging pump which may be driven from the engine. This mechanical pump recharges the accumulator when the engine is running so that the system is primed and ready for the next start.

The hydraulic starting system marketed by Hydreco Hamworthy under the trade name of *Startorque* uses a hydraulic cranking motor fitted with a Bendix drive pinion which engages with teeth on the engine's flywheel gear ring. Cranking time is substantially longer than that obtained with the 'impulse action' system shown in Figure 1.19. Average operating figures released by the manufacturers show that, with correct choice of accumulator, it is possible to turn an engine at 375 rpm for approximately nine revolutions. The system is successfully applied to engines of up to 1500 $kW_m$ capacity.

Because hydraulic starters are completely independent of external sources of power, they provide ideal back-up (or secondary) starting systems for marine and off-shore standby generating sets. Their drawbacks are:

1. that cranking is limited by the size of the energy reservoir; and
2. the relative bulk of the reservoir and operating equipment.

For example, one reservoir charge would not give as long a cranking time as a conventional electric battery-powered system, and it takes about 30 seconds to recharge a reservoir by means of an engine-driven recharging pump. Where the cranking motor is correctly matched to the engine specification, the *Startorque* system is capable of giving efficient starting down to -15°C. The minimum starting temperatures obtainable with 'impulse action' systems are rather limited by comparison.

*Electric starting systems* Perhaps the most popular form of starting is the electric system, which uses a battery as the energy source. Low voltage d.c. motors 'fitted with armature shaft pinions are arranged to mesh (through a Bendix-type drive) with a toothed rim on the engine flywheel. These systems are widely applied to high-speed engines and smaller units in the medium-speed range. Some high-speed engines may require only one starter motor, whereas larger engines in that class, and medium speed engines, may need two motors with a common synchronizing control.

Motors are either of the *axial* or the *co-axial* type. Those in which the complete armature assembly moves forward axially to give enagagement of the starter pinion with the flywheel teeth are known as the axial type. The terms *inertia-drive* or *run-off helix* starters are also used to describe them. They are sensitive to engine speed variation and may disengage before the engine is firing properly. Good designs must provide for continuous contact between pinion and flywheel gear ring - even if temporary torque reversals occur during the engine starting process [20].

Co-axial starters are solenoid operated types, in which only the pinion dome moves forward to engage the f1wheel gear ring. The movement is made under reduced power to minimize engagement shock and reduce wear on the flywheel gear teeth. A mechanical locking device ensures that the pinion remains firmly enmeshed with the flywheel teeth (despite any irregular engine firing) until the motor solenoid is de-energized. A spring fitted to the front end of the pinion assists starter disengagement and prevents any tendency for the pinion to move towards the rotating flywheel when subjected to vibration or shock forces.

Whatever their type, starter motors should incorporate safeguards against overspeeding whilst the engine accelerates to its normal running speed.

Starters may also be described as being of the *hold-on* type or of the *non-hold-on* type. The hold-on starter is one in which the pinion does not automatically disengage from the engine flywheel. It is primarily applied where starts are manually controlled or where the start signal ceases when the engine is at self-sustaining speed. Conversely, the non-hold-on starter is one in which the pinion automatically disengages when the engine is up to speed. It is fitted to automatically or remotely started engines, and to engines in multiple installations where the ambient noise makes it difficult for attendant staff to hear an engine cranking and to judge the correct moment to release a starter push button.

Occasionally, when a starter is energized its pinion teeth butt directly against the flywheel teeth, and fail to engage with them. Because a motor's engagement winding is only short-term rated, it becomes overheated if this condition persists for longer than about 15 seconds. One manufacturer overcomes this problem by offering a so-called 'repeat start relay' for use with its non-hold-on starters. The relay senses failure of the pinion to engage and gives repeated energize and de-energize signals to the engagement winding until engagement is effected.

The most frequently used voltages are 12 and 24 V; but 6 V, for small engines, and 32, 48 or 64 V for the top end of the electrically-started range of engines, are not uncommon.

A cost"effective alternative to starter motors may be applied on generating sets below 15 kW rating. It uses a d.c. starting winding within the generator to crank the engine. The same winding charges the starter battery, when the engine is running.

Various types of battery may be employed. These are briefly described in Appendix B of this Handbook.

*Air starting systems* The energy source for air starting systems is compressed air, stored in receivers. The air may be used in one of two ways:

1. in a motor, flange-mounted on the flywheel housing; or
2. directly admitted into some, or all, of the engine cylinders, to move the pistons downwards on their working strokes until firing occurs.

*Air motor systems* Air motor starting is applied to the range of engines that would otherwise use electric starter motors. As with the electric motor, the sliding pinion of the air motor engages with the flywheel gear ring and is usually driven through a Bendix coupling and speed reduction gearing. Motors may be of the positive displacement multi-vane and gear types or of the turbine type. Working air pressures may range from 3 bar to 30 bar.

Air is supplied to the motor through a filter/water trap, an airline lubricator, and an operating valve. A pressure-reducing valve may be required, depending upon the storage pressure in the compressed air receiver. Motors for remote or automatic starting duty incoporate a device for engaging the Bendix gear with the flywheel gear ring, before applying full air pressure to the rotor. Engagement is then maintained until the engine reaches self-sustaining speed. At that stage a speed sensing device automatically cuts off the air supply to the starter motor and the pinion disengages.

*Direct air systems* These are traditionally used for starting medium and low speed engines. Compressed air is admitted to each of the engine cylinders, in their proper firing sequence, through non-return valves, either from a cam-shaft driven distributor or through mechanically operated valves. The air admission takes place when the piston is a few degrees past top dead centre, at the end of the compression stroke. The air supply is then cut off at about half stroke - in the case of four-stroke engines. (On two-stroke engines, the cut-off should occur before the piston uncovers the ports in the cylinder liner [20]). The expanding air drives the piston downwards until the exhaust valves open to vent the cylinder.

The shafts of engines, in which less than five cylinders are fitted with starting valves may have to be rotated into a flywheel position where one of the pistons is at the commencement of its combustion stroke. Provision is usually made for the fuel to be automatically cut off when air is admitted, in order to prevent a combustible charge being forced into the cylinder.

*Compressed air supplies* It is usual for the compressed air for either form of starting to be stored in one or more receivers, at pressures between 15 and 30 bar. Air charge is maintained by a small compressor (single- or two-stage, depending on the pressure required) driven by an electric motor, an i.e. engine, or by the main engine itself. It is usual to provide back-up auxiliaries on large or critical installations. The primary compressor may then be driven by ~n electric motor and the standby unit by an i.c. engme.

Air receivers are pressure vessels and, as such, will be required to comply with statutory regulations regarding design, installation, and periodic testing. See Chapter 13.

*Starting aids* Starting difficulties, particularly in low ambient temperatures, are more usual on the smaller high speed engines. This is because their large 'surface-area/cylinder-volume' ratios tend to dissipate the heat of compression. Also, restrictions on the size and weight of starting equipment limit the amount of starting torque available. Various starting aids may be used. Proprietary devices include:

1. heater plugs - to provide hot spots in combustion chambers;
2. electrically heated, and combustion-type, manifold air heaters;
3. manual and automatic systems, in which special ether-based fuels are sprayed into the engine's air intake or manifold while the engine is being cranked.

Decompression mechanisms may also be used to hold off either the inlet or the exhaust valve(s) on each cylinder, during the initial starting period. Full compression is restored when steady cranking speed is attained. The engine should then run up to self-sustaining speed.

The most effective way to promote combustion in a 'cold' engine is to provide an artificial environment for tpe engine and its ancillary equipment. Such conditions are intrinsic in base-load power stations, and shipboard installations.

It is customary to maintain coolant and lubricating oil temperatures above 30°C to promote quick starting on emergency generating plant. Thermostatically controlled immersion heaters, deriving their supply from the primary source of power, are fitted in the engine cooling system and in the engine sump or lubricating oil tank [20]

### Governors

The engines in generating plants use variable speed governors, set to operate at a predetermined synchronous speed. Governor choice is dictated by:

1. the engine type;
2. the application (e.g. independent operation, feeding an isolated load; or parallel operation with similar generators and/or with a utility supply);
3. the standard of governing required (classes of governing accuracy and their parameters are defined in BS5514: Part 4 (ISO 3046: Part 4)); and
4. the available inertia (or the flywheel effect) of the combined engine and generator.

Governors vary from the simple all-speed mechanical type, through various forms of mechanical-hydraulic and electrohydraulic types, to all-electric or electronic types. See Chapter 6 for more details on engine governing.

### Engine monitoring

The strategic temperature, pressure, speed and flow parameters of an engine's primary and ancillary systems need to be regularly monitored in order to interpret the engine's behaviour and performance. This information must then be relayed to those personnel responsible for the planned maintenance of the plant.

Makers' instruction manuals give a good indication of the degree of instrumentation required. Much also depends upon the build specification for the particular engine.

Parameters such as those listed below may be monitored, as and where applicable [3].

- coolant and raw water temperatures, pressures and flows;
- lubricating oil temperature and pressure;
- differential pressures across fuel and lubricating oil filters;
- coolant temperatures at outlets from individual cylinders;
- exhaust temperatures at individual cylinders, and before and after turbochargers;
- charge air temperatures and pressures;
- starting air pressure;
- the speeds of engines, pumps, compressors, and other key auxiliaries;
- fuel temperature and pressure;
- fuel and lubricating oil tank levels;
- cylinder pressure (using mechanically-driven or transducer-operated indicators).

Abnormal operating conditions may be detected by sensors whose output signals are fed into alarm/shutdown logic controls. Various combinations of indicative and protective action are possible. These include:

- two-stage alarm and shutdown;
- simultaneous alarm and shutdown; and
- alarm only (visible and audible).

See Chapter 10, which deals with prime mover and generator protection; and Sub-section 15.4.1 of Chapter 15 for a discussion on 'condition monitoring'.

## 1.8 Waste heat recovery

The thermal efficiency of RIC engines operating in electrical generating plant varies between 30 and 45 % - the higher levels being obtained from large

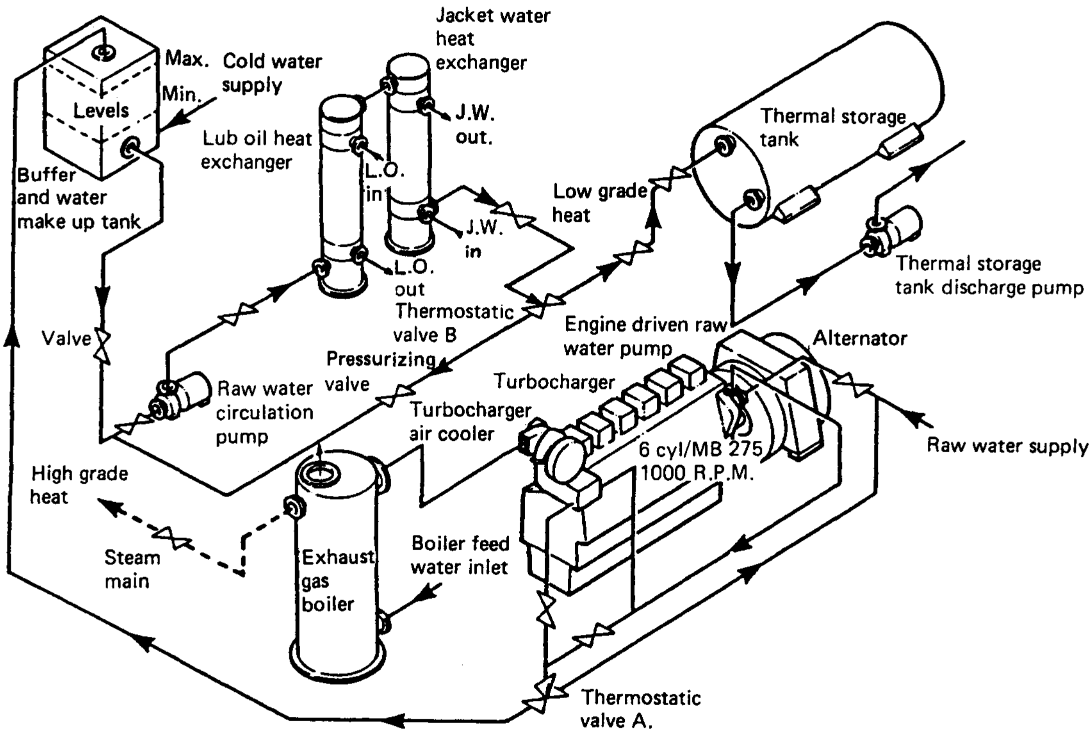



**Figure 1.20** Schematic diagram of a typical CHP system (Courtesy: Mirrlees Blackstone (Stockport) Ltd.)

engines (see Chapter 2). This means that up to 70 % of the heat input from the fuel is being rejected to engine coolant, exhaust, lubricating oil, and to radiation. Roughly 50 % of this waste heat is recoverable (the actual amount retrievable will vary with the type and design of engine) to give an overall thermal efficiency of more than 80 %.

Engine heat recovery schemes may include some. or all, of the following equipments - depending upon the consumer's thermal needs. A typical scheme is shown, in diagrammatic form, in Figure 1.20 [21].

1. A waste heat boiler for the exhaust gases - to produce either steam or hot water. Exhaust temperatures are in the range 300 to 500°C for c.i. engines and 400 to 600°C for s.i. engines. (Note: It may be necessary to add a condensing boiler where part-load running results from reduced electrical power and heating demands. This is because the exhaust gases may be cooled below the dew point.)
2. A thermal storage vessel, for so-called low grade heat circuits, fed from the secondary coils of engine coolant and lubricating oil heat exchangers, and from charge air coolers - using engine- or motor-driven raw water circulating pumps. It is not possible to use the jacket water for lubricating oil cooling because its temperature needs to be high for heat recovery purposes. A separate raw water supply should be provided for lubricant cooling - as shown in Figure 1.20.
3. A raw water buffer storage tank, and an expansion or make-up tank.
4. Oil-fired or electrically powered boost or line heaters, if and where required.

There is little difference between a turbocharged and a naturally aspirated four-stroke c.i. engine, as far as full heat recovery is concerned. The former may yield more exhaust heat, but the latter compensates for this by giving higher jacket heat. The exhaust gas yields from two-stroke engines (albeit at lower temperatures) are comparable with those from naturally aspirated four-stroke engines of the same output. This is only at high loads. The yield falls off rapidly at lighter loads.

The s.i. gas engine has near-constant exhaust temperatures at all levels of load because it operates on a constant air-to-fuel ratio_ The power output can only be controlled by varying the amount of fuel/air mixture admitted to the cylinders. The exhaust gas mass reduces as load is reduced.

In contrast, the c.i. engine operates on a variable air-to-fuel ratio. Its exhaust temperature decreases with reducing load. Typically, a turbocharged diesel engine may have a 30 % drop in temperature from full- to half-load. There is also more heat rejection to the cooling system on gas engines than there is on c.i. engines. This is a result of the latter's more efficient combustion cycle [11].

A typical heat balance for a 2 MW c.i. medium speed engine-generator, giving 1.8 MW in the dual-fuel mode, is shown in Table 1.1 [3].

**Table** 1.1 Heat balances for a 2 MW dual-fuel generator

| *Heat balance at full load* | *Diesel* (%) | *Dual-fuel* (%) |
|---|---|---|
| To electricity | 38.5 | 39 |
| To exhaust | 36 | 34 |
| To jacket water | 11 | 10 |
| To lubricating oil | 4.5 | 4 |
| To charge air | 4 | 2.5 |
| To radiation etc | 6 | 6 |
| To unmixed gases | – | 4.5 |
| | 100 | 100 |

The heat recoverable from the exhaust gases of a c.i. engine is of the order 250000kcal/h/MW; and about 350000 kcal/h/MW is recoverable from the jacket water.

Using *exhaust heat recovery* alone, it is possible to produce 0.5 kg of steam per kWh at a pressure of 8.5 kglcm². This figure doubles to 1kg of steam per kWh with *full heat recovery* (i.e. from jacket water, lubricating oil, and exhaust). It can be raised to 2.5 kg/kWh, if the jacket water is pre-heated in an automatic boiler fired from the same fuel as the engine [3].

A *combined heat and power* (CHP), or *co-generation,* system implies the generation of two forms of energy in a single conversion process. For example, an RIC engine producing mechanical energy for an a.c. generator and heat for:

- district heating; or
- industrial and commercial premises (including heat to absorption chillers for computer air conditioning); or
- production processes.

The description *'total energy scheme'* should only strictly apply to one in which the 'total' energy requirements of a site are provided by a central heat and power station, with no connection to a utility supply network. The Energy Act of 1983 has made it possible for the more efficient industrial and commercial CHP plants in the United Kingdom to obtain reasonable financial returns by exporting electrical power to Area Boards or to neighbouring consumers.

The commercial viability of a CHP plant hinges on its being able to run at, or near, full load for the greater part of its annual operation. Sizeable CHP installations have been commissioned in recent years, both in the UK and in Europe. Most have favoured multi-engined systems, employing 1.5 to 2 MW unit sizes with dual-fuel operation. The advantage of the multiple-generator scheme is that it gives flexibility and enables individual units to be operated at near-maximum output levels under varying power and heat load conditions. This serves to optimize the overall thermal efficiency of the CHP plant.

The following points should be noted:

1. It was once considered uneconomic to fit heat recovery systems to units below 500kW; because the heat balance was low, and the cost of recovery disproportionately expensive. Conditions have changed since the Energy Act of 1983 and there has been a marked increase in the number of small CHP installations in the UK - many as small as 40kW.
2. The site heating load should be at least 252000 kcal/h and the heat-to-power ratio more than 0.75:1.

The value of heat-to-power ratios depends upon the amount of low grade heat used. The range of values to be expected is as follows [22]:

| | |
|---|---|
| 0.5:1 to 1:1 | where heat recovery is from exhaust gases only. |
| 0.8: 1 to 2: 1 | with heat recovery from exhaust gases and engine coolant. |
| Up to 5:1 | with after-fired exhaust gases and heat recovery from exhaust and cooling water. |

In *after-fired* (or *after burning)* exhaust schemes, a combustion chamber is placed between the engine's exhaust outlet and the waste heat boiler. Fuel is introduced into this chamber; and burnt in the exhaust stream. There is sufficient oxygen in the exhaust residual (particularly from turbocharged engines) to ensure efficient combustion. By controlling the fuel supply to the combustion chamber, a constant heat input can be maintained at the waste heat boiler - irrespective of load variations. The system is ideally suited to those sites where a regular steam supply is required at constant pressure [6].

After-firing can treble heat production (see Figure 1.21). The total fuel consumption is about 1.5 times that of an installation without it. The overall fuel conversion efficiency is improved; and approaches 90 %.

Energy input and distribution for a typical system is shown in the Sankey diagram of Figure 1.22 [23].

As a general rule, s.i. engines cannot be after-fired. The exceptions are those types which employ the 'lean-burn' principle (i.e. run on high air-to-fuel

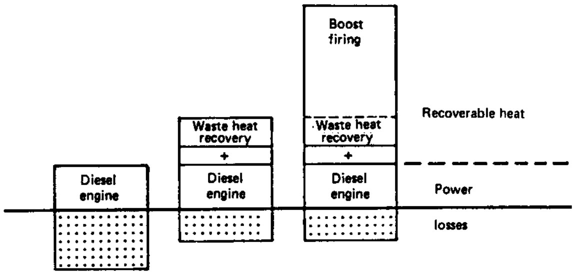



**Figure 1.21** The effect of installing engine waste heat recovery and boost firing (Courtesy: NEI Allen Ltd.)

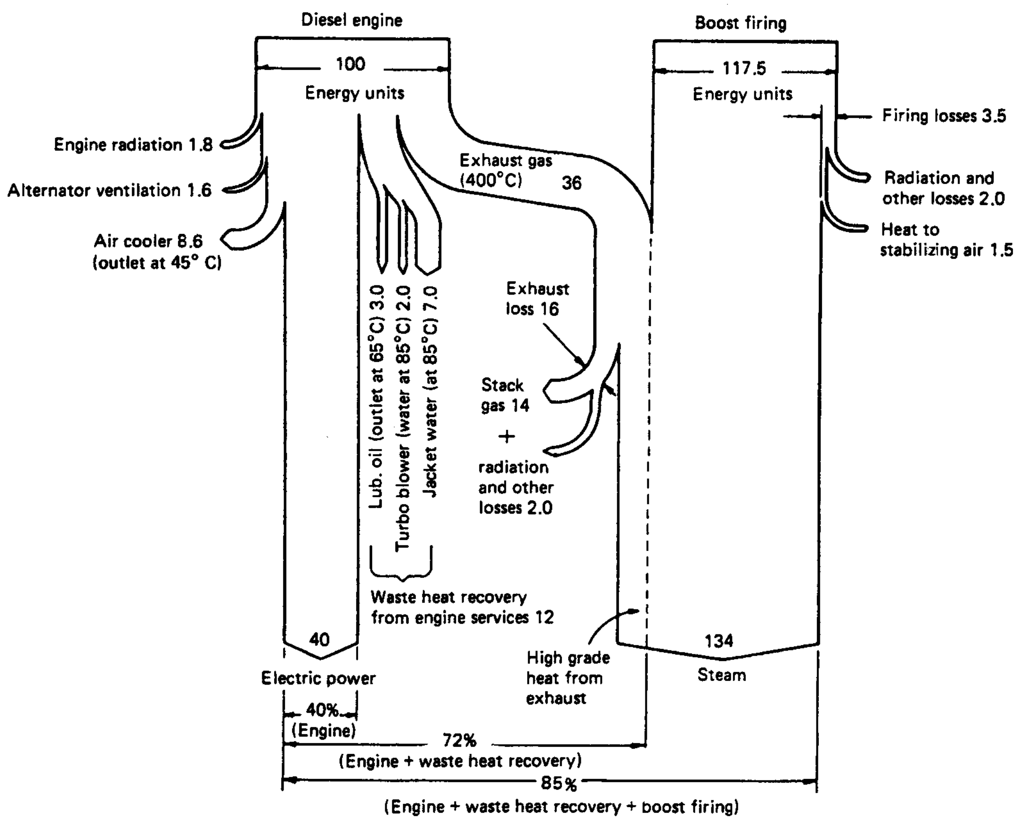



**Figure 1.22** Sankey diagram showing energy flow and efficiency of a diesel engine with waste heat recovery and boost firing (Courtesy: NEI Allen Ltd.)

ratios and therefore have a surplus of oxygen in the exhaust).

It is possible to improve the overall efficiency of a CHP system by the use of heat pumps. One such scheme, developed by Ergen of Milan, uses two integrated packages [24]. The first consists *oj* a diesel or gas engine generating set fitted with heat recovery equipment to give a total thermal efficiency of up to 85 %. Heat energy is recovered from engine coolant, lubricating oil, charge air, and the exhaust gases. The second package has a water-to-water heat pump which uses the power produced by the generator of the first package. The heat pump's task is to requalify the low grade heat of industrial effluents (which would otherwise be lost by discharge into rivers, etc.), and produce additional hot water for the industrial process itself. The combined effort of the two packages raises the total plant efficiency to exceptionally high values. A special high temperature loop is designed into the system. It receives heat in cascade from the heat pump, the engine coolant system, and the engine exhaust gas heat recovery system. A central automatic control panel operates the two main packages. Control can be programmed for either electric power or heat output priority. Depending on the mode selected, the controls give fine regulation between the two extremes of:

1. meeting the site's electrical power, and any consequent heat demands; and
2. using all the generator output to drive the heat pump and maximize hot water production for on-site processes.

The generator may be used to provide standby power to essential loads within the process plant. In these circumstances, heat pump operation is interrupted.

## 1.9 Referenced standards

Reference has been made, in this chapter, to the following British Standards. The identical document of the International Organization for Standardization (ISO) is shown in brackets.

| | |
|---|---|
| BS 5514: Part 4 (ISO 3046/IV) | *Specification for RIC engines: performance speed governing* |
| BS 5673: 1979 (ISO 1205 - 1972) | *Designation of the cylinders of reciprocating internal combustion engines* |
| BS 5675: 1979 (ISO 2276 - 1972) | *Definition of right-hand and left-hand single bank reciprocating internal combustion engines* |



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### 1.10.2 Other information sources

The text-books listed in the References have been used by the author in the preparation of this chapter. A very good introduction to the thermodynamics, design and development of s.i. and c.i engines, is given in the two volumes by Benson and Whitehouse [8].

Other useful sources of information are:

1. the house journals, and technical literature of major engine and equipment manufacturers;
2. the journals of learned societies such as the Institution of Mechanical Engineers, and papers published by the Institution of Diesel and Gas Turbine Engineers;
3. international trade journals and magazines specializing in prime-movers and engine-powered equipments such as: *Diesel Engineering; Diesel and Gas Turbine Worldwide; High Speed Diesel Report* and *European Power News.*

# 2 Power rating and performance

Contents

## 2.1 Introduction

This chapter defines the basic applications of generating plant and considers the environmental and performance factors that have an influence upon the sizing of plant. The significant terms relating to engine power, and the accepted methods of specifying ratings and kinds of power are explained. The International and National Standards referenced within the text are listed in a concluding section of the chapter.

## 2.2 Generator applications

In our context a 'power generator' or a generating set consists of a reciprocating internal combustion (RIC) engine coupled to an a.c. generator; complete with the appropriate mounting and drive bearing elements, and with the auxiliaries required for operation. It is of course possible to employ one or more engines to drive the generator (or generators). The auxiliary equipment would include, but not necessarily be confined to, such items as:

1. the engine starting system;
2. the engine speed governing system;
3. the generator voltage regulating system;
4. the engine and generator cooling systems;
5. the engine air intake and exhaust system;
6. the engine lubricating oil system; and
7. the engine fuel system (liquid or gaseous fuel).

The generating set in an installation (be it fixed, mobile or transportable) would then be provided with the necessary equipment and devices required to control, monitor, and protect the prime mover and the generator, and to switch the electric power generated. See Chapters 9 and 10.

### 2.2.1 Generator operational modes

A.C. generators powered by RIC engines are employed in three main roles (also see Chapter 5):

1. On primary or base-load duty, in locations where there is no utility supply; or as an independent power source to ensure continuity of supply. where an 'unreliable' public supply system is available. Included in this category would be total-energy and co-generation schemes.
2. For peak-lopping (or peak-shaving) duty to supplement and/or reduce the cost of electricity supply from a utility source.
3. As standby to a power supply from a utility.

These modes of operation fall into two categories:

(a) those where generators are required to run continuously, without a time limit; and
(b) those where some time limits are set.

Applications are not confined to land-based installations. Categories 1 and 3 also apply to marine (shipboard and off-shore) installations.

### 2.2.2 Performance criteria

Certain types of load have a direct bearing on the sizing of generating plant and demand a particular quality of supply. Performance parameters need to be clearly defined and specified for each application. The supply characteristics required for high-technology, sensitive loads (such as data processing equipments and computer installations) will be quite different to those that need to be specified for less sophisticated loads, such as general-purpose domestic and industrial systems. Some, or all, of the following performance parameters may need to be defined:

- load acceptance;
- transient and steady-state voltage and frequency regulation; and
- waveform characteristics (harmonic limitation).

Also see Section 2.5 in this chapter.

### 2.2.3 Ratings and classifications

The power rating of a generating set should be expressed in $kW_e$ at rated frequency, and at an assumed power factor (coslj» of 0.8 lagging (unless stated otherwise). It represents a statement by the manufacturer of the power which the unit will deliver under a specified set of circumstances. This declaration should include:

1. the ambient and operating conditions of the plant; and
2. the kind of power provided.

There are, as yet, no International or British Standard specificaiions for RIC engine driven a.c. generating sets. A multi-part draft proposal (ISO/DP 8528), prepared by the International Organization for Standardization Technical Committee TC 70/SC 2/WG 1, is now in circulation to the national committees of individual member countries. Hesketh [1] reported in June 1986 that preparatory work had taken nearly three years. Final publication of the Standard is not expected before the mid 90s. This timescale reflects the complexity of the task. ISO 8528 will relate to existing international design standards for RIC engines, rotating electrical machines, HV and LV switchgear, and control gear. Its purpose is to define ratings and performance parameters for generating sets as entities. It is an ambitious undertaking which should be of significant benefit to both manufacturers and purchasers of plant.

Meanwhile, in a commendable effort to fill the gap, the trade association of the major independent

British manufacturers of generating sets - the Association of British Generating Set Manufacturers (the ABGSM), has produced, in its Technical Memorandum No.1, a rating standard for diesel powered generating sets. While it is only a recommendation, and is voluntarily applied by ABSGM member companies, it is a good 'state of the art' guide, deserving of wider acceptance.

### 2.2.4 Power categories

The international standards applicable to RIC engines (ISO 3046) and to electrical generators (IEC 34) specify the methods of declaring power rating. The four kinds of power that may be declared for prime movers are defined in ISO 3046: Part 1 (BS5514: Part 1 and DIN 6271):

1. *Continuous power:* a power which an engine is capable of delivering continuously between the normal maintenance periods stated by the manufacturer, at stated speed and under stated ambient conditions, the prescribed maintenance being carried out.
2. *Overload power:* a power which an engine may be permitted to deliver, at stated ambient conditions, immediately after working at the continuous power. It is expressed as a percentage of the continuous power for periods and speeds appropriate to the application. It is customary to permit 110% of continuous power for periods up to 1 hour.
3. *Fuel stop power:* a power which an engine is capable of delivering during a stated period corresponding to its application, and at stated speed and under stated ambient conditions, with the fuel limited so that the fuel stop power cannot be exceeded.
4. *Service power:* a power determined under the ambient and operating conditions of an engine application.
   To establish the service power, one needs to take the following factors into account:

   (a) the ambient conditions - temperature, barometric pressure and relative humidity; and the maximum and minimum temperature of the cooling water available;
   (b) the normal duty of the engine;
   (c) the expected interval between maintenance periods;
   (d) the nature and the amount of attendance required;
   (e) the specification and lower calorific value of the fuel to be used;
   (f) any other information appropriate to the service application (guidance on this is given in BS 5514: Part 1, clauses 12 and 13).

These power ratings must be net values at the engines output shaft. Due allowance should therefore be made for any auxiliary equipments, which could absorb significant power in themselves. The engine manufacturer's statement of power should be supported by a list of auxiliaries. Some items, such as fuel injection pumps, exhaust turbochargers and charge air coolers, are considered as engine components, without which the engine could not operate at its declared power and are not classed as auxiliaries.

Certain items of equipment are *essential* for the continued or repeated use of an engine. They may be engine driven or they may derive their power from a source other than the engine. Those in the first category are defined as *dependent,* and those in the second category as *independent* auxiliaries. Typical items are: lubricating oil pressure pumps; cooling water pumps; radiator cooling fans; fuel feed pumps; air cleaners; and exhaust silencers. If the items use power supplied by the main engine-driven generator, they are classified as dependent auxiliaries. Examples of typical auxiliaries are listed in Annex A ofBS5514: Part 1. The net brake power must be measured when the engine is using only its *essential dependent auxiliaries.*

In American practice (ANSI/ASME PTC 17) the term *'Code Engine Assembly'* is used to describe an engine assembly complete with essential apparatus for self-sustained continuous operation. Generally these consist of the equipment required for: fuel introduction; air induction (i.e. scavenging or supercharging); ignition; lubrication; and primary engine and charge-air cooling.

Looking at the power requirement from the 'consumers' viewpoint, we would expect a continuous power rating to cover base-load duty. The overload power rating would apply to generators on standby-to-utility supply and on peak-lopping duties, where the maximum running times are not likely to exceed 100 hours and 1000 hours per annum, respectively. Applications using the maximum, or fuel stop power rating should be confined to emergency plant of the short-break or no-break type, described in Chapter 11. Engine manufacturers will restrict operation at maximum power to short-duration periods (of the order of minutes), provided these are followed by reasonable periods of operation at reduced output. It must be accepted that the engine's durability is affected and that engine life may be reduced.

Prospective engine users should be wary of loosely defined rating classifications other than those listed above. Standby rating; continuous duty with time-limitation rating; reserve rating; and intermittent rating are but a few of the classifications that crop up. Engine manufacturers should be asked to declare ratings in ISO terms. Most do.

It is important that the engine purchaser selects the kind of rating most suited to the generating set's intended service. The proposed ISO 8528 should help the end-user define, more precisely, the kind of service he requires the set to give, in his particular application.

We shall now consider the other significant element in the generating set: the alternating current (a.c.), or synchronous, generator. The term *alternator* is deprecated and does not appear in the British Standard Glossary (BS 4727: Part 2 Group 03). However, it occasionally appears in descriptive literature and specifications - old usages die hard ..

The rating of any rotating electrical machine is a statement of the limitations assigned to it by the manufacturer, and marked on its rating plate. The rated output of a generator is quoted in kV A and kW, assuming an operating power factor of 0.8 lagging.

Generator technology is dealt with in Chapters 3 and 4. Section 3.7 of Chapter 3, discusses power ratings, the factors affecting output, and de-rating.

Different ratings may be assigned to the same frame size machine. The standard definitions for *continuous maximum rating* (c.m.r.) for industrial (IEC 34-1 and BS 4999: Part 101) and marine (BS 2949) applications are very similar. In each case, unlimited operation at the declared output and under the specified conditions is permitted but the machine has no sustained overload rating. Because performance criteria for marine generators must be met at 50°C and not the 40°C applicable to industrial machines, the marine c.m.r. is lower than its industrial counterpart.

BS 4999 is a comprehensive standard for all types of rotating electrical machines. The standard specifically applicable to generators driven by RIC engines is BS 5000: Part 3. This recognizes that the prime mover is customarily permitted to develop an output 10 % in excess of its rated output. It warns that, at 110 % load, a normally rated generator may exceed its full-load temperature rise by 'considerably more than its 10 K margin', and 'that any significant usage of this 10 % overload capacity will shorten the insulation life of the machine'. It should be appreciated that the insulation of a machine driven by an engine operating at a maximum (or fuel stop) rating could age at a rate 4 to 8 times greater than that associated with operation at the machine's c.m.r. level. See Section 3.4.4 of Chapter 3 for a more detailed discussion of this topic.

## 2.3 Related terminology

### 2.3.1 Power

The power of a prime mover is its useful rate of working. When it is measured at its driving shaft(s), against a *brake* resistance, it is defined as *brake power.*

Brake power *(Pe)* may be derived from the expression:

$$Pe = (Pme.s.A.w.N)/k$$

Where $Pme$ = is the brake mean effective pressure (to be defined later)
$s$ = the working stroke of the engine piston
$A$ = piston area (i.e. the area on which the mean effective pressure works)
$w$ = the number of firing or working strokes per cylinder in a specified time
$N$ = the number of cylinders in the engine
$k$ = a constant, whose value depends upon the units used

With the exception of wand $k$, these are the symbols established in Addendum 1 - 1982 of ISO 2710 (BS5676: Add 1: 1983) for use with RIC engines.

The power may be expressed in $kW_m$ or in horsepower (hp). The units used in the formula must be 'consistent'. In the case of SI units, force, length, and time must be expressed in Newtons, metres, and seconds, respectively; and the constant $k$ is 1000. This gives power in $kW_m$. For a result in imperial horsepower, $k$ is 33000, and the units used must be pounds, feet and minutes.

1 horsepower (imperial) = 0.746 $kW_m$
1 horsepower (metric) = 0.736 $kW_m$

Metric horsepower may be expressed in either CV *(cheval vapeur)* or in PS *(Pferdestarke).*

The *indicated power (Pi)* is the theoretical total power developed in the engine cylinders by the gases on the combustion side of the working pistons. It is based upon the actual mean pressure measured inside the engine cylinders (i.e. the indicated mean effective pressure - imep or, simply, mip), as obtained from an *indicator diagram.* The indicated power is always higher than the brake power. The difference between them being the power required to overcome friction within the engine and to drive essential dependent auxiliaries.

### 2.3.2 Efficiency

The first of the *efficiencies,* which have a bearing on diesel engine performance is the *mechanical efficiency* which is equal to the brake (or effective) power divided by the indicated power. It gives a comparison between the 'actual' power available at the engine flywheel and the total power developed in the working cylinders.

Mechanical efficiency, $\eta_m = Pe/Pi$
= kW or hp (brake)/kW or hp (indicated)

The *mechanical losses* in an engine (i.e. friction losses plus power absorbed by auxiliaries) are roughly proportional to speed and are fairly constant, at fixed speed, regardless of the load. Therefore, as the load on the engine decreases, the mechanical losses become *relatively* greater, and the mechanical efficiency reduces more rapidly. It is one of the reasons why it is undesirable to allow an engine to run for prolonged periods at less than 30 % of the torque which it is capable of developing [2].

The mechanical efficiency of diesel engines is of the order of 70 % to 85 % at full load. A unit with a full-load $\eta_m$ of 75 % would, typically, have an efficiency of 60 % at half load; and 50 % at one-third load.

The next definition to be considered is that of *thermal efficiency.* It gives an indication of the effectiveness of an engine in converting the heat energy of the fuel into work.

The *indicated thermal efficiency* is important in engine research and development. It is the ratio of the indicated power, to the *thermal* energy supplied by the fuel, over a given period of time. It is of little practical value to plant operators, who are more interested in the efficiency of conversion of the fuel's energy into actual (or brake) power at the engine shaft i.e. the engine's *brake thermal efficiency* ($\eta_{et}$).

$$\eta_{et} = \text{(heat converted into actual work)/(heat input)}$$
$$= \text{brake (or actual) output/heat supplied}$$

Care must be taken to ensure that the same units are used to express both output and heat-supplied values.

Working in SI units, the brake power output $(P_e)$ would be expressed in $kW_m$. Over a period of one hour, this is equivalent to a thermal output of $(3600 \times P_e)$ kilojoules.

The heat supplied by the fuel $= m \times cv$, where $m$ is the mass of fuel used per hour, expressed in kg. It is directly related to the engine's fuel consumption rate (i.e. its *specific fuel consumption, b),* as declared by the engine maker, in kg/kW-hour. Therefore

$$m = b \times P_e \text{ kg}$$

$cv$ is the calorific value of the fuel, expressed in kJ/kg. It is usual to use the net or *lower calorific value* of the fuel [2].

The above formula for $\eta_{et}$ may then be written as:

$$\eta_{et} = 3600\ P_e/(b.P_e \times cv)$$
$$= 3600/(b \times cv)$$

Given the *specific fuel consumption* (sfc) of an engine and the calorific value of the fuel used, the brake thermal efficiency may be calculated. Conversely, knowing the declared brake thermal efficiency of an engine and the heating or calorific value of the fuel to be used, it is possible to estimate its fuel consumption.

For example, if an engine has a brake thermal efficiency of 40 % and uses a fuel whose lower calorific value is 42000 kJ/kg (10300 kcal/kg), its specific fuel consumption would be given by the expression:

$$b = 3600/(0.40 \times 42000) \text{ kg/kWh}$$
$$= 0.214 \text{ kg/kWh}$$

By definition, brake thermal efficiency accounts for all the losses in an engine when the work performed by the gases (the indicated power) is converted into net power, at the engine's output shaft(s). These losses include both the thermal losses within the cylinders, and the mechanical losses when the *gaseous work* is converted into output at the shaft. Therefore

brake thermal efficiency = (indicated thermal efficiency) x (mechanical efficiency)

i.e. $\eta_{et} = \eta_i \times \eta_m$

For this reason, it is sometimes called *overall efficiency [3].*

Typical values of brake thermal efficiency for RIC engines are:

| | |
|---|---|
| Diesel (c.i.) engines | 43 % |
| Dual fuel (c.i.) engines | 38 % |
| Gas (s.i.) engines | 36 % |

What is known as *volumetric efficiency* also has an effect on engine power. It is a term only applied to four-stroke, naturally aspirated engines. It is defined as the ratio of the actual volume of air taken into the cylinder during the suction stroke, to the volume of piston movement (its *swept volume* or *piston displacement* $(V_s)$, which is the product of the piston's stroke and its cross-sectional area). The volume of air admitted is stated in terms of *standard reference conditions* (defined later).

Volumetric efficiency, $\eta_v$ = (volume of air admitted)/(swept volume)

Volumetric efficiency gives a comparison of the mass of air actually admitted into the cylinder, with the mass of air corresponding to the swept volume. In naturally aspirated engines the mass of the air admitted is always less than the mass of the swept (air) volume. This is because its temperature is higher and its pressure lower than the supplied, or atmospheric, air. The higher temperature results from the presence of hot residual gases in the *clearance space*[1] and from the heat transferred to the

[1] The *clearance space,* which includes the combustion chamber, is the space in the cylinder into which the piston never intrudes. The air charge is compressed into this *clearance volume* $(V_e)$.

admitted air in its contact with the hot surface, of cylinder walls, cylinder head and piston crown. The pressure drop due to air flow resistance through inlet valves/ports and intake manifolds, accounts for the lower pressure.

Engine power is directly related to volumetric efficiency. The lower the $\eta_v$ the less the power developed. Lower volumetric efficiency means that there is a smaller mass of air in the cylinder. This, in turn, means that less fuel can be burned and less power can be developed. In order to increase an engine's power capacity it is necessary to improve its volumetric efficiency. This is done [3]

1. by taking air from a point in the engine room where the air is cooler; or
2. by improving the valve timing so as to increase the pressure at the end of the induction stroke.

The volumetric efficiency ratio will be less than unity, for naturally aspirated engines. It is of the order of 0.75 to 0.85, the higher ratio obtaining at slower engine speeds.

We have established (in Chapter 1) that, on turbocharged engines, the intake air on the induction stroke is not drawn in by the downward movement of the piston alone, but is forced in by the compressor of the turbo-blower. The amount of air in the cylinder is, therefore, not directly related to the piston displacement and is considerably more than that corresponding to the swept volume. Thus, the term volumetric efficiency does not apply to turbocharged four-cycle engines [3]. The ratio of *charging efficiency* ($\eta_{CH}$) is used instead. It is define4 as the ratio of the mass of air trapped in the cylinder to the maSs of air which could be trapped at the boost air pressure and temperature [4]. The *trapped volume* of the cylinder is the cylinder volume at the commencement of the compression stroke. It is not the same as the swept volume, but, for any engine, the ratio of trapped to swept volume is constant [4].

The two-stroke engine relies on a *scavenging period,* in its operating cycle, to sweep out any residual exhaust products that remain in the cylinder, from the previous cycle[2] (see Chapter 1). This is achieved by supplying air to the cylinder while its exhaust and scavenge ports are simultaneously opened. In practice, some of the supply air is lost to the exhaust and the cylinder is not scavenged of all residual products (the new charge is therefore not pure air). It is necessary to supply a larger volume of air than would theoretically be necessary to fill the cylinder's swept volume. The *scavenge efficiency,* $\eta_{sc}$ is a measure of the engine's effectiveness in removing the burned gases and filling the cylinder with a fresh air charge. It is expressed as the ratio of the mass of air supplied to the cylinder to the mass of air corresponding to the cylinder volume at scavenge air temperature and pressure. This ratio is normally greater than unity for two-stroke engines with an external air supply [4]. $\eta_{sc}$ is largely dependent upon the arrangement of the exhaust and scavenge air ports and valves. The power capacity may be increased by taking the air for the scavenge blower from a point in the engine room where the air is cooler [3].

[2] Medium speed engines also have wide valve overlap and a relatively long 'blow through' period.

### 2.3.3 Compression ratio

The efficiency of any engine working on an ideal constant-volume cycle depends upon its *compression ratio* (or more precisely, its volumetric compression ratio). This is the ratio between the greatest and least volumes of air in a cylinder during one cycle [5]. This volume is at its greatest when the piston is at its lowest position and is about to start upward in the compression stroke. It is at its least when the piston is at its highest position in that stroke. The volume corresponding to the latter position is the clearance volume. The 'greatest' volume equates to the sum of the cylinder's swept volume and the clearance volume. The compression ratio ($\varepsilon_c$) is therefore given by:

(swept volume + clearance volume)/(clearance volume)

Increasing the compression ratio effectively increases the *expansion ratio.* This is the ratio of the total volume at the end of the power stroke to the volume at the beginning of that stroke. Both ratios are dependent upon the clearance volume. Reducing that volume gives an increase in both ratios.

The greater the expansion of the gases, the more the heat taken out of them. Because heat energy is converted into mechanical power, it follows that the higher the expansion ratio the more heat energy is converted into power. Improvement in thermal efficiency is not, therefore, due to the compression itself but rather to the fact that the higher compression results in more complete expansion. This, in its turn, converts more of the thermal energy of the combustion products into *mechanical work [3].*

In the ideal engine (i.e. one without friction and other losses), the calculated relationship between indicated thermal efficiency ($\eta_{ti}$) and $\varepsilon_c$ varies from 34.3 % for a $\varepsilon_c$ of 3, to 63.9 % for a $\varepsilon_c$ of 18. The 'rate' of gain in $\eta_{ti}$ tails off as the compression ratio becomes higher [3]. In practice, compression ratios between 12:1 and 19:1 are usual for diesel engines. The lower ratio applies to medium-speed engines and ratios of the order 15:1 to high-speed engines. There has been a recent trend to higher compression ratios in heavy fuel engines to ensure complete combustion and to reduce fouling [6].

The air temperature in the cylinder at the end of the compression stroke depends very much upon the compression ratio. The temperature must be high enough to cause instantaneous ignition of the fuel when it is introduced thereby improving the ability of the engine to start unaided from cold. In practice, in order to limit the maximum cylinder pressure to a level which does not prejudice the durability and reliability of the engine, the engine designer has to compromise between the requirements for ease of cold starting and the limiting stresses imposed by the engine's running gear when operating at maximum power. Factors such as

1. piston boss loading,
2. big end and main bearing loading, and
3. cylinder head gasket sealing integrity,

will influence the maximum cylinder pressure which can be employed [7].

As compression ratios increase, the need to limit the maximum cylinder pressure, in turbocharged engines, to an acceptable level may result in the use of a compression ratio which is too low for unaided cold starting [8].

### 2.3.4 Brake mean effective pressure

We have seen, from the expression for brake power *(Pc)* given in Sub-section 2.3.1, that an engine's actual output is related to:

- the number of cylinders;
- the area and working stroke of the pistons;
- the working strokes per cylinder in a given time (directly related to engine speed); and
- a factor we called the *brake mean effective pressure* (bmep).

The bmep can be considered as that average and constant pressure which, if applied throughout one stroke to a, frictionless piston of the same size and stroke as the actual piston, would produce the same power as the actual piston gives per cycle.

Brake mean effective pressure cannot be measured directly. It must be calculated from the brake power, knowing the engine speed, the piston diameter, and its stroke. The formula is developed from that given in Sub-section 2.3.1.

$P_{me} = P_e.k/s.A.\ w.N$ or, substituting $\pi d^2/4$ for $A$

$P_{mc} = 4.P_e.k/s.\pi.d^2.w.N$

Consistent units should be used when working in either kW or imperial horsepower values for brake power.

Clearly, engine *rating* is directly proportional to the bmep, for an engine of known dimensions and speed. The designer's objective is to rate his engine as highly as possible but there are limits beyond which he must not go. Among the salient engine features to be considered are:

1. the combustion chamber;
2. the fuel injection system;
3. the cylinder head;
4. the crankcase; and
5. the running gear, which includes connecting rods, pistons and bearings.

The combustion and cooling characteristics of the engine playa large part in limiting the rating of an engine. More fuel needs to be burned to get increased power but this means hotter combustion gases. Because the air drawn into the cylinder remains fixed for all practical purposes (unless the engine is pressure charged), there is a limit to the amount of fuel that can be injected into the cylinder before incomplete combustion results - with its attendant problems of fuel wastage and smoky exhausts. Also, the cooling jackets are unable to cope with the excessive heat generated - leading to the overheating of engine parts and their possible failure.

Manufacturers rate their engines on the basis of a bmep that guarantees satisfactory continuous operation. The bmep of an engine, for a certain power rating and speed, affords a good clue as to how closely it has approached its design limits. Medium-speed engines are now rated at about 21 to 22 bar and high-speed engines at 10 to 16 bar [6]. High bmep generally means inferior load-acceptance performance. See Section 2.5 and associated Figure 2.2.

It has been predicted that developments in high-speed diesel engines for electrical power generation will centre on increasing mean effective pressures without penalizing fuel consumption or load acceptance. Mean effective pressures will rise to around 20 bar, with fuel consumption being possibly reduced to levels below 0.200 kg/kWh. This should be accomplished without the need to increase piston speeds [9]. Power is directly proportional to piston speed, and the dynamic forces within an engine vary as the square of it.

## 2.4 Service power ratings

Of the number of factors affecting the on-site rating of generating sets, perhaps the most significant is that relating to the condition and quality of the air which is available for engine aspiration and for generator and engine cooling.

Since the RIC engine is an air-aspirating machine, its output is affected by changes in the temperature and pressure of the air it 'breathes'. Ambient temperature, altitude (barometric pressure) and relative humidity (a measure of the water vapour present in the air) all affect the density of the air entering the combustion chamber - and hence the engine's performance. An increase in ambient temperature means that the (warmer) air in the engine cylinder is less dense. Likewise, there is a reduction in air density at higher altitudes because the atmospheric air pressure decreases.

Any reduction in air density results in less oxygen being contained in the swept volume of the engine. This, in turn, means that less fuel can be burned in the engine cylinder. The amount of fuel burned has a direct bearing on the specific power output of the engine.

### 2.4.1 Standard reference conditions

It is important for the prospective engine user to know the *reference conditions* upon which ratings are based in order to compare the declared performances of engines offered for a specific application. The power adjustment factors used by one engine maker in formulating a service power rating may then be evaluated against those used by others, and the validity of the factors questioned, if wide divergences are found to exist.

Power ratings should be quoted to the *standard reference conditions* (s.r.c.) contained in the applicable National Standards of the engine maker concerned. For British built engines this is BS 5514: Part 1: 1987 (IS03046/l: 1986). The German DIN 6271 closely follows both the British and the International standards. The following standard reference conditions apply in BS5514: Part 1: 1987:

| | |
|---|---|
| Total barometric pressure, *Pr* | = 100 kPa (100kN/m" = 1000mbar) |
| Air temperature, *T*, | = 298 K (25°C) |
| Relative humidity, <Pr | = 30 % |
| Charge air coolant temperature, *Tel* | = 298 K (25°C) |

These are different from those of the Second Edition (1982) of the Standard, in the following respects:

Air temperature was 300 K (27°C)
Relative humidity was 60 %
Charge air coolant temperature was 300 K (27°C)

It is permissible to use the Second Edition's reference conditions until 1992. Where this is done, the assumed values should be stated.

Manufacturers should declare the 'ISO power' available from engines at stated standard reference conditions. They are also required to state which of the formulae (if any) in Table 1 of BS 5514: Part 1 apply to the power rating. ISO standard powers, based on the conditions of Edition 3 (1987) of the Standard, are fractionally lower than those which assume Edition 2 conditions.

The standard conditions used in American practice are those defined in the Society of Automotive Engineers publication SAE 11349: Dee 1980-*Engine Power Test Code.* They are: 29.61 in. (7521 mm) Hg barometer at 77°F (25°C) inlet air temperature.

Incidentally, RIC engines used to provide electric power on ships for International Association of Classification Societies (lACS) unrestricted service must be rated for the following ambient conditions:

| | |
|---|---|
| Total barometric pressure | = 100 kPa |
| Air temperature | = 318K (45°C) |
| Relative humidity | = 60 % |
| Sea water temperature (charge air coolant inlet) | = 305 K (32°C) |

The standard reference conditions for generators (given in IEC34-1: 1983, and the equivalent BS4999: Part 101) are:

| | |
|---|---|
| Cooling air temperature | below 313 K (40°C) |
| For machines with closed circuit cooling, coolant temperature at cooler inlet | below 298 K (25°C) |
| Altitude | up to 1000 m above sea level |

The following standard reference conditions, defined in IEC 439 (BS 5486: Part 1) and IEC 298 (BS 5227), apply for switchgear and controlgear equipments: .

| | |
|---|---|
| Ambient temperature (temporary maximum) | = 313 K (40°C) |
| Relative humidity | = 50 % at 313 K |
| Altitude | up to 2000 m above sea level (m.a.s.l.) |

Clearly, different standard reference conditions apply to the three major components of the generating set; the engine, the generator and the associated switchgear. The generating set builder must ensure that all these components are included at their correct rating and duty.

### 2.4.2 Re-rating for service conditions

Net outputs need to be adjusted to arrive at predicted on-site or 'service power' ratings, when equipment is required to operate under conditions differing from the standard reference conditions.

*Engines.*

Section 10 of BS 5514: Part 1 sets out the method for re-rating RIC engines. It lists the formulae to be applied for this purpose, and Annexes B to G offer tables and examples to help simplify and explain the methods of calculation.

Since the calculations are fairly complicated (see Annex G of BS 5514: Part 1), most engine manufacturers reduce the formulae to simplified forms stating the percentage reduction in power for a certain increase in temperature and altitude above the BS 5514 s.r.c. levels [10] . For example, the K Major range of engines manufactured by Mirrlees Blackstone (Stockport) are derated as follows:

1. for altitude - 1 % for every 125 m above 359 m.a.s.l.;

2. for ambient air temperature - 4 % per lOoC above 25°C;
3. for intercooler water - 3 % per 10°C above 25°C.

The last of these is of most importance in those semi-tropical and tropical installations where raw water is not available in sufficient quantities. If a conventional radiator is then employed to cool the water for the intercooler, it is only possible to secure a charge air temperature of about 8°C above the ambient air temperature - resulting in large power derating. A solution to this problem is to use an air-to-air charge cooling system (see Chapter 1). Very close approach temperatures are possible with this system and it is normally unnecessary to derate the engine in respect of air manifold temperature, except in very high ambient temperatures [10]. On the debit side, a heavy first-cost penalty is incurred from the very large radiators required.

Some engine manufacturers present their data in the form of de-rating curves. A typical example is shown in Figure 2.1, for the Perkins Engines (Shrewsbury) Type CV 12 engine operating at 1500 and 1800rpm synchronous speeds [7].

It will be seen from Figure 2.1(a) that, at 1500 rpm, the engine need not be derated at 40°C until that temperature is combined with an altitude higher than 3150 metres. Power derating is necessary at altitudes above 2300 m for an ambient of 55°C, e.g. a derating of 5 % is specified at an altitude of 2750m. At 1800rpm, however (Figure 2.1(b», deration is necessary at lower altitudes for given ambient temperatures. For example, at 40°C derating begins at altitudes above 2000 m, and at 55°C deration is necessary at altitudes above 1200 m.

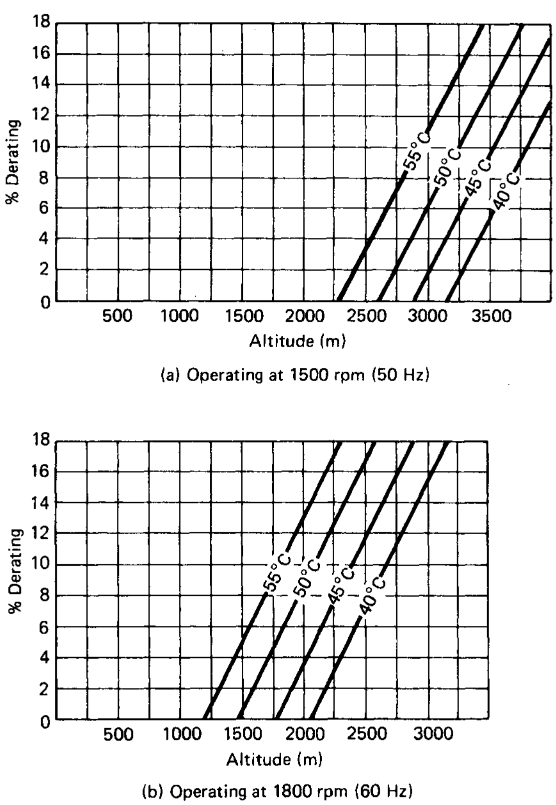


**Figure 2.1** Derating data for a generating set engine (Courtesy: Perkins Engines (Shrewsbury) Ltd.)

These sets of curves show that an engine which has a rationalized specification to cover operation at two synchronous speeds cannot have optimum derating performance at both speeds. It may be offered with a range of power ratings. At the lower end of the range, the temperature/altitude derating lines are, effectively, moved to the right - along the *x-axis* of the graphs (Figure 2.1(a) versus Figure 2.1(b». This is because the engine's performance parameters are further below their limiting levels because of the lower rating and fuel setting. In other words, at these lower ratings, the engine may be operated at higher altitudes and temperatures before the limiting levels are reached [7].

Manufacturers derive the data for these curves from engine development tests conducted at the continuous power ratings. These may be followed by tests in environmental chambers in which high altitudes and high ambient temperatures are simulated. Alternatively (and more usually), the data are derived from computer programs based on BS 5514 [7].

The majority of engines in generating plant are turbocharged and intercooled. The high intake-air mass flows produced in them compensates for increasing altitude. Turbocharged engines are, therefore, only derated for altitude by a fraction of that required for an equivalent naturally aspirated engine [10].

Turbocharged and intercooled engines need not be derated for high humidity conditions. As it is rare in any part of the world for high humidity to be combined with very high ambient temperature, a derating exceeding 6 % for humidity is seldom, if ever, warranted for naturally aspirated engines.

### *Generators.*

Generator ratings largely depend upon the final temperatures attained in the copper of their windings. Due allowance must therefore be made for the ambient temperatures in which they operate. Also, because the air density falls and the mass of cooling air flow is reduced, it is necessary to apply derating when machines are operated at high altitude. This ensures that the permissible temperature rise of the windings is not exceeded.

Technical data supplied by machine manufacturers always include the derating factors to be applied for operation in high ambient temperatures and at high altitude. See Section 3.7 of Chapter 3.

*Switchgear.*

The switchgear components most affected by operation at high temperatures and high altitude are air type circuit breakers and current carrying conductors - such as cables and busbars. Re-rating is needed for service conditions outside standard reference values. See Chapter 9, and Section 9.17.2 in particular.

## 2.5 Performance factors affecting plant sizing

The on-site electrical power required from the generating set determines the size of prime mover required. The efficiency of the a.c. generator needs to be included in the calculation. Thus:

$$kW_m = kW_e/\eta_g$$

Where $kW_m$ is the prime mover power rating in kilowatts
$kW_e$ is the electrical power supplied to the load (usually the c.m.r rating of the generator)
and $\eta_g$ is the efficiency (per unit) of the generator

For example, a $500kW_e$ demand, using a generator of 92.5 % full-load efficiency would require an engine capable of delivering on site,

$$500/0.925kW_m = 540.5kW_m$$

It should be appreciated that the efficiency of a generator varies with the load applied to it. Typical per-unit values for four-pole machines operating at 0.8 power factor (pf) are:

| | Full load (FL) | 0.75 FL | 0.5 FL |
|---|---|---|---|
| 100kYA(80kW) | 0.91 | 0.91 | 0.89 |
| 300kYA (240 kW) | 0.92 | 0.92 | 0.90 |
| 1000kYA (800 kW) | 0.95 | 0.95 | 0.93 |

In general, the efficiency of machines increases with size. See Sub-section 4.2.1 of Chapter 4 for a full discussion on the topic.

The performance required of the generating setis often a more significant factor when sizing the prime mover and the generator than the calculated site rating - which is directly related to the steady-state power demanded by the connected load. One needs to consider:

1. the application of the generating set;
2. the load power factor;
3. the profile and the diversity factor of the connected load;
4. any intermittent and cyclic loading; and
5. the characteristics of dynamic loads.

Generators on standby duty may be required to accept the total electrical load within a few seconds of starting from cold. The load acceptance performance of an RIC engine is related to the type of combustion air supply system it uses. Non-turbocharged engines will accept full rated load in one step, without much difficulty. Engines in this category are those of the naturally-aspirated type; and those pressure charged models which employ mechanically driven compressors. Turbocharged engine performance is limited by that bmep which corresponds to the engine's declared ISO standard power. High bmep generally means inferior load acceptance performance. i.e. the permissible load step does not rise in proportion to the engine's normal full-load capability. The phenomenon is caused by *turbocharger lag.* This is basically the time between load 'on' and charge-air boost pressure building up in the air manifold. The latter must precede any increased fuelling.

Curve A of Figure 2.2 (which is derived from Figure 2 of BS 5514: Part 4 - *Speed governing)* shows that the maximum possible sudden load increase, in a single step, for a turbo-charged four-stroke engine is about 75 % of the declared power at site conditions - at 11 bar bmep. At 20 bar bmep, only 40 % rated load may be applied in one step. It is understood that the curve relates to a warm engine. Where turbocharged engines are used it is necessary to apply load in several stages. Conversely, if large percentage load steps are a requirement of the duty cycle, it becomes necessary to either specify low-rated engines (in terms of bmep) or to use an engine of higher rated output.

It will be seen from Figure 2.2 that, if the turbocharged engine's bmep, at declared power at s.r.c. were 13.5 bar, the limit of first-stage load application would be 60 %. Once this load has been successfully accepted by the engine, the remaining 40 % of full load may be applied to the generator. At bmep's above 13.5 bar, an engine may have to be loaded in several stages. Typically, a high-speed engine rated at 16 bar would need to have full load applied in three stages of 50 %, 37 % and 13 %, respectively. A medium-speed engine rated at 20 bar might only accept a sudden load of 40 %, followed by staged increments of 30 %, and 20 %, of service load capability. The curves in Figure 2.2 are typical examples and not generally representative. Actual characteristics should be obtained from engine manufacturers.

Load acceptance capability will vary from engine to engine. Performance will depend on the generating set's inertia and the engine's turbocharging characteristics. The pulse turbocharging system provides a better response to load change than the constant pressure system which is normally used on two-stroke engines [10].

Performance specifications should define the transient frequency and voltage characteristics required for sudden application and rejection of connected

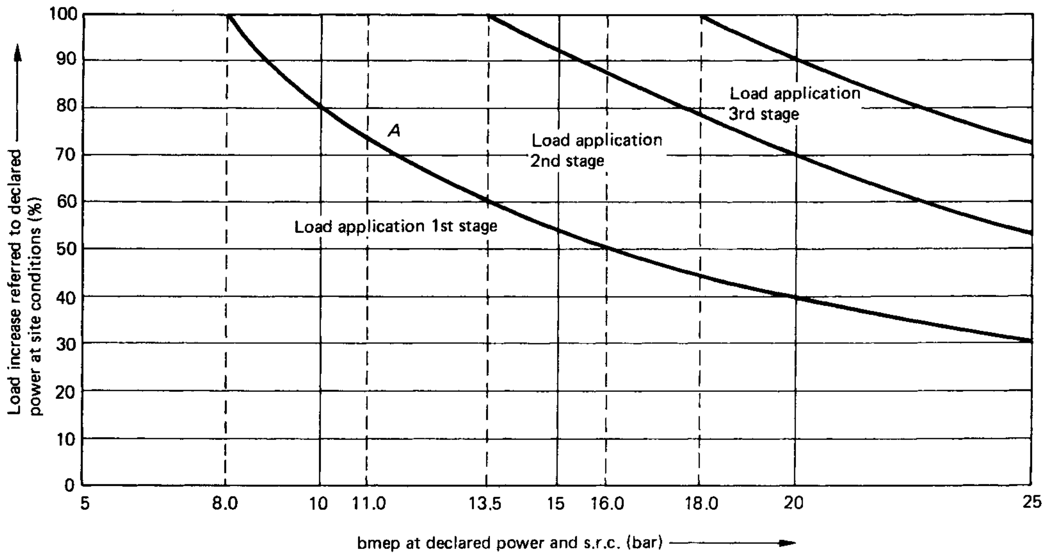


**Figure 2.2** Sudden load application on four-stroke turbocharged engines, as a function of b.m.e.p. at declared power

loads. The key areas which the generating set designer must then consider are:

1. the engine's speed governing system (see Chapter 6);
2. the engine's turbocharging system (see Chapter 1);
3. the turbocharged engine's bmep, at declared power;
4. the generator's automatic excitation control system (see Chapters 3 and 4); and
5. the mass moment of inertia of the combined diesel-generator system (see Chapter 5).

The load power factor (pf) has a direct bearing on the sizing of both engine and generator. It is usual to assume that the working power factor is 0.8 lagging although in practice it is seldom this low. Electrical loading is expressed in kVA. True power (kW), which is the product of the kVA and the power factor, is that which is obtained from the output shaft of the engine. The higher the power factor the more the output required from the engine. If the load pf is actually 0.9 (and not 0.8, as assumed), 12.5 % more power would be required from the prime mover.

We shall see in later discussions (Section 3.7 of Chapter 3) that, for a given output, the lower the system power factor, the larger the size of generator to furnish that power. It is necessary to derate machines for operation at power factors below the design level of 0.8 lagging. Typically, a derating factor of 0.96 would be required for operation at 0.75 pf.

When considering the characteristics of any connected load, it is important to identify those elements which demand close-tolerance input power parameters - such as voltage and frequency regulation. These would include so-called *technical loads*, e.g. computer, data processing, and telecommunication systems. Certain other elements in the load profile may impinge upon these demands by adversely affecting the generating set's steady-state and/or transient behaviour. These would include:

- the intermittent, impacting loads imposed by induction motor starting;
- non-linear loads, such as convertors and inverters;
- cyclically varying loads, such as radio transmitters and identification beacons; and
- regenerative loads such as lifts and cranes.

The characteristics and effects of some of these elements are examined in some detail in Section 5.4 of Chapter 5.

## 2.6 Referenced standards

Listed below are the British Standards to which reference has been made in this chapter. Where there are corresponding International Standards, these are shown in brackets. The extent of their agreement with the British Standards varies. Some are completely identical and have dual-numbering. Others have substantial technical equivalence, with differences perhaps in wording and presentation.

BS 2949 (IEC 92-5) - *Rotating electrical machines for use in ships*

BS 4999 - *General requirements for rotating electrical machines*

This is a multi-part standard. Those parts of particular relevance in our context are:

Part 101 (IEC 34-1) - Sections 3, 4 and 5 - *Specification for rating and performance*

BS 5000: Part 3 (IEC 34-3) - *Generators to be driven by reciprocating internal combustion engines*

BS 5227 (IEC 298) - *A.* C. *metal-enclosed switchgear and controlgear of rated voltage above 1 kV and up to and including* 72.5 *kV*

BS 5486 - *Specification for factory-built assemblies of switchgear and controlgear for voltages up to and including 1000 V a.c. and 1200 V d.c.*

This is a multi-part standard. The Part which deals with definitions and service conditions is:

Part 1 (IEC 439-1) - *General requirements*

BS5514 - *Specification for reciprocating internal combustion engines: performance*

This is in six parts. Those of significance in our context are:

Part 1 (ISO 3046/1) - *Specification for standard reference conditions and declarations of power, fuel consumption and lubricating oil consumption*

Part 4 (ISO 3046/4) - *Speed governing*

BS5676: Addendum 1: 1983 (ISO 27l0/Add 1) - *Symbols* - which establishes the symbols to be used for defined terms in the field of RIC engines.

## 2.7 References


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# 3

# A.C. generators - general

**Contents**

## 3.1 Introduction

The objective in this chapter is to describe the general features of a.c. generators. A rotating machine consists of two essential parts: the stator and the rotor. In the a.c. generator the stator carries the armature winding in which the electromotive force (e.m.f.) of the machine is induced, and from which the machine's output is taken. The rotor carries the main field system which derives its magnetization from d.c. excitation. Practical excitation sources and systems are considered in the context of the need to establish acceptable load/voltage characteristics for machines. Typical machine arrangements are presented with an emphasis on the 'brushless' generator, and descriptions of its rotor and stator components and constructions.

The permissible temperature rise within a machine depends upon its rating and upon the class of insulation used. The properties of insulating materials, the causes of their failure, and the evaluation techniques applied in insulation system engineering are therefore discussed. The importance of ventilation and cooling in control of the thermal conditions within a machine is also stressed.

The chapter concludes with standard definitions of power rating and reviews the factors which affect ratings.

## 3.2 Generator excitation characteristics

When a self-excited, shunt wound, d.c. generator feeds a load, it experiences a drop in terminal voltage, due to the inherent resistance and reaction of the armature. This drop is further accentuated by the weakened excitation resulting from the lower terminal voltage. The amount of excitation required to maintain rated voltage, over the range· from no-load to full load, is small, and may be obtained by incorporating a secondary (series) excitation winding which carries load current.

The load/voltage characteristics of the shunt wound machine and of the compound wound machine (using field coils partly in series and partly in parallel with the armature windings) are shown in Figure 3.1. The terminal voltage is controlled by varying a field rheostat (the *shunt field regulator)* which is in series with the shunt field.

The load/voltage characteristic of a conventional a.c. synchronous generator is very similar to that of the shunt wound d.c. generator, but the reason for the terminal voltage drop on load application is a bit more complex and is largely affected by the *power factor* of the load. Figure 3.2 [1] shows terminal voltage plotted against load current, at three extremes of load power factor, for a constant value of excitation current.

The characteristic at unity power factor load is the quadrant of an ellipse, whose semi-axes are the induced, open-circuit, phase electromotive force (e.m.f.), $E_{ph}$, and the sustained short-circuit current ($I_{sc}$). At zero power factor lagging, the graph is a chord of this ellipse; at zero power factor leading, the characteristic is a straight line subtended back to intercept the horizontal axis at $-I_{sc}$, for constructional purposes only. Intermediate power factor characteristics will fall within these extremes. All start at the no-load point ($E_{ph}$) and end at the sustained short-circuit current, $I_{sc}$.

(It should be noted, here, that the *inherent voltage regulation* of a generator - which is due solely to the fundamental characteristics of the generator itself - is defined as the change in terminal voltage resulting from a load change, the speed being maintained constant and excitation at the full-load value. It is expressed as:

$$\epsilon = 100\,[(E_{ph} - V_{ph})/V_{ph}\,\%$$

where $V_{ph}$ is the terminal phase voltage at full load, and
$E_{ph}$ is the open-circuit phase voltage, for the same field excitation.)

The effects of *armature reaction* and stator *leakage reactance* combine to cause the required excitation current to vary over a wide range in order to keep the output voltage constant. See Chapter 4 for definitions of power factor and reactances and for an explanation of the per-unit (p.u.) system. The consequences of lagging power factor are clearly illustrated in the set of excitation curves of Figure 3.3 [2]. In order to maintain constant output voltage at a power factor of 0.8 lagging for which the machine was designed, the per-unit excitation required at full rated output (1.0 p.u. kVA), is 2.2. If the machine was required to operate in an overload condition at reduced power factor (p.L), the excitation required for constant voltage would be considerably greater. For example, at 120% rated output and at 0.5 p.f. lagging, the excitation current required would be 2.8 p.u. This is 27% greater than that required at designed full load. This enhanced excitation would greatly increase the amount of heat dissipated in the field windings and excessive field temperatures could occur. Generally, armature heating is the limiting factor on machine output in the range from unity to rated power factor, whereas, at lower power factors field heating is limiting.

It should be appreciated that the operating power factor is not a characteristic of the machine itself. It is solely determined by the nature of the load. It is therefore important, when ordering a machine, to

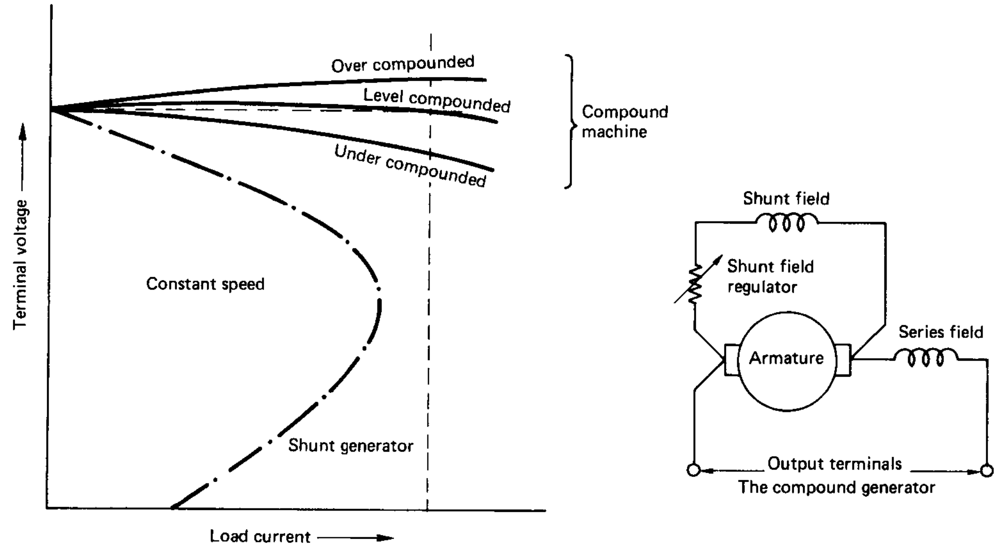



**Figure 3.1** External load–voltage characteristics of d.c. generators at constant speed

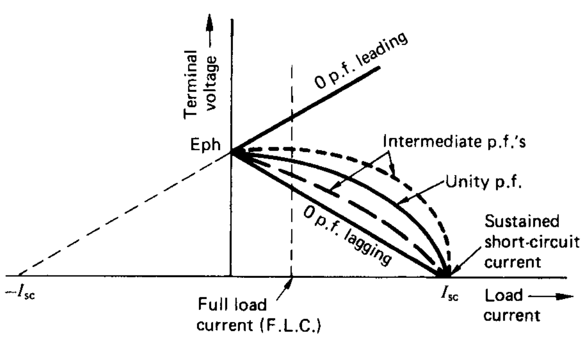



**Figure 3.2** Voltage characteristics of a generator

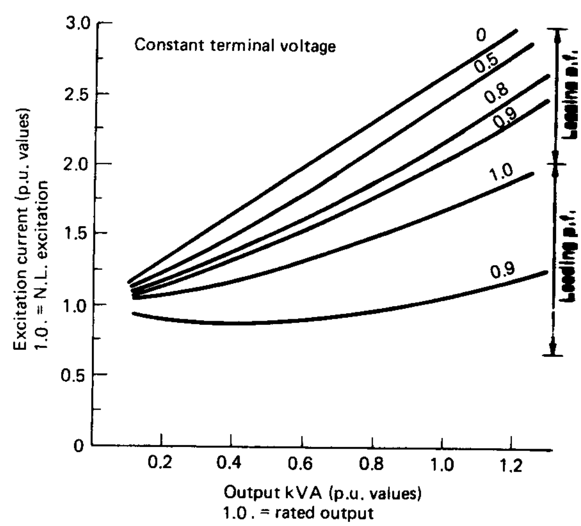



**Figure 3.3** Typical excitation curves for a generator

make a realistic estimate of the load power factor. See Sub-section 3.7.1.

### 3.2.1 Excitation system requirements

The characteristics of Figure 3.3. show that the range of excitation required for rated kVA output at power factors between 0.9 leading and 0.8 lagging is 1.1 to 2.2 p.u. The excitation voltage required to circulate these currents through the generator field coils will therefore need to have the same 'spread'. One has to allow for changes in field winding resistance arising from variations in ambient and running temperatures, and cater for possible transient conditions, such as the switching-in of induction motors with high inrush currents and low starting power factors. It is therefore necessary to provide margins above and below this steady-state range. Typically, excitation voltage ranges of the order of 4:1 are employed.

Figure 3.4 [2] shows typical excitation power requirements for generators at various (50 Hz) synchronous speeds. Taking the case of a 1 MVA machine running at 1500 rpm, its steady-state excitation power demand may only be 0.005 p.u.; but it may be as high as 0.009 p.u. under *field forcing* conditions.

### 3.2.2 Practical excitation systems

Practical excitation systems may be divided into three generic groups:

1. *Static excitation* which consist entirely of static equipment, i.e. no rotating machines are involved other than the generator itself. The machine's field excitation is derived from its own armature terminals, through an assembly of static components, such as current and voltage transformer-rectifiers. The excitation current is fed to the generator field coils - through slip rings if necessary, as in the case of rotating field machines. It may include a small automatic voltage regulator (AVR), but its basic design does not require one. See Chapter 7.
2. D.C. *excitation* - employing a rotating d.c exciter, with or without an a.c. or d.c. pilot exciter.
3. *A.* C. *excitation* - employing a rotating a.c. exciter, with or without a pilot exciter.

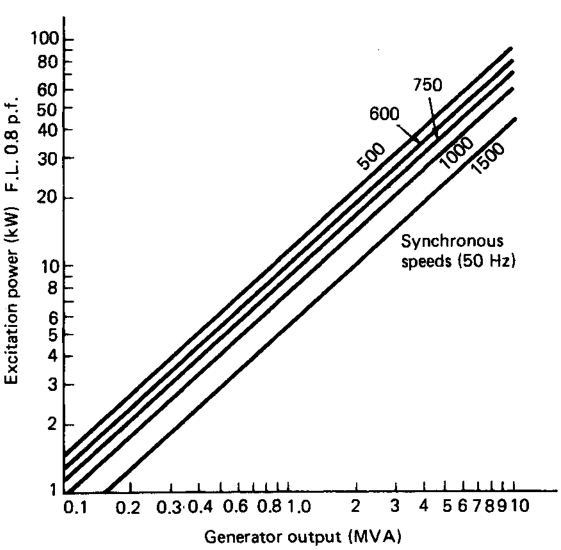



**Figure 3.4** Approximate excitation power requirements, over a range of generator outputs and speeds

Figure 3.5 [2] shows typical systems, in block diagram form, for generators of the sizes we are considering. Automatic voltage regulators are closed-loop or feedback and error-actuated devices capable of controlling their output to maintain an accurate steady-state voltage at a generator's terminals, irrespective of load, speed, and temperature variations. The AVR may supply either an exciter field or the generator's main field windings, depending upon the capacity of the AVR itself. With the exception of the a.c. excitation systems of diagrams 6 and 7, all the arrangements shown in Figure 3.5 are equally applicable to rotating armature machines.

The development of a.c. excitation systems has eliminated the d.c. exciter except on large, low speed, hydro-generators.

## 3.3 **Some typical arrangements**

The two basic categories of conventional and compound machines are described in the following typical arrangements. Advantages and disadvantages and comparative performances are discussed.

### 3.3.1 Conventional separately excited machines

Very few generators are marketed with a d.c. exciter, as in the arrangement of Figure 3.6. With improvements over the years in the performance of magnetic materials and the insulations available to the machine designer, it has been possible to obtain greater outputs from machines of a given frame size. This increased the loadings on the commutators and brushgear of d.c. exciters and placed greater emphasis on the need for careful maintenance by operating staff. Service problems were fairly common, particularly where access for maintenance was difficult or in hostile environments such as the high ambient temperatures and oil-laden atmospheres of sea-going ships. In high response systems there was always the risk of flashover at the commutator

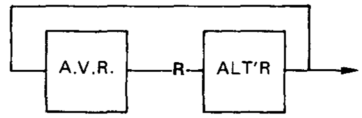
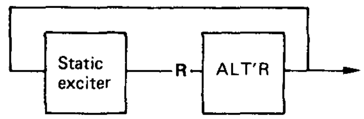
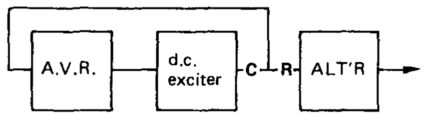
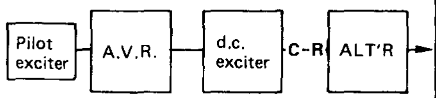
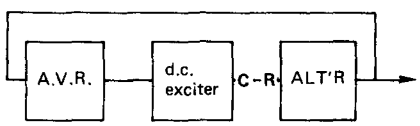
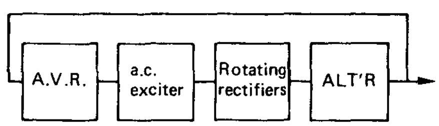
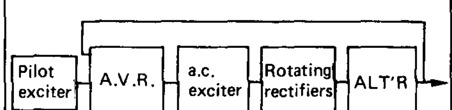
| Group | Block diagram | Comments |
|---|---|---|
| Static excitation | <br>1. | – Self-excited machine<br>– Large capacity static A.V.R.'s (up to 10 kW excitation power or more)<br>**R** indicates sliprings |
| | <br>2. | – Referred to as a self-excited compounded machine |
| d.c. excitation | <br>3. | A relatively small A.V.R. acting on exciter field to control fairly large outputs<br>**C** indicates commutator |
| | <br>4. | Field of main exciter fed from pilot exciter to give a superior voltage response to that obtained from the above system |
| | <br>5. | – High performance A.V.R. fed from the terminals and controlling the exciter field<br>– Systems 3, 4 and 5 are for so-called conventional, separately-excited generators |
| a.c. excitation | <br>6. | The output feeds the a.c. exciter field through the A.V.R.<br>– Systems 6 and 7 are referred to as brushless separately-excited generators |
| | <br>7. | Incorporating a pilot exciter with a field of permanent magnets. This affords correct operation under machine fault conditions and gives certainty of voltage build-up on starting |

**Figure 3.5** Excitation systems classified by group

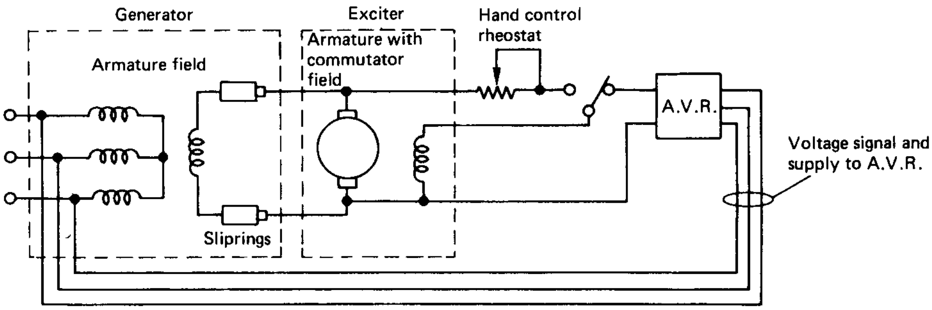



**Figure 3.6** Conventional, separately excited generator with d.c. exciter

during load changes which require strong *field forcing.* Also, machines on standby or emergency duty were very prone to sliding contact deterioration after prolonged periods of shutdown. A major reason for the development of the system described below was the need to eliminate the high cost and inconvenience of maintenance on commutators and brushgear.

The principle of the *brushless generator* - dispensing with slip-rings, commutators, and brushes - was first mooted in the 1930s. But the bulk and capacity of contemporary metal rectifiers (selenium) meant that the scheme was of theoretical interest only. The advent of the more compact, high power germanium and silicon junction semiconductor rectifiers (in the late 1950s) made the earlier idea an attractive technical and commercial proposition.

An a.c. exciter is an integral part of a brushless generator. The generator itself consists of two machines (see Figure 3.7). The *output* stage comprises a rotating field exciting a stationary armature (the stator) which provides the machine's output power. The excitation for this rotating field comes from the rotating armature of a multi-pole a.c. generator (the exciter) fitted to the main generator shaft. The a.c. supply from the exciter armature is rectified by shaft-mounted diodes and fed to the main field in the machine's output stage. Connections are made through leads either attached to the shaft or threaded through the centre-bore of the shaft. Controlled rectifiers (thyristors) have been used to improve the dynamic performance of the very largest turbo-generators and hydro-generators, but the complexity of the control circuitry, and the problems of transmitting control signals to the shaft without using slip-rings and brushes, have precluded their use on the range of machines under consideration.

Control of the a.c. generator's output voltage is effected by controlling the exciter field (see Figure 3.7). The power supply for the exciter field may be obtained in one of several ways:

1. from a separate 3-phase permanent magnet generator (p.m.g.), as shown in Figure 3.7(a);
2. from the output terminals of the generator itself, as in the self-excited system of Figure 3.7(b); or
3. an auxiliary stator winding located in the same slots as the generator's main armature windings.

All three arrangements have certain advantages and disadvantages. Some of these are highlighted below.

*Separate p.m.g.*

- Gives certainty of voltage build-up on starting.
- Improves the generator's steady-state overload capacity.
- Gives good fault clearance control, since the AVR power supplies do not collapse when short circuits are applied to the generator. This is particularly important for co-ordination of protection on supply distribution circuits.
- Affords fairly good voltage response, after large load-step changes.
- Will add to the cost of a machine.

*Direct self-excitation*

- Affords the simplest and cheapest form of excitation supply.
- Requires auxiliary short-circuit maintenance equipment if protective device discrimination is required on downstream circuits. This is because the generator voltage normally collapses when a three-phase short-circuit occurs. In some circumstances (e.g. on some single load installations) this inherent overload protection may be used to advantage, to prevent damage to the generator's prime mover.
- Delays in response, and recovery to normal voltage, are not greatly different from those systems which use p.m.g.s or auxiliary stator windings.
- Difficulties are experienced in generating sufficient residual voltage at the main generator terminals on start up. Measures taken to overcome this may include:

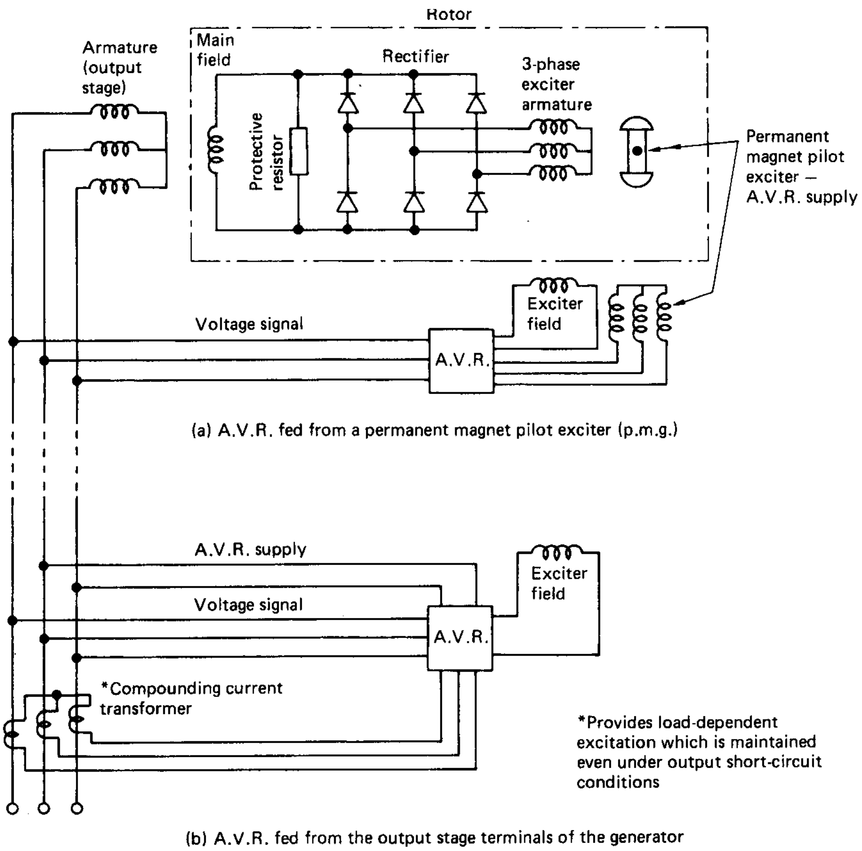



**Figure 3.7** Basic circuit diagrams for brushless excitation

- special magnetic laminations in the exciter or the generator;
- tuned resonant or *Boucherot* circuits in the AVR;
- *field flashing* by means of a separate battery supply; and
- permanent magnet interpoles or permanent magnets inserted in the pole faces of the exciter stator.

All these measures add, in varying degree, to the first cost of a machine.

It should be said that self-excitation is going out of favour. Modern laminated exciters have little residual, and cases of failure to build-up were increasmg.

*Auxiliary stator winding*

- Ensures that power is available even under short-circuit conditions.
- Relies on residual magnetism to build up voltage on run-up, just as in the self-excited arrangement.
- The added cost to a machine is usually higher than the p.m.g. arrangement.

The output frequency from an a.c. exciter need not necessarily be the same as that of the main output stage of the generator. Frequencies between 20 Hz and 150 Hz are adopted, in practice [3]. The lower limit is usually set by the degree of d.c. smoothing available from the machine's main field winding, and the upper limit by the permissible losses in the exciter. This wide frequency range offers the machine designer scope for rationalization. For example, by selecting an 8-pole configuration, a single design of exciter may be used to cover a synchronous speed range of 300 to 1800 rpm. See Sub-section 4.2.2 of Chapter 4 for the relationship between speed, number of poles, and frequency.

Most a.c. exciters employ a 3-phase armature winding which is also regarded as perhaps the best arrangement for recifier connections.

### 3.3.2 Rectifier circuits

The rectifier circuits most commonly used are:

1. 3-phase bridge (Figure 3.8(a));
2. 3-phase star (Figure 3.8(b)); and
3. 6-phase star - requiring a 6-phase exciter armature winding (Figure 3.8(c)).

The bridge connection has a lower ripple output and permits a more economical exciter design than the other two arrangements. For example, for a given exciter, a third more output can be obtained from a 3-phase bridge rectifier than from a 6-phase star arrangement. Whilst the star connections may give poorer exciter utilization (because they draw current from anyone phase for a shorter period in each cycle) they require simpler mechanical arrangements. This may make the 3-phase star circuit more economically attractive on smaller machines. The 6-phase star connection is used on the largest machines, where diode rating could be a limiting factor.

Most a.c. exciters have a 3-phase armature winding feeding into a bridge rectifier. Wherever possible, a single rectifier is used in each branch. Equal load sharing is difficult with parallel-connected rectifiers. Also, series or parallel modes require the use of fuses. This adds complexity to the mechanical arrangement.

The design of the exciter/rectifier system on a brushless machine must allow for all likely operating conditions - in particular:

1. Sudden load changes demanding rectifier currents larger than those on full load.
2. A sudden short circuit at the generator's terminals inducing a heavy current in the generator field rectifiers. If the number of poles on the a.c. exciter field is equal to, or is a triple multiple of, that of the generator, one branch of the bridge rectifier will carryall the peaks of the induced main field current. Line-to-line and line-to-neutral short-circuits cause an additional double-frequency component to be induced in the main field winding. This results in current overloads, and possible high reverse voltages, being applied to the rectifiers - albeit for very short periods, until steady-state field conditions obtain.
3. Unbalanced generator loadings which also induce double-frequency field currents and stress the rectifiers - as described in 2 above.
4. The results of rectifier failure. If a diode short-circuits, a heavy current flows in that particular arm of the rectifier bridge. Exciter output falls, the AVR winds up, and the exciter field increases. One phase of the exciter will burn out very quickly. On the other hand, if the diode should fail to an open circuit the exciter will continue to function effectively, and there is no problem in allowing the machine to run for a while with a single arm of the bridge out of circuit. The open-circuit diodes should be replaced at the next shutdown, lest worse befall. One solution often used by manufacturers is to install high speed fuses in series with the diodes - particularly, when there are two or more parallel current paths in the bridge. A diode short-circuit failure then, effectively, gives an open-circuit condition. Fuses do, however, add complication to the mechanical arrangement of the rectifier. It is desirable to have some indication of the presence of a faulty diode, so that steps may be taken

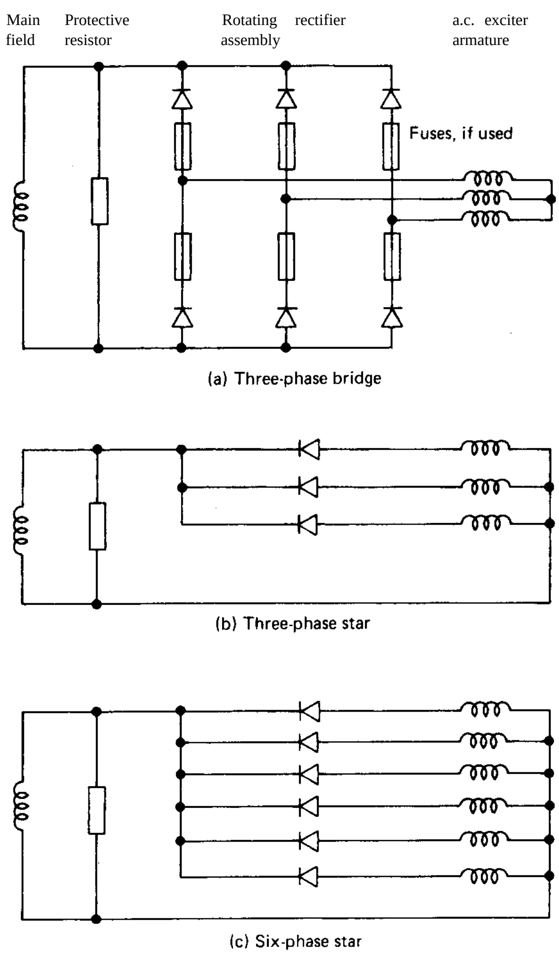



Figure 3.8 Rectifier circuits

to replace it at the next convenient shutdown period. Various methods have been employed to monitor diode failure. Two of these are described later in this Sub-section.

5. Faults in field windings, causing collapse of excitation and damage to exciters and rectifiers- unless protective measures are taken (see Section 10.4 of Chapter 10).
6. Faulty or careless synchronizing. In the severest cases, this may give rise to field currents approaching twice the value obtaining during a symmetrical 3-phase short circuit at the generator terminals. In such circumstances, the machine itself will probably suffer damage, and it would be impracticable, and unnecessary, to design the rectifier system for such eventualities.
7. Loss of synchronism when a generator, operating in parallel on a system, is either loaded beyond the limit of stability or its excitation supply or prime mover fails. In this condition, a slip-frequency voltage is induced in the rotor - in much the same way as in an induction motor. The result can be that the inverse voltage appearing across the rectifiers is very much higher than it would be during normal operation. This voltage may be limited by permanently connecting a protective resistor across the main field winding. (see Figure 3.8). The resistor should have a value approximately ten times that of the field winding resistance. It is good practice to include the resistor whenever a brushless generator is to operate in parallel with others. Since it is always in circuit, it dissipates a proportion of the exciter output and therefore reduces the efficiency of the generator - albeit, marginally. Another effective measure is to employ a surge diverter to protect the diodes against these voltage surges.

Diodes must be chosen to take due account of all these conditions and allowance should be made for the transient voltages and forward surge currents likely to be encountered.

### *Monitoring of diode failure*

A means of continuously monitoring the operating conditions of diodes, in each path of a rectifier circuit is desirable. This may be done using dynamic (direct) methods or by indirect methods.

Dynamic methods are, inevitably, complex and expensive. Their use is rarely justified on the size of machine under consideration. Stroboscopic techniques have been employed to observe the condition of series fuses, but remote observation is not possible. Paths may fail to open-circuit because of diode mechanical failure or cable breaks, and not be observed.

Relatively inexpensive indirect monitoring methods are employed on medium and large diesel-generator plants. Two are shown schematically in Figure 3.9. They make use of the fact that, when a diode fails to open-circuit (either within the diode itself or because a series fuse blows) a ripple current is induced in the exciter field as a result of the unbalanced loading of the a.c. exciter. If a single diode fails, the predominant component of imbalance is the half-wave d.c. drawn by the healthy diode in the faulty phase. A d.c. field is created in the exciter armature. This, in turn, induces a detectable ripple in the exciter field (see Figure 3.1O(a)). The ripple has the same frequency as the exciter output - its magnitude being as much as 50% of the d.c. component. A small current transformer (c.t.), whose primary is connected in series with the exciter field, is used to detect this ripple. The secondary of the transformer, which has a large number of turns of fine wire, is loaded into a high resistance, across which a neon lamp or any other suitable warning device is connected [4].

Because the voltage regulator feeding the exciter field is invariably energized from an a.c. source, a small amount of ripple is always present in the exciter field current. Its level is inherently much lower than that induced by a faulty diode. It is therefore possible to check the operation of the ripple detector by temporarily disconnecting the resistor loaded across the current transformer (Figure 3.9(a)).

In the second method [5], shown in Figure 3.9(b), the c.t. secondary is loaded into a relay which uses a finely tuned resonant circuit to detect and amplify the ripple induced in the exciter field on diode failure. The action of relay R is 'slugged' to prevent

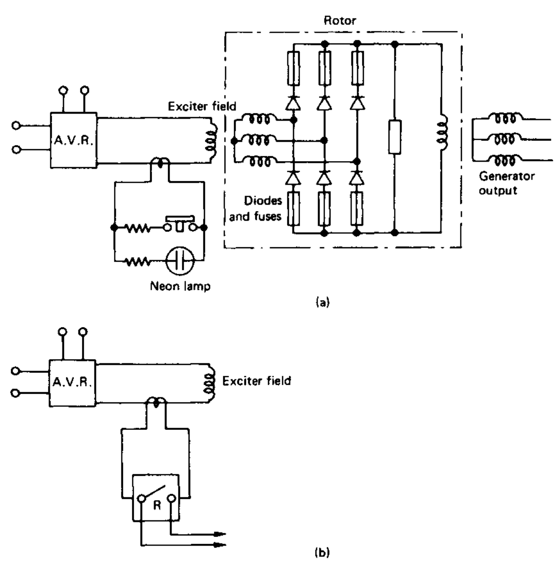



**Figure** 3.9 Indirect, diode monitoring at the exciter field circuit spurious operation by reactions in the exciter field circuit resulting from transient faults at the terminals of the main generator.

Figure 3.10(a) shows the shape of the a.c. component of the exciter field current that is imposed upon the direct current when one diode is open-circuited in the rectifier bridge. Figure 3.10(b) shows the a.c. component when one diode is short-circuited.

### 3.3.3 Construction features of brushless machines

#### *The rotor*

The shaft is either machined from a high tensile steel forging or is turned from steel bar. The latter practice usually applies to the smaller generators. Shaft stiffness is an important consideration. The shaft should be capable of coping with the peak stresses caused by torsional vibration conditions (or *torsionals)* in the rotating system - which comprises both engine and generator.

*Torsional vibration* The combined engine and generator rotors constitute an elastic shaft system - even where the generator is solidly coupled to the engine crankshaft. Imagine that the free or non-drive end of the crankshaft is rigidly clamped and constrained against movement, and that a displacement or torsional twist is applied to the generator shaft. This twist will induce a reactionary force or torque in the shaft system, tending to return it to its pre-twist position. If the generator shaft is then suddenly released the combined shaft system will oscillate (rotationally) about an equilibrium position. It will do so at a natural frequency which will be constant for that particular shaft system. Unless there is some damping influence, the shafts may continue to vibrate indefinitely.

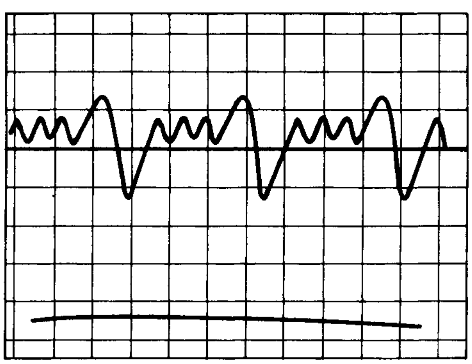
A detailed treatment is outside the scope of this chapter. The subject is usually well covered in specialized literature on engine theory and principles. The reader's attention is particularly directed to Chapter 1 of [6] and to [7].

Problems arise when the natural frequency (or frequencies) of a shaft system coincides with any impulse or forcing frequency. The engine speed at which this occurs is called the *critical speed.* As far as coupled engine-generator shafts are concerned, the major disturbing forces are those produced by the firing impulses in the engine cylinders. For example, a six-cylinder, four-stroke engine running at 1000 rpm would produce 3000 impulses/min (i.e. (6 x 1000)/2). The impulse on the crankshaft as a result of anyone cylinder firing is not just a single sinusoidal frequency occurring once per engine cycle; the wave-form is far more complex. Significant harmonics of the fundamental impulse frequency may be present, and up to 10th-order components are possible. Half-order components may also exist on four-stroke engines. All these components must be considered in the torsional analysis made to determine the critical speeds of a particular shaft system.

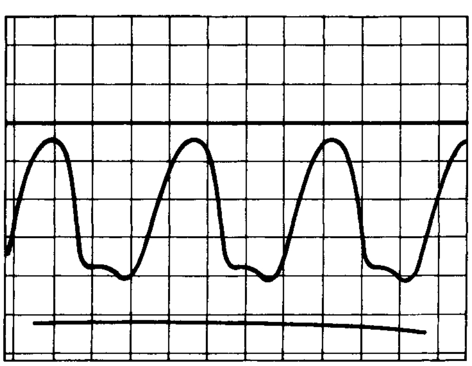
In principle, the greater the number of cylinders, and the longer the engine crankshaft, the more modes of (shaft system) vibration are possible. On constant speed applications, however, only the first two modes are usually of any significance, and impulse frequency components beyond the two-node mode are ignored.

At worst, if torsional vibrations are allowed to build-up to a large enough amplitude they mey lead to shaft fracture. Failure is unlikely to be immediate. It usually occurs as a result of stress fatigue after several hundred hours of operation at critical speed(s). Other less drastic effects, all symptomatic of torsional problems, may include:

1. excessive vibration of pipework and component support brackets - eventually leading to their failure;
2. pronounced increase of engine vibration (particularly at the non-drive end of the engine),



(a) One diode of the bridge open-circuited



(b) One diode of the bridge short-circuited

Figure 3.10 Field current of an a.c. exciter

accompanied by a general impression of rough running;
3. excessive wear on engine gear trains;
4. accelerated wear of flexible couplings in generator drives;
5. unsatisfactory parallel operation of generators.

An engine-generator combination should be analysed at the design stage to ensure that the torsional conditions of the system are satisfactory for the intended duty. The purpose of the analysis must be to identify the speed(s) at which any severe criticals will occur. Ideally, these should be far-removed from the synchronous speed of the generator, so that, on run-up, the machine passes very quickly through any 'criticals'.

The frequency of torsional vibration of a single mass system may be expressed (6] as:

$$f = 1/2\pi \sqrt{q/I} \text{ Hz}$$

where $q$ is the shaft stiffness (Nm/rad), and $I$ is the moment of inertia of the mass attached to the shaft (kg m$^2$).

For a transverse or axial vibration

$$f = 1/2\pi \sqrt{s/m} \text{ Hz}$$

where s is the stiffness per metre of deflection (N/m), and $m$ is the mass attached to the shaft (kg).

It is possible, therefore, to change the natural frequency of a system so that it will not coincide with any impulse or forcing frequencies. This is done by adjusting the values of $q$ and $I$ (or sand *m).* Significant factors in these adjustments are:

1. the size of the engine flywheel;
2. the number and size of crankshaft balance weights;
3. the material and dimensions of the generator shaft; and
4. the inertia of the generator rotor.

Most of these can be altered - albeit, with varying degrees of difficulty.

Use may also be made, in shaft systems, of viscous or hydrodynamic *torsional dampers* (also called *nodal dampers).* These dampers are fitted within the engine itself. Considerable care must be exercised in the choice of flexible couplings between engine flywheel and driven shaft. Most proprietary couplings are not designed to accomodate large misalignments between driving and driven shafts. It is important that correct alignment is made on installation. The main effect of a flexible coupling is to lower the natural frequency of a composite shaft system. But this may also introduce lower orders of vibration, with potentially high rotor stresses. A flexible coupling should, therefore, only be used after a torsional analysis has confirmed that its stiffness is suitable for the proposed shaft system.

BS5514: Part 5 (ISO 3046/5) establishes the general requirements for torsional vibrations in the shaft systems of generating sets driven by R.I.e. engines. It specifies that the 'supplier' of the set shall be responsible for ensuring that the torsional vibration conditions of the set are satisfactory. It defines the supplier as either the engine manufacturer or the manufacturer of the driven machinery (in our context, the generator) or a third contractor, who is usually a generating set assembler - in some cases this could be the user of the plant. The onus rests with the supplier to make the necessary calculations and/or measurements of torsionals in the shaft system, or to present 'torsional clearance' records from previous installations which used similar combinations of engine, generator, and coupling. This is of particular importance on marine applications where Classification Societies require evidence of calculations or measurements.

If the engine-generator combination is known to be a new one, a 'third contractor' would be well advised to ask the engine manufacturer to investigate the torsional characteristics of the proposed set - assuming, of course, that the contractor is not capable of tackling the task. The engine manufacturer will require the following information for the analysis:

1. the engine type (and its serial number, if already purchased);
2. the frame size, type and speed of the proposed generator;
3. the generator rotor details - in particular, a shaft drawing giving dimensions and material(s), rotor inertias, and the method of attachment of rotor (s) to the shaft;
4. a detailed drawing of the generator's half-coupling, indicating the method of fixing to the shaft, the number and diameter of the coupling bolts and their pitch circle diameter, the diameter of the locating spigot, and any dimensional tolerances and limits;
5. details of any flexible coupling to be used. (Note: a flexible drive coupling will be required for all double-bearing generators.)

*The components of the rotor* The rotor shaft carries the main poles and field windings, the exciter armature, and the rectifier assembly. Detailed mechanical arrangements will naturally depend upon the practice of individual manufacturers. Two types of magnetic field structure are used:

1. the salient pole type; or
2. the cylindrical (or round) rotor - also called the *smooth-core* type.

Which is adopted for a specific application depends upon the size of the machine, its speed, and the dynamic response required of the generator. High-speed turbo-generators and small diesel-generators of 2-pole or 4-pole construction employ cylindrical rotors. Lower speed hydro-generators and the medium to large diesel-generators use salient pole rotors. Figure 3.11 shows the flux patterns and highlights the differences between both types. The armature (stator) windings have been ignored, for convenience, at this stage of the description.

The field winding in the cylindrical rotor is a *distributed* winding, placed in slots, and giving a near-sinusoidal 2-pole field. The steels selected for the shaft and the poles are of low *reluctance,* as both components are in the flux paths. The magnetic quality of reluctance may be considered, for the purposes of this treatment, as somewhat analogous to the property of resistance in an electrical circuit.

*Salient pole rotors* Various constructions are used. Figure 3.12 shows typical arrangements. The pole bodies (or cores) of some 4-pole machines may even be forged integral with the shaft, and shaped by a planer. The pole shoes (or tips) are forged from high tensile steel and are bolted to the pole faces by means of tensile steel bolts. After assembly, the shoes are machined to give the correct profile face (for a graded air gap between the rotor pole and the stator surface) for a good sinusoidal output voltage wave-form.

The constructions illustrated in Figure 3.12 employ a hub (or spider) on the rotor shaft. This spider may be forged integral with the shaft, and suitably keywayed to accept the pole bodies. Alternatively, it may be made up of steel profiled plates welded together or clamped by through-studs to substantial end support (or compression) plates. The fabricated spider assembly is bored, keywayed, and mounted direct on to the shaft, as shown in Figure 3.12(b). Where rotor peripheral speeds are greater than 28 *mis,* the preferred method of assembling pole bodies to spiders is by dovetailing - using a press fit or taper keys. Some manufacturers employ T-slots instead of dovetails. Solid poles may be secured to a shaft spider using bolts only. The

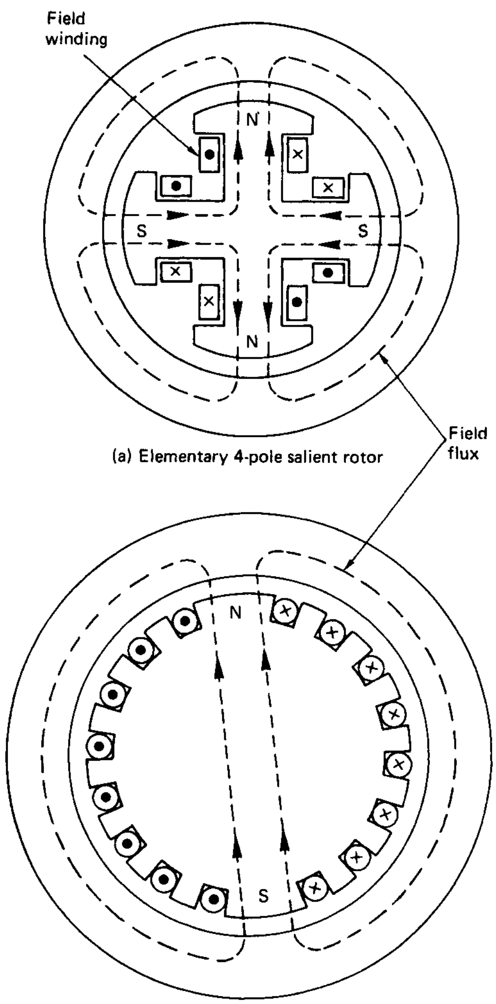



**Figure 3.11** Diagrammatic arrangements of salient pole and cylindrical rotors

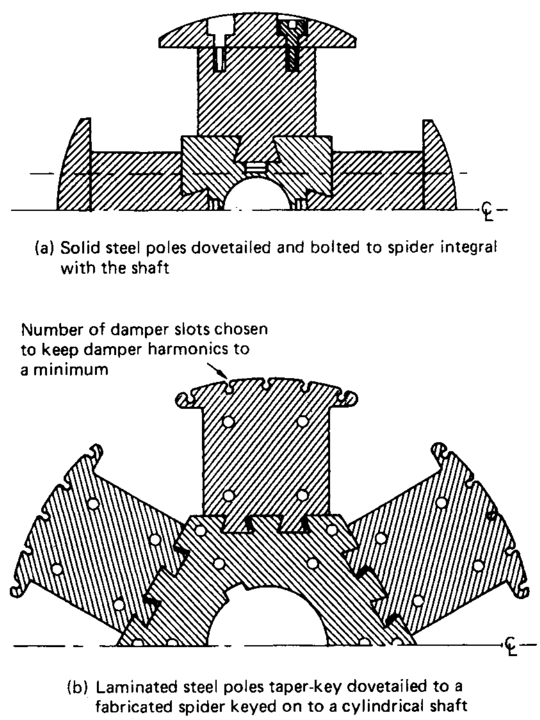



**Figure 3.12** Typical sectional arrangements of salient pole rotors

need for squirrel cage damper windings in the tip faces of laminated poles usually precludes the use of such securing bolts. See Sub-section 8.12.3 of Chapter 8 for an explanation of the purpose of *damper windings.*

On certain applications (e.g. on radio transmitter loads), a heavy spider may be constructed into the machine to give the high inertia required for the diesel-generator - especially where it is not possible to increase the mass of the flywheel on the engine itself.

Another form of rotor construction is that illustrated in Figure 3.13. The rotor core pack is built up from stampings (or laser cut laminations), each consisting of four poles in cruciform arrangement, complete with pole tips and damping winding holes. Note the ventilation ducting in the pole bodies, and the copper end-lamination (one at each end of the core pack) which is used to interconnect the pole face damping bars.

*Main field windings* The field coils on small machines, and on medium output slow speed machines, are usually formed from round or rectangular section, enamel-covered, copper wire. This is often wound directly on to the pole bodies. (See Figure 3.14.) The turns of the multi-layer coils are usually bonded to each other, and to the main glass tape insulation on the poles, with a synthetic resin. This not only strengthens the coils in the mechanical sense, but also gives good heat transfer properties. Figure 3.14 shows the cruciform rotor on a winding machine, and Figure 3.15 shows the wound rotor before it is mounted on its shaft.

The coil strength and rigidity necessary for high-speed machines is obtained from pre-formed strip-on-edge windings, using copper strip bent edgewise. The pole bodies are insulated with a resin-bonded, mica-based insulation (such as *micafolium)* built up to give the required thickness. Resin-bonded mica, or polyamide paper, may be used for inter-turn and earth insulation. Strong fabric insulation boards are used for the end flanges of the coils, and the coils are heated and consolidated under hydraulic pressure. The pressure applied must be greater than that likely from centrifugal forces at overspeed conditions.

The limiting temperature rises in a machine usually occur at the field coils. The designer's objective is to have as much copper surface exposed to cooling air as is possible, in order to improve heat dissipation from the coils. One method employed on strip-wound coils is to arrange for uniformly spaced turns (say, every fourth turn) to be extended to form cooling fins. See Figure 3.16. The fins have the effect of exposing more copper to the cooling air and also serve to stir the air as it passes over the edges of the coil turns. The individual coil turns on large machines (those with long poles) may sometimes be

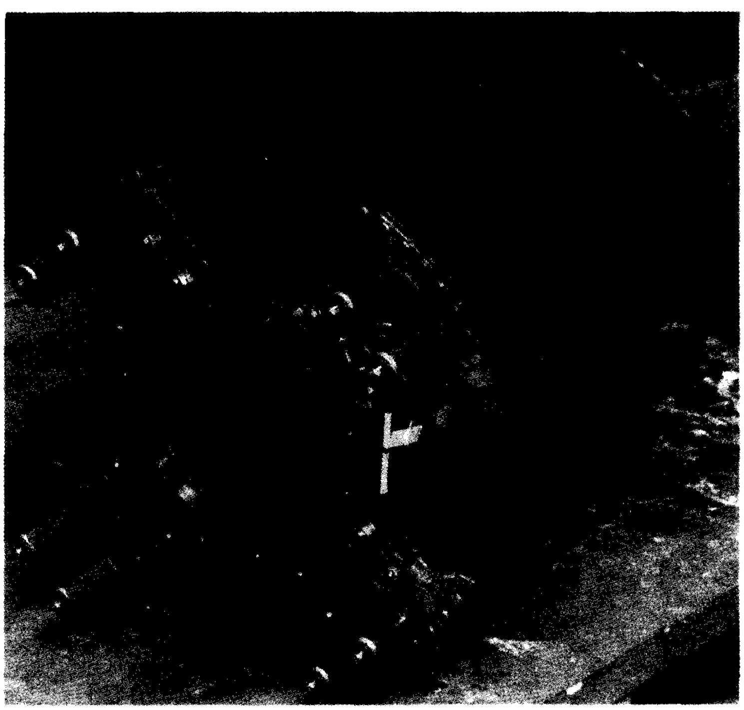


**Figure 3.13** 4-pole, cruciform type, rotor core pack (Courtesy: GEC Alsthom Large Machines Ltd.)

**Figure** 3.14 4-pole rotor on field winding machine
(Courtesy: GECAlsthom Large Machines Ltd.)

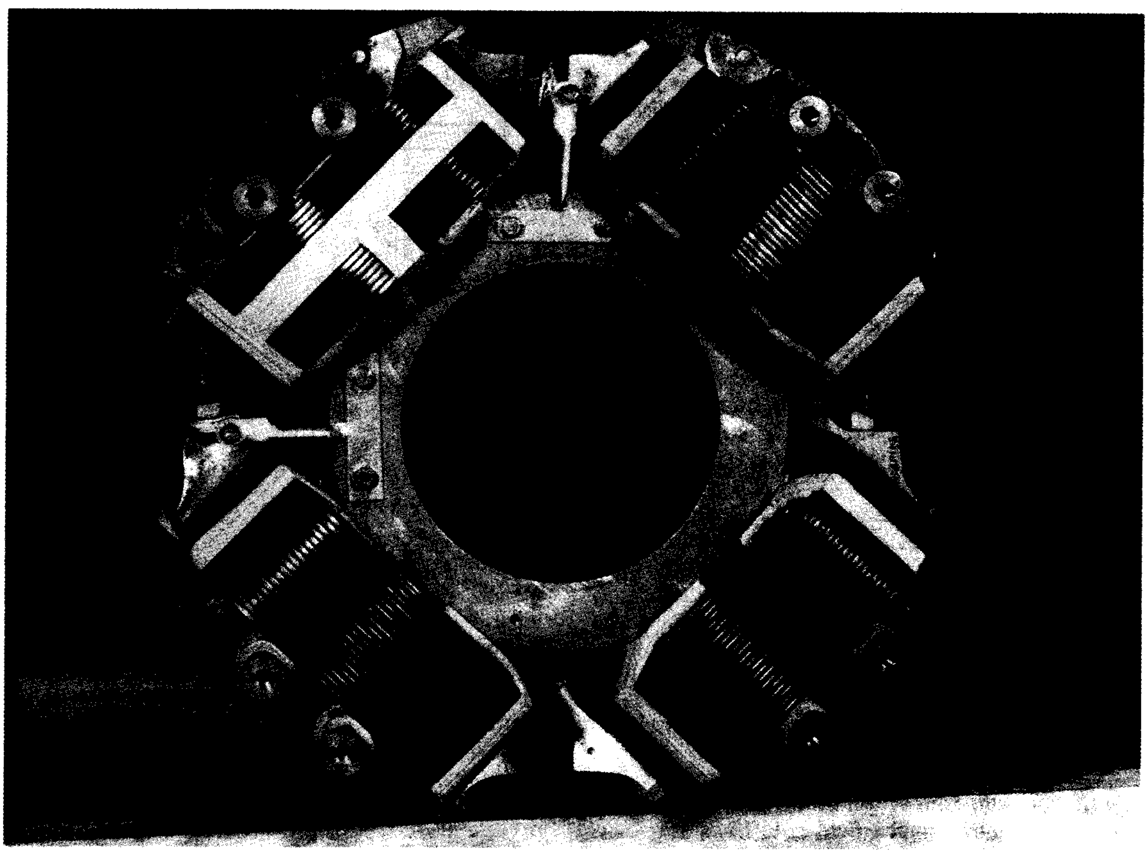


**Figure** 3.15 Wound rotor, prior to mounting on shaft
(Courtesy: GECAlsthom Large Machines Ltd.)

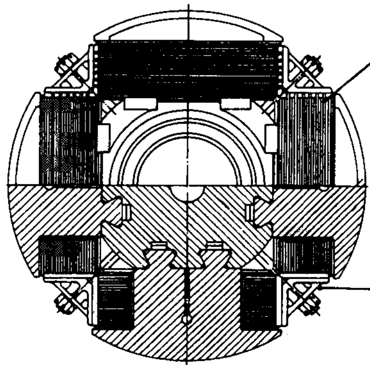



**Figure** 3.16 A typical sectional arrangement of a solid pole rotor
(Courtesy: Laurence, Scott and Electromotors Ltd.)

fabricated from copper strips, dovetailed and brazed together at the corners. It is then easier to introduce wider strips at intervals throughout the coil to provide cooling fins.

Non-magnetic wedges, or vee-blocks, may be fitted along the sides of the coils of high speed machines. They serve to constrain the tangential component of the centrifugal forces acting on the coil sides. The use of too many supports will obstruct the cooling air flow. Provision should also be made for reducing the effects of the centrifugal forces on coil ends and connections. It is usual to bring them down as close as possible to the shaft; and rigidly clamp them in position. See Figure 3.15.

*Main and auxiliary exciter arrangements* These vary with the rated output and speed of machines. Figure 3.17 shows some arrangements. Each has its own particular advantages.

Exciter armatures may be placed inboard or outboard of the non-drive end bearings - depending upon their size. The exciter stator frame may then be:

- incorporated within the main generator frame (arrangement (d));
- flange-mounted and overhung from it (arrangement (c)); or
- foot-mounted, on larger machines, either on a common diesel-generator baseframe or on separate foundation blocks (arrangements (a), (b) and (c)).

Those arrangments, such as (a) and (d) which afford maximum accessibility to the rectifier unit are to be preferred.

The non-sinusoidal wave-forms of armature current favour star connection of the exciter armature. Damper windings in the field pole faces are desirable, though not essential, as they help to reduce the commutation peaks of the voltage wave-form impressed across the rectifier diodes. For the same

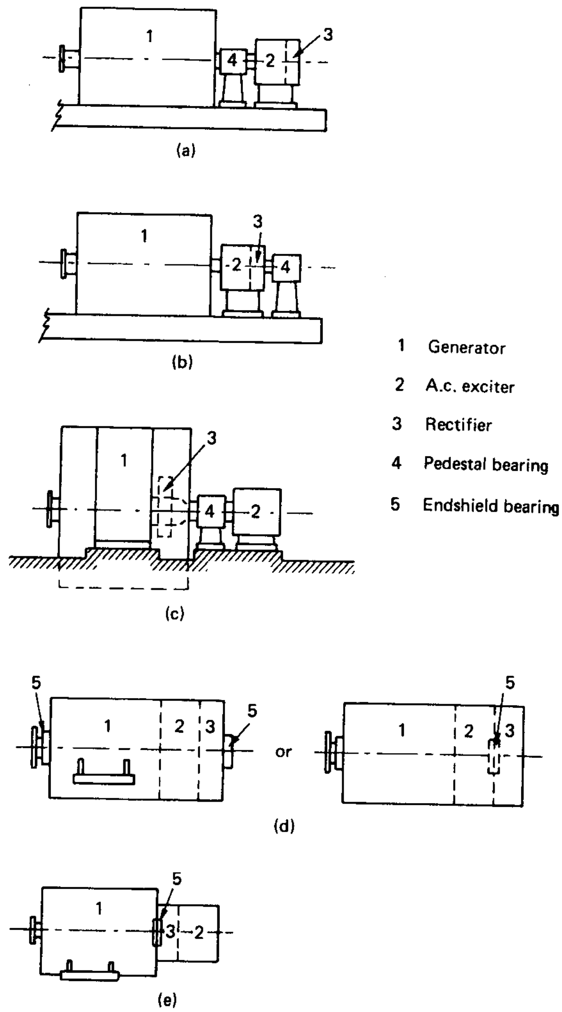



**Figure** 3.17 Mechanical arrangements of brushless generators

reason, the exciter armature slots are often skewed [8].

Figure 3.18 shows the details of an outboard a.c. exciter on a 10 MVA generator. The armature and the rectifier ring are fitted to the free end of the generator in an arrangement similar to that of Figure 3.17(a). The rotor, whose exploded view is shown in Figure 3.19, typifies the machine arrangement of Figure 3.17(d).

In order to reduce the overall length of the machine, it is possible to mount the main exciter and an auxiliary exciter within the generator carcass - preferably inboard of the endshield bearing. The machine illustrated in Figure 3.45 has an auxiliary p.m.g. exciter, and uses this form of construction. Where a separate foot-mounted exciter is employed,

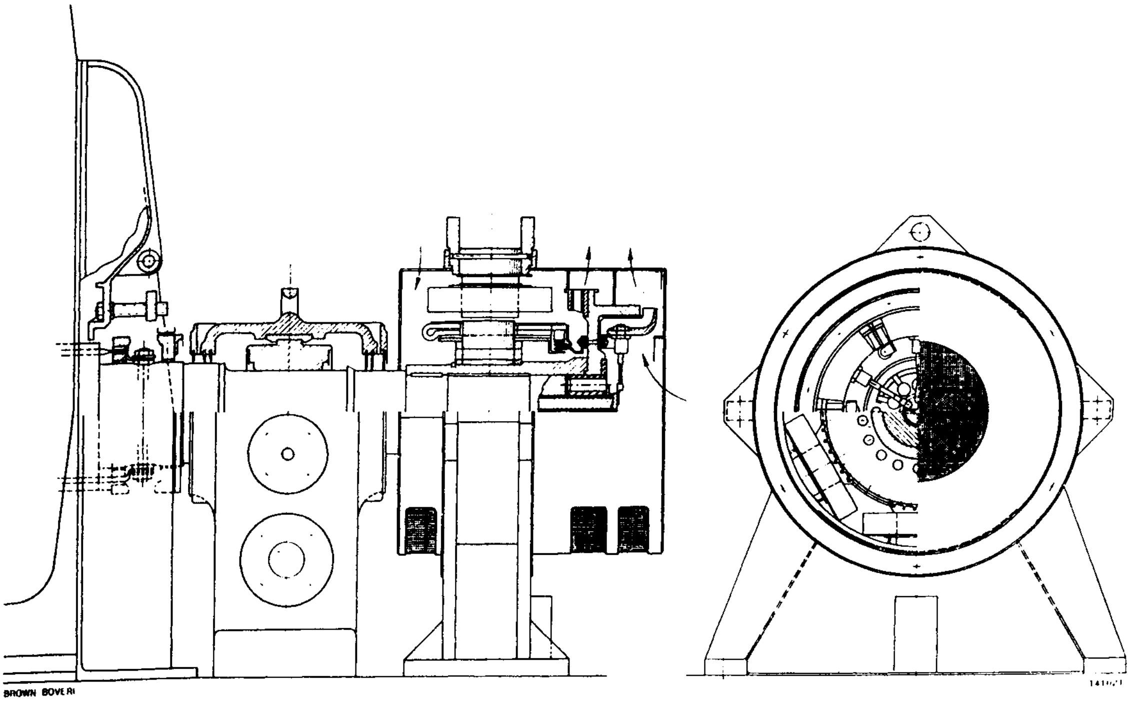



**Figure 3.18** A typical outboard exciter-rectifier arrangement (Courtesy: ABB - Asea Brown Boveri Ltd.)

the pilot exciter may be incorporated within the main exciter housing. A typical arrangement is shown in Figure 3.20. Note how the cooling air is first drawn over the rectifier assembly (nearest the drive coupling).

*The rectifier assembly* The inconvenience of shutdowns, and the difficulties often associated with access for replacement, require large safety factors on the diodes. The two considerations most affecting the design of an assembly are:

1. the requirements for cooling; and
2. the centrifugal forces likely to be exerted on the diodes.

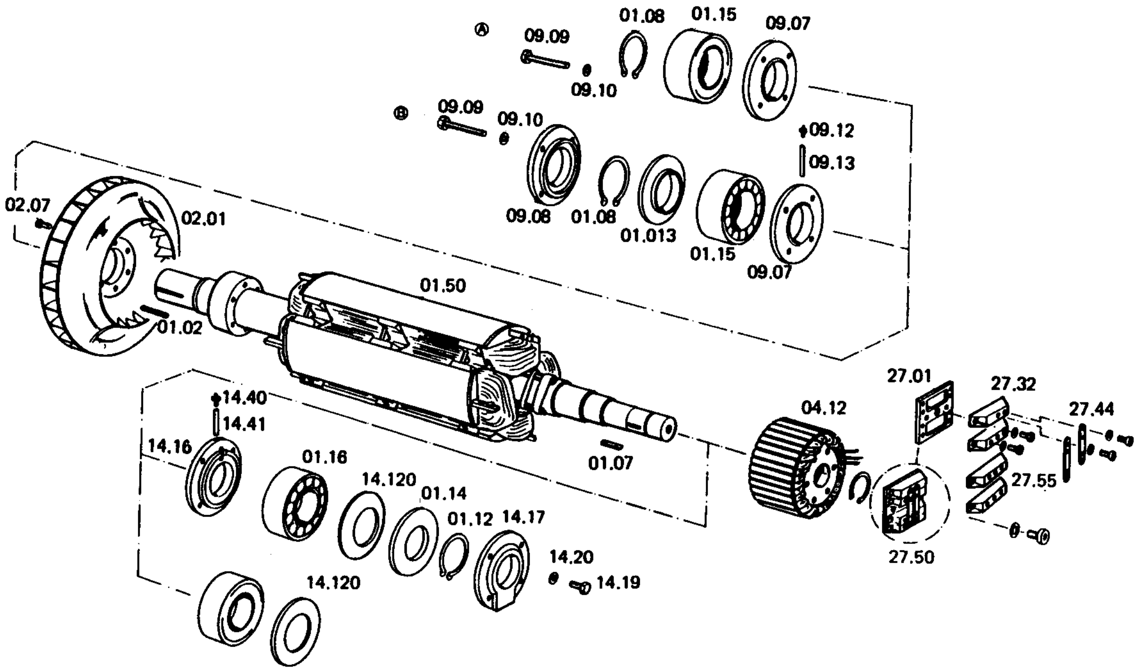
Relatively small and uncomplicated cooling fins may be fitted to rotating diodes. This is because of the generous supply of cooling air available. The fins do not need large mass and often two suffice. Due allowance should be made, however, for the thermal resistance of very thin cooling fins, because the design value of the diode's internal thermal impedance must not be exceeded.

Figure 3.21 shows a typical rotating rectifier bridge assembly. Connections are simplified by using diodes of positive and negative polarity, mounted each side of an insulated assembly plate. This manufacturer uses semi-conductor protection fuses in each arm of the rectifier on machines above a certain output.

The diode studs are radially located to ensure that the centrifugal stresses on a cell's crystals are purely compressive, and that the forces also act to press the cell base down onto the heatsink. It is also good practice to make the flexible connection to the top of the diode as short as possible, or to support the connection as near as possible to the diode. This minimizes the forces on the cell's ceramic insulator. Standard diodes, using hard solder construction techniques, are usually able to withstand the centrifugal forces and accelerations (up to 1000g) in machines operating below 1800 rpm. Where compression contact devices are used, the in-built forces on the silicon wafer (about 2200 $kg/cm^2$) are unlikely to be exceeded by the centrifugal forces. Note also, from Figure 3.21, that all the components are arranged in a symmetrical fashion, to give good dynamic balance.

The rectifier assembly is connected to the main field coils by cables either clamped to the shaft or passed through its centre - depending upon the relative positions of the coils and the rectifier. It is common practice to fit temporary slip-rings on the end of the rectifier assembly to take measurements of generator main field current and voltage during prototype investigations, and during works tests.

After final assembly the complete rotor is dynamically balanced to precision limits to ensure vibration-free running.




A) Sealed bearings, greased for life
B) Regreasable bearings

| | |
|---|---|
| 01.02 | Key, OS shaft end |
| 01.07 | Key, exciter |
| 01.08 | Circlip OS bearing |
| 01.11 | Circlip exciter |
| 01.12 | Circlip NOS bearing |
| 01.13 | Grease control ring, OS |
| 01.14 | Grease control ring, NOS |
| 01.15 | Bearing, OS |
| 01.16 | Bearing, NOS |
| 01.50 | Rotor, complete |
| 02.01 | Fan |
| 02.07 | Hex, head screw |
| 04.12 | Exciter rotor |
| 09.07 | Bearing cover, inner, OS |
| 09.08 | Bearing cover, outer, OS |
| 09.09 | Hex, head screw |
| 09.10 | Spring washer |
| 09.12 | Taper grease nipple |
| 09.13 | Grease tube |
| 14.16 | Bearing cover, inner, NOS |
| 14.17 | Bearing cover, outer, NOS |
| 14.19 | Hex, head screw |
| 14.20 | Spring washer |
| 14.40 | Taper grease nipple |
| 14.41 | Grease tube |
| 14.120 | Cup spring |
| 27.01 | Rectifier assembly |
| 27.32 | Voltage suppressor |
| 27.44 | Connection strap |
| 27.50 | Rectifier assembly complete |
| 27.55 | Rectifier module + - |

Figure 3.19 Exploded view of a rotor with inboard exciters
(Courtesy: The A van Kaick Neu Isenburg GmbH

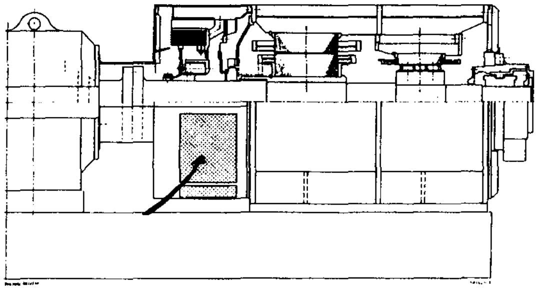


**Figure** 3.20 Typical arrangement of main and pilot exciters, with a common foot-mounted housing (Courtesy: ABB - Asea Brown Boveri Ltd)

**Figure** 3.21 One example of a rotating rectifier bridge assembly
(Courtesy: Brush Electrical Machines Ltd.)

## *The stator components*

The stationary parts of the generator comprise:

1. the main stator, which houses the armature windings of the generator;
2. the exciter stator, which carries the salient field poles for that machine; and
3. as and when required, the pilot exciter's stator, carrying the armature windings for that machine.

These elements may all be housed within the one common frame, as shown in Figure 3.45. Otherwise, separate foot-mounted enclosures are used - as illustrated in Figure 3.20; and in the mechanical arrangements of Figure 3.17 (a) to (c).

*The main stator* This consists of two parts:

1. the core or magnetic circuit; and
2. the armature windings placed in equally-spaced slots punched in the inner periphery of the rings (or segments) of the core.

*The stator core* The stator core consists of varnish-insulated, steel laminations. The laminated form is used because a solid stator would give very heavy eddy current losses (see Sub-section 4.2.1. of Chapter 4). A pre-assembled core pack of stamped or laser cut laminations, each in the form of a complete ring, may be used for small machines. The stampings are tightly pressed together and welded longitudinally along their outer periphery. The armature windings are inserted into the core slots and the complete pack is then pressed into the stator frame, where it is supported by in-built ribs, and pegged in position.

The standard widths of proprietary magnetic sheet steel limit the size of stator which can be built up in this way. Machines above 1 m in diameter generally use a segmental form of laminated construction. The core is built up of segments assembled within the stator frame, and located on axial keys or ribs. Substantial steel plates are located at each end of the core and the whole assembly is clamped into position under pressure. These endplates are usually profiled to include fingers, which project between the stator slots to support the flanks of the teeth. The resulting assembly is then rigid enough to prevent movement of the laminations under load influences and minimize noise and vibration.

The very smallest machines may still employ cast iron stator housings, but the modern practice is to use frames fabricated from rolled steel sections. Fabricated construction provides flexibilty in design by allowing a wide variety of enclosures and mounting methods.

Large machines may also use a combined stator core and frame construction of the type illustrated in Figure 3.22. The segmental stampings are assembled, under pressure, between two endplates, and on a central mandrel. Steel tie bars are welded around the periphery of the core pack while it is still on the mandrel. The endplates are extended to form supports for the stator feet. Additional stiffening rings (two are shown in the illustration) may be employed, depending upon the length of the frame.. These are welded to the tie bars and frame feet. The central mandrel is only removed when all welding operations have been completed. The bore is then machined and the endplates are faced and recessed for the endshields. This ensures that a uniform air gap is obtained between rotor and stator.

Core steel is usually of the cold-rolled, non-grain-oriented type, offering consistent mechanical

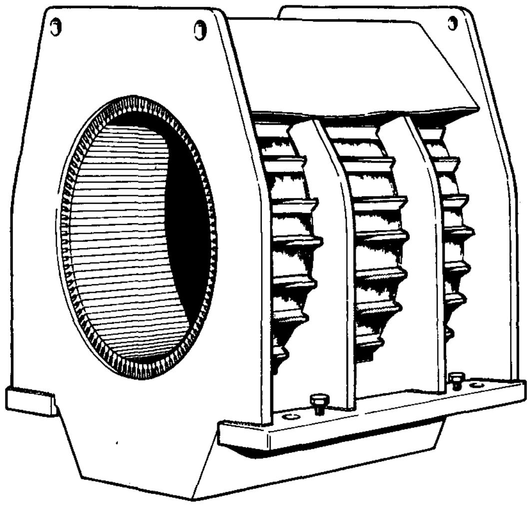


**Figure** 3.22 A fabricated stator frame/core assembly (Courtesy: Laurence, Scott Electromotors Ltd.)

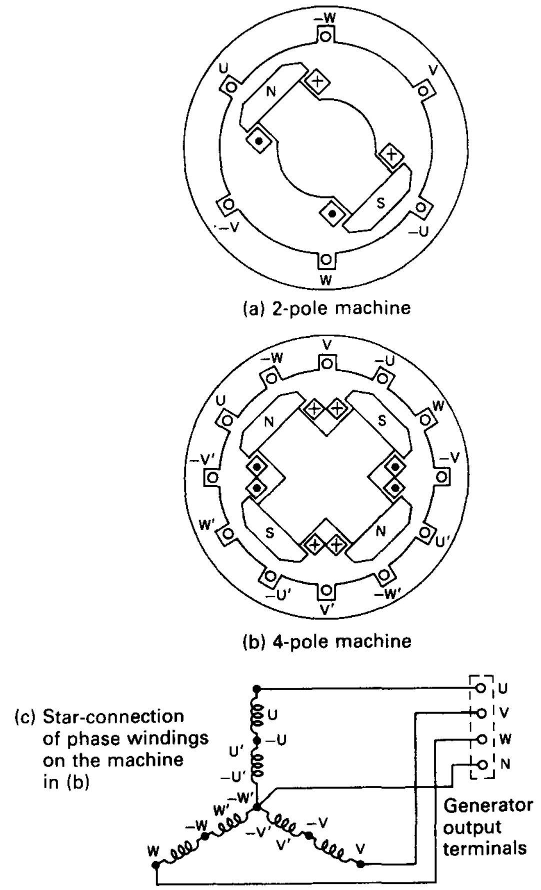



**Figure** 3.23 Elementary three-phase generators

properties, uniform thickness, and a good surface finish. Silicon content is between 2% and 5%. Higher levels would result in less ductile and more brittle steel, making it difficult to punch and shear satisfactorily during the manufacturing processes.

Radial ventilation ducts, using H or I profile 'vent spacer' laminations, are provided at regular intervals along the core length. These help to dissipate the heat generated by the iron losses (hysteresis and eddy current).

*Stator windings* A detailed exposition of the theory and practice of armature winding is outside our present scope. The subject is well covered in specialist literature on a.c. and d.c. machines. The reader's attention is particularly directed to the text-books by M.G. Say and H. Cotton (detailed in the Bibliography). Here, we shall discuss only the elementary concepts and review some of the practical features of winding design and application.

With the exception of the smallest machines (up to about 120 kVA), where single phase is offered as an option, industrial and marine generators are wound for 3-phase outputs. Diagrammatic representations of elementary 2-pole and 4-pole machines are shown in Figure 3.23. The three phases are designated U, V, and W, and end connections are omitted for convenience. The minimum number of coils required for each phase are shown, i.e. 1 per phase for a 2-pole machine, and 2 sets of coils per phase for a 4-pole machine. This implies that a *P-pole* generator must have a minimum of *P/2* sets of coils. In these elementary examples a single conductor is shown in each slot. In practice, several conductors are fitted in each slot, because windings are made from multi-turn coils.

Coils are designed to span an exact pole pitch, or less. Those of a full pole pitch are said to be *fully-pitched,* and those whose span is less than a pole pitch are *short-pitched* (also called *fractionally-pitched* or *short-chorded).* It is a feature of fully-pitched coils that they repeat themselves after every two poles. Several poles may need to be passed over before a fractionally-pitched arrangement repeats itself. Short-pitching of coils is one of the techniques used to reduce the harmonic content of the voltage wave-form generated. Others are salient pole profiling and stator slot skewing (usually, through one slot pitch).

Figure 3.23(c) shows how the two coils in each phase are connected in series to give an addition of the voltages generated in each. The 3-phase windings are usually star-connected. The common neutral point is brought out to the terminal box, giving what is called a *4-wire* output. Where specified, all six ends ofthe windings may be brought out, in which case, two terminal boxes may be provided.

Many manufacturers bring all twelve ends of the windings out to the terminal boxes of their smaller machines. It is then possible to obtain a wide range of voltages (at 50 and 60Hz, single or 3-phase) by simply interconnecting the appropriate terminals. See the charts in Figure 3.24.

A generator's output is effectively developed within the slots of the stator. The remainder of the stator merely affords a path for magnetic fluxes. In practical terms, the armature winding is *distributed* over several slots per pole. The more slots/pole/phase, the nearer the approach to a truly sinusoidal output voltage wave-form. The *concentrated* winding arrangement of the windings in the elementary machines of Figure 3.23 (using only 1 slot/pole/phase) is extremely inefficient and is never applied in practice.

Armature windings in the earliest a.c. generators were usually of the single-layer type, i.e. one stator slot housed only the conductors of one coil. Modern practice favours the use of double-layer windings. Here, the sides of two entirely separate coils are accommodated in each stator slot. One coil's side occupies the top of the slot and the other coil's side is in the bottom of that slot. Figures 3.25 and 3.27 illustrate the basic differences between the two types of winding.

*Single-layer windings* Single-layer windings are usually of the concentric type with *hairpin-shaped* coils (Figure 3.25(a)). They consist of a number of turns of insulated conductor wound in rectangular coils. The coils are inserted into semi-closed slots in the stator core. The practical difficulties of cross-over on the overhanging ends of the coils are overcome by cranking one projecting end of each coil so that it is lifted to pass over intermediate conductors. Top tier coils on one side of the stator then lie in the bottom tier on the other side of the stator (see Figure 3.25(b)). Concentric windings in course of construction are illustrated in Figure 3.26. End bracings, intended to give mechanical support for the overhanging portions of the winding (to prevent movement under onerous load conditions, and damage to the insulation), are fairly complex. One manufacturer's solution is illustrated in Figure 3.25(c).

Since the U-shaped coils are pushed into the slots from one end of the stator, it is possible to use semi-closed, parallel-sided slots of the form shown in Figure 3.25(d). The open ends of the coils are then bent into the required shape and the individual conductors are joined together, before being insulated with tape. This form of construction is expensive since it is labour intensive and requires a fair degree of operator skill. But, because of the ease with which a large number of coil turns can be secured, its choice is justified on machines generating voltages above 10kV. Concentric windings may be manufactured with fully-formed and insulated coils for insertion into open armature slots.

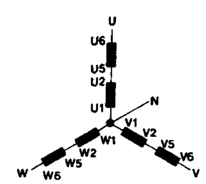
The total number of coils in a single-layer winding must always be exactly one-half the number of slots available in the stator since each slot is completely occupied by one coil side only. As a corollary to this,

**3 Phase 4 wire series star**

Generator output voltage & frequency

| FREQU.CY Hz | VOLTAGE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WINDING 1 | | | | WINDING 2 | | | |
| | PHASE PHASE | | PHASE NEUTRAL | | PHASE PHASE | | PHASE NEUTRAL | |
| | MIN | MAX | MIN | MAX | MIN | MAX | MIN | MAX |
| 50 | 380 | 440 | 220 | 254 | 346 | 400 | 200 | 230 |
| 60 | 460 | 500 | 266 | 288 | 415 | 480 | 240 | 277 |

Winding connection & arrangement

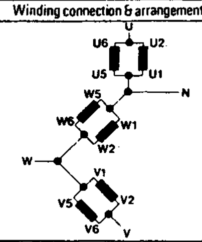



**Single phase 2 or 3 wire zig-zag**

Generator output voltage & frequency

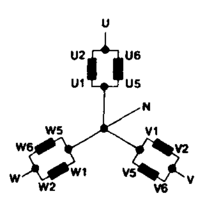
| FREQU.CY Hz | VOLTAGE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WINDING 1 | | | | WINDING 2 | | | |
| | PHASE PHASE | | PHASE NEUTRAL | | PHASE PHASE | | PHASE NEUTRAL | |
| | MIN | MAX | MIN | MAX | MIN | MAX | MIN | MAX |
| 50 | 220 | 250 | 110 | 125 | 200 | 230 | 100 | 115 |
| 60 | – | – | – | – | 240 | 280 | 120 | 140 |

Winding connection & arrangement




**3 Phase 4 wire parallel star**

| FREQU.CY Hz | VOLTAGE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WINDING 1 | | | | WINDING 2 | | | |
| | PHASE PHASE | | PHASE NEUTRAL | | PHASE PHASE | | PHASE NEUTRAL | |
| | MIN | MAX | MIN | MAX | MIN | MAX | MIN | MAX |
| 50 | 190 | 220 | 110 | 127 | – | – | – | – |
| 60 | 230 | 250 | 133 | 144 | 208 | 240 | 120 | 139 |




**3 phase 4 wire series delta with centre tap**

| FREQU.CY Hz | VOLTAGE | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WINDING 1 | | | | WINDING | | | |
| | PHASE PHASE | | PHASE NEUTRAL | | PHASE PHASE | | PHASE NEUTRAL | |
| | MIN | MAX | MIN | MAX | MIN | MAX | MIN | MAX |
| 50 | 220 | 250 | 110 | 125 | 200 | 230 | 100 | 115 |
| 60 | – | – | – | – | 240 | 280 | 120 | 140 |

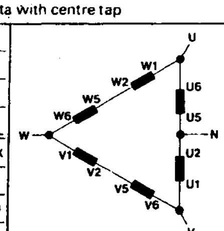



**Figure** 3.24 A typical single- and three-phase connection chart for a series of small generators (Courtesy: Brush Electrical Machines Ltd.)

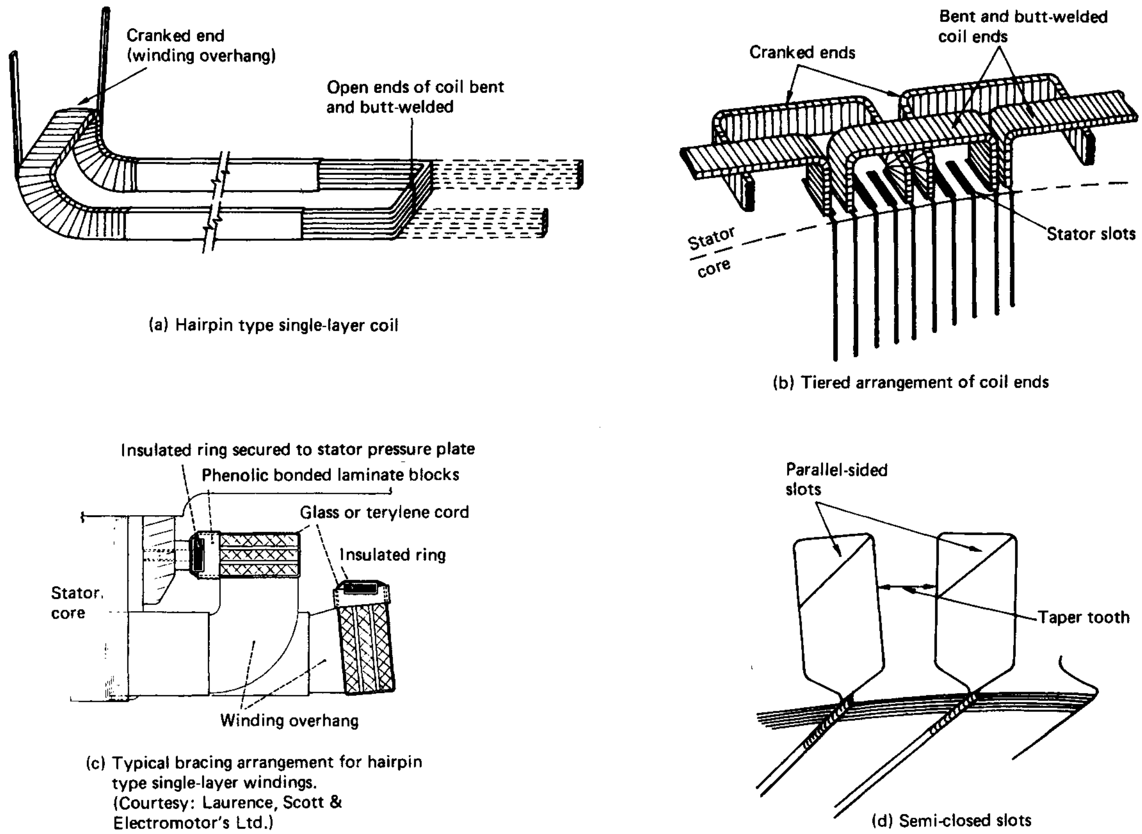



**Figure** 3.25 Single-layer coil illustrations

the number of stator slots per pole per phase must always be a whole number (an integer). For this reason, the single-layer winding is often referred to as an *integral-slot,* or *integral-pitch,* winding.

*Double-layer windings* The commonest form of double-layer winding uses 'diamond' shaped coils of the type shown in Figure 3.27(a). Each coil consists of several turns of insulated conductor wound into a flat loop. The diamond form is obtained by using a coil shaping machine. The two sides of the coil are clamped in the machine, which then pulls them apart and twists them to the angle required by their final span positions in the stator periphery slots.

Where the coils are fitted into open slots (the usual practice on high voltage machines - see Figure 3.27(d)), insulation is applied to them before they are inserted into the stator core. Then, following impregnation, the insulation on the slot portions of the coils is reinforced using a hot-wrap process in which each turn of tape is applied under tension and 'ironed' onto the coil. This insulation is consolidated by heating the coil sides in a press, the object being to obtain as good a fit as possible in the stator slot.

The overhang portions of heavy coils are bent up to form end loops (see Figure 3.27(c)). These afford a ready means of supporting and securing the overhangs, off bracing rings attached to the stator frame, by insulation brackets. The bracing rings are usually of glass fibre or a phenolic-bonded laminate. While the arrangement in Figure 3.27(c), and the illustration in Figure 3.28 show two bracing rings, it is not unusual to employ just one ring.

Wedges are used to anchor the coil sides into the slots. Where the machine design requires the flux pattern of a semi-closed slot, the wedge may be of the ferrite-loaded, fibre board type.

Whereas a single-layer winding has an integral pitch, it is not uncommon to find fractional-slot, and short-chording, arrangements in double-layer windings, i.e. the number of slots/pole/phase is not a whole number, but a fraction. Be they of integral- or fractional-slot form, the number of coils in double-layer windings must always be equal to the number of slots - in a uniformly slotted stator. On single-layer wound machines with odd numbers of pole pairs (e.g. 6, 10 or 14 poles) it is necessary to

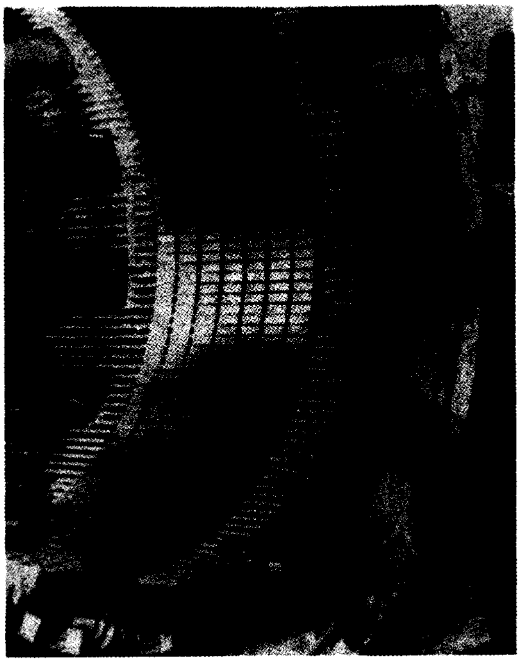


**Figure** 3.26 Hairpin stator winding, in course of construction (Courtesy: Laurence, Scott Electromotors Ltd.)

introduce a special set of cranked coils in one position on the stator periphery. On double-layer windings, however, the coils on a machine are always alike. Stator construction is therefore very much simpler than for single-layer coils. For this reason, modern practice favours the diamond winding, with its coils arranged in two layers in open form slots (see Figure 3.27(b)).

*Exciter stator components* The output windings of the p.m.g. auxiliary exciter (where applicable) and the (input) field windings of the main exciter are usually located close to each other. Several arrangements are possible. They may be mounted:

1. within a common, free-standing housing (Figure 3.17 (a) to (c) and Figure 3.20);
2. within a single, rolled steel, barrel frame which is flange-mounted to the non-drive endshield of the main generator frame (Figure 3.17 (e»; or
3. within the main frame itself (Figure 3.17(d) and Figure 3.45).

*A.* C. *exciter field windings* The a.c. exciter is an 'inverted machine', in that it is a rotating armature generator, with a stationary field system. The field windings may be wound onto salient poles or distributed in slots. The exciters of medium and large generators invariably employ salient pole systems. This is because of their better residual magnetic properties and the higher power amplification they give. The salient poles are usually of laminated construction to improve the time constant of the exciter and, with it, the overall transient response of the generator. Where the speed of voltage build-up is of importance, permanent magnet inserts may be used in the interpolar spaces to boost the residual magnetism. Occasionally, damper windings are fitted to the exciter pole faces. Their purpose is two-fold:

1. to alleviate the effects of the, inherently non-sinusoidal, exciter armature current wave-forms; and
2. to help reduce the commutation peaks impressed across the rectifier diodes [8].

Induction frequency-converters are also employed as a.c. exciters, but their use is largely confined to brush less synchronous motors and to special-purpose generators which are required to operate over a wide range of frequencies [8].

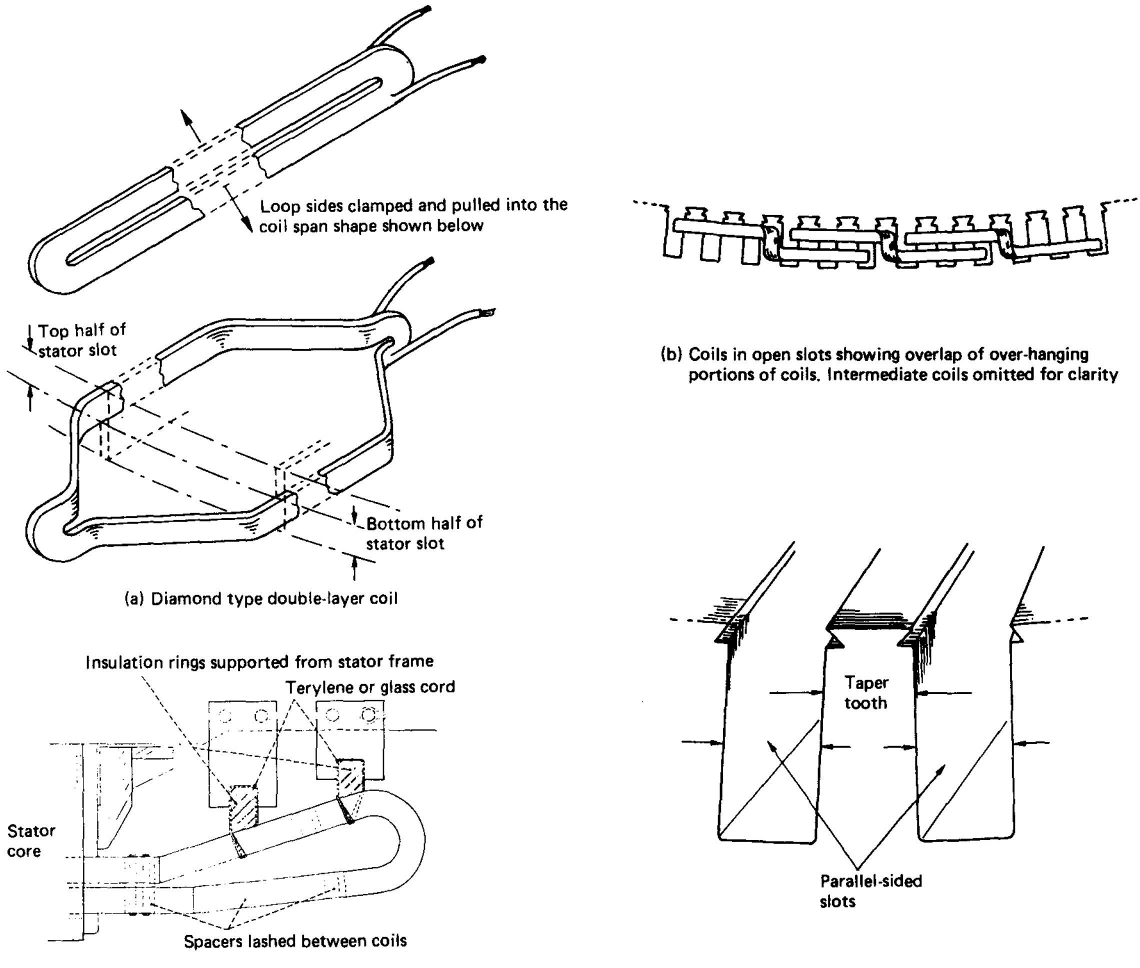
### 3.3.4 Compounded machines

We have established (in Sub-section 3.2) that, if the terminal voltage of a generator is to be kept constant as more load is applied to it, its excitation current must be increased to overcome the internal voltage drop within the machine. This voltage drop is largely due to the total reactance of the armature winding. In a.c. generator terms, this is the machine's *synchronous reactance* (see Sub-section 4.2.6 of Chapter 4). The induced voltage drop is greater for lagging power factor loads than it is for unity and leading power factor loads. Clearly, therefore, any additional excitation required to cope with increased load must be related to both the magnitude and the power factor of the load.

The load/voltage characteristics of shunt and compound wound d.c. generators are similar to those of direct self-excited and compounded a.c. generators. The current compounding systems of the latter are similar to those of the compound wound d.c. machine, in that they also employ shunt and series excitation circuits.

#### *Operating principles*

Compounding or self-regulating systems are basically designed to supply the field windings of the a.c. generator with a rectified current, derived from the vectorial addition of no-load and on-load components. The no-load component, obtained from the *shunt* (output voltage fed) circuit of the compounding system, is proportional to the generator's terminal voltage, and is independent of load. The on-load component is provided from a *series* (load current fed) circuit and is proportional to load current. Its spatial relationship to the no-load component is determined by the power factor of the load. The difference between the many proprietary




(a) Diamond type double-layer coil

(b) Coils in open slots showing overlap of over-hanging portions of coils. Intermediate coils omitted for clarity

(c) Typical bracing arrangement for double-layer coils (Courtesy: Laurence, Scott Electromotors Ltd.)

(d) Open slots

**Figure** 3.27 Double-layer coil illustrations

systems is the manner in which the vector relationship of the two excitation current components is obtained. This will become evident as we examine details of particular systems.

The basic system is that shown schematically in Figure 3.29(a) - supported by the phasor diagrams of Figure 3.30 [9]. The main field rectifier MR derives its supply from two paralleled sources. The shunt source is the output voltage from the terminals of the generator. The circuit includes an air-gap reactor $L$ and the capacitor C. The series source is the secondary winding of current transformer CT, whose primary carries the generator load current. If the two sources are reasonably matched, they may be regarded as supplying separate excitation current components, through MR, to the generator's field windings.

The action of the shunt circuit is best described by reference to the so-called Boucherot circuit of Figure 3.29(b). The load is shown as purely resistive. This is a valid proposition, because the rectifier and the field winding act, in combination, as a pure resistance in the context of the a.c. input to the rectifier. If the inductor $L$ and capacitor C have equal impedance values at the generator's rated freauencv, the load current is:

$$I_L = V_T/(R + j\omega L - \omega^2 LCR) \text{ [where } \omega = 2\pi f]$$
$$= V_T/j\omega L \text{ because } \omega^2 LC = 1 \text{ for an } L\text{-}C \text{ series resonance condition.}$$

For all practical purposes, the load current h is independent of the load resistance, is proportional to the applied voltage $V_T$, and lags 90° behind it. It is also inversely proportional to the frequency. This

**Figure 3.28** A double-layer 11 kV diamond winding in progress, with two bracing rings (Courtesy: Laurence, Scott Electromotors Ltd.)

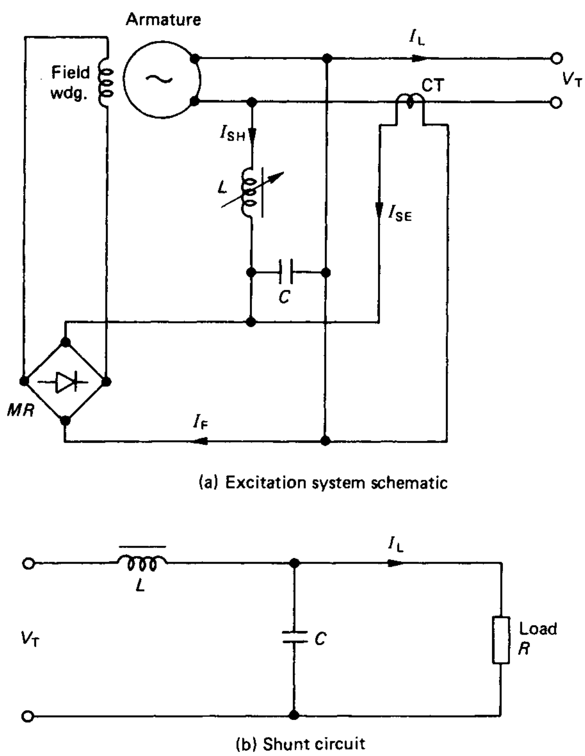



**Figure 3.29** Current-compounded excitation system for a single-phase generator

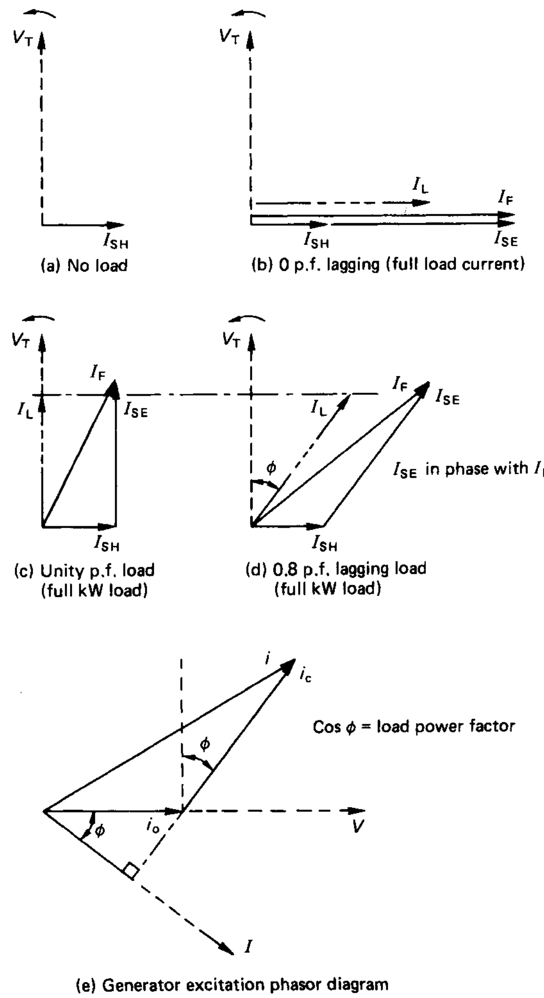



**Figure 3.30** Excitation current phasor diagrams

means that, as the generator's speed is increased, the shunt circuit automatically reduces the excitation (in proportion) and tends to maintain a constant terminal voltage. If we relate these conclusions to the circuit of Figure 3.29(a), we see that the shunt circuit supplies the rectifier **MR** with current which is proportional to (and lags 90° behind) the generator's terminal voltage. When the generator is unloaded, its excitation current is supplied from the shunt circuit only, and is proportional to the terminal voltage (see phasor diagram (a) in Figure 3.30). The value of the excitation current, in this condition, may be obtained from the generator's open-circuit characteristic (see Sub-section 4.2.6 of Chapter 4). It is then a relatively simple matter to determine the reactance required to give the level of field current $i_{SH}$ for rated terminal voltage $V_T$. The open-circuit terminal voltage is preset, on the testbed, by adjusting the air-gap in the inductor's magnetic circuit. Since the inductor's reactance is about four times the generator field resistance, voltage variations associated with self-heating of the field windings are virtually eliminated.

It is possible to exclude the capacitor from the shunt circuit, but this would necessitate increasing the size of the inductor to give a reactance value some 20 times the effective field resistance. The voltage amplification characteristics of the *L-C* series arrangement (the Boucherot resonant circuit) also ensures that the generator's residual voltage is rapidly built-up to its no-load l~vel. Some other means of initiating self-excitation would be needed if the circuit is omitted. Typical alternatives are: *field flashing,* from a separate d.c. supply source, or the use of a p.m.g. pilot exciter.

The need for an early and positive voltage build-up stems from the non-linear characteristic of rectifiers at low a.c. voltages. The forward voltage drop within the rectifier needs to be 'overcome' before a d.c. output is obtained from the rectifier.

We have seen that the shunt circuit provides a constant excitation current component ($I_{SH}$) which approximates to the generator's open-circuit excitation. When the machine is on load, a current component $I_{SE}$, directly proportional to the load current, is also fed to the main field rectifier from the secondary winding of current transformer CT. Since both are a.c. components, the resultant field current $I_F$ is their vector sum. Whereas the phase relationship between $I_{SH}$ and $V_T$ is fixed, that of $I_{SE}$ relative to $V_T$ will vary with the power factor of the load.

The 'polarities' of the connections are arranged to give the correct excitation for the e.m.f. required to maintain the terminal voltage at the desired value, at any load and power factor. The phasor diagrams of Figure 3.30(a) to (d) show the variation in excitation current for different power factor conditions. Note the close similarity of diagram (d) to the generator excitation diagram (e) which has been simplified by neglecting saturation and saliency. In diagram (e), *i* (the field current on load) is the sum of two components:

1. a no-load or shunt component $i_o$ which is proportional to terminal voltage, is independent of load, and is the image of the internal e.m.f. of the generator; and
2. a load or series component $i_c$ which is the excitation on short-circuit, and is the image of the *armature reaction.* See Sub-section 4.2.6 of Chapter 4.

A 3-phase version of the circuit in Figure 3.29 is normally used for 3-phase machines, but it is possible to use a single-phase excitation circuit (as shown) on small machines, when balanced loads are assured.

Static excitation systems of this type are called *functional* or *open-loop* systems. Unlike generators fitted with AVRs using error-operated feedback and self-correcting systems, compound machines are not aware of the accuracy of their voltage regulation performance and are unable to correct themselves.

Certain parameters (such as load current, power factor, prime mover speed, machine temperatures, and hysteresis) will call for detailed consideration at the machine's design stage to ensure that proper proportioning of the various self-regulating components, to one another and to the machine, is closely controlled. Should the machine's excitation requirements then vary from the predetermined design precepts as a result of changes in any of these parameters, the voltage regulation wiJI be affected. In practice, various operational factors may introduce errors, so that the voltage is not held constant at all load levels. Nevertheless, it is possible to achieve between 3 and 5% regulation with self-regulated compound machines of this type. A subsidiary, closed-loop system may be introduced - using a small AVR to trim the generator's excitation - where tighter voltage control is required.

## *Examples of compounded systems*

The common feature of all proprietary machines is that they have excitation systems that are partly voltage-fed, and partly current-fed. The chosen examples illustrate arrangements that are basically 'functional', but incorporate a closed-loop element to give greater accuracy of voltage control.

*Siemens constant-voltage generators* These machines, available in outputs up to about 1.5 MVA, have been widely used in marine installations - on cargo vessels in particular, where auxiliary machinery (e.g. multi-speed winches, windlasses, pumps, fans, and separators) forms a large part of the ship's load. It is critical that the voltage reductions caused by the direct-on-line switching of the (comparatively large) induction motors driving these auxiliaries are kept to a minimum; and are redressed in the shortest possible time. Operational and economic factors govern the capacity and physical size of shipboard generators. Great care is therefore needed in the selection of machines required to cope with the heavy current surges imposed by these loads. See Sub-section 5.4.1 of Chapter 5.

The load-dependent excitation system used in the Siemens machines is based on a circuit developed by Dr. Harz in the 1930s (see Figure 3.31). It consisted of:

- a 3-winding compounding current transformer (1);
- a voltage circuit reactor (2), with associated voltage build-up capacitors (3); and

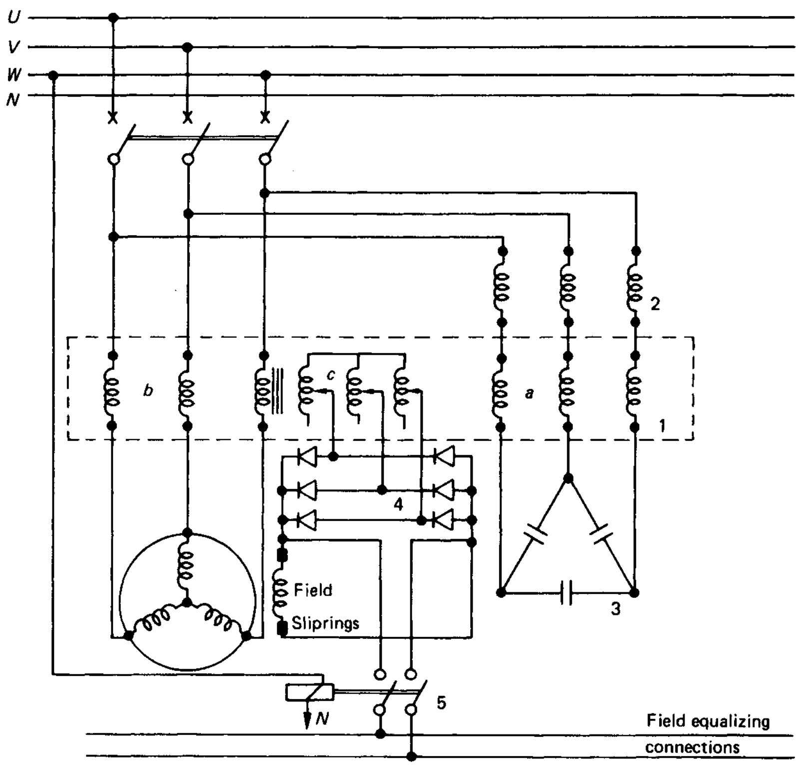



**Figure** 3.31 Load-dependent excitation system for a constant voltage generator (Courtesy: Siemens PLC)

- a 3-phase, bridge-connected, excitation rectifier (4) which fed the generator's rotating field windings through slip-rings.

The no-load excitation current is supplied by the reactor (2) which is in series with primary winding 'a' of the compounding C.t. (1). The on-load component is derived from the load current passing through the other primary winding 'b'. These two components are (vectorially) added in the secondary winding, 'c', of the compounding transformer. The resultant current is rectified (in (4», and fed to the generator field windings. The capacitors (3) are tuned for resonance with the reactor (2), at rated speed, to initiate self-excitation of the generator. This also ensures that the excitation current is independent of the combined resistance of field windings and rectifier, and is therefore unaffected by temperature rises within the windings. Since the load current in each phase acts independently in the excitation system, there is minimal deviation between phase voltages when the machine operates on unbalanced loads. Voltage regulation of ±2.5 % was achieved by machines using this excitation system.

If identical machines were operated in parallel, the circuit arrangement shown in Figure 3.31 was used. The field windings were connected in parallel through small contactors (5) by means of equalizing leads. The contactor coils were energized through auxiliary contacts on the generator circuit breakers. A 3-pole contactor was used to parallel the 3-phase voltage windings of the compounding transformers on machines of dissimilar rating.

In keeping with the modern trend, this manufacturer's generators now employ brushless excitation. They retain the self-excitation arrangement of the earlier machines but augment the system with a thyristor voltage regulator acting in a 'bucking' control mode to maintain constant output voltage (see Figure 3.32). This combination of load-dependent excitation and thyristor regulator is registered by the Company under the trade name of *Thyripart.*

The elements of the static excitation equipment (items 1 to 4) are as those in the scheme of Figure 3.31. Section 5a of the thyristor voltage regulator (5) contains the measurement and control circuitry. This includes a voltage set-point potentiometer which provides ±5 % stepless variation of the output voltage for load power factors between 0.8 lagging and unity. The plug (7) enables the use of a remote potentiometer for the same purpose. Section

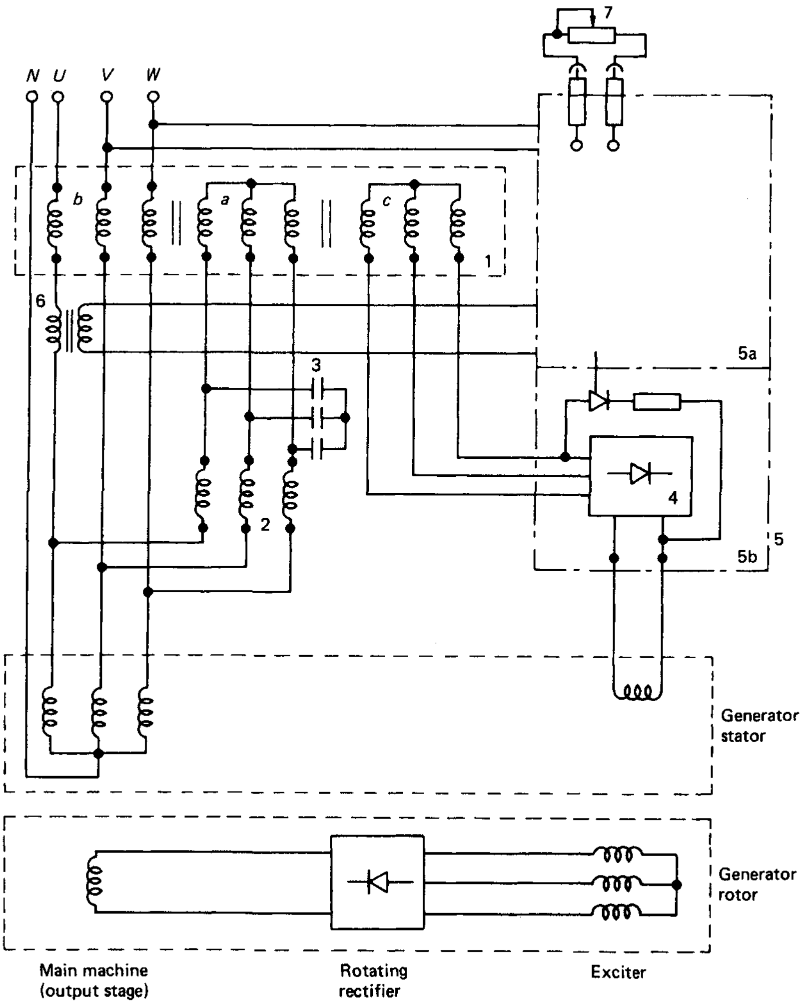



**Figure** 3.32 Block diagram of a load-dependent excitation system applied to a brushless generator (Courtesy: Siemens PLC)

5a also houses a voltage droop setting potentiometer, connected across the quadrature current transformer (6). It is used when the machine is required to share reactive load during parallel operation with other generators or with a utility supply. See Section 8.8 of Chapter 8. The field equalizing connections of Figure 3.31 are not needed.

Section 5b of the regulator contains the exciter field rectifier (4). The 'bucking' resistor and thyristor, in parallel with the excitation circuit, serve to reduce the field current to the exciter. The control circuit in Section 5a ensures that the current passed by the thyristor is proportional to the machine's terminal voltage. When large loads (causing dips in output voltage) are connected, the gate control circuit in 5a operates to block the thyristor so that no current flows through the parallel circuit. This arrangement gives an excellent transient response to large impacting loads. Should the regulator fail, for any reason, the bucking characteristic ensures that the terminal voltage rises above the maximum set point by only a very small percentage. The steady-state regulation is ±0.5 % from no-load to full-load, at rated power factor. It widens to ±2.5 % in parallel operation ..

The a.c. exciter acts as a rotary power amplifier in supplying excitation to the main field windings. The ratings of the static excitation components (1 to 4) are considerably lower than those for the earlier machines of Figure 3.31. In fact, the components are

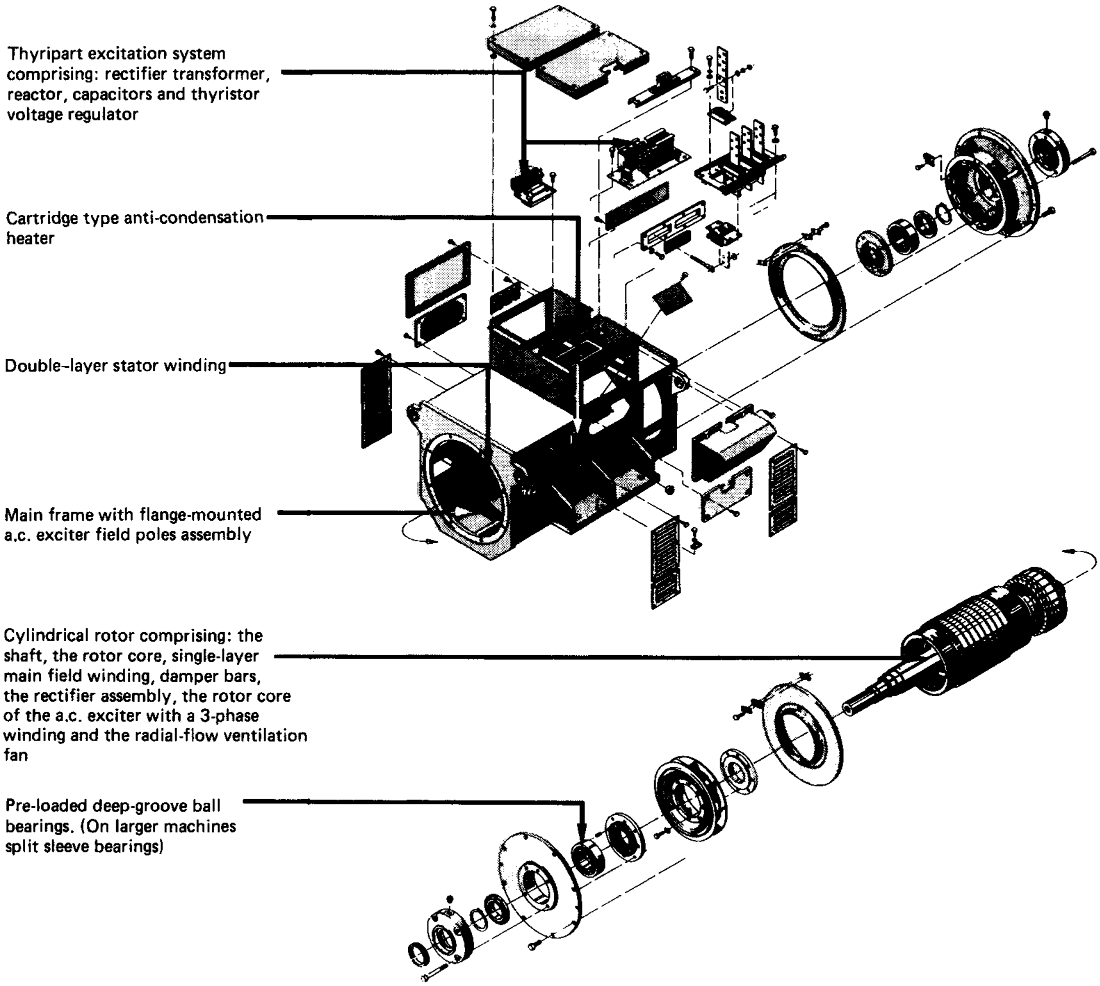



**Figure** 3.33 Exploded view of a series 1FC6 compounded. brushless generator (Courtesy: Siemens PLC)

small enough to be accommodated within a casing on top of the machine housing (see the exploded view of Figure 3.33).

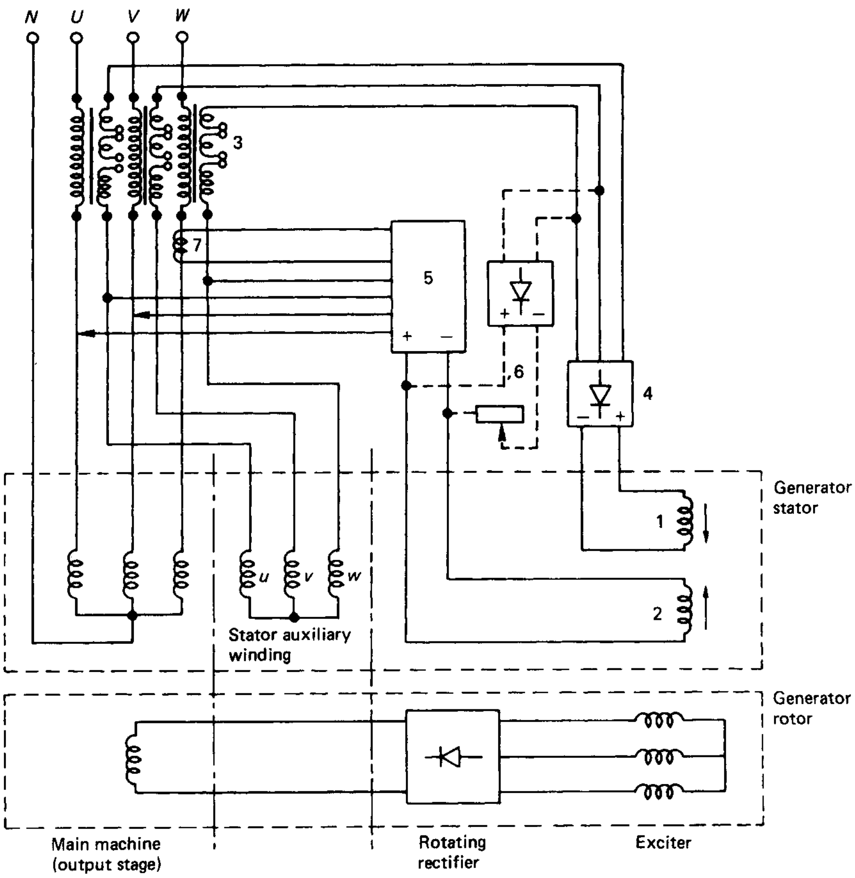
*Leroy-Somer compounded brushless generators* These machines are available in ratings up to 1.8 MYA. The principles of operation are illustrated in the block schematics of Figure 3.34.

The a.c. exciter has two field windings:

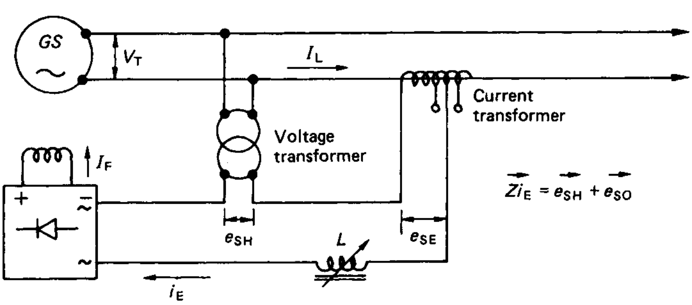
1. a compound winding (1); and
2. a regulation winding (2).

The first takes the form of an auxiliary winding within the main stator core pack. It is wound in the same slots as the main armature winding, but has a different slot pitch, so that it effectively acts as a voltage transformer in the system. The input voltage to the 3-phase rectifier bridge (4) is the vectorial addition of the 'shunt' voltage, supplied by this auxiliary winding, and a 'series' voltage induced in the secondary windings of the current compounding transformer (3). This transformer has its primary connected in series with the main stator winding. It has an adjustable air-gap and a tapped secondary winding which also acts as a variable inductor.

Diagram (b) of Figure 3.34 shows the basic single-phase equivalent of the compounding field circuit. $e_{SH}$ and $e_{SE}$ are the induced shunt and series voltages, respectively; and Z is the equivalent impedance of the field circuit. $L$ represents the secondary windings of the compounding transformer (3) in




(a) Compound excitation system of Leroy-Somer type ARES generator




(b) Single-phase a.c. compound system

**Figure** 3.34 Block diagram of a compounded, brushless generator, with two exciter field windings (Courtesy: Moteurs Leroy-Somer Ltd.)

diagram (a). The excitation for the compound field is pre-adjusted so that it is maintained at a higher level than that required for rated voltage at rated load.

The regulation winding (2) of the exciter field gets its supply from the stator auxiliary winding through the AVR (5). The polarity of winding (2) is arranged so that the current flow within it is in the opposite direction to that in the compound field winding. This gives the subtractive (or bu.cking) effect, partially countering the compound field and reducing the machine's output voltage towards its nominal value.

A useful feature of the machines is their ability to operate in manual control (albeit with coarser regulation) using the compound excitation circuit only, should an AVR fail. The manual circuit (6), shown dotted in diagram (a), consists of a rectifier bridge and a control rheostat connected to the regulating field winding.

Voltage droop settings for parallel operation are made by trimming an injector resistor connected across the secondary terminals of the quadrature current transformer (7). See Sub-section 8.8.1 of Chapter 8 for an explanation of quadrature current compensation. If parallel operation with an identical machine (i.e. one of the same type and power rating) is required in the 'manual' mode, the regulators of both machines should be disconnected and the like-polarity terminals of their compound field windings interconnected. A 10 ohms, 40 watt resistor should be connected between the two positive terminals.

Voltage regulation on these machines is ±2 %, independent of load conditions and of machine temperature rise. An internal trimmer gives ±5 % adjustment of terminal voltage.

*Current-compounded rotating armature machines* On the very smallest 2-pole and 4-pole generators (up to about 20kVA rating), it is not uncommon to find an 'inverted' machine arrangement. The field windings are stationary and secured to the stator frame, and the armature is carried on the shaft, with output leads brought out to a slip-ring assembly. These low-cost machines offer simplicity in operation and good reliability. Their excitation systems are of the open-loop, self-regulating type using transformer/rectifier units which derive their power from the generator's output terminals. The systems are similar to that shown in Figure 3.31. They are frequency sensitive, and output voltage varies proportionally with speed from one-half rated speed upwards. This characteristic makes them 'prime mover friendly', since driving engines are able to recover speed after large load steps, e.g. high starting torque motor loads. Brush gear and slip-rings are the major maintenance points, and need regular attention in dusty and oil-laden atmospheres.

## 3.4 Insulation

Apart from a negligible loss due to electromagnetic radiation, all the power losses in machines are converted into heat. See Sub-section 4.2.1 of Chapter 4. The heat generated has the effect of raising the working temperatures of the various parts of the machine above their surroundings. One of the designer's tasks is to engineer the machine's enclosure and its ventilation system to dissipate or remove the heat. On first start-up, heat losses are stored within the machine itself. Power losses increase with load, until a steady-state temperature is reached. The rate of internal heat production, and its transfer to the cooling medium (by a combination of radiation, conduction and convection), are then balanced. This may take several hours on large machines. The rating of the machine is determined by that load level at which the steady-state temperatures equal the permissible working temperatures of its component parts. Its output can only be enhanced by improving its cooling system or the heat-resisting properties of its electrical insulation.

### 3.4.1 Temperature rise

*Temperature rise* is defined as the difference between the machine's steady-state temperature and that of the incoming cooling medium, at rated output. For all practical purposes, it is constant - regardless of the cooling medium's incoming temperature. For example, if, on works tests, a 60°C steady-state temperature was recorded against an inlet cooling air temperature of 25°C, the rise would be 35°C. If the same machine were to operate in tropical conditions where the inlet air temperature was 45°C, the temperature rise would still be 35°C - giving a final steady-state temperature of 80°C.

The temperature rise limits in windings and other parts of machines are directly related to values of maximum continuous temperature assigned by National and International Standards authorities to various classes of insulating materials. See Table 3.1 in Sub-section 3.4.10.

### 3.4.2 The electrical properties of insulating materials

Insulators may be defined as materials which are poor electrical conductors, i.e. they have high electric resistance. Unlike metallic materials, they have a decrease in resistance with increase in temperature.

Those properties of insulating materials which are of particular significance in rotating electrical plant are:

1. *Insulation resistance* which is a combination of the resistances of leakage current paths directly

through the material, and along the exposed surfaces or edges. It is expressed in megohms.

2. *Resistivity* (or *specific resistance)* which may be expressed either as *volume resistivity* or as *surface resistivity.* The former is the resistance between opposite faces of a cube of unit dimensions, and is usually expressed in megohm-centimetres. For most insulating materials its value decreases with temperature, i.e its temperature coefficient is negative. The surface resistivity is the resistance between the opposite sides of a square, of unit dimensions, on the surface of the material. It is usually expressed in megohms per centimetre square. The volume resistivity of hygroscopic materials is affected by absorbed moisture; and the surface resistivity is affected by films of moisture and condensation, and by deposits of dust, metallic particles, and salts [11].
   The insulation resistance of a machine's windings is, therefore, always a good guide as to their condition in regard to absorbed or surface moisture.
3. *Electric* (or *dielectric) strength* which represents the ability of the insulating material to resist electric stress. In practice, the term is usually understood to mean the *electric strength at breakdown* [11]. It is defined as the maximum voltage that can be applied to the material without causing it to break down, rupture or puncture, under specified conditions of temperature, time, wave-form, and frequency. It is expressed in the form of a voltage gradient (typically, in kilovolts per centimetre). Breakdown level is affected by the thickness of the insulation tested, the time of application of the the applied voltage, and the test environment. Generally speaking, the electric strength of an insulting material varies inversely with its thickness and with the duration of applied voltage, and decreases with increasing temperature and moisture content.
   The dielectric strength is only of limited value to the machine designer, because the breakdown mechanisms which are likely to control the service life of installed insulation are far more complex than just over-voltage stressing. Nevertheless, it gives a good indication of the insulation's ability to withstand the *proof* (or *flash) tests* which are applied on completed machines.
4. *Permittivity* (or *dielectric constant)* is the characteristic of a material which determines its usefulness as a capacitor. It is defined as the ratio of the electric flux density in the material to that produced in free space by the same electric force. Put another way, it is the ratio of the capacitance of a capacitor with the specified material as the dielectric (between its plates) to that with air as the dielectric. Materials with dielectric constants up to 12 are considered to be good insulators. Those having higher values are preferred in capacitors.
   Knowing the permittivities, electric strengths, and thicknesses of the component parts of a composite insulation it is possible to calculate its breakdown strength. Conversely, given the breakdown strength required of a composite, it is possible to calculate the optimum thicknesses of the component materials consistent with the need to achieve both mechanical strength and 'workability' in the composite insulation. Typical examples would be micaceous tapes and sheets made up of mica flake, and various materials such as woven glass cloth, polyester film, polyester mat, etc.
5. *Dielectric losses* which occur in all dielectrics when they are subjected to stress from alternating voltages. These losses are due to (a) conduction current and (b) hysteresis.
   The conduction current *(Ie)* arises from the imperfect insulating qualities of the dielectric. It is in phase with the voltage and results in a power loss $(Ie^2)$ which is dissipated as heat. Dielectric hysteresis is defined as the lagging of the electric flux behind the electric force producing it. The energy loss attributable to it is also dissipated as heat.
   The total dielectric losses may be measured by an a.c. bridge network of the Schering type, and are expressed by:

$$\text{Dielectric loss} = VI\cos\theta$$

or

$$\text{Dielectric loss} = 2\pi fCV^2\tan\delta$$

where $f$ is the system frequency
$C$ is the capacitance of the dielectric, and
$\delta$ is the complement of the phase-difference angle $\theta$ ($<90°$) by which the total *apparent charging current I*, in the dielectric, leads the applied voltage $V$. It is called the *loss angle*.

Loss data are usually presented in graphic form as loss tangent characteristics: tan a/voltage and tan a/temperature.

### 3.4.3 The causes of insulation failure

Insulation failure is caused by one, or more, of the following mechanisms:

1. thermal effects;
2. mechanical damage;
3. electrical-stress concentration; and
4. chemical action.

#### *Thermal effects*

Many of the properties of insulating materials are temperature dependent. For example, the dielectric strength of some falls as temperature rises. **In** others an increase in temperature may change the physical dimensions of the material. This may be critical where the insulation is in close contact with other materials of differing coefficients of expansion, e.g. on stator windings, where insulation is bonded to conductors and firmly enclosed within the steel stator core.

Excessively high temperatures may also cause some materials to degrade and, in so doing, discharge gases which may have a deleterious effect on materials in close proximity. The *thermal degradation* of their electrical and mechanical properties, resulting from operation at elevated temperatures, is an important consideration in the selection of insulating materials for machines. Degradation is aggravated by the oxidation and brittle hardening of the material. Increasing the working temperature increases the rate of oxidation.

The deterioration of insulation is a function of both time and temperature. The rate of deterioration is such that the life of insulation may be expressed as an exponential - the Arrhenius Law [12]:

$$\text{Life} = \epsilon^{[A + (B/T)]}$$

or $$\log (\text{hours of life}) = A + B/T$$

where A and B are empirical constants derived by experiment, and
$T$ is the absolute temperature.

### *Mechanical damage*

Whilst some mechanical problems are directly associated with thermal effects, other mechanical stresses are also present in machines, and these could lead to insulation failure not initiated by temperature. Particular examples are:

1. The mechanical vibrations induced by the electromagnetic forces acting on current-carrying components. Typically, the stresses imposed on a stator coil side, by pull or bounce, each time a rotor pole passes over it. The pulsation occurs at a frequency which is twice that of the system's electrical frequency.
2. The bending forces (at system frequency) exerted on stator end-windings by short circuits.
3. The effects of centrifugal force on rotating windings.

### *Electric-stress concentration*

Normal operating voltages are often sufficient to cause electrical discharges in the air pockets or voids which may exist in insulation. This could result in the erosion of some materials. At worst, the discharges may lead to the formation of low-resistance or conducting paths within the insulation, causing eventual breakdown. This process may be accelerated if significant thermal or chemical degradation also occurs within the material. On high voltage machines there is a need to ensure that the slot insulation of line-end coils is substantially free of voids, otherwise electrical discharging will permit erosion of the organic materials used [13]. The possibility always exists of external *(corona)* discharges occurring at the surfaces of insulation which are at a different potential to adjacent metal parts. **It** is therefore usual to treat the slot portions and end-turns of HV stator coils with a semi-conducting medium (e.g. colloidal graphite varnish, graphite-impregnated polyester, etc.) acting as a *corona shield.* This ensures that the outside surfaces of coils make good contact with the laminated core, and prevents electrical discharging between the coil surface and core [13].

### *Chemical action*

The chemical constitution of organic materials is affected by the ingress of moisture, and by the presence of chemically-active materials - ionized air and oxygen, in particular. Oxidation, which may introduce hydrochloric acid into polymeric insulation, increases the conductivity and loss factor of insulants, and is the commonest form of chemical deterioration. The rate of degradation increases with temperature.

### 3.4.4 The ideal insulation system

From the previous discussions it is clear that the ideal insulation system for machines would have:

1. high dielectric strength at the predicted working temperatures;
2. high thermal stability, with low dielectric loss, at service temperatures and at system frequency;
3. good thermal conductivity;
4. good resistance to electrical discharge;
5. the necessary physical properties for the proposed application - in particular, mechanical strength over the range of service temperatures, chemical stability, and resistance to moisture, oil, and other environmental contaminants;
6. good workability and ease of application during the build processes; and
7. a life expectancy of the order of 20 years, when operating at rated temperatures.

### 3.4.5 Evaluation of insulating materials and systems

The evaluation of insulating materials and complete systems of insulation is a continuous process within the development laboratories of major machine manufacturers. Functional investigations are based upon accelerated life tests designed to simulate all the critical parameters that affect the service life of windings. On small machines with enamelled conductors, scaled-down models, called *motorettes*, are used to evaluate the conductor, interphase, and ground insulation. The models are subjected to cycles of thermal, electrical, mechanical and environmental stresses appropriate for the winding [14]. Electrical tests are used to check performance after each ageing cycle. High-voltage breakdown tests are also undertaken on selected samples. Knowledge of the effects of the factors used to obtain accelerated failure is used to estimate the equivalent service life [14].

Because it is difficult to design a model coil assembly for high-voltage windings, machine manufacturers have each developed their own functional test procedures. It is usual to use stator replicas with full-size end-windings, but with shortened cores. The effects of repeated thermal cycling are then investigated within enclosed rigs. During these tests the movements of the coil sides are accurately measured. This enables the temperature rise within the bars to be calculated. By providing a ducted air supply to the rig it is possible to simulate the effects of end-turn cooling. Special rigs may also be devised to determine the movement of end-windings under short-circuit conditions. This is done by injecting a current (corresponding to a 3-phase bolted short circuit at the generator terminals) into the windings and measuring the physical movement using position transducers. High-speed photography may also be used to study the movements with various end-turn bracing arrangements.

In all investigations of this type it is necessary to test a large number of samples so that statistical methods may be applied in analysing results [13].

### 3.4.6 Routine testing

Stator bars, coils, and other insulated components are subjected to non-destructive electrical tests during production. Similar tests are then repeated after the coils have been wound into the machine to confirm that no damage has occurred in the process. McNaughton [14] suggests that it is good practice to use test levels in decreasing order of severity at the various stages of winding construction. For example, since the high-voltage acceptance tests for the complete windings of an 11 kV machine would be 23 kV for 1 minute (BS4999: Part 143), it is usual to test the individual coils, prior to insertion, at about 30 kV; and, before they are connected up, at about 27.5kV.

Each manufacturer has established routine tests to confirm the quality of insulated components. These might include:

1. interturn tests on stators and rotors;
2. tests to determine loss-tangent characteristics;
3. high-voltage tests;
4. insulation resistance; and
5. on high-voltage stators: dielectric loss analysis, polarization index, electromagnetic or acoustic probe, and corona shield resistance checks.

### 3.4.7 In-service testing

GEC Large Machines pioneered diagnostic non-destructive site testing procedures in the late 1960s. Since then, considerable expertise has been built-up by that company (and other major manufacturers) in evaluating the information obtained. The test programmes are designed to monitor the condition of windings after periods of in-service ageing. Constructive assessments enable the user to plan outages, for any remedial work, in a controlled manner. Condition monitoring would be particularly appropriate to critical plants operating in marine and heavily polluted industrial environments, and in high ambient temperature conditions.

### 3.4.8 Thermal classification of insulating materials

The internationally recognized system of thermal classification was by class letters: Y, A, E, B, F, H and C. The old Class C, which applied to temperatures above 180°C, has been replaced by thermal classes 200 and above. See the table below (BS 2757: 1986 and IEC85: 1984).

| Thermal class | Temperature ("C) |
|---|---|
| Y | 90 |
| A | 105 |
| E | 120 |
| B | 130 |
| F | 155 |
| H | 180 |
| 200 | 200 |
| 220 | 220 |
| 250 | 250 |

If one of these classifications is used to describe a machine it represents the maximum temperature appropriate to that machine, under rated load and other conditions. The temperature limit for an insulation system is not necessarily related to the thermal capability of its individual constituents. BS 2757 points out that the thermal performance of the individual insulating materials may be improved by the protective character of the materials used with them. Conversely, incompatibilty between the materials in a system may decrease the appropriate temperature limit of the system below that for the individual materials. Problems such as this can only be investigated by functional testing - as described in Sub-section 3.4.5 above. A point to note is that the temperatures quoted for the thermal classes are the permitted temperatures of the insulation and not the temperature rise of the machine. Standards for electrical machines usually specify temperature rise rather than actual temperature - see Sub-section 3.4.10.

The old method of characterizing the thermal capability by generic type or chemical designation (e.g. Class A: impregnated cotton, silk, fibre, etc.) has proved to be inadequate, since much depends upon the way in which individual materials are combined with others, and upon the special functions they are called upon to fulfil. Now the preferred basis for assessing the thermal endurance of insulation systems is by relevant service experience. Where such experience does not exist, appropriately designed functional tests should be carried out (BS 2757). IEC standards define precise test methods and end-points for assessing specific material properties [15]. See Section 3.9.

### 3.4.9 Resin-rich and vacuum pressure impregnation systems

The *thermoplastic* resin insulating systems of the 1940s and 1950s have been replaced in modern machines by systems using *thermosetting* synthetic resins, such as epoxides and polyesters, combined with micaceous materials. Two fundamentally different manufacturing processes have been developed over the years. Both have their advocates. They are the so-called *resin-rich* and the *dry taped* or *vacuum pressure impregnation* (v.p.i.) processes.

The resin-rich method is a logical development of the older thermoplastic insulation systems. Coils are wound as flat loops using micaceous tape or enamel insulation, and their slot portions are consolidated under heat and pressure before being pulled-out into their diamond shapes. The main insulation material (e.g. resin bonded woven glass or mica tape) is then applied before the slot portions are re-consolidated to their pre-specified dimensions. The term resin-rich derives from the fact that the main insulation tapes contain sufficient resin to give adequate curing and consolidation without the need for further resin to be added. Any surplus resin is squeezed out to give void-free insulation. End-windings are treated either with the same resin-rich tape or with a fully-cured flexible flake-based mica tape to allow easy and damage-free fitting of coils into the stator core. Where size makes it practicable, assembled stators are then usually immersed in a flexible solvent varnish and stoved. This has the effect of curing all the partially cured resins that would otherwise have remained in the windings.

In the v.p.i. process the dielectric is applied dry to coils and bars, and has only sufficient resin within it to hold together its micaceous base and its reinforced backing tape. After insulation, the completed coils are subjected to a vacuum/pressure cycle during which all air and moisture is removed (vacuum drying stage) before they are immersed in a solventless epoxy or polyester resin and impregnated under high pressure. They are heat cured to thermoset the resin. A modified procedure, known as the *global impregnation process* has been developed for medium-sized stators [16]. Here, the pre-insulated coils are wound directly into the stator core and then connected and braced using dry materials. The assembled stator is placed in a large tank where it is vacuum-dried and then pressure-impregnated with solventless synthetic resin. The complete unit is finally stoved so as to thermoset the resin which impregnates the windings and their bracings. Figure 3.35 shows a typical vacuum pressure impregnation plant. Some idea of scale is given by the attendant at the control panel. The tank into which the stator core pack is being lowered for its vacuum drying and pressure-impregnation cycle is capable of accommodating stator units up to about 10 MVA rating.

Figure 3.36 shows a stator pack after vacuum pressure impregnation. The winding is rated for 3750 kVA and is suitable for 11 kV, 50 Hz and B.8kV,60Hz.

Service experience has shown that windings with resin-rich and v.p.i. insulation systems are technically superior to the older thermoplastic materials. In the recent past, systems based on resin-rich materials have tended to predominate in the United Kingdom. Because these processes are more labour intensive than those for v.p.i. windings, many manufacturers, having re-assessed their production techniques against design, cost, and performance demands, have adopted global impregnation processes for their small- and medium-sized machines. This,

Figure 3.35 A vacuum pressure impregnation plant (Courtesy: Brush Electrical Machines Ltd.)

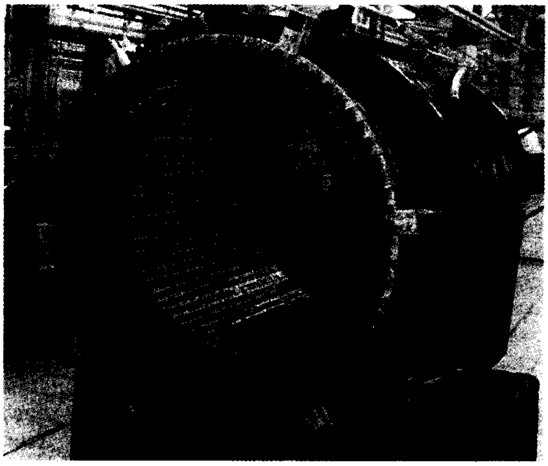


Figure 3.36 High tension wound stator core pack, after v.p.i. treatment (Courtesy: GEC Alsthom Large Machines Ltd.)

despite the fact that the system initially requires fairly expensive capital plant.

As far as the user is concerned, resin-rich coils are more easily replaced in the field. Partial repairs may be made using fully-processed spare coils, which retain their flexibility over long periods in storage. It is necessary to hold a spare, completely-wound, stator core if a quick replacement is required for a v.p.i. processed machine. This may be an acceptable outlay where several machines of the same rating are installed on one site.

### 3.4.10 Limits of temperature rise for machines

The national and international standards of temperature rise for all rotating electrical machines (other than those used in rail and road vehicles) are defined in BS4999: Part WI (IEC34-1). BS2949 (IEC92-5) relates to electrical rotating machines for use in ships. Table 3.1 compares the limits of temperature rise permitted in the stator and field windings of brush less a.c. generators indirectly cooled by air.

Sub-clause 16.3 of BS 4999: Part WI details the adjustments that need to be made to the temperature rise limits to take account of site operating conditions (such as elevated altitude and/or ambient temperature) for machines indirectly cooled by air.

### 3.4.11 Determination of temperature rise

The temperature rise of a part of a machine is the difference in temperature between that part of the machine, measured by one of the (appropriate) methods described below, and the machine's coolant. BS 4999: Part WI recognizes four methods of determining the temperature of windings:

Table 3.1 A comparison of permissible temperature rises assigned to thermal classes of insulation (see Note 1)

| | 854999: *Part 101: 1987* | | | | | 852949: 1977 *(see Note 2)* | | |
|---|---|---|---|---|---|---|---|---|
| Class of insulation | A | E | B | F | H | A | E | B |
| Ambient temperature (0C) | 40 | 40 | 40 | 40 | 40 | 50 | 50 | 50 |
| Stator windings - temperature rise (K) (see Note 3) | 60 | 75 | 80 | 105 | 125 | 50 | 60 | 70 |
| Field windings - temperature rise (K) (see Note 4) | 60 | 75 | 80 | 105 | 125 | 50 | 60 | 70 |
| Hottest spot temp. permitted by BS2757 (0C) | 105 | 120 | 130 | 155 | 180 | 105 | 120 | 130 |

*NOles* - applicable to BS 4999: Part 101:

1. These limits are for measurement of rise by the resistance method.
2. BS 2949 quotes figures for classes A, E and B only; classes F and H are subject to agreement between manufacturer and purchaser.
3. Machines having outputs above 2tXlkW (or kV A) but less than S(J(XlkW (or kVA).
4. All windings except those in cylindrical rotors. low resistance field windings. and single-layer windings with exposed bare or varnisbed metal surfaces.

1. the resistance method;
2. the embedded temperature detector (e.t.d.) method;
3. the thermometer method; and
4. the superposition method.

The different methods must not be used as a check against each other.

#### *The resistance method*

This is the method that should generally be applied. The temperature rise of the windings is determined by the increase of its electrical resistance. The temperature rise $(t_2 - t_a)$ is obtained by the formula:

$$t_2 - t_a = [(R_2 - R_1)(235 + t_1)/R_1] + t_1 - t_a$$

where
- $t_2$ is the temperature of the winding at the end of the test (0e)
- $t_a$ is the temperature of the coolant at the end of the test (0e)
- $t_1$ is the temperature of the winding cold - at the moment of the initial resistance measurement
- $R_2$ is the resistance of the winding at the end of the test (D)
- $R_1$ is the resistance of the winding at temperature $t_1$ (D)

The resistance $R_1$ is measured when the machine has been at rest for a sufficient time to ensure that the temperature of the winding $(t_1)$, measured by thermometer, is practically that of the coolant.

Measurement of resistance $R_2$ requires a quick shutdown of the machine at the end of the temperature test. BS 4999: Part 101 recognizes acceptable time delays for obtaining initial readings. These are shown in the table below. If the initial resistance reading cannot be made in the required length of time, it should be made as soon as possible afterwards, and additional readings should be taken at 1 minute intervals, until these readings have begun a distinct decline from their maximum values. A curve of these readings, plotted on a semi-logarithmic scale (see Appendix A of BS4999: Part 101) is then extrapolated to the time delay specified in the table below for the rated output of the machine.

| Rated output $(P)$ (kW or kVA) | Time delay after shutdown (s) |
|---|---|
| $P \leq 50$ | 30 |
| $50 < P \leq 200$ | 90 |
| $200 < P \leq 5000$ | 120 |
| $5000 < P$ | By agreement |

For materials other than copper, the number 235 in the above formula should be replaced with the reciprocal of the temperature coefficient of resistance (at 0°C) of the material. The appropriate number for aluminium is 225.

A quick estimate of the temperature rise of copper windings makes use of the fact that the resistance of copper increases by about 0.4 % per °C. For example, if $R_2$ is 24 % higher than $R_1$ the temperature rise of the winding is approximately 60°C (i.e. 24/0.4).

### Embedded temperature detector method

The temperature is determined by means of (at least six) temperature detectors built into the machine during construction, at points that are inaccessible after the machine is completed. The detectors may be resistance elements, thermocouples, or thermistors. BS 4999: Part 101 specifies the location of the temperature detectors for various coil arrangements, and for end windings. This method of measurement should be used for machines rated at 5000kW (or kVA) or more, but it should not be used for stator windings which have only one coil-side per slot.

### Thermometer method

This method is only recognized for measurements on:

- the smallest machines - up to 600 W (or VA);
- single-layer windings; and
- routine tests on machines manufactured in large quantities.

Where a purchaser requires thermometer readings in addition to those obtained from the resistance or e.t.d. methods, BS 4999: Part 101 stipulates that the temperature rise (so determined) shall not exceed:

For Class A winding insulation - 65 K
For Class E winding insulation - 80 K
For Class B winding insulation - 90 K
For Class F winding insulation - 115 K
For Class H winding insulation - 140 K

The time-constant of the thermometers should be as small as possible. The bulbs should be in firm contact with the surfaces to be measured and should be covered (except at their contact interface) with a low thermal conductivity material - such as felt or cotton wool - acting as a thermal shield to prevent loss of heat to the surrounding air.

Readings should be taken at short time intervals, after the machine has been shutdown. A carefully planned procedure and an adequate number of people are required to obtain quick readings. If the initial readings are taken within the timescale given in the table on this page, they may be regarded as the final temperatures. Otherwise, it becomes neccessary to plot a cooling curve (as described earlier), and extrapolate back to the instant of stopping the machine to obtain the required figure for operating temperature.

### Superposition method

In this method resistance measurements - in accordance with the procedure described in the resistance method - are made without interruption of the a.c. load current, by applying a small d.c. measuring current superposed upon the load current. Details of the method are given in IEC 279 (see Section 3.9). Misleading results may be obtained if the measuring current is not pure d.c. or if parasitic-induced e.m.f.s are present [15].

### Coolant temperature measurement

On open machines which are cooled by the surrounding air the ambient air temperature is obtained from the mean of several temperature detectors placed around and half-way up the machine at distances up to 2 m from it. On those machines which have separately mounted heat exchangers, the temperature of the *primary coolant* is measured at the point where it enters the machine. On closed machines (with machine-mounted or internal heat exchangers) the temperature of the primary coolant is measured where it enters the machine. The temperature of the secondary coolant (see Section 3.5) is measured at the point where it enters the water-cooled Or air-cooled heat exchanger.

## 3.5 Machine ventilation and cooling systems

Before the advent of computer-aided methods, machine designers used hand calculation methods to determine the thermal conditions inside a machine. Use was made of empirical data based on sound research and development work. Designers tended to work to rather conservative temperature-rise targets. As a result, machines seldom ran close to the maximum temperatures assigned to the classes of insulation used.

Modern computer-aided design (CAD) techniques have removed much of the guesswork from the design process, and the designer is now able to select machine parameters that are closely matched to computer-produced thermal network data, e.g. steady-state and transient heat flows, and temperature distribution within machines. This allows windings to be rated closer to their full thermal capability, and machine efficiency is optimized.

The temperature rise in a machine (a direct result of the heat losses within cores and conductors) is only moderated by its ventilation and cooling system. Equilibrium temperature is reached when the rate at which heat is produced is balanced by the rate at which the cooling system dissipates it. Cooling becomes more difficult as machine size increases. This is explained by the fact that, whereas the surface area from which the heat losses must be dissipated increases as the square of the dimensions, the magnitude of the losses (because they approximate to machine volume) varies as the cube of the machine's dimensions.

The purpose of the coolant is to remove (by conduction) the heat generated within the machine. When the primary cooling medium is air, the heat transfer process is considerably enhanced by airflow turbulence. This explains why machines are fitted with rotor fans, and why they employ internal baffling, or radial and axial ducts, to direct the cooling air to where it is best utilized in the cooling process. Heat transfer efficiency will vary with the type of ventilation used. This, in turn, is closely related to the machine enclosure. See Section 3.6.

While small, high-speed machines (especially those of cylindrical rotor construction) usually have axial ventilation, medium and large machines customarily use combined radial and axial ventilation schemes (see Figure 3.37). Here, the coolant air is drawn in through the non-drive endshields and splits along several paths. One of these is through the rotor assembly. Another is along the air-gap between the stator and the rotor and then through

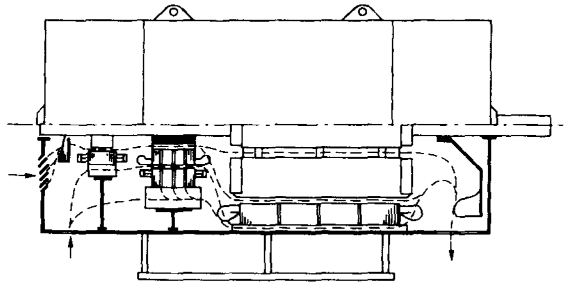


**Figure** 3.37 Combined radial and axial ventilation in a cooling air circuit

radial ducts in the stator core. The third path is usually through the end-windings and around the back of the stator core.

It is theoretically possible to build machines with orthodox winding constructions up to 100 MYA using air as the primary cooling medium. In practice, the upper limit is about 30 MYA before *direct-cooling* methods, using hydrogen or water, are applied. Direct-cooling permits considerable reduction in the amount of 'active' materials (iron and copper) required per unit output. For example, above 30 MYA the specific weight (kglkW) of a hydrogen-cooled machine is about one-half of that of an equally rated air-cooled machine. Even more dramatic reductions are possible with water-cooled stator windings. Machines of the size under consideration will inevitably employ air as the cooling medium. We may therefore ignore the 'direct-cooling' methods usually associated with large turbo-generators.

BS 4999 : Part 106 (IEC 34-6) assigns designations to the methods of cooling rotating electrical machines. It gives a simplified code for the most widely used types of machines, and a more complete classification covering all types of cooling systems. Cooling methods are classified using symbols and short definitions which indicate those components that are not regarded as part of the machine.

In our context, there are two basic classifications to be considered:

1. ventilated (or open-air circuit cooling); and
2. closed-air circuit.

The following definitions (BS 4999) cover the terms in general use.

*Cooling* A procedure by means of which heat resulting from losses occurring in a machine is given up first to a primary coolant by increasing its temperature. The heated primary coolant may be replaced by new coolant at lower temperature, or may be cooled by a secondary coolant in some form of heat exchanger.

*Primary coolant* A medium (liquid or gas) which, by being at lower temperature than a part of the machine and in contact with it, removes heat from that part.

*Secondary coolant* A medium (liquid or gas) which, being at a lower temperature than the primary coolant, removes the heat given up by this primary coolant by means of a heat exchanger.

*Heat exchanger* A component intended to transfer heat from one coolant to another while keeping the two coolants separate.

*Open circuit cooling* A method of cooling in which the coolant is drawn from the medium surrounding the machine, passes through the machine and then returns to the surrounding medium.

*Closed circuit cooling* A method of cooling in which a primary coolant is circulated in a closed circuit through the machine, and if necessary through a heat exchanger. Heat is transferred from the primary coolant to the secondary coolant through the structural parts or in the heat exchanger.

*Coolant circuit components* are said to be:

*Dependent* when they are dependent for operation on the operation of the main machine.

*Independent* when they are independent of the operation of the main machine.

*Integral* when they form part of the machine and can only be replaced by partially dismantling the machine.

*Machine-mounted* when they are mounted on the machine and form part of it, but can be replaced without disturbing the main machine.

*Separately mounted* when they are associated with the machine, but are not mounted on or integral with it.

The *Simplified Code* designates cooling and ventilation methods by means of the letters IC followed by two characteristic numerals. The first numeral signifies the cooling arrangement and the second numeral the method of supplying power to circulate the coolant. The designation most commonly applied to generators is ICOl (for open-air circuits) where air is drawn into the machine by an integral fan, and usually flows axially through the machine to be expelled at the drive end (see Figure 3.38). When the surrounding air contains any quantity of fine dust or sand (and particularly when some humidity or oil vapour is also present) air passsages may become blocked. This leads to increased temperature rise and eventual winding failure. Inlet air filters should be fitted under these conditions.

A form of totally enclosed construction should be specified when a machine is required to operate in extremely dirty conditions or in the open air without any weather protection. For ratings above about 75 kVA, it is economical to use closed-air circuit ventilation systems incorporating separate air-cooled or water-cooled heat exchangers. These are commonly referred to as *closed air circuit air cooled* (CACA) and *closed air circuit water cooled* (CACW) systems, respectively. Simplified arrangements of both types are shown in Figure 3.39 and typical treatments are illustrated in Figures 3.40 and 3.41.

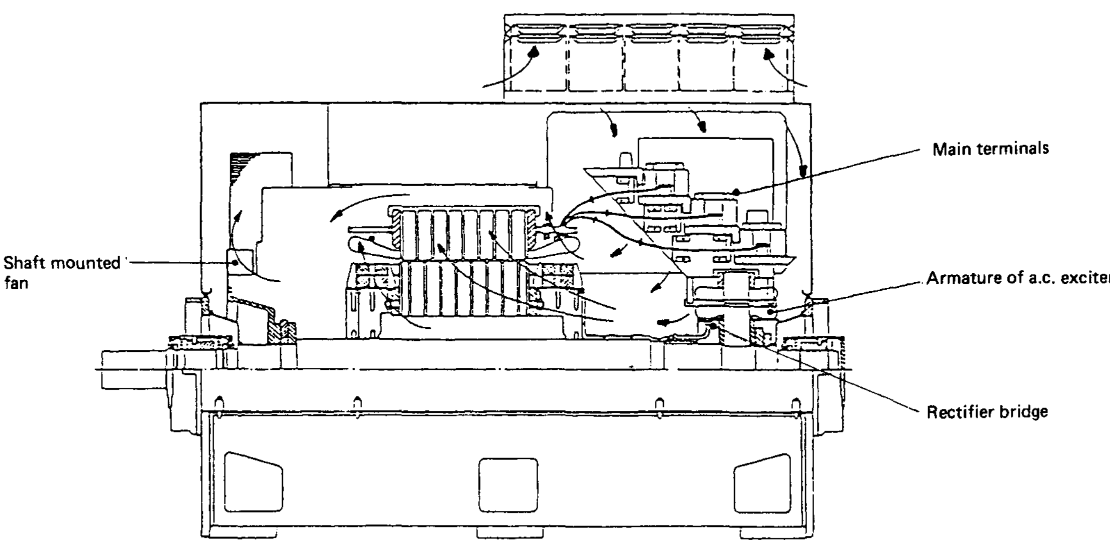
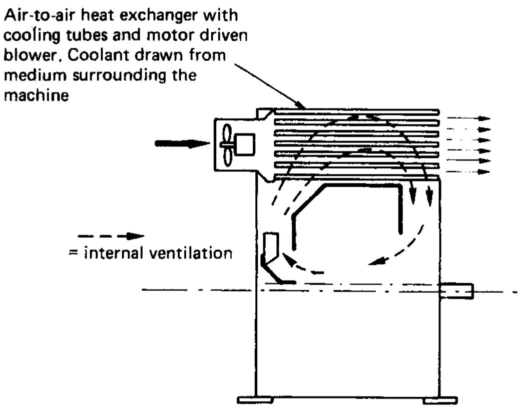
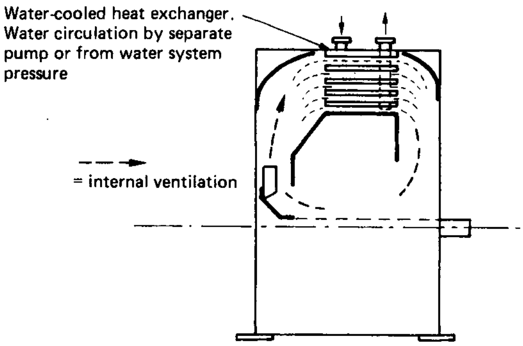



**Figure 3.38** Typical cooling arrangement IC 01 for an enclosed, ventilated generator (Courtesy: ABB – Asea Brown Boveri Ltd.)




(a) Totally-enclosed, closed air circuit air cooled (CACA) machine




(b) Totally-enclosed, closed air circuit water cooled (CACW) machine

**Figure 3.39** Closed air circuit ventilation and cooling systems

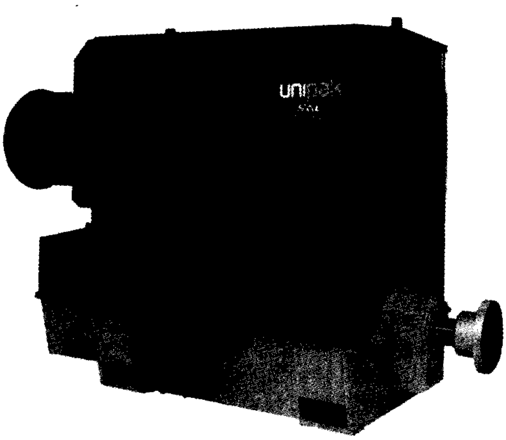


**Figure 3.40** Generator with a CACA enclosure (Courtesy: GEC Alsthom Large Machines Ltd.)

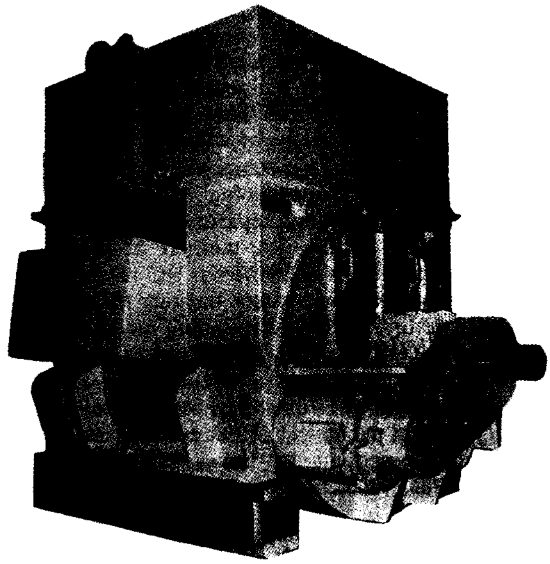


**Figure 3.41** 938kVA. 8-pole brush less generator with CACW enclosure (Courtesy: Laurence. Scott and Electromotors Ltd.)

The machine-mounted fans (providing cooling air to the closed-circuit heat exchanger of the generator) shown in Figure 3.40 usually derive their power from the generator's own supply terminals. In such cases, they are classified as *dependent circulating components* - identified by the appropriate second characteristic numeral 3 in the IC coding system. Were they to be powered from a separate supply source, they would be classified as independent of the operation of the main machine. The second characteristic numeral of their code classification would then be 6.

The flanged connections for the coolant water flow and return to the machine mounted heat exchanger may be seen at the top centre of the enclosure illustrated in Figure 3.41. It is the usual practice on marine generators to provide the means for converting the CACW system to an open-circuit air-cooled ventilation arrangement (Code IC 01) - with unaltered rating. This affords emergency operation in the event of coolant system or cooling element failure. Conversion is usually by means of removable covers fitted to the enclosure - one may be seen at the tQP of the non-drive end of the machine illustrated in Figure 3.41. Incidentally, the shaft extension on this machine is for driving a compressor. Heat exchangers are available in both salt water and fresh water versions, and may be of either the single- or double-tube type.

The complete coding system is fairly complicated and of limited interest to the user. Designations consist of:

1. the letters IC;
2. for each cooling circuit, a group of one letter and two characteristic numerals.

The nature of the coolant is designated by letters. For example: A for air, H for hydrogen, N for nitrogen and W for water, etc.. When all coolants are air, it is permissible to omit the letters stating the nature of the coolants.

Just one example of application of the complete coding system will have to suffice for this treatment. The cooling method classified is that of the machine in Figure 3.39(b). Because more than one coolant circuit is used, the designation consists of:

1. A group, of one letter and two numerals, for the external circuit - in our case, W (for water) 37. The first numeral 3 indicates that the external coolant is conveyed to the machine through an inlet pipe or duct, and is then discharged from the machine through an outlet pipe or duct remote from the medium immediately surrounding the machine. The second numeral 7 indicates that coolant circulation is by an entirely separate and independent component or by external coolant system pressure, e.g. supplied from a water distribution system.
2. The group for the circuit which is nearer to the machine windings (i.e the primary coolant circuit) - in our case, A (for air) 71. The first numeral 7 indicates that the primary coolant circulates within a closed circuit, and gives its heat to the secondary coolant (which is not the medium surrounding the machine) in a heat exchanger which is built into, and forms an integral part of, the machine. The second numeral 1 indicates that the primary coolant is inlet pipe or duct circulated within the machine.

The cooling system for this machine is therefore designated IW 37 A 71. It is one that should be adopted where:

- the surrounding air cannot be used for direct cooling;
- the heat losses from a machine must not be radiated into the immediate plant room area; or
- a particularly low noise level is required of the installation.

Figure 3.42 illustrates a method frequently used on large installations, where cooling air is ducted from outside the power station through the building foundations. This prevents recirculation of warmed air within the generator hall and ensures a positive air flow through it. Where filters or heat exchangers are fitted, these are mounted in the foundations or in the basement of the building. Adequate space needs to be provided within the foundation design to give easy access to the machine for maintenance.

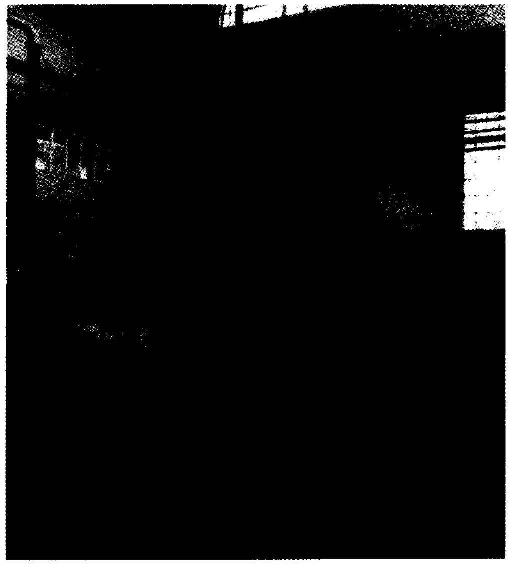


**Figure** 3.42 A 10MW generator fitted with an air duct which enables cooling air to be drawn through lower ground floor spaces (Courtesy: Brush Electrical Machines Ltd.)

## 3.6 Machine enclosures

A machine enclosure has a two-fold purpose:

1. to control and guide the flow of the cooling medium; and
2. to protect the machine against the environment in which it operates, and to protect personnel from live and moving parts within the machine.

The distinction between the two is emphasized by the IC codes for cooling systems, and the IP codes for degrees of protection. Before these codes were adopted, the descriptions of machine enclosures, while appearing to be fairly precise, led to various design interpretations by constructors. *Enclosed ventilated drip-proof* (EDVP) and *splash-proof* (SPLP) were two such classifications.

The IP system for enclosures (BS 4999: Part 105) indicates, by means of a two-numeral code, the protection afforded against contact with live and moving parts, and against ingress of solid objects and moisture. The first digit indicates protection against contact and foreign bodies. The second refers to the protection against harmful ingress of water. Machines housed indoors usually have enclosures that come within IP 21 to IP 23 categories i.e. they are 'fingerproof', and range from drip-proof to spray-proof. Machines operating outdoors may vary from IP 44 to IP 55, where protection extends from the exclusion of solid bodies greater than 1 mm to 'dust sealed', and from splash-proof to hose-proof.

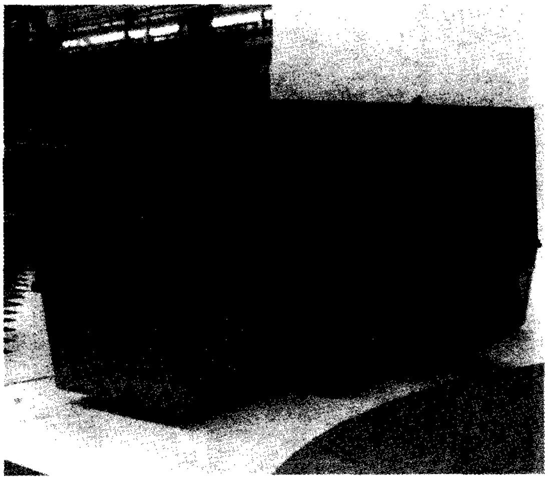


Figure 3.43 Generator with a screen protected. drip-proof enclosure (Courtesy: GEC Alsthom Large Machines Ltd.)

GEC Large Machines uses a modular component concept in its *Unipak* machines. On a given size of machine, the base details are constant and variations in enclosure classification are obtained by simply changing machine covers. The principle is illustrated by comparing the machine in Figure 3.40 (IP 54/IP 55) with that shown in Figure 3.43 (IP 21).

Suffix letters may also appear in a coding. The letter S indicates that protection against water ingress was tested with the machine not running. M indicates that the test was conducted with the machine in operation. The absence of a qualifying letter means that the protection was tested both with the machine running and with it not running. The letter W, appearing between IP and the code numerals, implies that the machine is *weather-protected*, i.e. its 'design reduces the ingress of rain, snow and airborne particles under specified conditions, to an amount consistent with correct operation'.

## 3.7 Power rating

The performance of electromechanical devices is set by the saturation characteristics of their ferromagnetic materials and by thermal and/or rotational factors. The limit on rotating machines is basically thermal and is governed by the permissible temperature rise of the windings.

The *rating* of a machine is a statement of the numerical values of the electrical and mechanical quantities assigned to it by the manufacturer, and marked on its rating plate. The *rated output* is the numerical value of the output included in the rating (BS4999: Part 101). For a.c. generators, it is the *apparent* electrical power at the terminals expressed in kilovolt-amperes (kVA). The rated, operating power factor (p.L) is assumed to be 0.8 lagging unless otherwise specified.

BS 4999: Part 101 lists nine *duty types,* two of which (Sl: continuous running, and S2: short-time) may be used to define generator duties. It is usual, however, to rate generators in terms of *maximum continuous rating* (cont) which is defined as the load at which the machine may be operated for an unlimited period under specified conditions. The machine has no overload rating *per se.* Where machines are to be driven by RIC engines, the applicable British Standard (BS 5000: Part 3) requires that they be capable of delivering 110% of their maximum continuous rating at 'rated voltage and rated speed for one hour during any period of twelve consecutive hours running, provided that the inlet coolant temperature during the overload period is below that corresponding to the maximum cooling temperature for which the machine has been rated, by not less than 13K. No temperature rise limits are specified for this overload condition'.
*(Note:* in terms of temperature *intervals,* 1°C = 1K) BS 5000: Part 3 goes on to note that

> an engine complying with the requirements of BS 5514: Part 1 is permitted to develop, for limited periods and with a limited frequency, an output in excess of its rated output. The excess is customarily 10 per cent of the rated output for periods and frequencies which vary with the application and conditions. However, a generator with maximum continuous rating (to BS4999: Part 101) has no specified sustained overload capacity.
>
> The reference temperature for the BS 5514: Part 1 engine overload is 27°C and, with this inlet coolant temperature, a generator rated for the general service and operating conditions defined in BS 4999: Part 101 is permitted an additional 10K temperature rise. At 110 per cent load however, a normally rated generator may exceed its full-load temperature rises by considerably more than this 10K margin, and it should therefore be recognized that, even with the 13K reduction in ambient temperature specified in this clause, any significant usage of this 10 per cent overload capacity will shorten the insulation life of the machine.

In this context, see also Sub-section 3.4.3.

BS 2949 *(Rotating electrical machines for use in ships)* defines the *continuous maximum rating* (c.m.r.) as the level at which the machine may be operated for an unlimited period under the conditions specified on the rating plate. Again, the machine has no overload rating. Because performance criteria must be met at elevated ambient temperatures (50°C, as opposed to the 40°C of BS 4999), the marine c.m.r. is lower than its industrial counterpart. Overall steady-state temperatures of windings and insulation are the same, however, for both applications. See Table 3.1 in Sub-section 3.4.10.

In American practice, a *standby duty rating* is often specified (NEMA MGI-22). While this permits a higher output than the conventional international continuous maximum rating (BS 4999 & IEC 34-1), it does so at the expense of widened performance criteria, enhanced temperature rise, and reduced life expectancy. It is a rating assigned to emergency power sources and not to prime-power generators.

### 3.7.1 Factors affecting output rating

The international temperature reference condition for land-based generators is a maximum of 40°C. (The corresponding figure for machines installed in ships operating in unrestricted service is set by the major Marine Classification Societies at either 45°C or 50°C.) It follows, therefore, that machines indirectly cooled by air must be derated when operating in higher ambient temperatures. This ensures that the temperatures attained within them do not exceed the limits set by the class of insulation used. See Sub-section 3.4.10. If operation in an ambient of less than 40°C is considered, higher outputs may be obtained, since an enhanced temperature rise is permissible for the same actual temperature within the machine. Most standards will permit upratings for temperatures below 40°C but increases in temperature rise limits are usually restricted to a maximum of 30 K. (e.g. BS 4999: Part 101 sub-clause 16.3.4). Advantage is seldom taken of this, because uprating is usually at the expense of performance not related to temperature, e.g. transient performance. Conversely, when a machine is derated for higher temperatures a useful spin-off is an improvement in its non-temperature related performance.

*Derating for temperature*

Typical rating factors are given in the following table (3.2) for a range of machines indirectly cooled by air, and using thermal class H insulation [17]. Column A lists data based on the full temperature rise permitted by the insulation system. Column B lists

**Table** 3.2 Typical rating factors

| *Ambient temperature* (0C) | *Rating factors* ($K_T$) *Column A* | *Column B* |
|---|---|---|
| 40 | 1.0 | 1.0 |
| 45 | 0.97 | 1.0 |
| 50 | 0.94 | 1.0 |
| 55 | 0.91 | 0.97 |
| 60 | 0.88 | 0.94 |

corresponding factors for temperature rises relating to one grade of insulation lower than that fitted, i.e. Class F. A restriction of this kind is often placed by marine equipment users who may, typically, specify that Class F machines operate within Class B temperature rise limits.

The maximum site rating of a generator is obtained from:

Site kVA = (listed kVA) x (rating factor)

or $S_{site} = S_{nom} \times K_T$

*Example*

What would be the maximum site rating of a generator, fitted with Class H insulation, whose nominal rating is 105 kVA when operating in an ambient of 50°C; and restricted to:

(a) a temperature rise of 12SOC(Class H)
(b) a temperature rise of 100°C (Class F)

*Solution*

The rating factor for condition (a) is 0.94

so that, $S_{site}$ = 105 x 0.94 kVA
= 98.7kVA

In condition (b) $K_T$ = 1.0

so that, $S_{site}$ = 105 x 1.0 kVA
= 105kVA

*Derating for altitude*

Ratings for machines complying with BS 4999 and IEC 34 are based on inlet coolant temperatures of 40°C and site altitudes not greater than 1000m above sea level. It is necessary to apply derating factors at higher altitudes because the density of the air falls and the mass flow of cooling air is reduced. Clause 16.3 of BS 4999: Part 101 details the adjustments that must be made to the limits of temperature rise for machines indirectly cooled by air to take account of specified conditions of altitude and/or maximum temperature (or resulting conditions for maximum primary coolant temperature of a machine with water-cooled heat exchanger).

When machines operate at altitudes above 1000m, permissible temperature rises must be reduced at a rate of 1% of the value assigned to the class of insulation, for every 100 m above that altitude. For example: where the permissible temperature rise of the a.c. windings on a Class F machine larger than 5000 kW is 100°C, the rate of reduction to be applied is 1.0°C for each 100 m increment.

It may be assumed that the reduced cooling resulting from altitude is compensated by a reduction in maximum ambient temperature below 40°C. Where the coolant temperature is not specified for site altitudes between 1000 m and 4000 m, BS 4999: Part 101 tables a range of assumed coolant temperatures for the various classes of insulation, based on the 1% reduction per 100m of the permissible temperature rise. See the table below.

**Table** 3.3 Assumed maximum ambient temperatures at altitudes up to 4000m. (Table IV of 854999: Part 101)

| *Altitude* (m) | *Temperature* eq *Class of insulation* A | E | B | F | H |
|---|---|---|---|---|---|
| 1000 | 40 | 40 | 40 | 40 | 40 |
| 2000 | 34 | 33 | 32 | 30 | 28 |
| 3000 | 28 | 26 | 24 | 19 | 15 |
| 4000 | 22 | 19 | 16 | 9 | 3 |

Manufacturers include altitude derating factors in the technical data on their machines. For instance, the following factbrs are applied to the Siemens A G Class F type 1FC6 generators (illustrated in Figure 3.33).

**Table** 3.4 Altitude derating factors

| *Altitude* (m) | *Rating factor* $K_A$ |
|---|---|
| 1000 | 1.0 |
| 1500 | 0.97 |
| 2000 | 0.94 |
| 2500 | 0.91 |
| 3000 | 0.87 |
| 3500 | 0.82 |
| 4000 | 0.77 |

*Derating for power factor*

When discussing the excitation characteristics of machines (in Section 3.2), we established that the excitation current required to maintain rated voltage increased as the load power factor reduced. This, in turn, has the effect of increasing the heat to be dissipated within the field windings. Insulation and cooling systems must be capable of coping with this extra heat. Machines are normally rated for 0.8 power factor lagging. Derating therefore needs to be applied if the machine is required to operate for prolonged periods at power factors below this level.

The following data (Table 3.5) for the Siemens A G type 1FC6 machines typify the derating factors that need to be applied.

*Combining deratings for temperature, altitude, and power factor*

Where a combination of high ambient temperature, high altitude, and low power factor exists, the appropriate rating factors must be multiplied together to give an overall rating factor, *Ko.* The

**Table** 3.5 Typical derating factors

| *Lagging power factor* | *Rating factor* $K_{pf}$ |
|---|---|
| 0.8 to 1.0 | 1.0 |
| 0.7 | 0.97 |
| 0.6 | 0.91 |
| 0.5 | 0.89 |
| 0.4 | 0.87 |
| 0.0 | 0.84 |

following example illustrates the use of correction factors - often presented in graphic form, as in Figure 3.44.

*Example*

Operating conditions:

| | |
|---|---|
| Ambient temperature | 45°C |
| Altitude | 1500m a.s.l. |
| Load power factor | 0.75 lagging |

*The problem*

What listed kVA should be used to give a site rating of200kVA?

*The solution*

The rating factor $(K_T)$ for a temperature of 4SOCis 0.96 (Figure 3.44(a»

The rating factor $(K_A)$ for an altitude of 1500m is 0.97 (Figure 3.44(b»

The rating factor $(K_{pf})$ for 0.75 lagging pJ. is 0.96 (Figure 3.44(c»

$$\text{The overall rating factor, } K_o = K_t \times K_A \times K_{pf}$$
$$= 0.96 \times 0.97 \times 0.96$$
$$= 0.89$$
$$\text{Site kVA} = \text{listed kVA} \times K_o$$
$$\text{Listed kVA} = \text{site kVA}/K_o$$
$$= 200/0.89$$
$$= 225\text{kVA}$$

It is often possible in such cases to improve the load power factor. See Sub-section 4.2.3 of Chapter 4. An improvement to 0.8 power factor lagging would mean a reduction of some 4% in the listed kVA of the machine.

## 3.8 Typical brushless generators

It is appropriate to conclude this chapter with illustrations of typical brush less machines. That shown in Figure 3.45 is of a 4-pole machine rated at about 150kVA. Item 9 in the list of component parts (the voltage control unit) may be accommodated in an enlarged version of the terminal box (10).

The illustration in Figure 3.46 supports those of Figures 3.40 and 3.43 which depict machines in the same series. It shows an assembled generator with one of two cartridge sleeve bearings located on the fabricated baseframe. The foot-mounted cartridge is

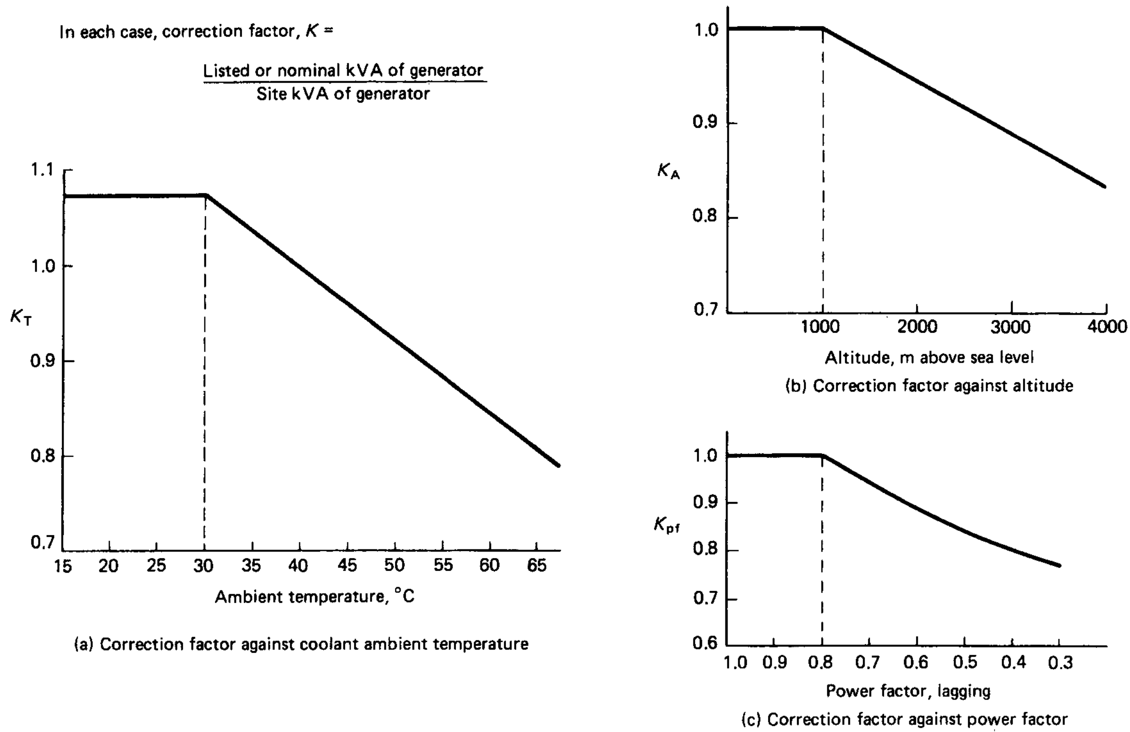



Figure 3.44 Correction factors for ambient temperature, altitude and power factor

insulated from the base by means of epoxy glass shims and sleeved bolts and dowels. The main and auxiliary exciter rotor components are outboard of this non-drive end bearing. Figure 3.43 shows the same machine with fitted enclosure covers. A feature of the machine's cooling and ventilation system is the ducts in the base frame, which channel the cooling air from the main air circuit to the overhung exciters and then into the output stage of the machine.

## 3.9 **Related standards**

This section lists those British Standards which have been referenced in the text. The IEC documents (given in brackets) are corresponding standards. They are not necessarily identical to the related British Standards but have varying degrees of agreement with them. Also included are those world regional standards which are universally recognized within the generator industry.

### 3.9.1 British and International Standards

BS 4999 - *General requirements for rotating electrical machines*

Part 101 (lEC 34-1) - *Specification for rating and performance*

Part 105 (IEC 34-5) - *Classification of degrees of protection provided by enclosures for rotating machines*

Part 106 (IEC 34-6) - *Classification of methods of cooling*

BS 5000 - *Specification for rotating electrical machines of particular types or for particular applications*

Part 3 - *Generators to be driven by reciprocating internal combustion engines*

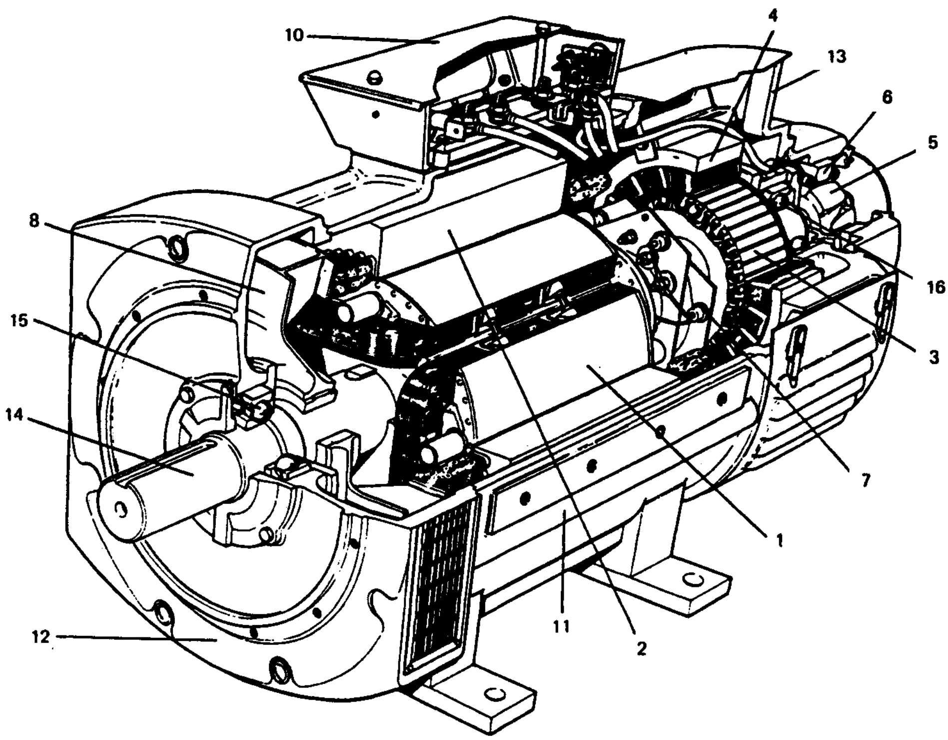
BS 2757 (lEC 85) - *Method for determining the thermal classification of electrical insulation*

BS 2949 (IEC 92-5) - *Specification for rotating electrical machines for use in ships*

### 3.9.2 World regional standards

*North America*

In the USA: National Electrical Manufacturers' Association (NEMA) specification NEMA MGI-22 gives general requirements for machines; and NEMA MGl-1.65 deals with insulation systems.




| Plate ref. | Description | Plate ref. | Description |
|---|---|---|---|
| 1 | Main rotor | 9 | V.C.U. (A.V.R.) not illustrated |
| 2 | Main stator | 10 | Terminal box |
| 3 | Exciter rotor | 11 | Frame |
| 4 | Exciter stator | 12 | Drive endbracket |
| 5 | Permanent magnet rotor | 13 | Non-drive endbracket |
| 6 | Permanent magnet stator | 14 | Shaft |
| 7 | Main rectifiers | 15 | Drive end bearing |
| 8 | Fan | 16 | Non-drive end bearing |

**Figure** 3.45 Cutaway illustration of a 4-pole, double bearing, brushless generator (Courtesy: Newage International Ltd.)

In Canada: The Canadian Standards Association (CSA) specification CSA C22-2 relates to general requirements for machines.

*Continental Europe*
In West Germany: Verband Deutscher Elektrotechniker specification VDE 0530 covers the rules for electrical machines, including the classification of insulating systems. Other related specifications, published by the German Industrial Standards Association, include DIN 40 050 which classifies types of enclosure and degrees of protection and DIN 42 950 which covers types of construction and mounting arrangements.

Other countries: Less frequently encountered are the Swedish Standards SEN 26 01 0J *(General),* SEN 26 0105 *(Mounting Arrangements),* SEN 26 01 *06 (Methods of Cooling)* and SEN 26 01 07 *(Mounting Arrangements).* The French Standard for rotating machines is NF C51-100. Without exception, Continental European manufacturers will supply machines complying with IEC34.

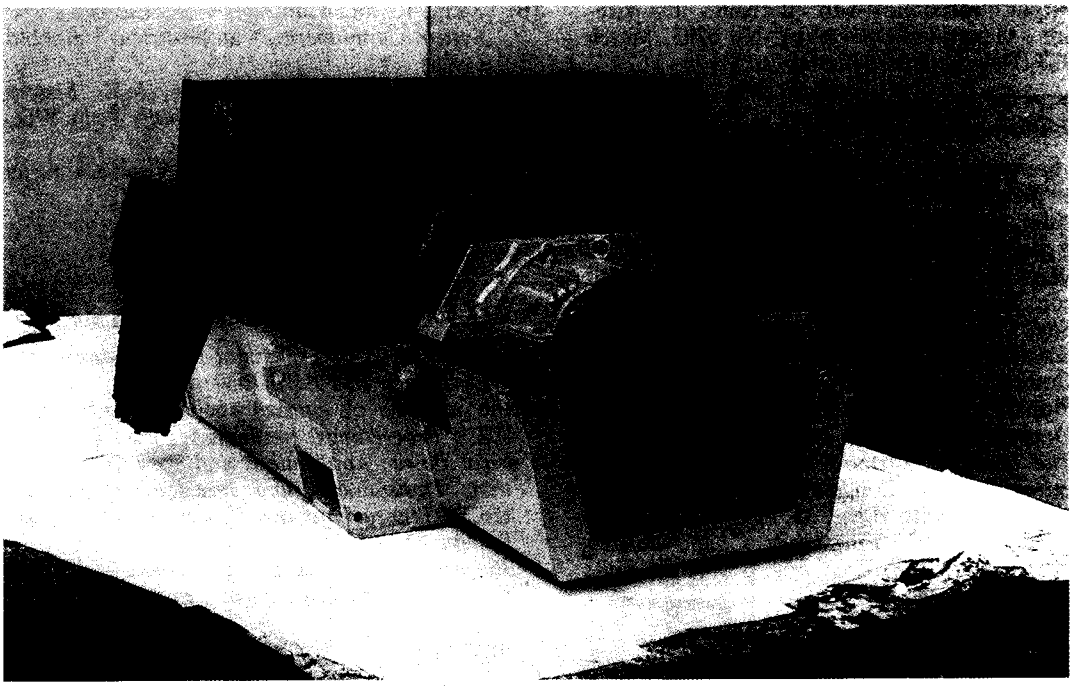


**Figure** 3.46 Assembled generator, showing brush less exciter components (Courtesy: GEC Alsthom Large Machines Ltd.)

## 3.10 References and bibliography

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### 3.10.2 Bibliography

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(7) Nasar, S.A. and Unnewehr, L.E. *Electromechanics and Electrical Machines,* John Wiley & Sons, (1979).
*(8)* *The A.C. Generator Manual,* Newage International Ltd, Stamford, England.


Additional useful sources of information are:

- the house journals of major manufacturers, e.g. *GEC Review* and *ABB Review.*
- the journals of learned societies, such as the IEE's *Proceedings,* particularly, Part B - *Electrical Power Applications* and Part C - *Generation, Transmission and Distribution;* and the IEEE *Transactions on Power Apparatus and Systems* (PAS).
- *Electrical Power and Energy Systems* - a journal published every three months by Butterworth.

# 4

# A.C. Generators - performance characteristics

**Contents**

## 4.1 Introduction

Generator design and construction were discussed in Chapter 3. We shall now consider the principal characteristics that determine machine performance, under both steady-state and transient conditions; and review the terminology and definitions commonly associated with performance. A full treatment is beyond the scope of this chapter, and requires a far more extensive background in electromagnetic circuit theory than the reader is expected to have. The simplistic descriptions that follow are intended to convey an approximate physical picture of the conditions that apply in both steady-state and transient operation.

## 4.2 Steady-state operation

Here we shall review the behaviour of the a.c.generator on load, in steady-state conditions. Steady-state is defined as: *'the state which prevails when only inherent or natural changes occur, i.e. no deliberate change* is *made to, or a fault occurs on, any part of the supply system'* [1]. The principal interacting characteristics, under these conditions are:

- field current;
- armature current;
- terminal voltage;
- load power factor; and
- the machine's efficiency.

We have established (in Section 3.2 of Chapter 3) that the field current required to maintain rated voltage at a machine's output terminals varies with the power factor of the load (see Figure 3.3). On single operation (i.e. when a generator is supplying a 'dedicated' load), any change in load demand must be met by a response from the prime mover's governor, working to adjust the input torque so as to keep the *system* frequency constant. The generator's excitation system must simultaneously regulate the field current in order to maintain the terminal voltage at its rated value. Where several generators operate in parallel, each generator is usually required to deliver its fair and proportionate share of the total load. The *active* and *reactive* power demands of the electrical system must be shared between the generators. The interrelation between the principal operating characteristics within each individual generator, and between generators (particularly, the effects of excitation and governor control), is markedly different from the single-running case. The parallel operation of generators is described in Chapter 8.

### 4.2.1 Efficiency

The operation of every energy-transforming device is accompanied by the loss of some input power. By definition, the *efficiency* of a machine is the ratio of output to input power - expressed in the same units, and usually given as a percentage. It is, therefore, a dimensionless quantity. *Total loss* is the difference between the input and output power.

The various equations for efficiency ($\eta$) are all derived from the basic expression:

$$\eta = \text{Power output/Power input}$$
$$= P_{out}/P_{in}$$

In terms of output and losses:

$$\eta = \text{Power output/(Power output + Power loss)}$$
$$= P_{out}/(P_{out} + P_{loss})$$
$$= 1 - [P_{loss}/(P_{out} + P_{loss})]$$

In terms of input and losses:

$$\eta = \text{(Power input - Power loss)/Power input}$$
$$= (P_{in} - P_{loss})/P_{in}$$
$$= 1 - (P_{loss} - P_{in})$$

The latter formula is a very useful way of expressing the performance of a machine because it shows how the relative losses are subtracted from the *ideal* (unity) efficiency. The ratio: *Losses/input* may be defined as the *deficiency* of a machine, and is perhaps a better criterion of machine performance than the more commonly used term, efficiency. Clayton [2] iIlustrates this point with a neat example.

*Example*
Consider two 1000 kW machines; one with an efficiency of 93 %, and the other with an efficiency of 95 %. The difference in efficiency does not appear, at first sight, to be significant. The corresponding deficiency figures, however, throw more light on the relative merits of the machines; and indicate that one machine is about 40 % more wasteful than the other.

Developing the argument a bit further, the input at 93% efficiency is 1075.3kW (= 1000/0.93), whereas, at 95 % it is 1052.6kW. The losses for the less efficient machine are therefore some 23 kW (1075-1052) more than those for the other machine - about 43 % more. Assuming 4000 hours operation per year, at a fuel energy value of 0.8 p/kWh, the more efficient machine would give an annual saving of £ 736 in running costs.

Some caution must be exercised when comparing the efficiencies of machines as it is important to satisfy oneself that the methods of measuring and computing declared values are the same in each case.

In general, machine efficiency increases with size. Typical values are as follows:

| Rating, kW | Efficiency |
|---|---|
| 1 | 0.75 |
| 5 | 0.85 |
| 10 | 0.87 |
| 20 | 0.88 |
| 50 | 0.90 |
| 100 | 0.92 |
| 1000 | 0.95 |

## The nature of losses

Machine losses may be divided into:

1. *Iron losses* - magnetic losses;
2. *Copper losses* - electrical losses; and
3. *Windage and friction losses* - mechanical losses.

*Iron losses* include the eddy-current and hysteresis losses in the laminations of the core, and the pole face and endwinding-region losses (mainly eddy-current and hysteresis loss, at high harmonic frequencies). *Hysteresis loss* stems from the property of magnetic materials known as the *hysteresis effect,* which always accompanies the magnetization of ferrous materials. It is caused by the lag in the variation of magnetic flux in a material, behind the variation of the magnetizing force (current) applied to it.

When the alternating flux within a machine 'cuts' the core, it induces, or generates, an electromotive force (e.m.f.) within the material of the core, in much the same way as it does in the armature windings which are slotted within the core. The resulting currents tend to circulate locally (in closed eddy paths) within the core material - hence the term *eddy-currents.*

If the core were solid, it would have very low electrical resistance and the eddy currents induced within it would be very large. The result would be an excessive build-up of heat within the machine. In order to avoid this, the core is constructed of thin sheets of magnetic material *(laminations)* separated by very thin layers of electrical insulation. See Sub-section 3.3.3 of Chapter 3. This, effectively, confines the eddy currents to high resistance paths. The overall effect is to reduce the *eddy-current loss* in the magnetic material. Eddy-current loss is approximately proportional to the square of the lamination thickness, and inversely proportional to the electrical resistivity of the material.

For the purposes of our discussion, we need only say, at this stage, that iron losses are dependent upon the magnitude and the speed of the rotating magnetic flux within the machine, i.e. upon its density and its frequency. Core flux is unaltered for constant applied voltage and frequency (the conditions that pertain in a voltage-regulated synchronous generator), and it is not greatly affected by variations in load current. Iron losses may therefore be considered as roughly constant and fairly independent of load.

*Copper losses* are the power losses in the resistances of the stator and rotor windings. They are made up of the $I^2R$ losses in the armature (stator) windings carrying the load current, and those in the field circuit (the so-called *excitation losses).* Also grouped under the heading of copper losses are those which are termed *stray losses.* These are mainly caused by changes in flux distribution arising from load variations. They may comprise additional losses in magnetic paths (in either active iron, or other metal, parts), and eddy current losses in the armature winding conductors and in any binding bands, etc. Their exact values are difficult to determine. Recourse is often made to empirical *factors of experience,* e.g. an allowance of up to 50% of the 'pure' $I^2R$ copper losses. Armature copper losses and these stray losses may be included under the heading *load losses.*

Mechanical losses are defined as *constant losses* because they are functions of the speed only. They include the *friction loss* between shaft and bearings, and the total *windage loss* produced by the motion of the main rotor and by any exciter rotors forming an integral part of the machine. This loss group also includes the power absorbed by integral fans.

It should be appreciated that windage is not only a source of power loss - which is converted into heat, but it is also (on the credit side) a realistic means of dissipating machine heat, through convection. See Section 3.5 of Chapter 3.

It can be shown that, for any constant load power factor, the *maximum efficiency* of a machine coincides with that load at which the *constant losses* equal the *load losses.* See Figure 4.1.

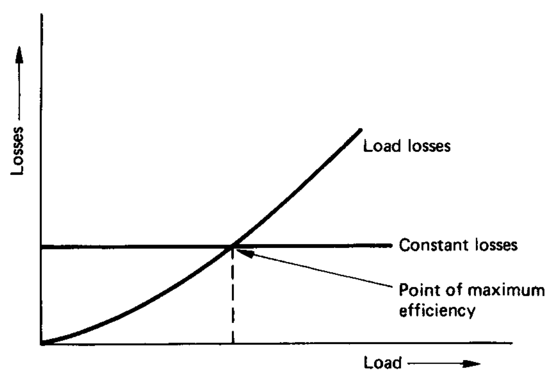



**Figure 4.1** Characteristics of losses plotted against load, for constant load power factor

Copper loss is equal to the product of current squared, and resistance ($I^2R$). For a given kW output, and at constant terminal voltage, the load current $I_L$ may be expressed as:

$$I_L = kW/U_l \cos\phi$$

so that, $I_L \alpha 1/\cos\phi$

but, since copper loss is proportional to $I_L^2$, it must be proportional to $1/\cos^2\phi$. This means that, as power factor falls, the magnitude of the copper and excitation losses increase. Relating this to the earlier expressions for efficiency (which is adversely affected by losses), we may conclude that efficiency will be reduced as the power factor falls below unity. This fact is demonstrated in Figure 4.2.

### *Determining efficiency by measurement*

Recommended methods for determining the losses and the efficiency of rotating machines are given in a number of national standards. The following discussion only summarizes the provisions of such standards. Reference should be made to the following standards, for fuller details:

- BS 4999: Part 102 (IEC 34-2 & IEC 34-2A) - *Methods for determining losses and efficiency from tests.*
- VDE 0530 - *Rules for electrical machines*
- American National Standards Institute (ANSI) Standard C50

Efficiency may be measured either *directly* or *indirectly*. In the *direct method,* the power supplied by the tested machine, and the power absorbed by it, are measured directly. The machine is driven at rated speed by a *calibrated* motor - one whose losses have been accurately predetermined. The mechanical power obtained from the motor's output shaft may then be derived from the electrical power the motor absorbs. An alternative method uses a dynamometer or a motor driving through a torsion-meter. This enables the torque transmitted to, and hence the mechanical power absorbed by, the test machine to be determined. Two identical machines may be tested in a *back-to-back* configuration. In the mechanical back-to-back test (Figure 4.3(a», the total losses of both machines are calculated from the difference between the electrical input to one machine and the electrical output from the other. In the electrical back-to-back test (Figure 4.3(b», the total losses of both machines equate to the input power drawn from the electrical power system. Direct measurement methods are only appropriate when the difference between output and input for the test machine(s) is large enough to swamp the effect of the inaccuracies that inevitably occur in measurements. For example, with a power measurement accuracy no better than 1%, the efficiency can be 2% in error, and the error in total losses can be 2% of the total input power. Direct measurement offers a convenient and acceptable form of test on machines smaller than 30kW (where efficiency is usually less than 90%). Where efficiencies are expected to be above 85%, the inaccuracy of the direct method is generally greater than that obtained from indirect measurement.

*Indirect measurement* implies the measurement of the actual losses in a test machine under a particular condition. These losses are then added to the power

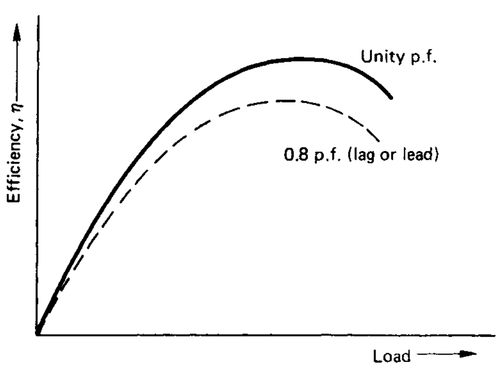
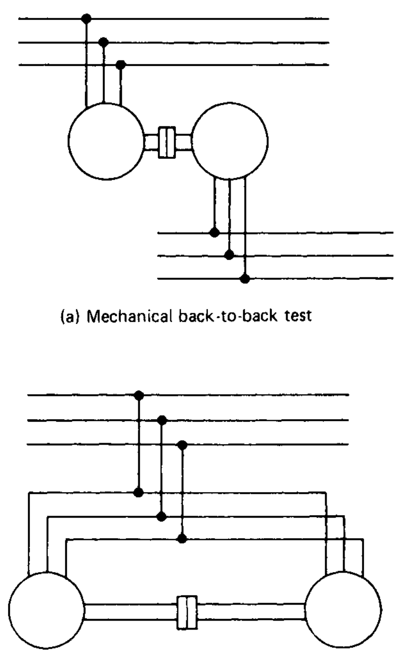



**Figure 4.2** Efficiency curves for varying power factor



(a) Mechanical back-to-back test

(b) Electrical back-to-back test

**Figure 4.3** Efficiency measurement, back-to-back tests supplied by the machine to give the absorbed power. One of the following methods may be used:

1. the determination and summation of separate losses - the so-called *loss summation* method; or
2. the determination of total losses.

Unless otherwise specified or agreed, the guaranteed efficiencies of machines are understood to have been determined by indirect measurement, using method 1 above.

British Standard BS 4999: Part 102 stipulates (in Section 4) the losses to be included in determining the efficiency of synchronous machines. It describes (in Clause 11) the methods of determining efficiency, using either *summation of losses* or *total loss measurement* techniques. While the preferred method of determining the constant losses is by a unity power factor test at rated voltage and frequency, other options are listed in the standard. These include *calorimetric* and *retardation* test methods.

A *calorimetric test* is one in which a machine's losses are deduced from the heat produced by them. The losses are calculated from the product of the amount of coolant and its temperature rise, and by the heat dissipated in the surrounding media. Two distinct methods may be employed:

1. Direct measurement: in which the difference between the outlet and inlet temperatures of the cooling medium, as well as the quantity of cooling medium (per unit of time), are measured, and are used to determine the total losses.
2. Comparative measurement: in which the temperature rise of the cooling medium (measured when the machine is loaded) is compared with the temperature rise caused by an electrically-measurable amount of losses. For example, the machine is first run on load, and then at no-load, but over-excited. The watts, which account for the power losses, are measured when the machine is running unloaded.

The *retardation test* is particularly applicable to slower speed salient pole machines, which have considerable inertia. The constant losses in the machine are deduced from the rate of speed deceleration when only these losses are present, and while the machine is slowing down between two predetermined speeds (typically, from 110% to 90% of rated speed). If the machine's flywheel effect is known, the constant losses at rated speed may then be calculated from the change of speed per unit of time.

A final point worth noting is that, where $J2R$ losses are being considered, winding resistances, determined by d.c. measurement, are usually corrected to a reference temperature, which is related to the class of insulation used. The reference for Classes A, E and B insulation is 75°C, and 11SOC is used for Classes F and H. The formulae for the temperature corrections are:

$$R75 = (310°C/235°C + t)\ Rt \text{ and}$$
$$R_{115} = (350°C/235°C + t)\ Rt$$

where $Rt$ = resistance of the windings at $tC$
$R75$ = resistance of the windings at 7SOC
$R_{1l5}$ = resistance of the windings at U5°C

## 4.2.2 Speed-frequency relationship

By definition (BS4727: Part 2, Group 3 - *Rotating machinery terminology), synchronous speed* is the speed of rotation of the primary magnetic flux. At synchronous speed the rotating magnetic field created by the armature currents in the stator travels at the same speed as the field created by the field current in the spinning rotor. The latter is the speed of the rotor itself.

Faraday's law of electromagnetic induction governs the operation of a generator. It states that, when a conductor is moved in a magnetic field, an *electromotive force* (e.m.f.) is induced in the conductor. This e.m.f. is proportional to the speed at which the conductor is moved, and to the density of the magnetic lines of force. When the conductor is in the form of a loop (as in the winding of a generator) and rotates in a magnetic field, a sinusoidal alternating voltage is produced. If the loop is closed to form a load circuit, an alternating current (also with a sinusoidal wave-form) flows in the circuit. Its direction changes periodically, i.e. its instantaneous value alternates between a positive maximum, or peak value, and a negative maximum value. A complete 'set' of these positive and negative values is known as a *cycle*. This leads to the definition of *frequency* as being 'the number of cycles generated per second'. If the duration of each cycle is $T$ second, the frequency (j) is, by definition, $l/T$. It is expressed in *hertz* (Hz). *Tis* 20 ms, for a frequency of 50 Hz; and 16.7 ms, for 60 Hz.

Each time a stator conductor in the winding loop is passed by a pair of rotor poles, the e.m.f. induced within it undergoes a complete cycle of variation. If the generator has $p$ pairs of poles, there will be $p$ cycles of variation during each revolution of the rotor shaft. Where the speed of the shaft is $n$ revolutions per minute (rpm), the frequency of the generated e.m.f. is determined as follows:

since $f$ = number of cycles/second
= (number of cycles/revolution) x (number of revolutions/second)
= $p.n/60$

If the speed and the frequency are specified, the number of poles required is fixed by this relationship, which gives the characteristic property of a synchronous machine. Synchronous machines must run at *synchronous speed* - a term which, in itself, can only be meaningful when related to the frequency of the induced e.m.f.s within the machines. The relationship between $f$, $p$ and $n$ affects the choice of speed for a synchronous generator.

The following table (4.1) lists the synchronous speeds, at 50 and 60 Hz operation, corresponding to the number of pole pairs fitted.

**Table** 4.1 Synchronous speeds relating to the number of pole pairs fitted

| *Number of pole pairs* - p | *Synchronous speed* - n 50Hz | 60Hz |
|---|---|---|
| 1 | 3000 | 3600 |
| 2 | 1500 | 1800 |
| 3 | 1000 | 1200 |
| 4 | 750 | 900 |
| 5 | 600 | 720 |
| 6 | 500 | 600 |
| 7 | 428 | 514 |
| 8 | 375 | 450 |
| 10 | 300 | 360 |

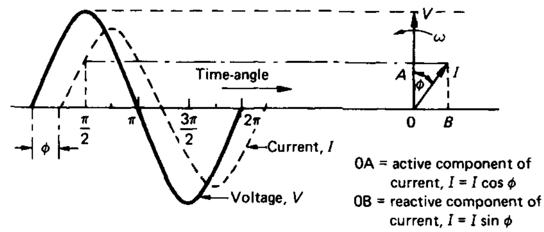
The successive differences in speed reduce considerably as the number of pole pairs increases, e.g. 1500rpm between 2- and 4-pole machines at 50Hz, compared with only 53 rpm between 14- and 16-pole machines. The latter difference is so small as to be of little significance as far as any meaningful increase in prime mover output is concerned. At the other end of the scale, the 1500 rpm step is inhibitingly large, since intermediate speeds between 3000 and 1500 rpm are inadmissible for 50 Hz operation.

The relationship $f = p.n/60$ may also be expressed in electrical and mechanical *radians:*

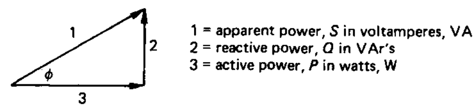
Where w is the radian frequency of the voltage wave and is equal to *27rf,* and $w_m$ is the mechanical speed of the machine, in radians per second.

### 4.2.3 Power factor

When a voltage of sinusoidally alternating waveform is applied to a pure resistance load (i.e. one free from inductance and capacitance), the load current has the same frequency as the voltage, and varies directly with it. Voltage and current waveforms are then said to be *in phase.* If the load is not purely resistive, but contains elements of inductance or capacitance, the voltage and (load) current waveforms are not in step and are said to be *out of phase.* In other words, the peak values of the two alternating quantities now occur at different points in the time cycle (see Figure 4.4). At one extreme, for a




(a) Current lagging behind voltage – phase displacement φ




(b) 'Addition' of true and reactive power

**Figure** 4.4 Phase displacement. and phasor diagrams for power factor

purely inductive load, the current *lags* the voltage with a *phase displacement* of 90°, whereas, at the other extreme, a purely capacitive load results in a current phase displacement of 90°, in the *leading* sense. Depending upon the nature of the load, the *phase angle* may therefore vary between the limits of +90° (lead) and -90° (lag). Inductive and capacitive elements are said to be *energy-storing,* and resistive elements *energy-consuming.*

Since power (defined as the rate of transfer, storage, conversion or dissipation of energy) is a product of voltage and current it must be a function of time in sinusoidally alternating current circuits, The *average value* of power over one period, or a whole multiple of a period, is given by:

$P = UI\cos\phi$ expressed in watts (or kW, MW, etc.)

Where the angle $\phi$ is the phase angle between the *phasors* that represent the two time-varying quantities – voltage and current (see Figure 4.4), and $P$ is the *true power*. The product $UI$ (of the *effective*, or *rms*, values of voltage and current) is called the *apparent power* ($S$) and is expressed in volt-amperes. See Sub-section 4.2.4.

The cosine of the angle $\phi$ is called the *power factor* (pf) of the circuit. It is the factor (or coefficient), always equal to or less than unity, by which the apparent power must be multiplied to obtain the true power (i.e. $P = S$ . pf).

In a load circuit where the current phase displacement is $\phi$, the current $I$ may be resolved into two components; one in phase with the voltage, and the other at 90°C ($\pi/2$) to it, i.e. in *quadrature* with it. The former, equal to $I\cos\phi$, is called the *wattful* component, and the latter, equal to $I\sin\phi$, the *wattless* component. They are also referred to as the *working* and *idle* components, respectively. The product $UI\sin\phi$ is termed the *reactive power* ($Q$), and has the same dimension (but not the same numerical value) as the active power. It uses the unit *VAr* (hence: kVAr, MVAr, etc.)

The power factor is given by:

$$\cos\phi = P/S$$
$$\text{i.e.} = I^2R/UI \text{ or } IR/U$$

If $Z$ is the impedance of the circuit, in ohms,

$$U = IZ$$

Substituting in the above expression for power factor, we obtain:

$$\text{power factor, } \cos\phi = IR/IZ = R/Z$$

The expression power factor = *PIS* always holds good, whereas, pf = *IR/U* (or *RIZ)* is only valid when both the voltage and the current wave-forms are sinusoidal. This is because the latter expressions are derived from phasor diagrams which, in themselves, are based upon sinusoidally varying quantities (see Appendix 4.1). For example, if the wave-forms are in any way *complex,* and contain harmonic quantities - each of which may have different phase angles - no single angle can be used to derive the power factor. Also, with complex waves, the power factor can never have the same value as it would have with sinusoidal waves, of the same effective value. The only exception to this is a purely resistive circuit [3]. The overall power factor of a circuit containing harmonics cannot be described as either lagging or leading; it is merely the ratio of *PIS.*

## *The practical implications of power factor*

The physical size and cost of a.c generation, transmission, and utility equipment is approximately proportional to its kVA rating. We have established (in o;ub-section 4.2.1) that the efficiency of a machine is reduced as its operating power factor falls. This is because of the larger current and, therefore, greater copper losses within it. For a given output, the lower the system power factor the larger the generator must be to furnish that power, and the greater, also, the cross-sectional area of the cable conductors required to transmit the power. Economic factors also include the rating of the switchgear necessary to distribute the power. The following example illustrates this point.

*Example*
A 3-phase generator rated at 1000kVA and 400 volts would be capable of a maximum continuous current output of 1445A, without exceeding its safe operating temperature level. If the power factor of the load is unity, the *true power* required from the prime mover would be 1000kW, plus the losses within the generator. But, if the load power factor were 0.7, the prime mover need only supply 700kW, plus generator losses. It is, therefore, effectively developing only 70% of the power of which it is capable. Also, the cables connecting the generator to the load are capable of transmitting l000kW if the load power factor were unity, but only 700 kW at 0.7 pf (1445 A in each case), for the same conductor temperature rise

The higher, therefore, the load power factor the greater the *true* power that can be generated by a given generator and transmitted by the given cables. Conversely, the lower the overall system power factor the lower the energy transmission efficiency becomes, with a consequent increase in the cost of the electric energy provided. The following table [4] shows that, as the power factor is reduced:

- more current is demanded from the supply source than is necessary for the actual power required;
- there is an appreciable increase in the resistance losses in the system (proportional to the square of the current);
- there is increased voltage drop throughout the system; and
- the excitation power is increased.

Inefficient plant utilization of this kind imposes economic penalties on the consumer.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Power factor | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.33 |
| Relative current increase | 1 | 1.11 | 1.25 | 1.43 | 1.67 | 2.0 | 3.0 |
| Relative resistance losses | 1 | 1.23 | 1.56 | 2.05 | 2.8 | 4.0 | 9.0 |

## *kVA, kVAr, kW and power factor relationships in graphical form*

The relationships between combinations of any three of the variables apparent, reactive and true power, and power factor are often conveniently expressed in graphical form. See Figures 4.5 and4.6 [5].

The collineation nomogram of Figure 4.5 offers a method for determining power factor, given the absolute values of the reactive and true power measurements recorded. Obviously, the units of measurement must be of the same *order,* e.g. kVAr and kW, MVAr and MW. The value of the power factor is read off the right-hand scale, at the point where the straight line joining the measured values of reactive and active power intercepts it. In accordance with I.E.C. convention, the power factor is *lagging,* when the VAr and watts values have the same sign, and it is *leading* when one of the two power values has a negative sign.

The chart of Figure 4.6 permits reactive power to be determined, given values of true power and the power factor. Use of the chart is described in the sub-section which follows.

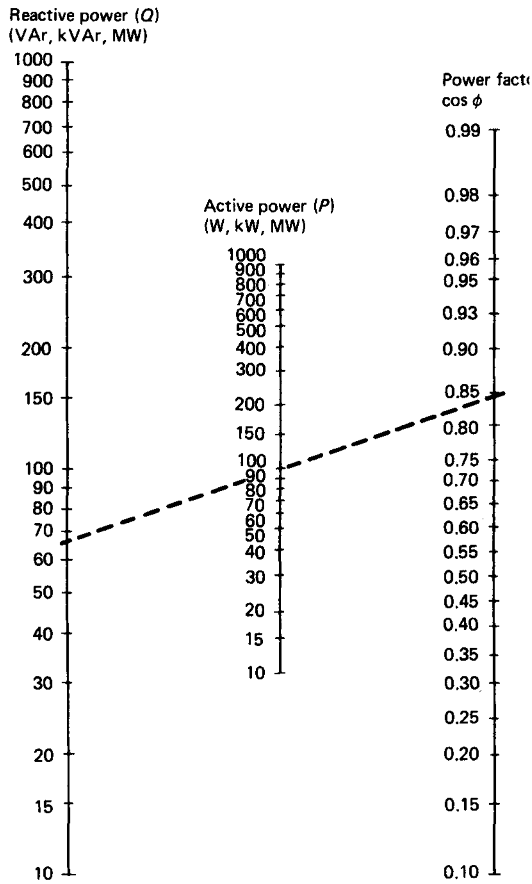



**Figure 4.5** Nomogram for determining power factor given the active and reactive values of power

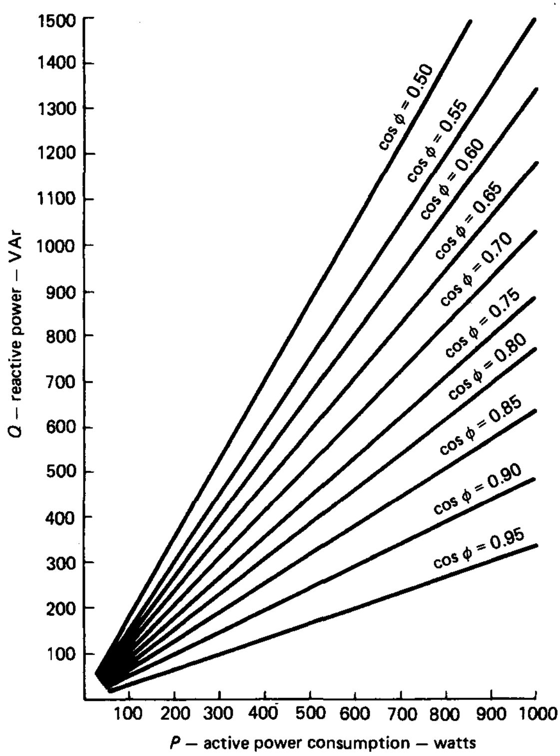



**Figure** 4.6 Relationship of true power to reactive power for varying power factor

## *Power factor improvement*

The greater part of the electrical load in industrial installations consists of plant which requires reactive current (e.g. induction motor driven machinery, and welding apparatus) and which draws more current from the supply than is required to provide the necessary power to operate it. The 'extra' current is used in magnetizing the electrical machines. The power factor *(P/S)* of such an installation may be expressed as:

pf = current effectively used/current supplied

The principal methods used for system power factor improvement are:

1. Synchronous motors (driving pumps, fans, compressors, etc.) with their working power factor adjusted, through excitation control, to give operation at unity or leading power factor. The motors will only contribute to power factor correction whilst they are running. Generally, they are an uneconomical proposition for outputs less than 400kW.
2. Synchronous condensers, which are, effectively, synchronous motors used solely for power factor correction and voltage regulation. Because of their cost, they are only of value in the largest installations or supply systems.
3. Capacitors, which have the merit of being far less costly than either 1 or 2, are easy to install, and require, virtually, no maintenance. Application flexibility is achieved in one of several ways.
   (a) by *individual correction* using capacitors directly connected to the supply terminals of individual, low power factor, items of plant;
   (b) by using manually controlled capacitors, located at key points within the plant, and switched-in when the appropriate sections of plant are in operation;
   (c) an arrangement, similar to (b), wherein the capacitors are automatically switched in and out of circuit by contactors as the load varies.

Figure 4.4 shows that lagging power factor is caused by current, drawn by a purely *inductive* device, lagging behind the voltage by 90°. In contrast, a capacitor draws a current which leads the voltage by 90°. A capacitor connected across the inductive device, and rated to draw a current equal in magnitude to that drawn by the device, will completely cancel the lagging current. In practice, full compensation of this kind is uneconomical and it is unusual to take power factor improvement beyond about 0.95.

The following example shows how one determines the reactive output of the capacitors needed to effect improvement of power factor to a targeted value.

*Example*
It is required to improve the power factor of a 600 kW section of plant from its existing 0.7, to 0.95 lagging. What must be the reactive output of the capacitors needed for this improvement?

*Solution* I
Referring to the chart in Figure 4.6, we see that the value of watt less (or reactive) power corresponding to 600kW and a power factor 0.7, is approximately 610 kVAL Similarly, the reactive power corresponding to the corrected value of 0.95 pf is only 200 kVAr. The capacitor required to compensate for this difference must therefore be sized at 410 kVAr (= 610 - 200).

*Solution* II
The size of capacitor for a required degree of power factor correction is given by the expression :

**Rating (in kVAr) = kW ($\tan \phi_1 - \tan \phi_2$)**
**Where kW = 3-phase active power**
**$\phi_1$ = the angle corresponding to the initial power factor**
**$\phi_2$ = the angle corresponding to the corrected power factor**

In our example, the angle (in degrees) corresponding to a power factor of 0.7 is 45.6°, and the angle corresponding to a power factor of 0.95 is 18.2°. Substituting in the above expression, we have:

kVAr = 600 (tan 45.6° - tan 18.2°)
= 600 (1.02117 - 0.32878)
= 600 x 0.69239
= 415

Power capacitor manufacturers provide convenient tables listing multiplying factors, derived for the bracketed portion of the above expression. The relevant line from one such table [4] is reproduced below. It gives us the factor (0.692) required for our problem.

The kVAr output of power capacitors varies directly with the square of the applied voltage, and directly with system frequency. Indiscriminate connection of 'standard' units, to systems of voltage and frequency higher than their rated values, should be avoided.

### 4.2.4 Alternating wave-form characteristics

The *root-mean-square (r.m.s.),* i.e. the square root of the *mean* of the *squares* of the instantaneous values of current *(ii'* $i_2$, etc. in Figure 4.7) over the half-cycle of an alternating current, is the *effective* value of that current. It is defined as 'that *direct* current that would produce the same heating effect in the same resistance'. Similarly, the effective or Lm.S. value of an alternating voltage is 'the value of that *direct* voltage which produces the same heating effect, when applied to the same resistance'.

The *mean* value of a periodic *symmetrical* wave is that applicable over the half-period (i.e. $\pi$ radians) since the mean over a complete period ($2\pi$) is zero (see diagrams (a) and (b) of Figure 4.8). The mean values of sinusoidal, and full-wave rectified wave-forms, are given by the *peak* value (also called *maximum* or *crest* value) multiplied by $2/\pi$ (= 0.637). The mean value for a pulsed and asymmetric half-wave rectified sine wave-form (diagram (c)) is given by:

peak ÷ $\pi$
or peak x 0.318

If $I_p$ is the peak value of a sinusoidal alternating current, the r.m.s. value is given by:

$I_{rms} = 0.707\, I_p$

This also holds good for the full-wave rectified wave-form. It can be shown that the relationship, $I_{rms} = 0.5\, I_p$ applies to the half-wave rectified sine wave-form.

There are two other quantities that are often mentioned in the context of sinusoidal alternating wave-forms. These are, the ratios *form factor* ($K_f$) and *crest* or *peak factor* ($K_p$). They are defined as follows:

Form factor is the ratio of the r.m.s. value of an alternating wave to its mean value, taken over half a period and beginning at a zero point.

$K_f$ = r.m.s./mean

**Table** 4.2 Multiplying factors

| *Initial pf* | *Multiplying factors when the desired power factor is:* 0.8 | 0.85 | 0.90 | 0.91 | 0.92 | 0.93 | 0.94 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | Unity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.70 | 0.270 | 0.400 | 0.536 | 0.564 | 0.594 | 0.625 | 0.657 | 0.692 | 0.728 | 0.769 | 0.817 | 0.878 | 1.020 |

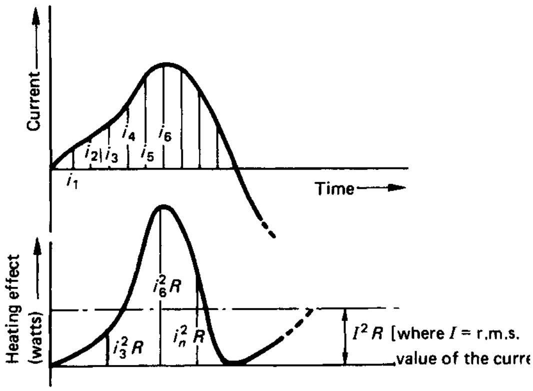
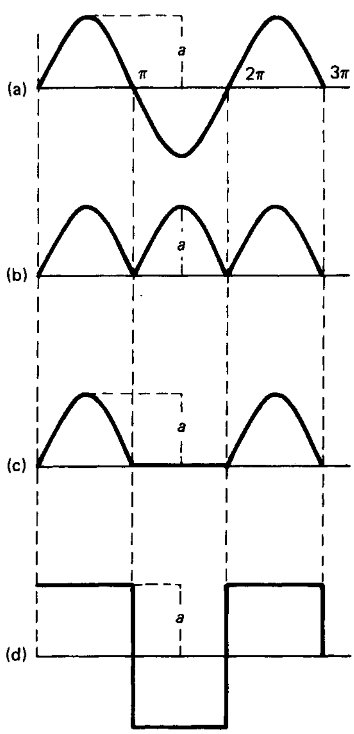



**Figure 4.7** Periodic current wave-form




| Wave-form type | Values of alternating quantities | | | |
|---|---|---|---|---|
| | r.m.s. | mean | $K_f$ | $K_p$ |
| Sinusoidal | $a/\sqrt{2}$ | $a(2/\pi)$ | 1.11 | 1.41 |
| Full-wave rectified sine | $a/\sqrt{2}$ | $a(2/\pi)$ | 1.11 | 1.41 |
| Half-wave rectified sine | $a/2$ | $a/\pi$ | 1.57 | 2.0 |
| Rectangular | $a$ | $a$ | 1.0 | 1.0 |

**Figure** 4.8 Example wave-forms with associated alternating quantities

Crest factor is the ratio of the peak value of an alternating or pulsating wave to its r.m.s. value.

$K_p$ = peak/r.m.s.

Values for both factors are shown, against the appropriate wave-forms, in Figure 4.8.

The form factor of a complex (i.e periodic but non-sinusoidal) wave-form is of particular significance in electrical instrumentation. Moving-iron, electrodynamic, and electrostatic instruments always read the true r.m.s. value of a parameter. Moving-coil or rectifier instruments have scale deflections proportional to the full-wave rectified mean current flowing in their coils. They are calibrated in r.m.s. values, which assume sinusoidal wave-form inputs. In other words, their readings are mean values multiplied by the form factor 1.11. If the measured wave-form has a form factor $K_f$, the mean value of the parameter is the rectifier instrument reading divided by 1.11. The true Lm.S. value of the measured wave-form is, therefore, given by:

The form factor of a complex wave-form may be determined by measuring the parameter on a true Lm.S. instrument and comparing the measurement with a reading taken on a rectifier instrument [7]. The form factor of the wave-form is then given by:

Periodic, but non-sinusoidal, complex wave-forms with identical positive and negative half-cycles, and only two zero values per cycle, may be represented by a Fourier series of the following form:

A current wave-form of this type, consisting of the sum of the sine waves of a *fundamental* and a series of *harmonics* 2, 3, ..., *n* times that of the fundamental, may result from:

1. a non-sinusoidal e.m.f. source;
2. a sinusoidal source, applied to non-linear loads (see Chapter 5);
3. a combination of 1 and 2.

The Lm.S. value of a current of this form,

## *Terminology, definitions and specifications*

One occasionally encounters performance specifications which set limits for form and crest factors. Typically, these are between 1.28 and 1.00 for form factor, and between 1.45 and 1.37 for the crest factor [8].

Another performance characteristic often mentioned in specifications is that of *divergence,* which is defined (1] as: the instantaneous difference between corresponding ordinates of a distorted wave and its fundamental, expressed as a percentage of the measured r.m.s. voltage.

The superseded British Standard BS 4999: Part 40: 1972 – *Characteristics of synchronous generators*[1] employed the term *wave-form deviation*, and stipulated that deviation on the line-to-line wave-form could be measured along the ordinates of the wave-form or obtained from a suitable wave analyser, where each individual harmonic was measured. Where ordinate measurement was made, the voltage wave-form was considered to be sinusoidal if none of the instantaneous values *d* diverged from the instantaneous value *g* of the fundamental, by more than 10 % of the peak value *s*, for generators from 300 kVA up to 3000 kVA; or by more than 5 % of the peak value *s*, for generators above 3000 kVA. See Figure 4.9. The peak value of the fundamental was considered to be $\sqrt{2}$ times the r.m.s. voltage, measured by a precision class voltmeter. When a wave analyser was used, the wave-form was considered to be sinusoidal if no harmonic (up to the 25th) exceeded 10% of the fundamental wave amplitude, for generators between 300 and 3000 kVA. This limit reduced to 5 % for machines larger than 3000 kVA.

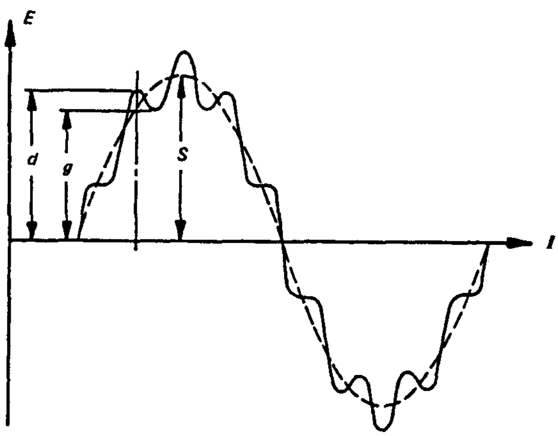



**Figure 4.9** Measurement of wave-form deviation (from BS 4999: Part 40: 1972, courtesy: British Standards Institution)

[1] Several clauses of BS 4999: Part 40 have been included in BS4999: Part 101, with the notable exception of that relating to *wave-form deviation* as described in this text. BS4999: Part 101 places emphasis (in its Section 11) 011 requirements for limiting the telephone harmonic factor- (THF) on machines above 300kW or kVA. See the later discussions on THF.

When setting a limit for wave-form deviation, the specifier must accept responsibility for ensuring that his power utilization equipment does not, in itself, cause significant distortion of the supply system wave-form when the generator is loaded. In other words, the circuit which the generator supplies should be virtually non-deforming. BS 4999: Part 101: 1987 - which partially supersedes the old Part 40 - defines a non-deforming circuit as one in which the current is virtually sinusoidal when supplied by a sinusoidal voltage. None of the instantaneous values in the current wave-form should differ from the instantaneous value of the same phase of the fundamental wave by more than 5 % of the amplitude of the latteL

*Harmonic content* is an important characteristic of wave-forms. Some user-specifications may set limits on harmonic content in addition to divergence criteria. An *individual harmonic* is defined [1] as an oscillation of sinusoidal wave-form having a frequency which is an integral multiple of the fundamental frequency. The Lm.S. amplitude of the individual harmonic is expressed as a percentage of the Lm.S. amplitude of the fundamental. The *total harmonic content* (THe) is defined [1] as the total Lm.S. value of the wave-form remaining when the fundamental component is removed from the complex wave. It is equal to the square root of the sum of the squares of each of the harmonic amplitudes and is expressed as a percentage of the Lm.S. amplitude of the fundamental component of frequency. A typical limit is 8 % on a line-to-Iine wave-form, for loads at unity to 0.8 pflagging. On a line-to-neutral basis, a typical THC limit might be 10 % and, under the same load conditions, the maximum individual harmonic might be limited to 2 %. Proprietary machines above 250 kVA generally achieve open-circuit levels of 1½ % on individual harmonics and 3½% - 5 % on THe.

Because of the wide variety of winding pitches that are possible, manufacturers' *typical* wave-form analyses should be treated with some caution. It is always wise to refer to the manufacturer when guaranteed performances are required. Quite rightly, manufacturers are loath to be committed to on-load performance as so much depends upon the power factor and the linearity of the load. Nevertheless, given precise details of anticipated load profiles most will quote fairly accurate maxima.

Compliance with specification on wave-form divergence and harmonic content does not precluge the possibility of interference with communication circuits. The maximum electrical noise levels created by machines are limited by agreement with the *International Telegraph and Telephone Consultative Committee* (CCITT). The permitted noise level is 2mV Lm.S., weighted to a frequency of 800 Hz.

Machine standards therefore specify acceptable values for what is termed the *telephone harmonic factor* (THF). For example, BS4999: Part 101 classifies the maximum values for THF, by generator rating, as follows:

| Generator rating | THF |
|---|---|
| 300 - 1000 KW or kNA | 5% |
| 1001- 5000kW or kVA | 3% |
| 5001 kW or kVA, and above | 1.5% |

Limiting values are not specified for individual harmonics as machines that meet the above requirements are considered to be operationally satisfactory.

THF is assessed from the line-to-line voltage wave-form of the generator and is related to the machine running on open-circuit, at rated voltage, and at normal speed. The range of measurement covers all harmonics from rated frequency up to 5000 Hz. Direct measurement may be made using a meter and an associated network specially designed for the purpose, or the THF may be computed from measured values for each individual harmonic voltage, using the following formula:

$$\text{THF}\ (\%) = (100/U).[E_1^2\lambda_1^2 + E_2^2\lambda_2^2 + \ldots E_n^2\lambda_n^2]^{1/2}$$

where $U$ = r.m.s. value, line-to-line, of the terminal voltage of the generator

$E_1, E_2,\ldots,E_n$ = r.m.s. values of the 1st to $n$th harmonics of the line- to-line terminal voltage

$\lambda_1, \lambda_2,\ldots,\lambda_n$ = weighting factors for frequency corresponding to the 1st to the $n$th harmonic

Numerical values of the weighting factors for different frequencies are given in Table IX of BS 4999: Part 101, together with a curve (reproduced in Figure 4.10), as an aid to interpolation.

North American practice uses the term *telephone influence factor* (TlF). Typical limits set by telephone companies for open-circuit TlF are given in the table below :

| kVA rating | Balanced TlF not exceeding |
|---|---|
| 62.5 - 299 | 300 |
| 300 - 699 | 250 |
| 700 and above | 150 |

The TlF values approximately corresponding with the 1.5 %, 3 % and 5 % THF values of BS 4999 are: 45, 100, and 200, respectively.

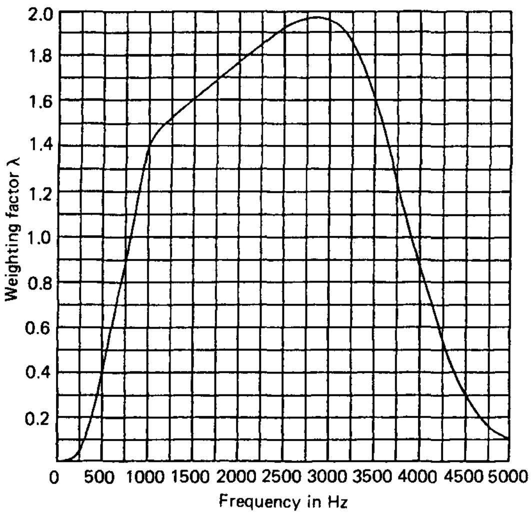



**Figure** 4.10 Weighting curve for computing Telephone Harmonic Factor (from BS4999: Part 101: 1987, courtesy: British Standards Institution)'

### 4.2.5 Voltage characteristics

The rated voltage *(Un)* of a generator is the r.m.s. value measured at the output terminals when the machine is delivering rated output. The *preferred* 3-phase line-to-line voltages in the UK are: 415, 3300, 6600 and 11000 volts at 50 Hz. A.C. voltages above 50 V, but not exceeding 1000 V between conductors or 600 V between any conductor and earth, are classified as *low-voltage;* and anything above this range as *high-voltage* (the European Committee for Electrotechnical Standardization (CENELEC) Harmonization Document HD 193). These two voltage classifications, LV and HV, replace the 'historical' bands of *medium voltage* (250-650 V), *high voltage* (650-3000 V) and *extra-high voltage* (3000 V and above), previously applied to machines. Three-phase voltages of 208,400,415, 440, 525, 2400, 4200, 5250, 6900, 13800, 15000 and 15750 may be specified in European (50 Hz) and American (60 Hz) practice. While the 60Hz supplies for marine installations are usually obtained from generators wound for 440 V, some tankers and passenger ships have used 3300 V (or 6600 V) for prime power. Note that in switchgear and transmission practice, the term *medium voltage* is used to denote the voltage range 1 kV to 36 kV.

*Output related to voltage*

BS4999: Part 101 (I.E.C. 34--1) recommends the following minimum outputs related to rated voltage:

| Voltage | kW or kVA |
|---|---|
| 3300 | 100 |
| 6600 | 200 |
| 11000 | 1000 |

Low kVA ratings, at high voltage are difficult to achieve in practice and are not economically viable. The minimum ratings listed above correspond to full-load currents between 17.5 and 52.5 amperes. Because multi-turns per phase and multi-turns per coil must be used, the conductors would be of *fuse-wire* dimensions; virtually buried in insulation. At the other end of the scale, high ratings at low voltages necessitate a small number of turns per phase, making it difficult to arrange the windings. Consequently, one finds that output ranges related to voltage, are usually restricted to those tabled below, for diesel generator plants:

| Voltage | Rating (MVA) |
|---|---|
| 415 | up to 1.5 |
| 3300 | 0.5 to 6 |
| 6600 | 0.8 to 10 |
| 11000 | 1 to 20 |

Figure 4.11 charts the voltage limits, related to generator output, preferred by machine designers.

*Terminology, definitions and specifications*

The following definitions cover those terms relating to voltage at the generator terminals under steady-state operation that are commonly included in specifications.

*Voltage modulation* is defined as the cyclic or random variations (or both) about a steady-state peak value of an alternating voltage, expressed as a percentage of that steady-state value of peak voltage. A typical limit specified is 2 %.

*Load range tolerance* (LRT) is defined as the permissible positive and negative variations (excluding transients and modulation) of voltage which can occur about a mean level of voltage, over the normal operating range of loads and power factors. The alternative term is *steady-state tolerance.*

*Constant load tolerances* are defined as the maximum voltage variation that can occur over (stated) periods of continuous operation at constant load. with no manual adjustment of the voltage. They are generally sub.-divided into *long-term* and *short-term* tolerances. Typical periods specified are 4 hours and 30 seconds, respectively. Note, that the *transielll*

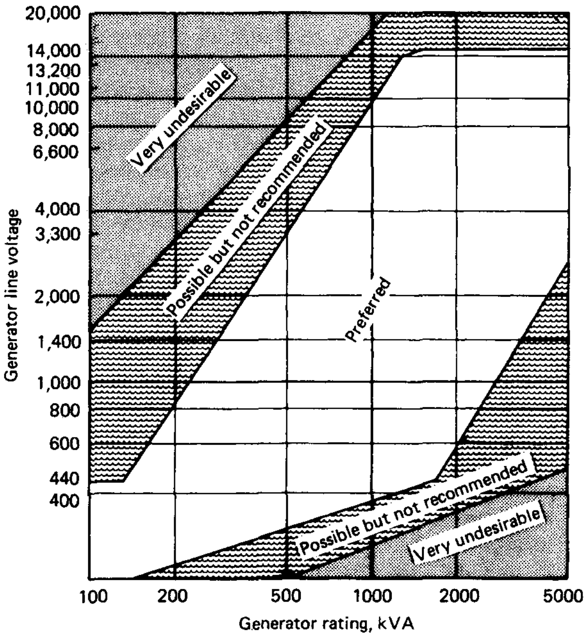



Figure 4.11 Assessment of suitability of stator voltage relative to generator rating (Courtesy: GEC Alsthom Large Machines Ltd.)

excursions that occur in the change from one (steady-state) load condition to another are excluded from constant load tolerance assessments. Typical limits for load range tolerance are ±5 %, and those for constant load tolerances are 3 % long-term, and 2 % short term.

*Generator phase voltage balance* is defined as the deviation between anyone value of phase voltage and the arithmetic mean value of the three phase voltages of a generator, when it is connected to a balanced three-phase load. Conversely, *voltage unbalance* is the maximum deviation, under steady-state conditions, between individual line voltages (or individual phase voltages) of three-phase supply systems, expressed as a percentage of the nominal. Typical limits specified for balanced and unbalanced voltage conditions are 1 % and 2 %, respectively.

*Voltage regulation.* The *inherent voltage regulation* of a machine has been defined (in Section 3.2 of Chapter 3) as a characteristic which is dependent on the magnitude and the power factor of the load. The cause of terminal voltage drop is inherent within the machine itself. There is more to say on this subject later.

A requirement for close regulation may make a machine uneconomical to build since it generally involves a long air gap and much field copper [9]. In any event, all modern machines are equipped with automatic voltage control equipment which serves to maintain a constant terminal voltage in the face of any disturbing influences such as speed or load changes, and temperature rises (see Chapter 7). In terms of performance, therefore, a generator's *voltage regulation* is important to a plant specifier. It is defined as: the difference between the r.m.s. values of voltage, as measured under steady-state conditions, between no-load and full-load, at any constant setting of the manual voltage adjustment on the machine's automatic voltage control equipment, i.e.

$$\text{Voltage regulation} = ((U_{NL} - U_{FL})/U_n) \times 100\,\%$$

where $U_{NL}$ is the adjusted value of voltage, at no-load
$U_{FL}$ is the voltage at full-load, and
$U_n$ is the nominal, or rated, voltage

Full-load current and power factor must be defined when specifying the voltage regulation limits.

The rise in terminal voltage when load is removed is usually less than the voltage drop when load is applied. This is because of the hysteresis within the iron circuits of the machine. It is therefore usual to record regulation performance for both conditions of load switching, i.e. full-load on - *regulation down,* and full-load off - *regulation up.* Transient voltage excursions are excluded (see Sub-section 4.3.2). Typical limits specified for voltage regulation are ±2.5 % at load power factors between unity and 0.8 lagging.

## 4.2.6 The concept of synchronous reactance

The inherent factors effecting the voltage drop at a machine's terminals are:

1. resistance,
2. armature reactance, and
3. armature reaction.

The first two introduce a voltage change proportional to load current. The third, although it contributes most to the voltage drop, is not proportional to load current.

*Resistance.* This is a straightfoward *IR* drop. The value used for *R* is the *effective a.c. resistance* of the armature windings and includes the effect of eddy currents in the armature conductors. It is some 1.5 times the d.c. resistance of the windings. The armature resistance drop is small enough to be ignored in calculations on large machines - being about 0.01 '% of rated terminal voltage. Resistance, of course, cannot be totally neglected, since its contribution to losses and machine heating is quite significant.

*Armature reactance.* The current flowing in the stator winding sets up a flux in the magnetic material forming the boundary of the slot, and in the air path of the slot. This flux is classified as a leakage flux because it is not associated with the main field (nor does it link with it) and therefore does not contribute to the useful flux of the machine. The other major leakage flux is the end-connection (or overhang) leakage flux. See Figure 4.12.

The total *leakage reactance (Xu)* gives rise to a voltage drop $IX_u$, which leads the current by 90° (71:/2 rad). Whereas calculation of the slot leakage flux is relatively easy, that for the overhang leakage is extremely complex as it is dependent upon so many variables.

*Armature reaction.* This is the modifying effect that the stator current has on the main field. We have established (in Section 4.2.2) that the field due to the alternating current in the three-phase stator winding rotates at synchronous speed, in step with the main (rotor) field. The magnitude and the position of the *magnetomotive force*[2], resulting from the stator current is dependent upon the value of the load current and its power factor. For example, with a zero power factor lagging load, the effect of armature reaction is to demagnetize the main field; whereas, at zero power factor leading, the effect is to directly magnetize it. Intermediate power factors give a combination of demagnetization and magnetization of the main field. For all conditions of load and power factor, therefore, the effect of armature

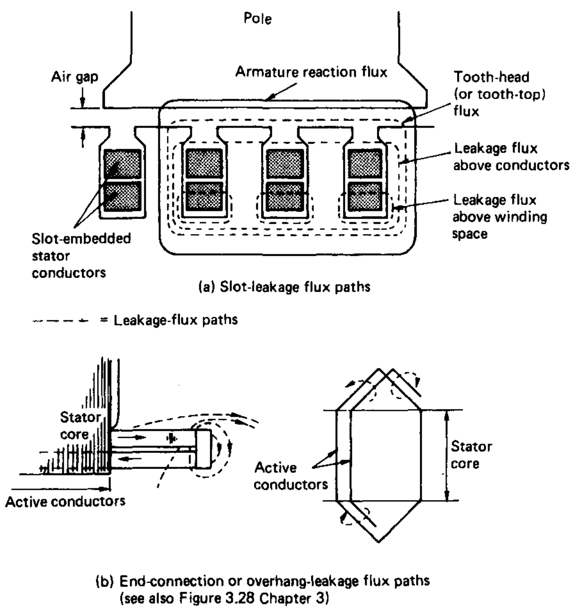



**Figure 4.12** Leakage flux paths

2 The magnetomotive force (m.mJ.) is analagous to the electromotive force (e.mJ.) and is defined as the circular integral of the magnetic field strength around a closed path.

reaction is to modify the main gap flux and, hence, the machine's generated e.m.f. In other words, the generated voltage varies with the flux per pole, which, in turn, varies with armature reaction m.m.f.

A loaded machine may be represented by the equivalent circuit and phasor diagrams of Figure 4.13 [9] (see Appendix 4.1 for an explanation of phasor diagrams). The effective armature resistance (Rae), the leakage reactance *(Xu),* and the *fictitious* armature-reaction reactance ($X_a$) are shown separated from the 'ideal' machine, in which the generated e.m.f. *(E()* is entirely induced by the flux produced by the m.m.f. (or the ampere-turns) of the main field alone. The phasor diagram of Figure 4.13(b) shows the net e.m.f. *(E)* resulting from the voltage drop $IX_a$ due to armature reaction. The term *air-gap voltage* is often applied to the e.m.f. *E.*

Terminal voltage *U* is less than *E* - by the phasor voltage drops IRae and $IX_u$ in the armature resistance and leakage reactance, respectively. The terminal voltage *U* may be directly obtained, from *Et* and the load current *I,* if Rae, *X.,* and *Xu* were combined in one impedance Zs, whose components are: Rae and *Xs, Xs* being the sum of Xae and *Xu* (see Figure 4.13(c) and (d». This total armature reactance *Xs* is called the *synchronous reactance,* and Zs the *synchronous impedance.* Because the synchronous reactance includes the *imaginary* armature-reaction reactance Xae, it is also a *fictitious* quantity.

Note that the phasor diagrams are drawn for one phase only. Although the armature-reaction effect is strictly due to the combined action of all three phases within the machine, its representation in a single-phase diagram can be readily justified [10].

For machines above a few hundred kVA:

- the armature-resistance voltage drop, or per-unit resistance, is less than 0.01 pu;
- the armature leakage reactance *Xu* is between 0.1 and 0.2 pu; and
- the synchronous reactance *Xs* is greater than 1.0 pu, and may be as high as 2.0 pu [11].

Generally, as machine unit size decreases, the per-unit resistance increases, and the per-unit synchronous reactance decreases. The per-unit system is described in Appendix 4.2 of this chapter.

## *The Potier diagram*

The space diagram of Figure 4.14(a) shows the relationship between the component m.m.fs in the air-gap of a simple 2-pole, unsaturated, cylindrical rotor machine. If the current in the conductor at P is at a maximum at a given instant, the direction of the armature reaction m.m.f. $F_R$ will be horizontal, and it will be rotating with synchronous speed. The conductor Q, θ° in advance of P, will be the seat of maximum induced e.m.f. θ is the angle between *E* and *I*, and is slightly greater than the power-factor

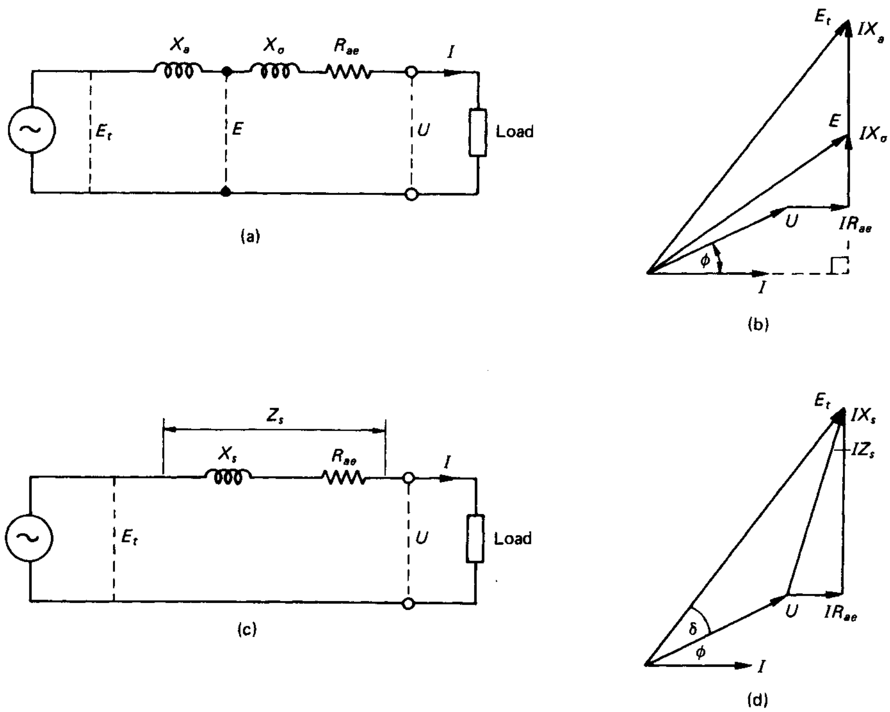



**Figure 4.13** Equivalent circuits, and phasor diagrams, of a generator on load

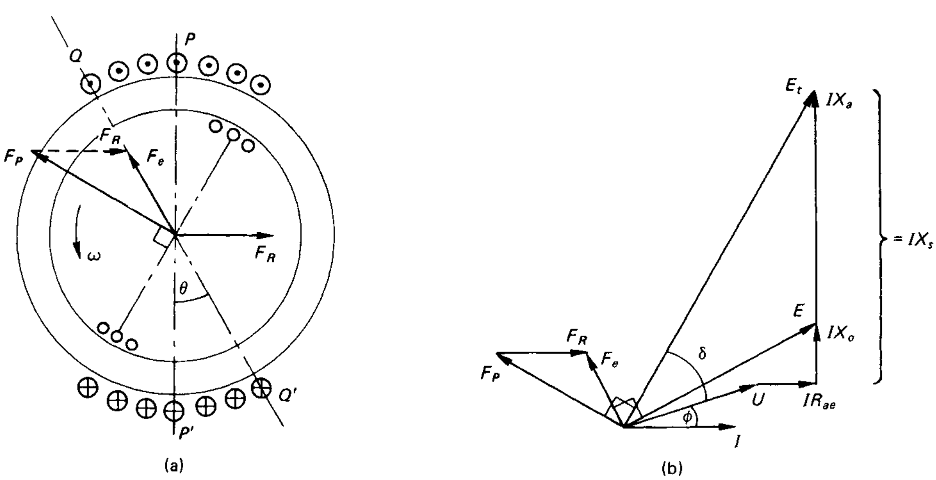



**Figure 4.14** The Potier diagram developed from the space diagram for m.m.fs

angle of the load. The effective m.m.f. axis ($F_e$) will also be in this direction. The axis of the main pole m.m.f. ($F_p$) must then be in such a direction that the phasor sum ($F_p + F_R$) is equal to $F_e$.

Transferring the m.m.f. phasors from this space diagram to a 'time diagram' (such as that of Figure 4.13(b)) completes what is known as the *Potier Diagram* (see Figure 4.14(b)). The armature reaction m.m.f. $F_R$ is in phase with the armature current $I$. The total effective m.m.f. $F_e$ lags e.m.f. $E$ by 90°; and the main field m.m.f. $F_p$ lags the induced e.m.f. $E_t$ by 90°.

## *Open- and short-circuit characteristics*

The lengths of the component phasors required to construct the Potier diagram are determined from tests. Indeed, proof of a machine's compliance with its design specification must, ultimately, be established by testing. The two tests employed are the open-circuit and the short-circuit tests. Each requires but a small prime mover to drive the machine on test (at constant rated speed) since no power output is involved.

In the *open-circuit test*, the generator is run at synchronous speed, with its armature terminals open-circuited. The main field is supplied with an adjustable excitation current. Because the machine is open-circuited, there is no armature current and, hence, no armature m.m.f. Nor is there any voltage drop across the armature resistance $R_{ae}$ or the leakage reactance $X_\sigma$ – see Figure 4.13(b). This means that the magnetic flux in the machine is entirely derived from the main field current. Readings of terminal voltage $U$ are taken against field current to give a magnetization curve, or an *open-circuit characteristic*, for the machine – curve OCC of Figure 4.15. The shape of the curve is such that rated voltage (on the ordinate) corresponds with a point beyond the 'knee' of the curve, to give best use of the stator core material. The lower portion of the curve is, for all practical purposes, a straight line which, when extended, gives what is called the *air-gap line* (or the *tangent line*). This represents the unsaturated condition of the main field. In a well-designed machine reasonable overvoltage must be obtainable before the main field goes into saturation, in order to cater for short-term overloads and poor power-factor conditions.

The OCC and air-gap curves are usually presented in per-unit form (Figure 4.15(b)), where 1 pu voltage is the rated voltage, and unity field current is that excitation corresponding to unity voltage, on the air-gap line. The ratio of 'no-load excitation' to 'air-gap excitation' is known as the *saturation factor* of the machine and is normally between 1.1 and 1.2.

The test which determines the leakage reactance ($X_\sigma$) of a machine is known as the *zero-power-factor*

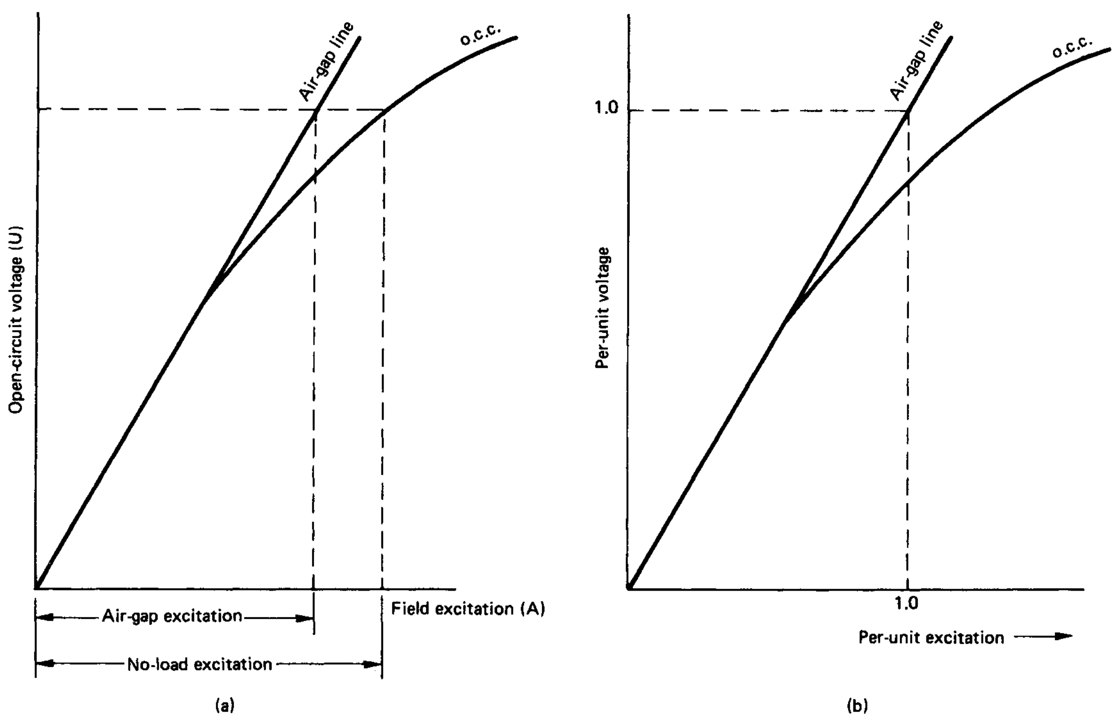



**Figure 4.15** Generator open-circuit characteristics

*load test.* It entails loading the generator with reactors or an under-excited synchronous motor, rated to take full-load and constant stator current, at zero lagging power factor. As with the open-circuit test, readings of terminal voltage are recorded against excitation current. The resulting magnetization curve (shown in Figure 4.16(a» is a replica of the open-circuit curve, but is displaced in both axes. These displacements are a result of the leakage reactance drop and the armature reaction m.m.f. By superimposing a tracing of the OCC on the zero power-factor curve, it is possible to establish *IFLX"* and armature reaction m.m.f. $F_R$ (see Figure 4.16(b». The value of *X"* so determined is slightly greater than the real value of the armature leakage reactance. It is termed the *Potier reactance,* $X_p$. Since all the machine losses for operation at rated conditioI}s are present during this test (the excitation losses are somewhat greater), the zero-power-factor test also affords a useful heat-run for the machine and gives temperature rises only slightly above normal full-load values.

Figure 4.17 shows a family of load magnetization curves for tests at various power factors for a machine delivering constant full-load current at three values of power factor. All the curves start at a point on the abscissa corresponding to that excitation current which gives rated full-load current in the armature winding when it is short-circuited.

In the *short-circuit test* the armature terminals are shorted through suitable ammeters. The machine is driven at constant rated speed and the main field current is gradually increased until a value of about twice rated full-load current is attained. Readings of stator current are recorded and then plotted against excitation current to give a *short-circuit characteristic* (SCe) as shown in Figure 4.18(b). On short-circuit, the armature winding provides a load which is almost at zero power factor lagging since it has negligible resistance. We have established that, at a zero power factor lagging load, the armature reaction m.mJ. is directly opposed to the main field flux and has a demagnetizing effect on it. The result is that the total m.mJ. under short-circuit conditions is small and the machine is thus operating well below its iron saturation level. The short-circuit current is therefore proportional to the excitation current, i.e. the short-circuit characteristic is, virtually, a straight line.

## *Synchronous reactance from the open- and short-circuit tests*

Figure 4.19 shows how the results obtained from the open- and short-circuit tests are used to determine

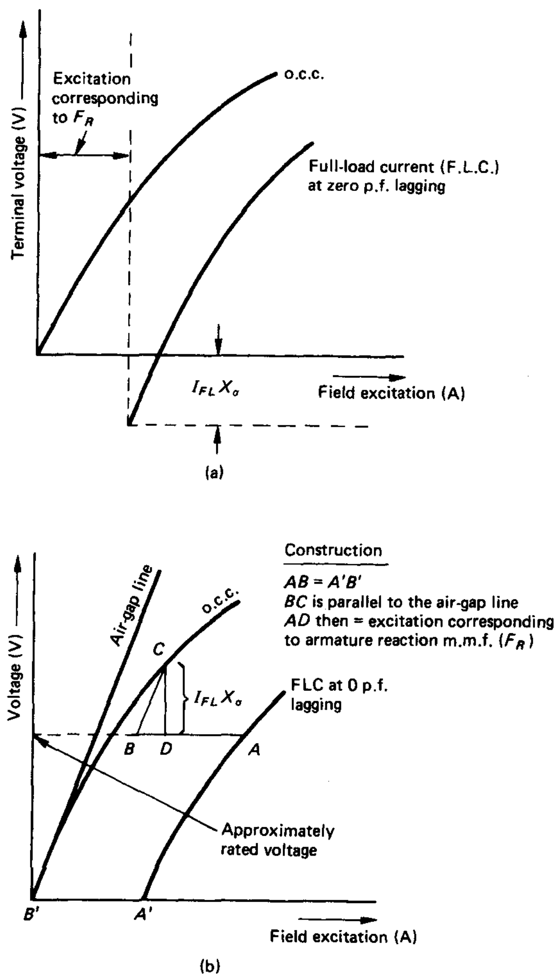



Figure 4.16 Illustrating the separation of leakage reactance and armature-reaction m.m.f. in the zero-power-factor test

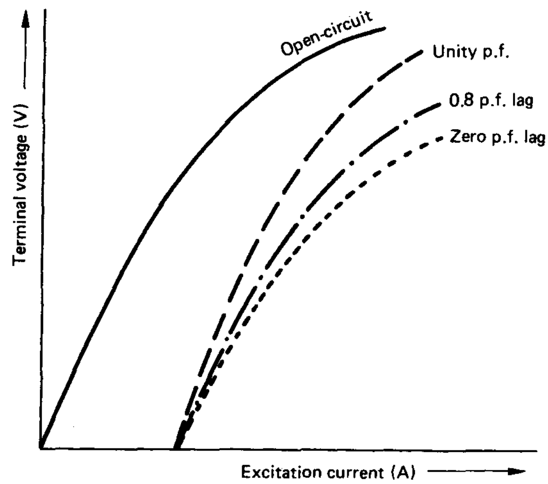
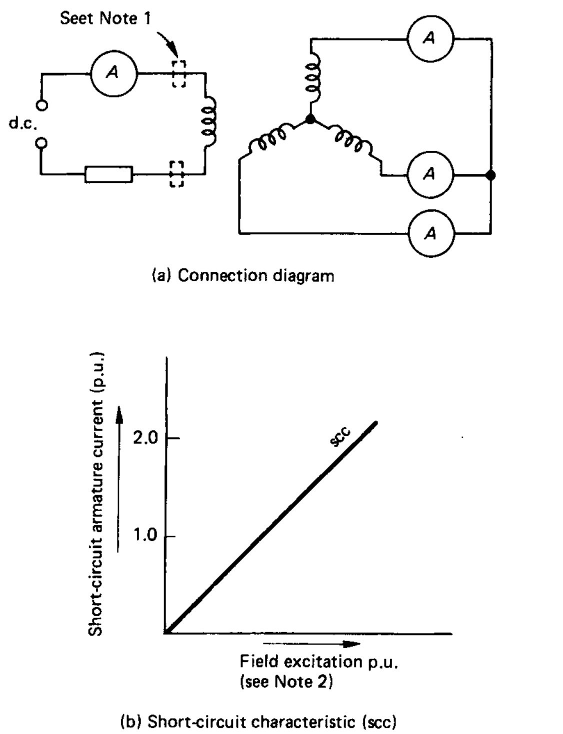



Figure 4.17 Load magnetization curves for various power factors




NOles:

On brushl ••• machines:

either (1) temporary slip rings are used to replace an overhung exciter armature (or rectifier assembly)

or (2) exciter field currents are recorded (these having been precalibrated against main field current, using. dummy load)

Figure 4.18 Connection diagram for short-circuit test; and short-circuit characteristic

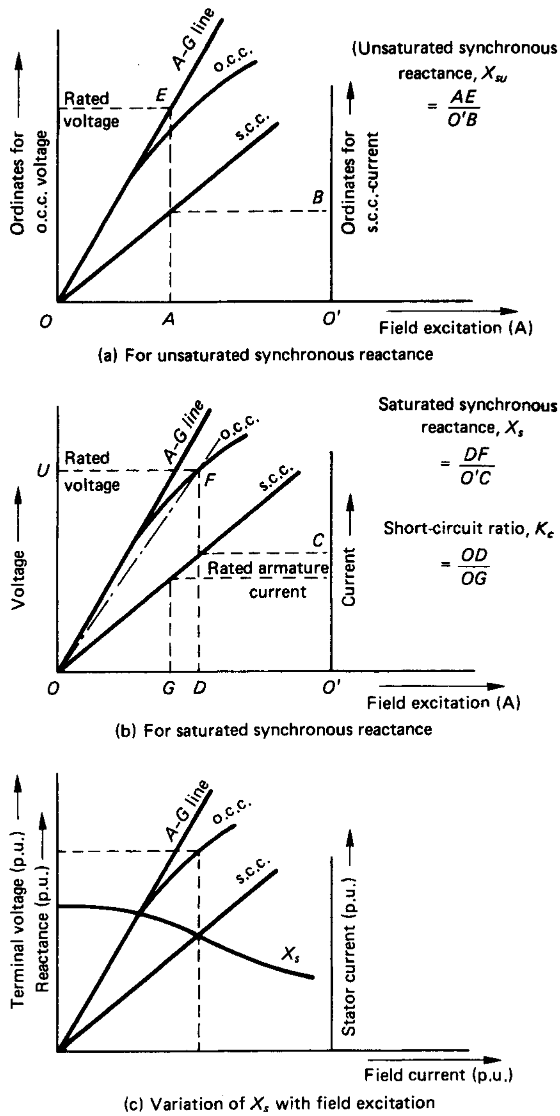



Figure 4.19 The application of open- and short-circuit characteristics in the determination of unsaturated and saturated values of synchronous reactance

the *unsaturated* and the *saturated* synchronous reactance values of a machine. Different ordinate scales are used for the open-circuit terminal voltage and the short-circuit armature current, while the excitation current, on the abscissa, is to a common scale.

The field current corresponding to rated terminal voltage on open circuit is OA; and is determined from the air-gap line (Figure 4.19(a». The voltage on the air-gap line must be used because the machine operates, on short circuit, in an unsaturated mode. This field current equates to an armature current of O'B, on the short-circuit characteristic - extended, if necessary, to cut the ordinate at A. The value of the unsaturated synchronous impedance (Zsu) is given by:

U ÷ the short-circuit current represented by ordinate O'B.

i.e. AE/O'B

The unsaturated synchronous reactance is given by:

$$X_{su} = [Z_{su}{}^2 - R_{ae}{}^2]^{1/2}$$

The effective armature resistance is negligible enough in most synchronous machines to be neglected. For all practical purposes, therefore, the synchronous reactance has a value equal to that o( the synchronous impedance. Where the open- and short-circuit data are expressed in volts and amperes the reactance will be in ohms. For per-unit data the reactance will be in per-unit notation.

Experience shows that if machine saturation is to be taken into account the construction of Figure 4.19(b) may be used to obtain the value of *saturatal synchronous reactance, Xs.* A straight line magnetization curve (OF) is constructed from the origin to a point on the OCC corresponding with rated terminal voltage. The *saturated reactance* value is then given by:

U ÷ the short-circuit current represented by ordinate O/e.

i.e. DF/O/C

The unsaturated value of synchronous reactance, related to the air-gap line, is clearly greater than that of the saturated reactance, and is the value that is usually quoted for machines. The saturated reactance value gives a good approximation for most calculations. Figure 4.19(c) illustrates the variation of *Xs* with field excitation.

A term often used is that of the *short-circuit ratio (Kc).* It is defined, in BS 4999: Part 104, as the ratio of the field current for rated armature voltage on open-circuit to the field current for rated armature current on sustained symmetrical short circuit- both with the machine running at rated speed. Referring to Figure 4.19(b), the short-circuit ratio is given by OD/OG. It is very nearly, but not quite, the reciprocal of the per-unit saturated synchronous reactance.

Because the short-circuit ratio of a machine largely determines the field excitation required to meet load demand, the value chosen must influence the design of the field winding and its cooling requirements. To keep within permissible thermal limits for a given output, a high short-circuit ratio would therefore require either a (physically) larger machine or more sophisticated cooling. The value required is achieved by choice of the air-gap length. *Kc* values are of the order of 0.7 to 1.5 for salient pole machines, in the range under consideration.

### 4.2.7 Loss measurements in open- and short-circuit tests

If calibrated motors are used to drive the tested machines on open-circuit and short-circuit tests (or if the mechanical power to drive the machines can be measured) power curves of the type shown in Figure 4.20 may be obtained. The generator needs to be excited from an external source, otherwise, allowance must be made for the excitation losses. Curve (a) shows the corrected power absorbed by the machine - ploued against a base of field excitation - in the open-circuit test. The power measured without excitation on the test machine equates to the windage and friction losses alone. As the main field is progressively excited, the mechanical input power (which is equal to the sum of the windage and friction loss and that due to the open-circuit core loss) increases almost parabolically.

In the same way, the measured mechanical input power on the short-circuit test provides information

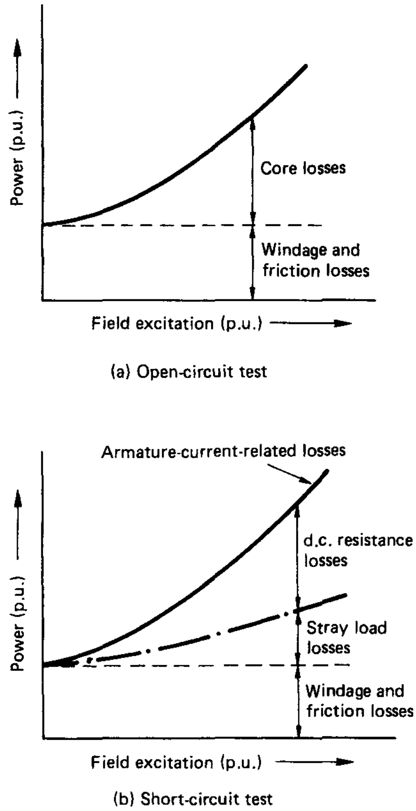



Figure 4.20 Power curves from open- and short-circuit tests

on the armature-current-related losses, in addition to the constant windage and friction losses. The former losses comprise the $I^2R$ copper losses in the armature winding and the stray load losses (see Sub-section 4.2.1). Figure 4.20(b) illustrates a typical curve of losses ploued against armature current. If the d.c. resistance loss (computed from the winding resistance measured and corrected for temperature during the test) is subtracted from the total losses, the resulting difference is the stray load loss - the dotted curve of diagram (b). On the reasonable assumption that most of the stray load losses are a function of the armature current, the effective resistance of the armature *(Rae)* may be obtained from the total armature-current-related loss, as follows [11]'

$$R_{ae} = \frac{\text{total armature-current-related loss}}{(\text{short-circuit armature current})^2}$$

It usually suffices to find the value of *Rae* at rated full-load current, and assume this to be constant.

### 4.2.8 Load-angle characteristics

The load-angle characteristic is defined as that which gives the relationship, in graphical or mathematical form, between the *rotor displacement angle* and the load, for constant values of primary winding voltage and excitation current.

A simple mechanical analogy may be used to illustrate this relationship [12]. The generator's terminal voltage is represented, in Figure 4.21, by the stator ring A. The poles of the rotor B are joined to the stator ring by means of stretched elastic cords. These are analogous to the magnetic lines of force crossing the air-gap of the machine. The stator ring must rotate at the same speed as the rotor because it is joined to it by the elastic cords. Under no-load conditions (assuming the support bearings have no friction) the stator ring and the rotor will be aligned as shown in Figure 4.21(a). The cords cross the gap radially and have no tangential forces acting upon them. The corresponding no-load phasor diagram is shown.

When load is applied to the stator, it is equivalent to imposing a retarding torque on ring A, which immediately lags behind the rotor. This lag will be resisted by the stress in the elastic coupling cords, which now span the *air-gap* in an oblique direction - as in Figure 4.21(b). A position of equilibrium is reached when the restraining torque developed by the elastic cords balances the retarding torque of the load applied to the stator ring. Therefore, when the model is loaded, stator and rotor continue to rotate at the same speed, but are separated by an angle 8 - the *load-angle*. There will be momentary differences in speed, during load changes, until the required load-angle is reached. If the model was a motor, and load was applied to its shaft, it would slow down until the necessary angle 8 was attained (see diagram (c)). This simple analogy has discrepancies, but it serves to illustrate the variation of load-angle with magnitude (and direction) of power flow. Load-angle plays an important part in the performance of a generator and, as we shall see later, is a major factor in its operational stability.

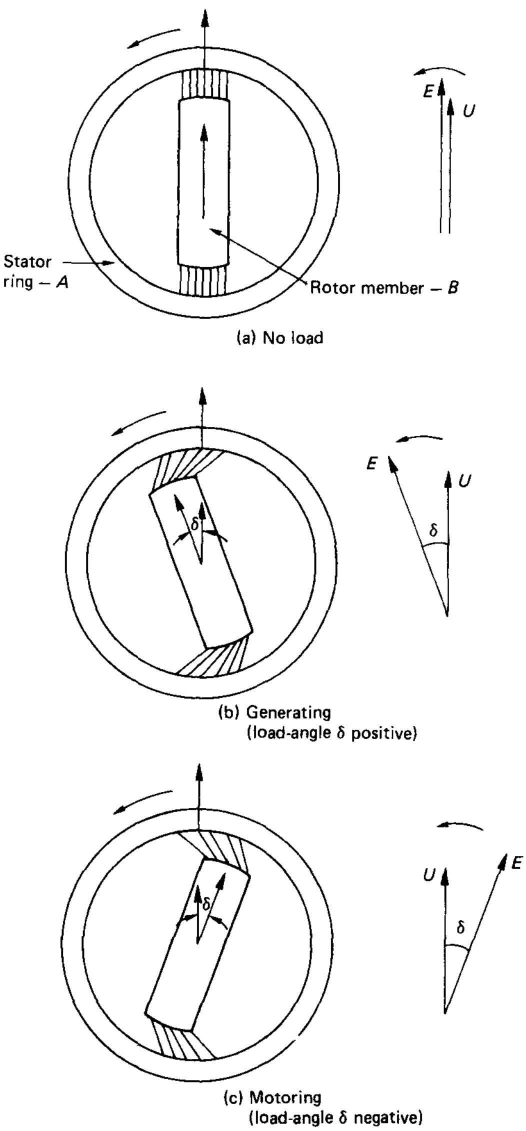



**Figure 4.21** A mechanical analogy for load-angle

*The cylindrical rotor machine*

It can be shown that the active power output of a cylindrical rotor generator is given by the equation:

$$P = E_t U \sin\delta / X_s \text{ per phase}$$

in which the armature resistance and saturation are neglected. *Et* is the per-unit excitation, *U* is the per-unit terminal voltage, *Xs* is the per-unit synchronous reactance, and 8 is the operating load-angle (see Figure 4. 13(d)). The excitation e.mJ. *Et* is assumed to be proportional to the main field current, and unit excitation is that required to produce rated voltage on open-circuit.

Accordingly, for a given excitation *Et,* any power change must be accompanied by a corresponding change in the load-angle 8; and the maximum power will occur when sin 8 = 1 or 8 = 90°. The *powerl* load-angle characteristic for a simple unsaturated round-rotor machine is therefore sinusoidal in shape; the positive and negative values of the load-angle referring to generator and motor action, repectively (see Figure 4.22).

As excitation *Et* (or terminal voltage U) increases, load-angle 8 reduces, for any given level of power (see 8" and 8' in Figure 4.22). The power output **per** unit angle of 8 *(.1P)* also increase!>.Both effects tend

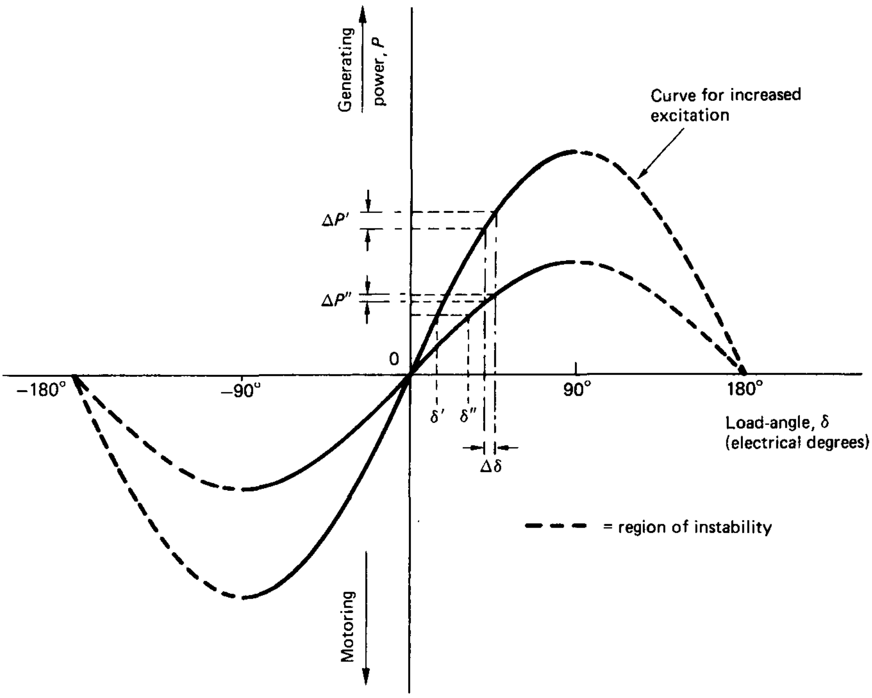



Figure 4.22 Power/load-angle relationship at two levels of excitation for a round-rotor machine

to make the machine more stable in operation. The limit for stability, as we shall see later, is 90°. Remember that this angle is expressed in electrical degrees (1 degree electrical = *p/2* degree mechanical).

## *The salient-pole machine*

The magnetic circuit of the salient-pole rotor is appreciably different in the *direct axis* (through the field coil) from that at right angles to it. It can be shown, from the geometry of the phasor diagram for the salient-pole machine (see Section 4.3 which follows), that the active power equation contains two terms. The first is similar to that for the round-rotor machine. The second introduces a second harmonic component, which is approximately proportional to 20, instead of 0. This second term introduces the *saliency effect.* It is the power corresponding to the reluctance torque, and is called the *reluctance power.* It is defined as the active power obtained with zero excitation. The two terms combine to give the resultant power/load-angle characteristic of Figure 4.23. The value of the angle 0 for a salient-pole machine is less than that for a round-rotor machine of equivalent *direct-axis synchronous reactance* $(X_d)$, delivering the same active power at the same excitation and terminal voltage.

Figure 4.24 [11] shows a family of power/load-angle characteristics for a typical machine, operating at constant terminal voltage (1.0 pu) and with various values of excitation *(E().* The ratio of direct-axis to quadrature-axis synchronous reactance $(X_q)$ for this particular machine was 1:0.6 (see Section 4.3). Only the positive values of 0 are shown. It is apparent from the curves that the reluctance power is only significant at low levels of excitation. Therefore, as far as power/load-angle computations are concerned, a salient-pole machine can be treated by simple round-rotor theory except at low excitation levels, or when very accurate results are sought.

## 4.2.9 Stability

The *stability* of any a.c. power system is defined as its ability to remain in synchronism when disturbed by load changes, by internal generator faults, or by external system faults. *Steady-state stability* is that inherent quality that allows a system to return to its initial operating condition after a minor disturbance. We have seen that the maximum power limit for a round-rotor machine corresponds with a load-angle of 90° electrical. On salient-pole machines this power limit occurs at slightly smaller angles. These

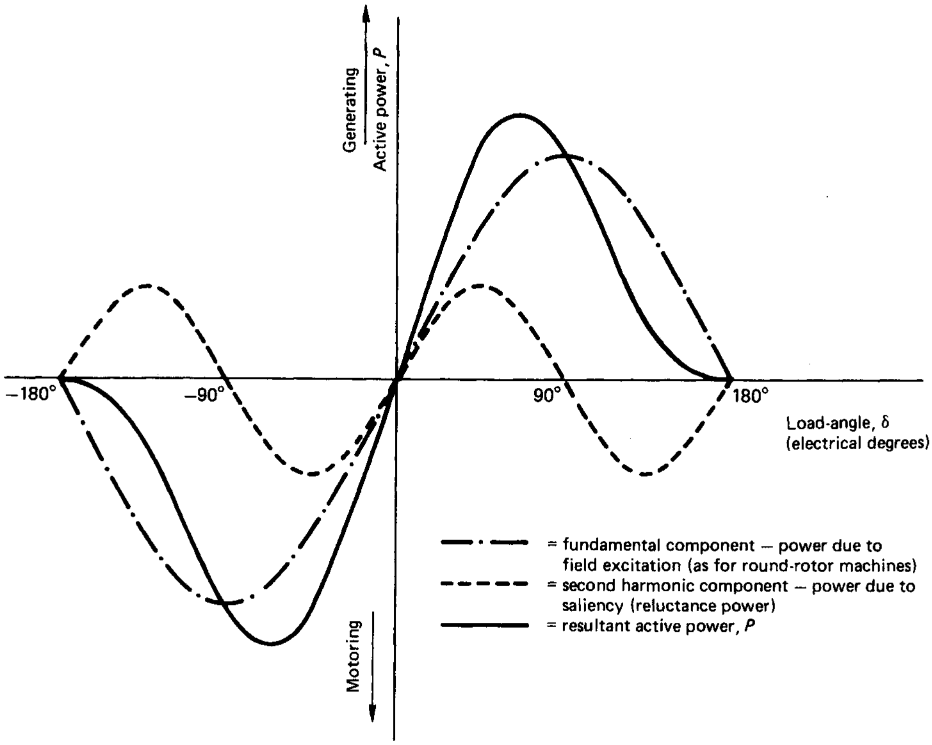
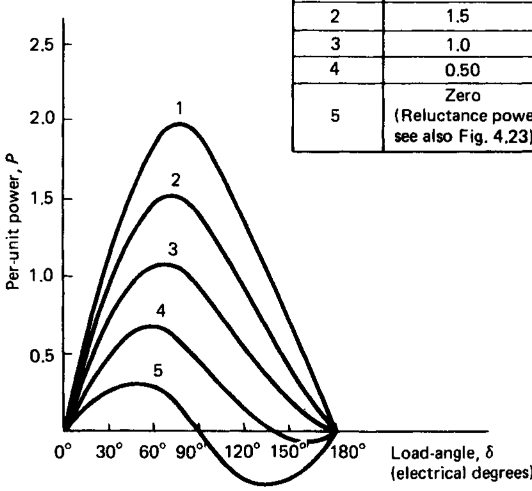



**Figure 4.23** Power/load-angle characteristic of a salient-pole machine




| Curve | Excitation level (p.u.) |
|---|---|
| 1 | 2.0 |
| 2 | 1.5 |
| 3 | 1.0 |
| 4 | 0.50 |
| 5 | Zero (Reluctance power, see also Fig. 4.23) |

**Figure 4.24** Load-angle characteristics at various excitation levels

load-angles correspond to the maximum steady-state power that can be transmitted to an external load and, generally speaking, a machine loses synchronism if its load-angle exceeds its steady-state limit of 90°.

*Transient stability* is the capability of a system to return to its steady-state condition after it has been subjected to a large disturbance - such as a sudden load change or a severe network fault. The ability of a machine to recover from such disturbances is governed by the maximum power that it can carry and still maintain synchronism.

The electromechanical equation for a synchronous machine is derived from the three torques which act on its rotating members [11]:

$$T_i + T_e = T_{Sh}$$

where $T_i$ is the inertia torque
$T_e$ is an electromagnetic torque
$T_{Sh}$ is the mechanical shaft torque provided by the prime mover

This relationship may be more conveniently expressed, in power form, as:

$$P_i + P_e = P_{sh}$$

The inertia power $(P_i)$ comes from the angular acceleration. The electromagnetic power $(P_e)$ has two components; the damping power, provided by damping circuits in the rotor, and the synchronizing power (see Chapter 8).

The power equation may be presented in non-linear form when investigating modes of electrodynamic behaviour and analysing ensuing transients. Analogue and digital computers have increasingly replaced the network-analyser in large-scale investigations. Studies are usually directed towards determining whether or not synchronism will be maintained after sizeable system disturbances. They are not confined to the properties of generators and their associated prime movers but are widened to include the many interacting control elements of the system, switching apparatus, transmission and distribution circuits, and the dynamics of connected loads. Detailed descriptions of these studies are beyond the scope of this chapter. They require a more extensive knowledge of control and feedback theory than the reader is expected to have. The text-books [11], [13] and [14] will be of particular value to those investigating the simpler problems. They show how graphical methods may be used to determine the maximum anticipated angle of rotor swing, and to assess the chances of maintaining synchronism after disturbance. The following discussion summarizes the methods used.

The power/load-angle characteristics in Figure 4.25 are derived, for a round-rotor machine connected to a large electrical system, from the equation for active power output: $P = E_t U \sin\delta / X_s$ (see Sub-section 4.2.8). This may be rewritten, so that, for any load-angle $\delta_n$, $P_n = P_{max}.\sin\delta_n$. Suppose the machine is operating on a load $P_a$, with a load-angle $\delta_a$ (as in Figure 4.25(a)) and that the load is suddenly increased to $P_b$, at load-angle $\delta_b$. The rotor gains some inertia, during acceleration from $\delta_a$ to $\delta_b$. This raises its speed beyond the synchronous level, so that it passes through the new equilibrium angle $\delta_b$ to a more advanced position $\delta_c$. A retarding torque is developed in the 'overshoot' region, $\delta_b$ to $\delta_c$, because of the excess of output over mechanical input. The rotor will continue to swing about the equilibrium angle $\delta_b$ until the machine's inherent damping dissipates the oscillation energy. The *transient stability limit* is reached at that value of $P_b$ which makes the first swing of the rotor terminate at an angle $\delta_c$ – equal to $(180° - \delta_b)$. The power deficit $(P_c - P_b)$ is then zero. The area ABC in Figure 4.25 represents the energy extracted from the rotating masses and transmitted to the load. In the same way, area CDE represents the energy released during retardation. The *equal-area criterion*, which applies to a single synchronous machine connected to an infinite busbar, requires that area ABC must not be greater than area CDE. If it is, the load-angle/time curve follows the pattern shown in Figure 4.25(c) and synchronism is lost.

The relationship between load-angle and time (shown in the swing curves in the lower halves of the diagrams in Figure 4.25) is determined by the *stored-energy coefficient* or *inertia constant*, $H$. This is defined as the ratio of the stored energy (in joules or watt-seconds) to the apparent power rating $S$ (in volt-amperes) of the machine. For example: a typical 250 kVA 4-pole salient machine has an inertia constant of 0.18 kW-seconds/kVA at 50 Hz. This equates to 0.26 kW-seconds at 60 Hz, since $H$ is proportional to $f^2$. $H$ should not be confused with $M$, another form of *inertia constant*, which expresses inertia in terms of the power (in watts) required to produce unit angular acceleration, i.e watts per electrical degree/s$^2$ or joules-seconds per electrical degree. The relationship between these two constants is given by:

$$M = S.H/180\,f$$

where S is the volt-ampere rating of the machine and $f$ is the system frequency.

Worked examples in text-books [13] and [14] demonstrate how, by considering small increments of time (of the order of 0.1 s), a point-by-point solution of a non-linear form of the swing equation, $P_i + P_e = P_{sh}$, is obtained. This is then used to calculate changes in angular acceleration, angular velocity and angular displacement, at each time interval, to give a plot of the swing curve.

Aylett [15] gives a method of obtaining a criterion for stability in two- and three-machine power systems, using an energy integral derived from

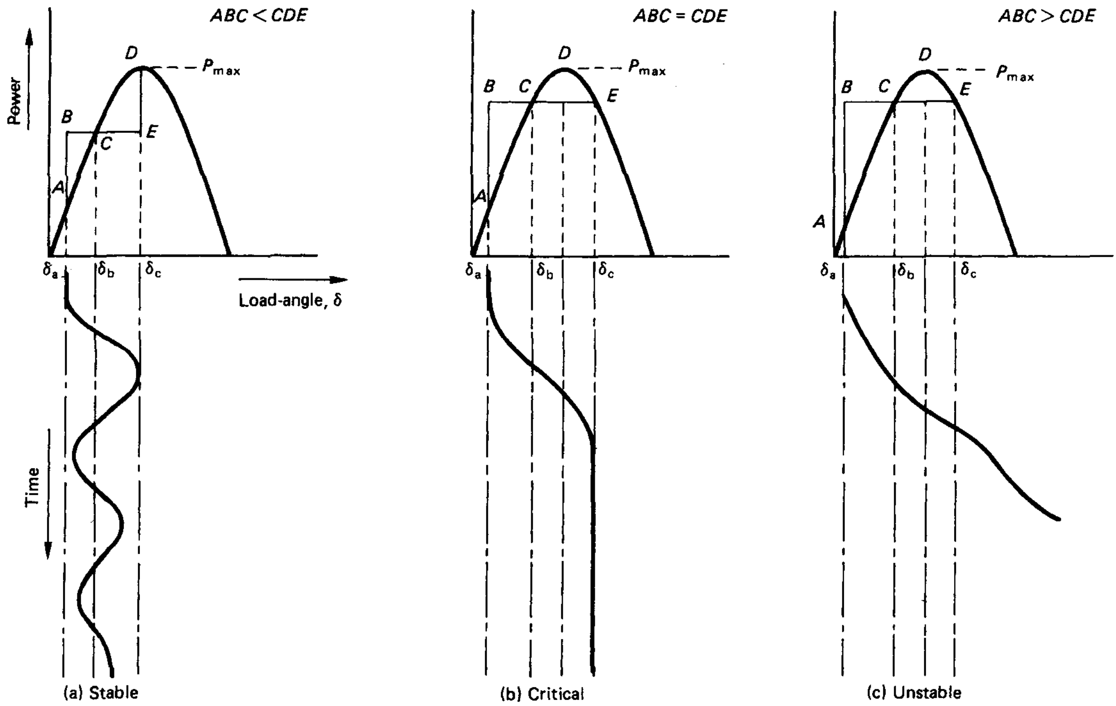



**Figure** 4.25 Load-angle/time curves (or swing curves) in the equal-area method of stability analysis

singular points of the non-linear, electro-dynamic equations. Swing equations may also be solved by graphical means. Ho [16], for example, describes a method which may be used for problems involving multi-machines, when damping is considered.

Stable operation is possible at very large rotor angles using fast-acting automatic excitation control. But, such control can only perform within prescribed system voltage boundaries. Operation at load-angles in excess of 90° makes a machine vulnerable to transient instability after a major fault has occurred on the system. Dinley [17] wearns that:

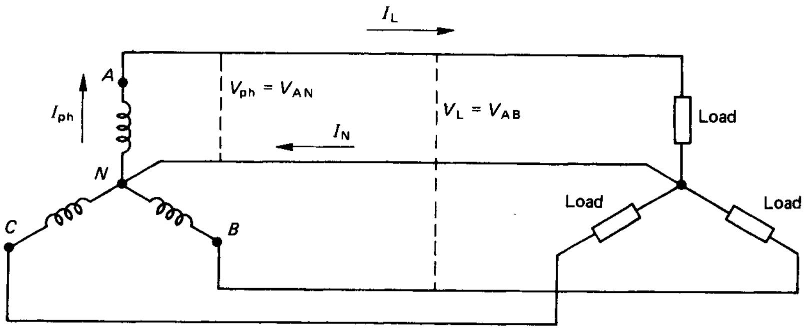
> '... the inclusion of governor and automatic-voltage-regulator effects in transient-stability problems makes it necessary to define *transient stability* with care. Even if a generator is *stable* on its first rotor excursion after a disturbance, there is no- guarantee that, in certain conditions, the amplitude of rotor oscillations will not build up subsequently to give instability. Conversely, a condition can be reached where the generator rotor *slips* one pair of poles after a disturbance is applied but then recovers and ultimately achieves synchronous stability. These two conditions ... appear to challenge one of the basic assumptions of the equal-area criterion of stability, i.e. that stability is decided during the first swing of rotor oscillation'

Perhaps the most effective aid to stability is the fast-acting circuit-breaker [13]. Fault clearances of the order of 100 ms allow insufficient time for a generator to acquire much additional kinetic energy (area ABC of Figure 4.25) and so jeopardize synchronous operation.

### 4.2.10 Load balance

A.C. distribution is usually 3-phase 4-wire, as shown in Figure 4.26(a). Industrial loads consist of 3-phase devices, such as induction motors and transformers, which are connected to the three line conductors, and are inherently *balanced* (i.e. the impedance in anyone of their phases is equal to that in either of the other two phases), so that the active and reactive power flows are the same, in each phase. Also, phase voltages and currents are equal, and are displaced 120 electrical degrees in time from each other. A *balanced load* may then be defined as one in which the individual line (or phase) currents of a 3-phase system are equal in magnitude, their vectorial sum being zero (see Figure 4.26(b». This is the ideal situation - one which is seldom achieved, in practice.

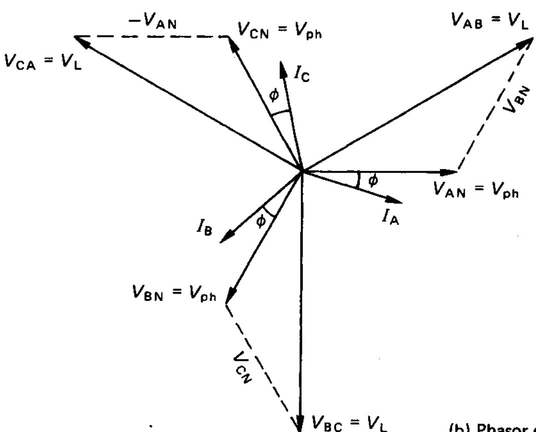
Miscellaneous loads (such as heating and lighting, small motors, and welding sets) are single-phase elements, which are connected between a line

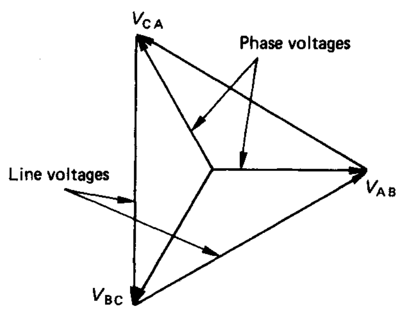



(a) 3-phase, 4-wire star-connected system

Phase voltage $V_{ph} = V_{AN}$, $V_{BN}$ and $V_{CN}$
Phase currents $I_{ph} = I_A$, $I_B$ and $I_C$
Line voltage $V_L = V_{AB}$, $V_{BC}$ and $V_{CA}$
Line current $I_L$

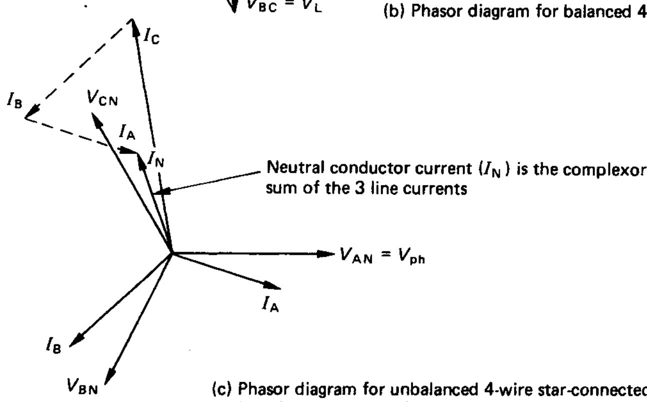
$V_L = \sqrt{3}, V_{ph}$
$I_L = I_{ph}$




Voltage complexors in alternative triangular form

(b) Phasor diagram for balanced 4-wire star-connected load




(c) Phasor diagram for unbalanced 4-wire star-connected load (with negligible feeder line impedance)

**Figure 4.26** Circuit and phasor diagrams illustrating load balance conductor and the neutral or star point - which may, or may not, be earthed. Whilst efforts are made to keep the 3-phase system balanced by evenly *distributing* these loads over the three phases, some degree of system imbalance is inevitable. There will be current in the neutral conductor; and inequality between the three line currents (see Figure 4.26(c». Any difference in the current loadings (or of the power factor) imposed on the individual phases of a generator will cause voltage imbalance at its terminals. Because the impedance of the line conductors remains unaltered the unequal line currents will give rise to unequal voltage drops. These, in turn, will result in further voltage imbalance at the loads. Calculation of this voltage imbalance is fairly complicated. It requires the unbalanced system to be converted to a balanced one using symmetrical components of current and impedance - the so-called positive, negative, and zero phase-sequence components. See Chapter 9.

BS 4999: Part 40 (now withdrawn) required 3-phase synchronous generators to be capable of carrying an unbalanced load of 0.25 pu (i.e. 0.25 $(I_{max} - I_{min})/I_{max}$. where $I$ is the line current) for short periods, of the order of minutes, provided the rated current is not exceeded in any phase.

Modern machines are capable of accepting, and operating with, quite large imbalance conditions; typically, where one or even two phases are at no-load or full-load. This is at the expense of the voltage regulation on individua1 phases. The effect of various phase-loading conditions is shown in the voltage regulation curves of Figure 4.27 [18]. A more evenly balanced voltage relationship is obtained when an automatic excitation control system uses three-phase sensing. The regulation band is moved so that it 'straddles' the nominal (or rated) value [18]. The following example illustrates this point.

The phase voltages in an out-of-balance condition, compared with nominal, were:

| | |
|---|---|
| Phase A-N | + 1% |
| Phase B-N | 0% |
| Phase C-N | - 6%, |

which represents an overall regulation of 7%.

A 3-phase sensing device serves to move this band about the nominal phase voltage and gives a ±3½% regulation - the overall regulation is still 7%.

### 4.2.11 Imposed vibrations

British Standard BS 5000: Part 3 - *Generators to be driven by reciprocating internal combustion engines,* defines the maximum vibratory conditions for machines and attached ancillary equipment. It takes account of the generator's self-induced vibration, the limits for which are set by BS 4999: Part 142.

*Torsional vibration*

A.C. generator rotors must be capable of continuously withstanding vibratory inertia torque amplitudes of ±2.5 $T$ (where $T$ is the rated full-load torque) over the speed range 0.95 to 1.10 pu, and ±6.0 $T$, when passing through critical speeds below 0.95 pu. The total inertia torque acting on the rotor should be taken into consideration in the 0.95 to 1.10 pu speed range. Calculations are based on the maximum rating of the set, including the 10% overload condition mentioned in Section 3.7 of Chapter 3. Torsional vibrations are discussed in Sub-section 3.3.3 of the same chapter.

*Linear vibration*

Generators should be capable of continuously withstanding linear vibration amplitudes of 0.25 mm, at between 5 and 8 Hz, and velocities of 9.0mm/s r.m.s., between 8 and 200Hz. Measurements are taken at any point on the main frame, or on separate pedestal bearing blocks where applicable. These limits only refer to the predominant vibration frequency in a complex wave-form. BS 5000: Part 3 includes a chart (reproduced in Figure 4.28) which shows these vibration levels in terms of amplitude and frequency.

*Electromechanical frequency of vibration*

See Chapter 8 for the definition of this term. It may be necessary to calculate the electromechanical resonant frequency of vibration of the combined engine-generator to ensure stable operation in the presence of possible disturbing frequencies from, for example, the mounting system, fuel system, or torque variations from the engine or load. The responsibility for this calculation lies with the *supplier* (defined in Sub-section 3.3.3 of Chapter 3) of the generating set.

*Unbalanced magnetic pull*

A strong magnetic attraction exists between stator and rotor when the generator is excited. If the rotor is centrally situated within the stator (i.e. there is complete air-gap symmetry), the radial forces will balance out. In practice, there is always some degree of asymmetry in all rotating machines, and the magnetic attraction forces are unbalanced. The resultant imbalance is called the *unbalanced magnetic pull* (u.m.p.). To a first approximation (and for eccentricities not greater than 0.1), u.m.p. may be considered to be proportional to the eccentricity of the machine's air-gap. There is only a small increase for larger radial deviations. *(Note:* eccentricity is expressed as a fraction of the symmetrical air-gap length.) Conditions will change with speed and load, and the pulsating nature of the resultant force may

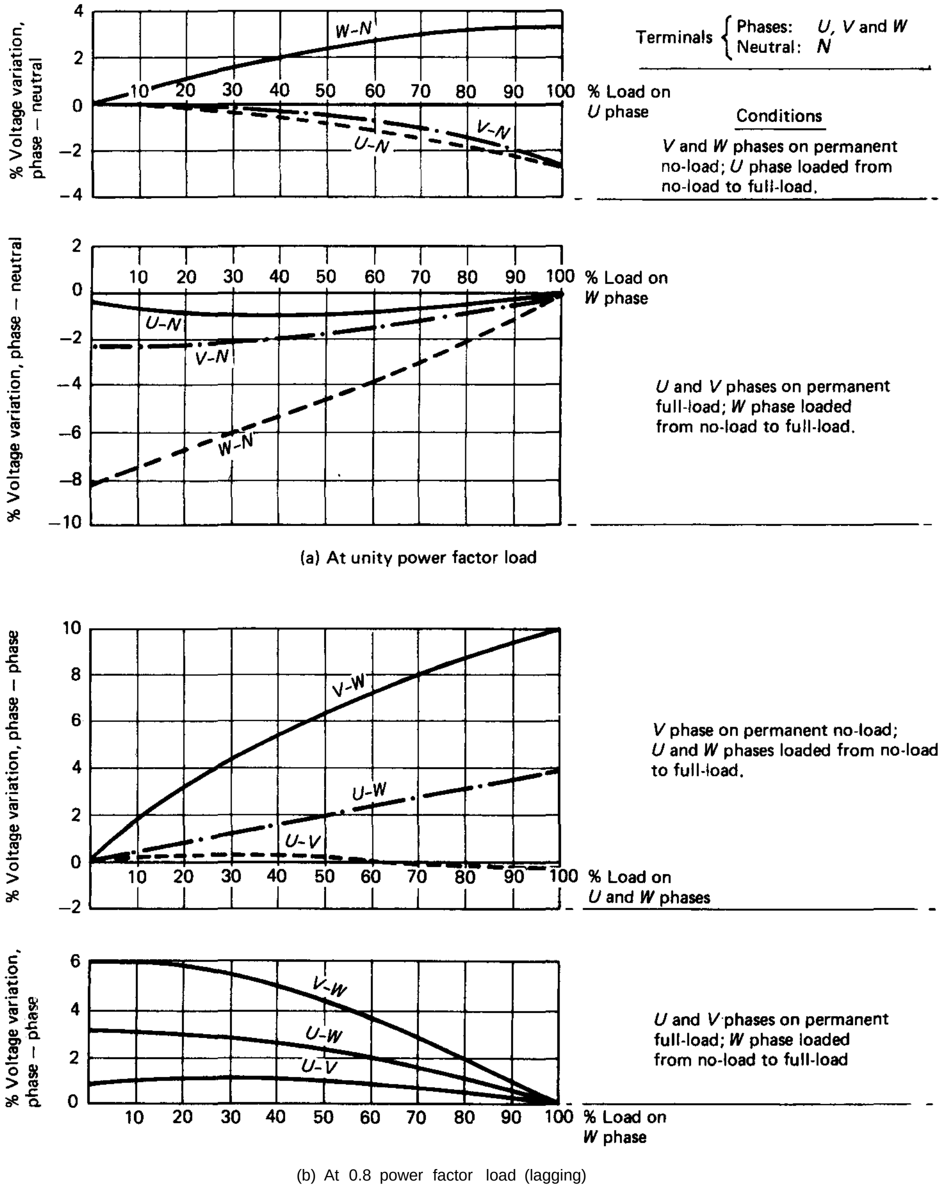



**Figure** 4.27 Voltage variation for unbalanced conditions at different power factors (Courtesy: Newage International Ltd.)

give rise to significant vibration. Conditions are worse if bearings are mis-aligned, so that stator and rotor axes are not parallel with each other. Machine manufacturers usually calculate for worst-case conditions and allow for the presence of unbalanced magnetic pull by using suitably stiffened shafts and adequately sized bearings. It is particularly important to ensure that the maximum working amplitudes of vibration are well within the tolerances of the selected bearings. Typical u.m.p. values lie between 15 and 20 kN/mm for salient-pole machines in the range 500 kW to 1.5 MW.

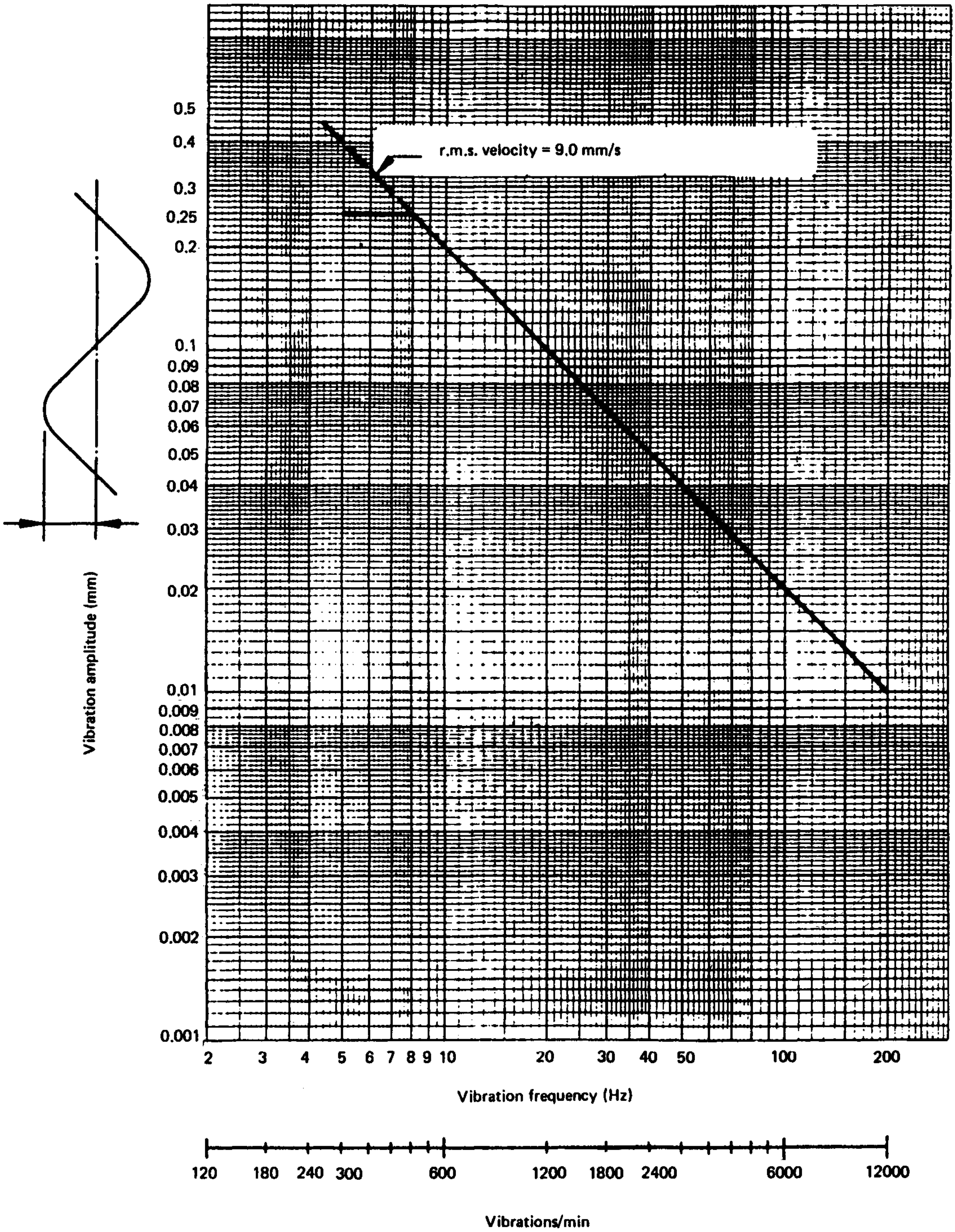



**Figure 4.28** limits of vibration on i.e. engine-driven generators (From BS5000: Part 3: 1980 Courtesy: British Standards Institution)

## 4.2.12 Two-axis theory and saliency

We have discussed (in Sub-section 4.2.6) the modifying effect that armature reaction has on the main field. In developing the Potier diagram for the cylindrical-rotor machine (Figure 4.14), we assumed that the armature reaction and the m.mJs were sinusoidally distributed, and that the reluctances of the magnetic circuits of armature and rotor field were spatially uniform. In the case of the salient-pole machine, the reluctances of the magnetic paths along the axes of the poles, and in the interpolar gaps, differ widely. The space and time diagrams of Figure 4.14 therefore need to be modified to take account of these differences. But, before we do this, we must determine the effect that the non-uniformity of the air-gap has on the flux distribution produced by the armature-reaction m.mJ.

Figure 4.29(a) shows the two components of the fundamental armature-reaction m.mJ. $F_a$ which rotates synchronously in space. They are: the polar or *direct-axis* component $F_d$, and the interpolar or *quadrature-axis* component $F_q$. The corresponding flux-density waves produced at the armature surface (neglecting any slot effect) are shown hatched in diagrams (b) and (c). The flux wave is badly distorted in the interpolar space since it has a large third harmonic content. *(Note:* this third-harmonic flux wave will generate third-harmonic e.mJs in the armature phases, but, because the armature windings are star-connected, these voltages do not appear at the line terminals of the machine.) The direct-axis and the quadrature-axis are thus defined in relation to the rotor and always rotate at the same speed as the rotor. Clearly, the armature-reaction m.m.L wave produces more flux per pole in the direct-axis than it does in the quadrature-axis. The difference is most pronounced when the axis of the armature-reaction m.m.f. wave coincides with the pole axis. This is not the case with a cylindrical-rotor machine, where the armature-reaction m.mJ. produces the same amount of flux regardless of its spatial relationship to the direct and the quadrature axes.

The axis of the armature-reaction wave lies somewhere between the direct-axis and the quadrature-axis, depending upon the phase relationship between the armature current $I$ and the excitation voltage $E_t$ (see Figure 4.13). When $I$ is in phase with $E_t$ it coincides with the quadrature-axis, and when $I$ is 90° (electrical) out of phase with $E_t$ it coincides with the direct-axis.

The Frenchman Blondel first suggested the simple, but effective, expedient of introducing two components of the armature m.m.f. wave - shown in Figure 4.29. This makes it unnecessary to compute a value of the armature-reaction reactance $X_a$, for every angular position of the armature m.m.f. Only two synchronous reactances need therefore be considered for salient-pole machines. The first is associated with the direct-axis, and the second with the quadrature-axis. They represent the maximum and minimum values, respectively, of the synchronous reactance of a salient-pole machine.

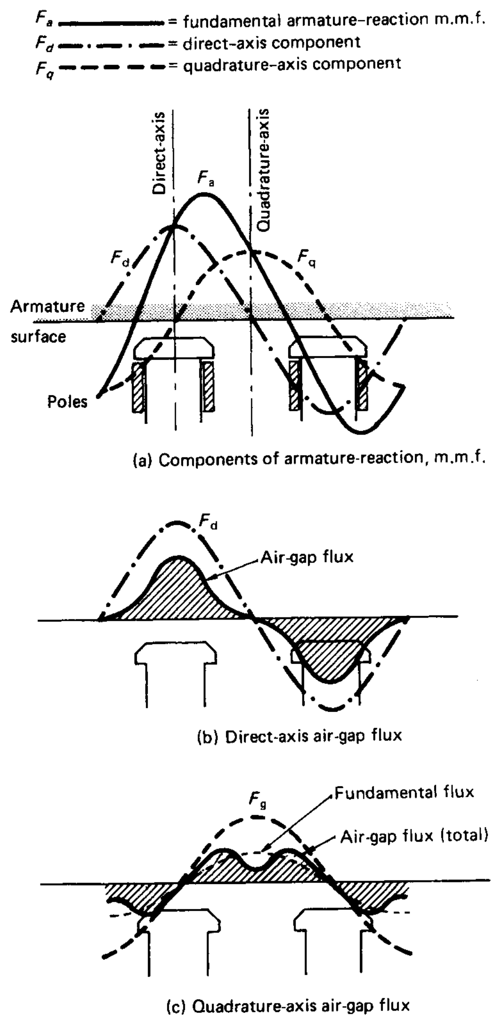



Figure 4.29 Air-gap m.m.fs and flux densities in a salient-pole synchronous machine

We have seen (in Sub-section 4.2.6) that the effect of armature-reaction could be represented by a 'fictitious' reactance $X_a$, to give the expression ($X_s = X'' + X_a$) for synchronous reactance. In the same way, we can assign separate values of armature-reaction reactance to the direct and quadrature axes components, to arrive at the following definitions of *direct-axis synchronous reactance* ($X_d$) and *quadrature-axis synchronous reactance* ($X_q$).

$$X_d = X'' + X_{ad}$$
$$X_q = X'' + X_{aq}$$

where $X_\sigma$ is the leakage reactance
$X_{ad}$ and $X_{aq}$ are the magnetizing (or armature-reaction) reactances in the direct-axis and the quadrature-axis, respectively.

The Potier diagram for the salient-pole machine is shown in Figure 4.30. Compare this with that for the cylindical-rotor machine, shown in Figure 4.14(b). The stator m.m.f. is the vector sum of two components acting along the direct and the quadrature axes. An empirical factor $K$ (always less than unity) is applied to the quadrature-axis component, $F_q$. This allows for the difference in reluctance in the two axes - making the quadrature-axis component of the armature reaction less effective than the direct-axis component. Factor $K$ is known as the *cross-reaction coefficient.* (The description *cross,* in this context, is synonymous with *quadrature.)* Its value depends on the constructional geometry of the machine and, in particular, on the ratio of the pole-arc to the pole-pi,tch.

$$K = (X_q - X_\sigma) \div (X_d - X_\sigma)$$
$$= X_{aq}/X_{ad}$$

It is important to appreciate that the two components of the armature current, $I_d$ and $I_q$, are related to the excitation e.m.f. $E_t$. Each is associated with a synchronous reactance voltage drop: $I_dX_d$ and $I_qX_q$ .

Values of $X_d$ and $X_q$ are determined by test. $X_d$, corresponding to the unsaturated state, is obtained from no-load saturation and sustained three-phase short-circuit characteristics (see Figure 4.19(a». The customary method for obtaining $X_q$ is from the *low slip test.* This is described in Clause 36 of BS 4999: Part 104: 1988. Armature voltage and current are usually recorded by oscillograph (see Figure 4.31). Neglecting armature resistance, the maximum and minimum values of $V/I$ give the direct-axis (unsaturated) and the quadrature-axis synchronous reactances, respectively.

That is

$$|x_d = u_{max}/i_{min}|$$

and

$$|x_q = u_{min}/i_{max}|$$

or

$$X_d = U_{max}/\sqrt{3}\, I_{min} \text{ ohms}$$
$$X_q = U_{min}/\sqrt{3}\, I_{max} \text{ ohms}$$

Typical values are: 0.8 – 1.6 pu, for $X_d$; and 0.65 – 1.0 pu, for $X_q$.

## 4.3 Transient operation

The preceding section dealt with those parametel'1i which affect the steady-state behaviour of generators. Of particular significance were:

- the synchronous impedance; and
- the energy-storing inertias, resulting from load changes or fault disturbances, which affect the machine's stability and are likely to cause it to lose synchronism.

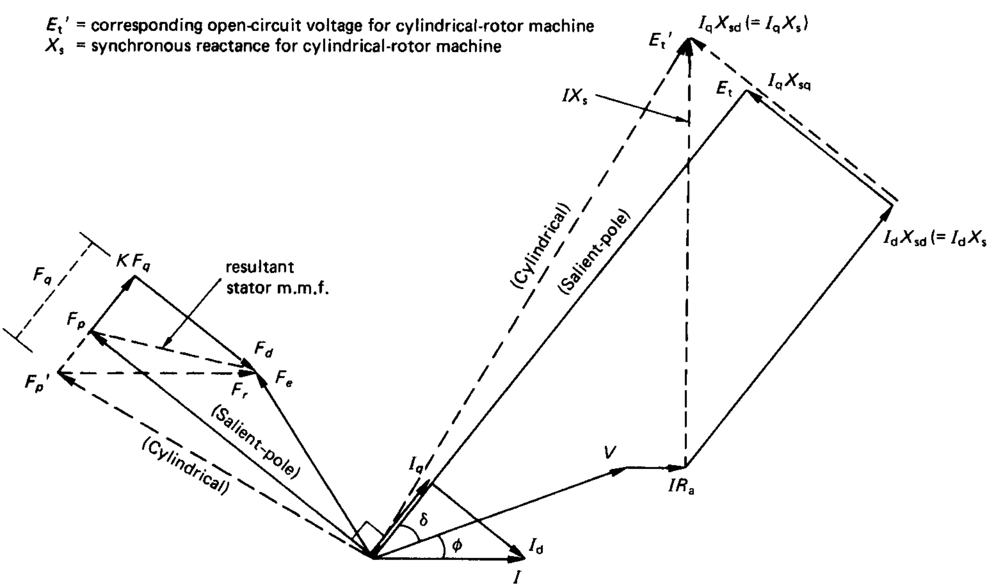



**Figure 4.30** The Potier diagram for a salient-pole machine

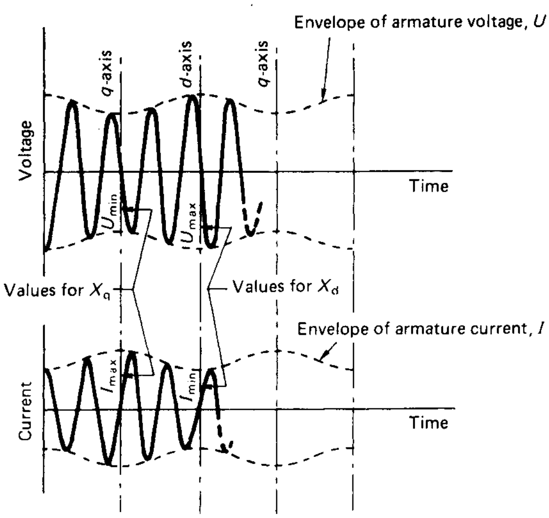



**Figure** 4.31 Determination of $X_d$ and $X_q$, by the slip test

When a generator is subjected to a fault condition, parameters are quite different from those of the steady-state. Transient conditions occur when there are major and sudden changes in the electrical circuits connected to the generator's terminals. The machine's subsequent behaviour is then influenced by such considerations as:

- the nature and location of the fault, the phases involved, and the network impedance up to the fault;
- the existing load on the machine, its excitation, and the responses of control elements such as prime-mover governor, automatic voltage regulator, and system protection devices.

The most dramatic changes occur on accidental short-circuits.

We shall confine our discussions to those conditions that pertain when a three-phase short circuit is applied in the immediate vicinity of a generator's terminals. The differences between the machine's steady-state and transient performances are most pronounced under these circumstances. It is necessary to characterize the machine by reactances and time constants, which will enable the initial magnitudes of the transient currents and their decay periods to be computed.

### 4.3.1 Transient and subtransient reactances

These two reactances influence a synchronous machine's performance following a sudden short circuit at its terminals. They affect the short-circuit capacity of the machine, and its transient-voltage behaviour. It is necessary to study the current flow in the armature under sudden short-circuit conditions in order to define both quantities.

The value of the peak current in each phase of a short-circuited generator depends upon the value of the induced e.m.f. within the machine at the instant of short circuit. If the e.m.f. is at its zero value, the short-circuit current is fully asymmetrical about its zero axis, and is at its maximum value. Conversely, when the e.m.f. is at its peak value at the instant of short circuit, the armature current is symmetrical about its zero axis, and is at its minimum value. See Figure 4.32. These two conditions represent the extremes. At intermediate points in time, the armature current is partially symmetrical and has a magnitude that lies between the values at these two extremes.

Figure 4.32(b) shows the maximum asymmetry condition. The value of the short-circuit current is twice that for the fully-symmetrical state. It depicts what is sometimes referred to as the *doubling effect,* where the stator current continues to rise after the

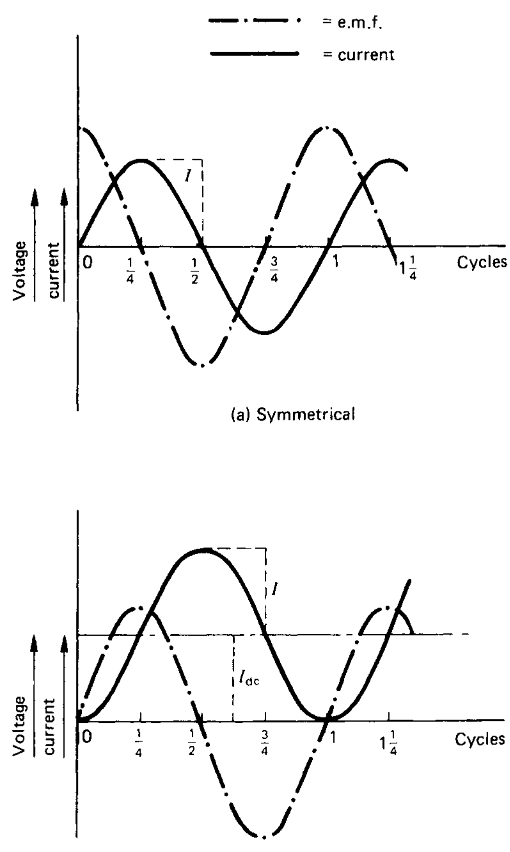



**Figure 4.32** Symmetrical and unsymmetrical short-circuit conditions

e.m.f. has reached its peak - provided the latter acts in the same *direction.* Peak short-circuit current occurs when the e.m.f. is at its zero level, i.e. one-half cycle later. The current wave-form contains a d.c. component $I_{dc}$ which will decay (exponentially) to zero; and an a.c. component of peak value $I$. Initially, however, the d.c. component serves to raise the a.c. component above the zero current axis, effectively doubling its peak value.

When a three-phase short circuit is suddenly applied to a machine, the instantaneous value of the pre-fault e.m.f. will be different for each phase. The armature phase currents will exhibit differing degrees of asymmetry. Figure 4.33 shows the type of short-circuit current oscillograms that are obtained in practice. Two of the three phases usually display marked asymmetry.

A larger scale version of the oscillogram for phase B is shown in Figure 4.34. The peak short-circuit current consists of the d.c. component and an a.c. component which has two marked degrees of decay. The rate of decay in the second period is several times slower than that in the first. The d.c. component decays very quickly to zero. The rate of decay is determined by the stator-circuit resistance and its equivalent inductance.

Asymmetry is usually ignored in most case studies. Symmetrical wave-forms (as in Figure 4.35) may be derived from asymmetrical ones by subtracting the offsetting d.c component, and replotting the wave; or tests may be repeated until a symmetrical wave-form is obtained, for one of the phases. It will be seen from Figure 4.35 that the current ultimately decays to a steady short-circuit value $I_{sc}$, where

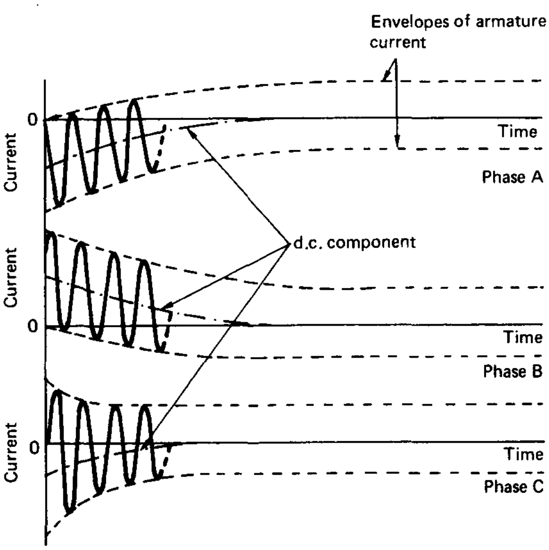



**Figure** 4.33 Typical oscillograms of short-circuit currents in the three phases of a generator

armature reaction has its full effect. The shape of the wave-form envelope (shown dotted in Figure 4.35) suggests that the wave may be divided into three discrete time regions. The first, covering the first few peaks, during which the current decrement is very rapid, is called the *subtransient period.* The second, which lasts much longer, and in which the decrement is considerably slower, is called the *transient period.* The third is the *steady-state period* of sustained short-circuit current. If the envelopes relating to the first two periods are extrapolated back to the zero time ordinate, two different values of short-circuit current obtain, $I''$ and $I'$. Clearly, different limiting reactance quantities must also apply for each condition. That which is applicable to the subtransient envelope is called the *subtransient reactance, X";* and that which relates to the transient condition is called the *transient reactance, X'.*

The subtransient reactance establishes the value of the instantaneous (r.m.s.) value of short-circuit current. When $X''$ is expressed in per-unit terms, its reciprocal gives the factor by which the machine's rated full-load current must be multiplied, in order to obtain the instantaneous short-circuit current value. So that, if

$$n.I_{FLC} = I''$$
$$n = 1/X''_{pu}$$

For example, the instantaneous short-circuit current of an 850kVA, 415V, 3-phase machine with a subtransient reactance of 0.16 pu would be given by:

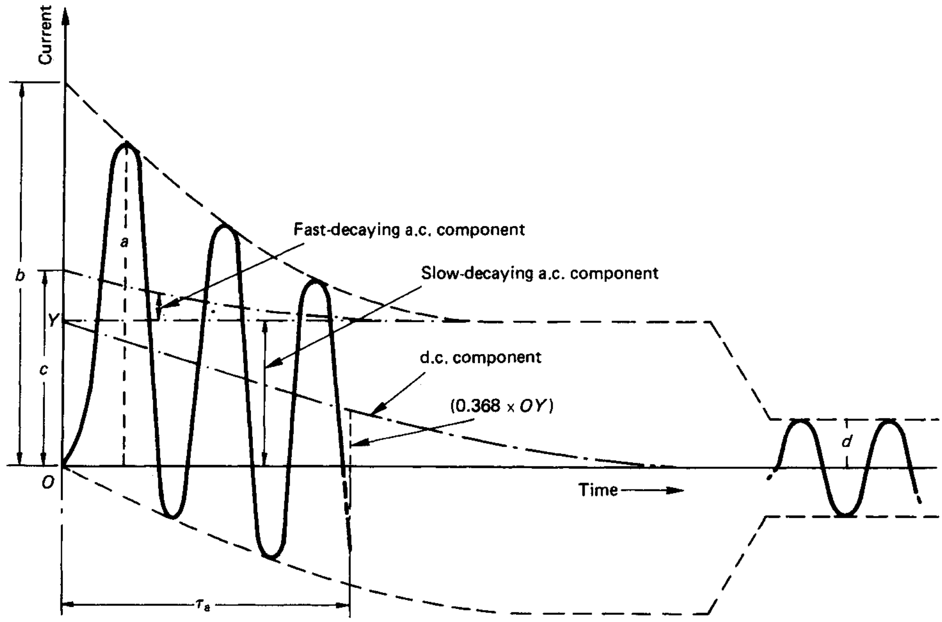
$$\begin{aligned} I'' &= (1/0.16) \times I_{FLC} \\ &= (6.25 \times 1183)\ \text{A} \\ &= 7394\ \text{A} \end{aligned}$$

The performance of a machine following a three-phase short circuit may therefore be characterized by three reactances; the subtransient, the transient and the synchronous reactances; and by two associated time constants.

The ratios given in Figure 4.35 to define the subtransient and transient reactances use the open-circuit terminal voltage $V_0$. This is not strictly accurate, since the values of $I''$ and $I'$ are directly related to the internal e.m.f. of the machine at the instant of short circuit. Because the value of the e.m.f. is only marginally higher than that of the terminal voltage, the substitution is justifiable for the majority of fault conditions.

The subtransient reactance is determined by the field (or rotor) leakage paths (i.e. those between armature, field, and damping windings) as well as by other damping metal parts (such as solid pole shoes), which are subjected to the effect of the field flux. The main influences are those of damper windings and of solid pole shoes.

The transient reactance is determined by the flux leakage between the armature and the field windings. A useful picture of the applicable conditions




$a$ = highest value of instantaneous current
$b$ = initial value of current corresponding to the envelope (of peak current values) projected to the start of the short-circuit i.e. time, $t = 0$
$c$ = r.m.s. value of the a.c. component of '$b$' at the time the short-circuit starts ($t = 0$) $= b/2\sqrt{2}$
$d$ = amplitude of sustained or steady-state short-circuit current, with no-load excitation
$\tau_a$ = armature (or direct current) time constant (see Sub-section 4.3.1)

**Figure 4.34** Typical offset wave-form of short-circuit current

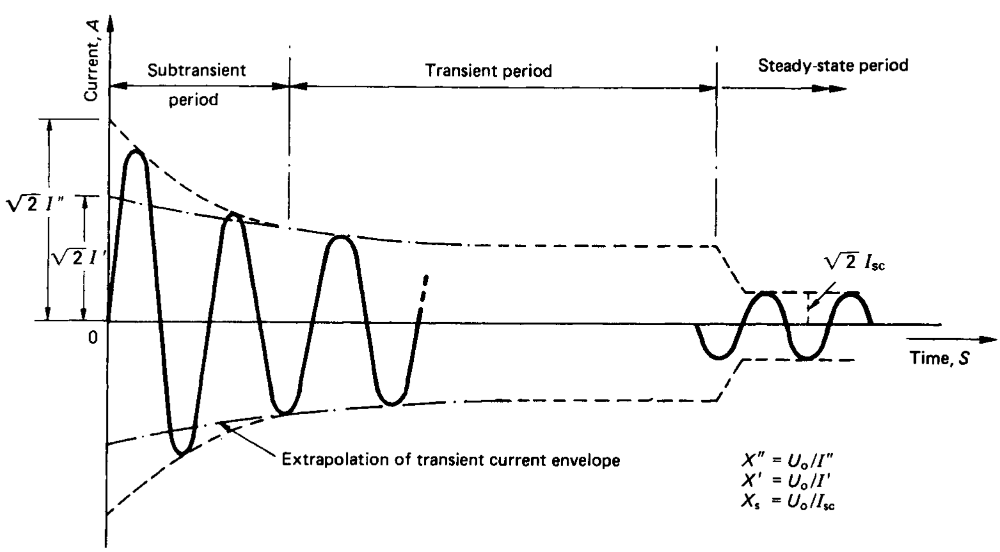



**Figure 4.35** Symmetrical short-circuit current wave-form (d.c. component excluded)

can be obtained by thinking of the field winding as the secondary of a transformer, whose primary is the armature winding [19]. Under transient conditions the field circuit resembles the short-circuited secondary winding of the transformer. The equivalent reactance of the transformer primary is analogous to the transient reactance of the armature winding. *(Note:* the transformer primary's open-circuit reactance is equivalent to the steady-state synchronous reactance of the generator.)

## *Applicable time constants*

A time constant may be defined as the duration of a transient phenomenon, computed from its characteristic. The short-circuit current envelope of Figure 4.35 (reproduced in Figure 4.36, in r.m.s. terms) is substantially exponential in form. There are two distinct time constants associated with the envelope; one for each of the decay periods - the subtransient and the transient regions.

The *subtransient time constant* TN determines the initial (fast) rate of short-circuit current decay. It may be defined as the time required for the rapidly changing component, present during the first few cycles in the short-circuit armature current, following a sudden change in operating conditions, to decrease to *lie* (= 0.368) of its initial value, the machine running at rated speed.

The *transient time constant* T' determines the subsequent (slower) rate of short-circuit current decay within the transient period. It may be defined as the time required for the slowly changing component of short-circuit armature current, following a sudden change in operating conditions, to decrease to *lie* (= 0.368) of its initial value, the machine running at rated speed.

A third time constant, and one associated with asymmetrical short-circuit current wave-forms, is the *armature* (or *direct current) time constant* Ta' It is the time required for the aperiodic d.c. component, present in the short-circuit armature current, to decay to *lie,* or 0.368, of its initial value.

## *Direct-axis and quadrature-axis quantities*

A distinction is generally made between the direct-axis and the quadrature-axis values of the subtransient and transient reactances Gust as it is for the synchronous reactance), and between their respective time constants. When computing the values of short-circuit currents, it is usual to use only the direct-axis values of the quantities. Terminology and related symbols are as follows:

$X''_d$ = direct-axis subtransient reactance
$X'_d$ = direct-axis transient reactance
$T''_d$ = direct-axis subtransient short-circuit time constant
$T'_d$ = direct-axis transient short-circuit time constant

The subscript q is substituted for d in the equivalent symbols for the quadrature-axis quantities.

Strictly speaking, direct-axis quantities should only be used on purely reactive networks. The three-phase short-circuit at the terminals of an *unloaded* machine is a prime example. Here the power factor of the *network* is very low because the resistive value of the armature winding is very small compared with its leakage reactance.

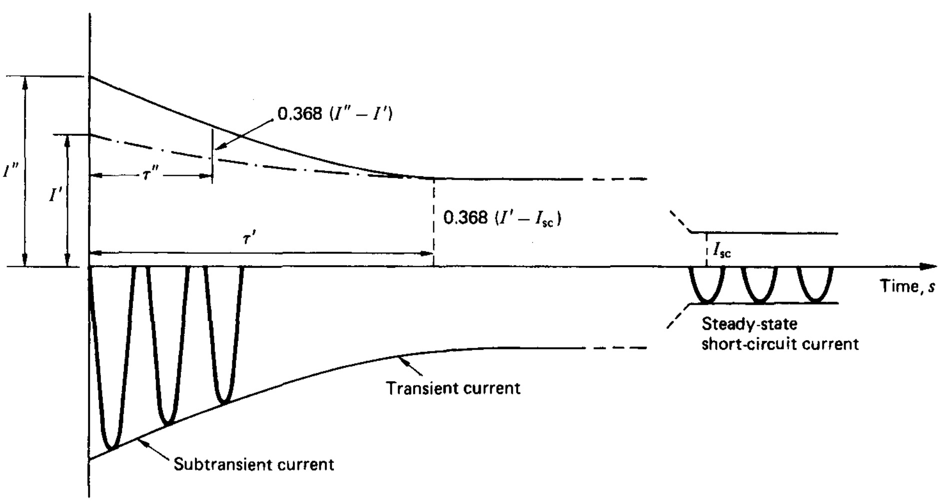



**Figure** 4.36 Time constants of symmetrical short-circuit current

If, however, the machine has an *active* power loading at the instant of fault, or if the three-phase fault occurs at some distant point in the system network (where a higher power factor may be expected), quadrature-axis conditions will apply and the appropriate reactances must be used. The three time constants, T", T' and Ta, may only be used for short-circuits at the machine terminals. Where external impedance is involved, short-circuit current decay is influenced by the machine inductances and by the external circuit constants.

Quadrature-axis rotor circuits have only damper windings or rotor iron in the interpolar space. If a salient-pole machine has damper bars, the induced currents will be of subtransient order and the q-axis synchronous reactance $X_q$ will be equal to the q-axis transient reactance $X'_q$. Also, X"q will have a lower value than $X'_q$. On the other hand, in a cylindrical-rotor machine, the quadrature-axis circuit has rotor iron only. In this case, the induced currents are more in the order of transient, rather than subtransient, value. For this type of construction, therefore, $X'q$ = X"q; with $X_q$ having a higher value.

For unbalanced short-circuit conditions (those not involving the three phases equally, e.g. line-to-line or line-to-neutral faults), the method of calculation involves the use of positive-, negative-, and zero-sequence symmetrical components. See Sub-section 4.2.10. The process is complicated by the fact that it is possible for the positive-sequence component to be further sub-divided into q-axis and d-axis subtransient, transient and synchronous reactances. When it is realized that, at best, the values for these quantities are only estimates, the complication is rarely worthwhile. As was stated earlier, calculations using only d-axis quantities give good enough approximations. In nearly all cases, the initial short-circuit current is the parameter of main interest. Its value is subtantially independent of the balance, or unbalance, of the short-circuit fault. The final, steady-state, short-circuit current is approximately the same for two-phase and three-phase short-circuits. That for single-phase short-circuits is about 50% higher [9].

Say [13] warns that the 'open' third phase in a line-to-line fault condition may be subjected to high overvoltages with a large harmonic content. The highest voltage level is given by:

[2.(X"q!X"ct)-1] pu.

Capacitance loading of the 'open' phase may raise its voltage level even higher - through resonance. It is therefore important to keep the ratio X"q/X"ct as near to unity as possible. Typical values of this ratio are between 1.3 and 1.5, for complete-cage dampers and for solid pole shoes.

## 4.3.2 Transient voltage

One of the most important requirements for a generator must be its ability to accept sudden heavy loads, with minimum disturbance to its terminal voltage. More so, when the machine is operating as one of a small group providing an independent power source - as on board ship, or as a single unit supplying a dedicated load, e.g. in mobile, or transportable, form. These machines do not have the back-up of an *infinite busbar*, such as a large utility power supply. They must therefore supply all the *wattless* current demanded by the load. Their transient voltage performance is largely dependent upon the kVAr (wattless) loads applied to them. Any large loads (and especially those of low power factor) that are suddenly switched on to a finite power source, will cause an instantaneous dip in the supply voltage.

The oscillograms of Figure 4.37 show recordings of the output voltage and current, and of the exciter field voltage and current, when 1.08 pu load at zero power factor lagging, is switched to a 565 kVA, 400 V, 3-phase, 12-pole, brushless generator. The machine employs an excitation scheme similar to

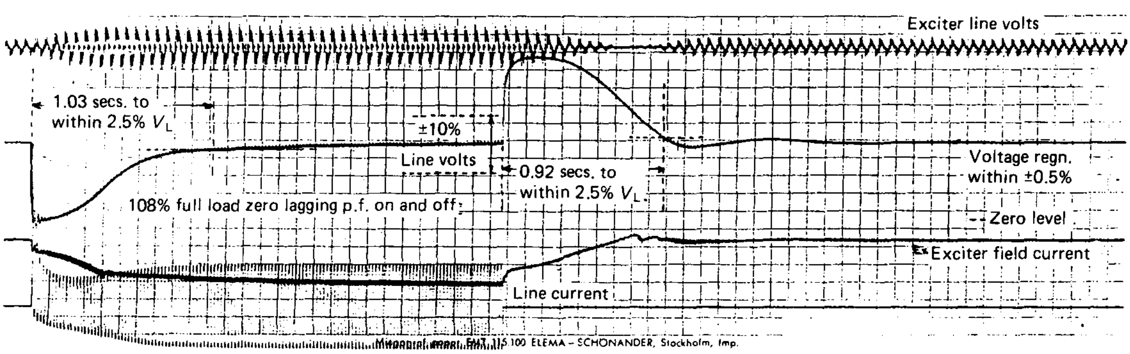



Figure 4.37 Transient recordings taken during regulation tests (Courtesy: Brush Electrical Machines Ltd.)

that shown in Figure 3.33 of Chapter 3. It uses a phase-compensated compounding circuit in parallel with a 'static' a.v.L to supply the exciter field.

A typical voltage-response characteristic is shown in Figure 4.38. The immediate voltage drop, from normal voltage to point A, is determined by the subtransient reactance of the machine. The per-unit magnitude of the 'dip' when full-load current at zero power factor lagging is suddenly applied, is equal to the per-unit value of the subtransient reactance. The voltage continues to fall, more gradually, to points B and C, because of the delayed effects of transient reactance and armature reaction. The rate of recovery to normal voltage is governed by the characteristics of the excitation system, and by the time constants of that system. The highly inductive main and exciter fields will contribute to a delay in recovery, before any automatic excitation controls can adjust the main field current, to match the new load condition. Much will then depend upon the amount of *forcing* excitation available. The higher the forcing, the more rapid is the response to the load change. There must be a time delay in an exciter-fed field system before the exciter 'reflects' any forcing voltage into the main field. The voltage recovery time is almost halved in compounded machines, in which the excitation circuit feeds the main field directly. The performance of an exciter-fed machine may be improved by raising the exciter's ceiling voltage. One possiblity is to use a larger exciter to give more margin for field forcing. Another way of reducing the overall time constant is to use a compounding circuit in parallel with the output from the a.V.L

The reverse process occurs when load is disconnected from a machine. There is a transient voltage rise which, again, is proportional to the subtransient reactance. But, the rate of recovery, for brushless machines operating at high power factors, is usually slower than when load is applied. The reason for this is that, while the a.V.L (and any associated compounding) can be made to force the exciter field down, the generator's main field is not electrically accessible and cannot be directly 'bucked' or reversed. There must, therefore, be a longer time delay while the exciter field decays and before the majn field excitation reduces. The exciter field decay may be hastened by employing negative biasing in the a.V.L, or by including an additional winding in the exciter field to give a subtractive, or bucking, effect to the primary winding. See 'Examples of *com*pounded systems', part of Section 3.3.4.

The subtransient reactance has a double significance in the transient performance of a machine. Not only does it determine the extent of the initial voltage drop (or rise) on load change, but it also governs (as we have seen in Sub-section 4.3.1) the level of instantaneous short-circuit current. The higher the value of subtransient reactance, the higher the voltage drop and the lower the instantaneous short-circuit current. Reducing the design value of the subtransient reactance will give lower voltage dips, but, since this increases the short-circuit current (and, therefore, the system fault level), the rated breaking capacity of associated circuit breakers may have to be increased. Lowering the subtransient reactance may also mean increasing the machine's frame size, with, possibly, less efficient use of its active materials. As always, it is a matter of compromise. The machine designer must carefully assess the anticipated impacting loads and the maximum acceptable fault levels for the installation before finalizing his design.

When large induction motors have to be started from a finite power source, such as a generator, it is important that transient voltage dips and voltage

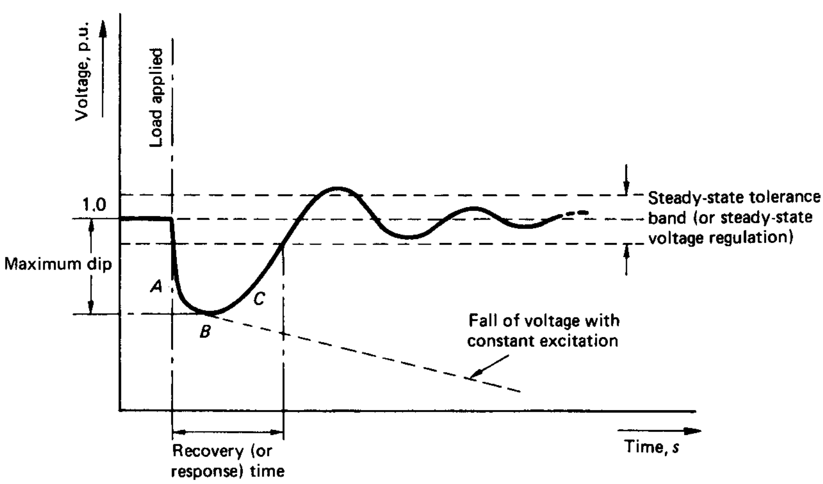



**Figure** 4.38 Transient voltage conditions for load 'ON' recovery times are kept within reasonable limits in order to minimize disturbance to other equipments in the connected load, and to ensure satisfactory starting of other motors. The sizing of generators for this type of duty is discussed in more detail in Chapter 5.

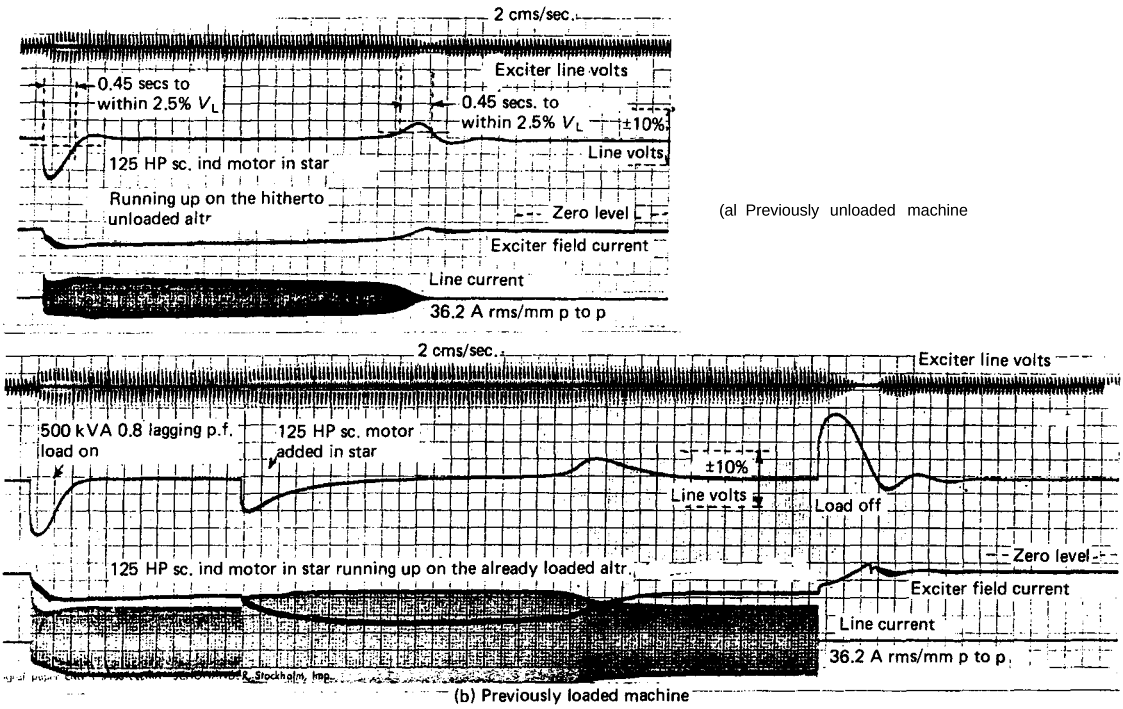
The initial voltage dip will be the same for machines of equal per-unit subtransient reactance - be they of the brushless or of the compounded type. What does differ in each case is the speed of recovery to nominal voltage. Here, performance is solely determined by the degree of field forcing that is available from the machine's excitation system, and by the excitation system's constituent time constants.

Another point worth mentioning is that the amount of voltage dip is independent of the level of load already carried by the generator, particularly where that load is of a mixed nature (i.e. it consists of heating, lighting, and general power). This fact is illustrated in the oscillograms of Figure 4.39. The traces show the line voltage transients when a 125 hp squirrel cage induction motor is started from a loaded, and a previously un-loaded, generator. The traces are for the start-and-run-in-star condition only. Corresponding delta-switching transients (not reproduced here) were equally comparable to each other.

BS 4999: Part 140 specifies various grades of voltage regulation, stipulating for each, the requirements to be met for both steady-state and transient conditions. BS2949 also covers the same subject (in its Clause 42), and offers the machine purchaser the choice of one of four conditions to be satisfied. With the exception of those sensitive-load installations where close control of voltage is required, the majority of installations will accept 20-25 % voltage transients. Indeed, on water pumping applications, where a generator may be subjected to motor starting kVAs of the order of 60 % of its capacity, customarily acceptable performances are: maximum voltage changes of 20 % , with recovery to within ±5 % of nominal voltage in 2 seconds, and to ±21h % within 5 seconds.

### 4.3.3 Some typical machine constants

The following values of short-circuit currents, reactances and time constants are for 4-pole, 6-pole, and 8-pole, 400 V, 50 Hz, type IFC6 generators manufactured by Siemens. Reactances (saturated) are expressed in per-unit terms, and time constants in seconds.




(al Previously unloaded machine

(b) Previously loaded machine

**Figure 4.39** Oscillograms of transients on induction motor starting (Courtesy: Brush Electrical Machines Ltd.)

Table 4.3 Values of short-circuit currents, reactances and time constants for 4-pole, 6-pole and 8-pole, 400 V, 50 Hz generators

| | | | |
|---|---|---|---|
| Rated output (kVA) | 500 | 830 | 1000 |
| Speed (rpm) | 1500 | 1000 | 750 |
| Max. asymmetric short-circuit current (peak value), A | 10500 | 18800 | 21800 |
| Steady short-circuit current (r.m.s. value), A | 2400 | 3800 | 4300 |
| $X_{sd}$ | 4.1 | 2.9 | 2.9 |
| $X_{sq}$ | 3.1 | 2.2 | 2.2 |
| $X'_d$ | 0.216 | 0.167 | 0.203 |
| $X''_d$ | 0.129 | 0.088 | 0.104 |
| $X''_q$ | 0.160 | 0.109 | 0.142 |
| Negative phase-sequence reactance, $X_2$ | 0.145 | 0.099 | 0.123 |
| Stator resistance, Ω | 0.022 | 0.020 | 0.017 |
| $\tau_a$ | 0.021 | 0.015 | 0.022 |
| $\tau'_d$ | 0.055 | 0.056 | 0.084 |
| $\tau''_d$ | 0.003 | 0.003 | 0.003 |

## 4.4 Related standards

Attention is directed to the International Standards listed in Section 3.9 of Chapter 3. Specific reference has been made to the following standards, in this chapter:

*British standards*

BS 4999: Part 101 (IEC 34-1) - *Specification for rating and performance*

: Part 102 (lEC34-2 and 2A) - *Methods for determining losses and efficiency from tests*

: Part 104 (IEC 34-4) - *Methods of test for determining synchronous machine quantities*

: Part 140 - *Specification for voltage regulation and parallel operation of a.c. synchronous generators*

: Part 142 (ISO 2373) - *Specification for mechanical performance: vibration*

BS4727: Part 2 Group 3 (IEC 50: Chapter 411) - *Rotating machinery terminology*

BS 5000: Part 3 - *Generators to be driven by reciprocating internal combustion engines*

BS 2949 (lEC 92-5) - *Rotating electrical machines for use in ships*

*World regional*

VD E 0530 (Verband Deutscher Elektrotechniker, West Germany) - *Rules for electrical machines.*

ANSI (American National Standards Institute) Std C50

## 4.5 References and bibliography

### 4.5.1 References


1. Ministry of Defence, Defence Standard 61-5 : Part 1I1ssue 2, April 1979 - *Terminology and definitions - electrical power systems below 650 volts.*
2. Clayton, A.E. *The Performance and Design of Direct Current Machines,* 2nd edn, Sir Isaac Pitman & Sons, reprinted 1949.
3. Cotton, H. *Electrical Technology* 7th edn, Sir Isaac Pitman & Sons (1957).
4. Capacitors for power factor improvement. Publication number P25, Bryce Capacitors Ltd., Helsby, Cheshire, UK.
5. A.E.G. Manual 'Generation, transmission, electrical installations' (Allgemeine Elektricitats - Gesellschaft, Frankfurt/Main, FER) English Edition of 7th Edition of the 'A.E.G. Hilfsbuch fur elektrische Licht- und Kraftanlagen' pp. 431 & 569.
6. Say, M.G. and Laughton, M.A. Network analysis. In *Electrical Engineer's Reference Boole,* 14th edn, (eds. M.G. Say and M. A. Laughton) Butterworths, London, 1985.
7. Shepherd, J., Morton, A.H. and Spence, L.F. *Higher Electrical Engineering* 2nd edn, Pitman Publishing, (1970).
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9. Say, M.G. *Design and Performance of Alte17Ulling Current Machines,* 2nd edn, Sir Isaac Pitmaa & Sons, reprinted 1949.
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11. Fitzgerald, A.E., Kingsley, C. Jr. and Kusko, A. *Electric Machinery* 3rd edn, McGraw-HilI. (1971).
12. Ogle, H.R. The parallel operation of alternators. Reprinted in Publication AP7002 frOOl *The Allen Engineering Review,* W.H. Allen &: Sons, now NEI-Allen Ltd., Bedford, UK.
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14. Buchan, M.F. *Electricity Supply,* Edward Arnold, (1967).
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16. Ho, K.W. Graphical method for solving transient stability problems. *Proceedings lEE,* IlI(2), 335-342, (1964).
17. Dinley, J.L. Computer studies of power-system transient performance. Article appearing in *Electronics and Power,* Jan. 1964, pp. 17-19, based on four papers in *Proceedings lEE, 1964*
18. Voltage regulation - unbalanced loads - generator data sheets Nos.6331 - 6336 issued January 1979, Newage International Ltd., Stamford, UK.
19. Stein, R. and Hunt, W.R. Jr. *Electric Power System Components - Transformers and Rotating Machines,* Van Nostrand Reinhold, (1979).

### 4.5.2 Bibliography

Cross-refer to Section 3.10.2 (Chapter 3 Bibliography). The Institution of Electrical Engineers has published, in its *Proceedings,* a number of papers on topics covered in this chapter. The following is a list of papers, which would be helpful to those wishing to study subject topics in more depth.

(1) Smith, I.R. and Nisar, P.A. Brushless and self-excited 3-phase synchronous machine. 1968.
(2) Harrison, D. and Jones, e.V. A new method of predetermining the regulation of alternators at unity and lagging power factors. 1948.
(3) Shen, D. W.e. Analysis of hunting phenomena in power systems by means of electrical analogues. 1953.
(4) O'Flaherty, T.M.M. and Aldred, A.S. Synchronous-machine stability under unsymmetrical faults. 1962.
(5) Steven, R.E. An experimental effective value of the quadrature-axis synchronous reactance of a synchronous machine. 1961.
(6) Prescott, J.e. and EI-Kharashi, A.K. A method of measuring self-inductances applicable to large electrical machines. 1958.
(7) Goswami, S.K. Synchronous-machine sudden 3-phase short-circuit. 1971.
(8) Shackshaft, G. New approach to the determination of synchronous-machine parameters from tests. 1974.
(9) Gove, R.M. Geometric construction of the stability limits of synchronous machines. 1965.
(10) Gopal Reddy, I. and Jones, e.V. line -line short circuit of synchronous machine: limitation of computer-aided machine analysis. 1971.

Three other papers, which may prove of value are:

(11) Parton, K.e. Synchronous machine behaviour under steady state and transient conditions. *The Engineer,* December 25, 1964, pp. 1046 - 1049.
(12) Hamilton, F.L. and Ellis, N.S. D.e. primary transients in power systems. *The Electrical Review,* May 31, 1963.
(13) Griffin, J. Behaviour of synchronous generators under fault conditions. *Electrical Times,* October 7,1977.

A very informative treatment of the subject is contained in:

(14) Hunt, A. Alternating-current generators. In *Electrical Engineer's Reference Book,* 14th edn, (eds M.G. Say and M.A. Laughton) Butterworths, London (1985).
(15) Ames, R.L. A.e. Generators - design and application, Research Studies Press (John Wiley and Sons Ltd. 1st edition, 1990.

## Appendix 4.1

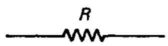
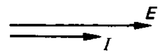
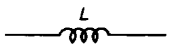
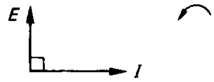
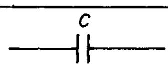
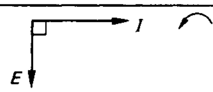
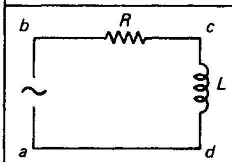
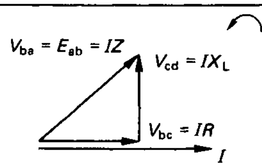
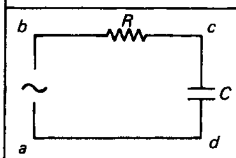
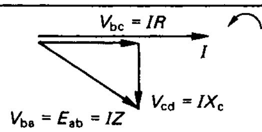
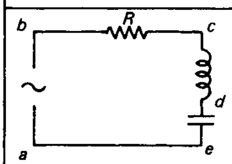
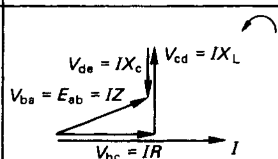
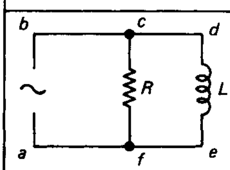
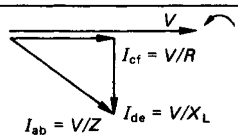
## Phasor diagrams and conventions

Phasor diagrams offer a convenient pictorial method of analysing electrical networks.[3] Sinusoidal alternating currents and voltages are represented by straight lines having definite length and direction. The lines themselves are called *phasors* and the diagrams in which their phase relationships are depicted are called *phasor diagrams.* Older textbooks tended to use the inexact description of *vector diagram* for this pictorial form of electrical circuit condition. The lines in these diagrams are more than just vectors (which, by strict definition, are meant to indicate direction only) since they can, and most often do, represent scalar quantities.

Whilst phasor diagrams may be drawn to represent the maximum values of sinusoidal quantities, they are more usually presented in r.m.s. terms. The customary conventions are listed below; and the composite chart of Figure 4.1.1 illustrates them.

1. The positive direction of phasor rotation is considered to be counter-clockwise, i.e. a phasor ahead of another, in a counter-clockwise direction, is said to *lead* it. The converse applies for the *lagging* sense. A phasor is then a directed line

3 The alternative method, using complex notations (representing instantaneous values of current and voltage) to determine sinusoidal response, is often inconvenient, if not unduly complicated.

| Circuit | Phasor diagram | Impedance | Power factor |
|---|---|---|---|
|   |   | $Z = R$ | 1 |
|   |   | $Z = j\omega L = jX_L$ | 0 (lag) |
|   |   | $Z = -j\dfrac{1}{\omega C} = -jX_C$ | 0 (lead) |
|   |   | $Z = R + jX_L$<br>$Z = \sqrt{R^2 + X_L^2}$ | $R/Z$ (lag) |
|   |   | $Z = R - jX_C$<br>$Z = \sqrt{R^2 + X_C^2}$ | $R/Z$ (lead) |
|   |   | $Z = R + jX_L - jX_C$<br>$Z = \sqrt{R^2 + (X_L - X_C)^2}$ | $R/Z$<br>Lagging if $X_L > X_C$<br>Leading if $X_C > X_L$ |
|   |   | $Z = \dfrac{1}{1/R - j.1/X_L}$<br>$Z = \dfrac{1}{\sqrt{1/R^2 + 1/X_L^2}}$ | $I_{cf}/I_{ab}$ (lag) |

**4.1.1** Phasor diagrams for series and parallel circuits

segment that rotates counter-clockwise around the origin at a constant angular velocity of ω radians per second ($\omega = 2\pi f$). ($2\pi$ radians = 360°; therefore, 1 radian = 57.30°.)

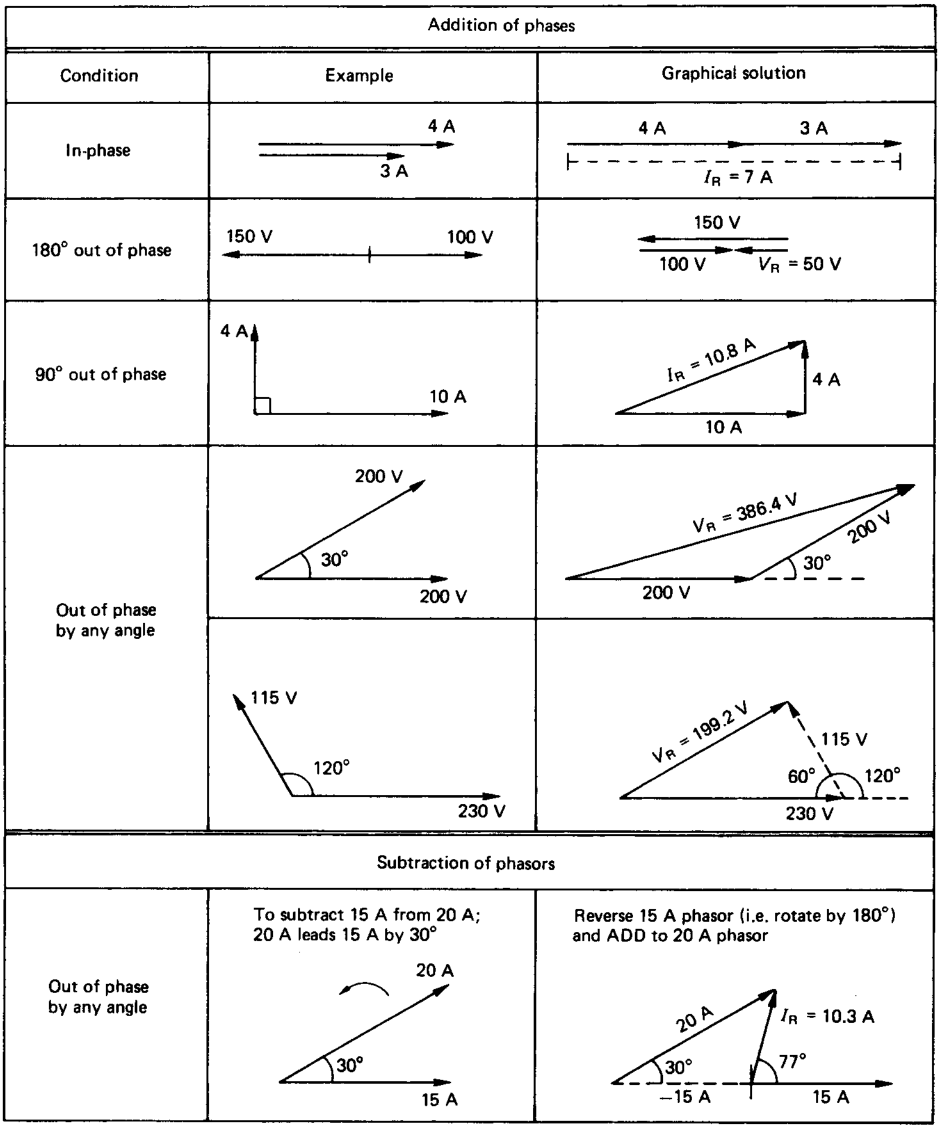
2. When series circuits are represented, the current phasor is usually shown on a horizontal line and is used as the reference for all other phasors in the diagram. This is logical, since the current is common to all components of the circuit. In the same way, where parallel circuits are involved, since a common voltage is applied to all circuit branches, the voltage phasor is the reference and is therefore drawn on a horizontal line.
3. It is not usual to employ the same scale for current and voltage phasors, in the one diagram. Where several phasors of each type appear on the same diagram, it is good practice to draw the voltage phasors to one common scale and the current phasors to another common scale.

The direction and the magnitude of phasors should be taken into account, when scalar quantities are added together, or subtracted from each other. Figure 4.1.2 illustrates the geometric constructions used.

## Appendix 4.2

## The per-unit system

In machine and power system computations it is often convenient to compare relevant quantities with equivalent values corresponding to a chosen




4.1.2 Addition and subtraction of phasors

base value. The physical quantities compared must be of the same dimension, so that the resulting ratios are dimensionless. The process is called normalization and the ratios are referred to as *per-unit values.*

The per-unit value of any electrical quantity may therefore be expressed as:

the actual value of the quantity ÷ the base value of the quantity

So that, for quantity *A:*

$$A_{pu} = A \div A_{base}$$

*A* may be voltage *U,* current *I,* power *P,* reactive power Q, apparent power S, resistance *R,* reactance *X,* or impedance Z (and reciprocals of the last three). While the base value may be arbitrarily chosen, rated or full-load values are the usual choice.

Per-unit quantities are similar to per cent quantities, except that 100 per cent is equal to 1 pu. Rated armature current is 100 per cent armature current, or 1 pu armature current.

Fundamental relationships must be observed for the conventional electrical laws to hold. For a single-phase system, therefore, the bases must be:

for $P$, $Q$, and $S$: $P_{base}$, $Q_{base}$, and $S_{base} = U_{base} \times I_{base}$ (4.1)

for $R$, $X$, and $Z$: $R_{base}$, $X_{base}$, and $Z_{base} = U_{base} \div I_{base}$ (4.2)

In practice, the values of $S_{base}$ and $U_{base}$ are chosen first and these are then followed by those for the other quantities in Eq. 4.1 and Eq. 4.2.

For example, putting per-unit reactance in the form $A_{pu} = A \div A_{base}$,

$$X_{pu} = X \div X_{base}$$

From Eq. 4.2, the base reactance is $X_{base} = U_{base} \div I_{base}$. If, as is normal practice, full-load values have been chosen for the bases, this expression for the base reactance may be rewritten as:

$$X_{base} = U_{ph\ FL}/I_{FL}$$

substituting for $X_{base}$ in $X_{pu} = X \div X_{base}$, we have:

$$X_{pu} = I_{FL}.\ X \div V_{ph\ FL}$$

In three-phase problems different bases must be chosen for phase and line quantities such that their relationships are valid for a balanced three-phase system [11].

3-phase values of $P_{base}$, $Q_{base}$, and $S_{base} = 3 \times S_{base\ ph}$ (4.3)

$U_{base\ L} = \sqrt{3}\ U_{base\ ph}$ (4.4)

$I_{base\ ph-\Delta} = (1/\sqrt{3}).\ I_{base\ ph-Y}$ (4.5)

For full-load base conditions, Eq. 4.3 may be expressed in a different form:

$$S_{base} = 3\ U_{ph\ FL}.I_{ph\ FL} = \sqrt{3}\ U_{L\ FL}.\ I_{L\ FL}$$

where the subscripts ph and L denote values per phase and per line, respectively.

The procedure with three-phase systems is to first choose the three-phase $S$ base and the line-to-line voltage. Using Equations 4.3, 4.4, and 4.5, the base values for phase voltages and currents may then be determined.

Equations 4.1 and 4.2 give the base values per phase. The base value for star-connected impedances would be obtained, from Eq. 4.2, by taking $U_{base}$ as the base voltage line-to-neutral; and $I_{base}$ as the base current, per star phase. Similarly, for delta-connected impedances, $U_{base}$ would be taken as the base line-to-line voltage and $I_{base}$ as the base current, per delta phase.

Note also, that dividing Eq. 4.4 by Eq. 4.5 gives:

$$Z_{base\ ph-\Delta} = 3 \times Z_{base\ ph-Y}$$

In making the right choice of bases for phase and line quantities, therefore, the distinction between these quantities, and the correct use of factors 3 and $\sqrt{3}$, is automatically ensured in 3-phase, balanced-load, machine calculations.

Where only one generator is involved, its own rating is used as the $S$ (volt-ampere) base. Where several generators (and possibly transformers also) are interconnected, an arbitrary choice of base $S$ is made and used for the overall supply system. The machines, in such cases, may not necessarily have equal ratings. Per-unit values will therefore have to be changed from the various volt-ampere bases to a common one which has the same voltage base. The following relationships then apply [11]:

$$(P, Q \text{ and } S)_{pu\ on\ base\ 2} = (P, Q, S)_{pu\ on\ base\ 1} \times S_{base\ 1}/S_{base\ 2}$$

$$(R, X \text{ and } Z)_{pu\ on\ base\ 2} = (R, X, Z)_{pu\ on\ base\ 1} \times S_{base\ 2}/S_{base\ 1}$$

### *Example*

A generator with a rating of 2500 kVA, and wound for 6600 V at 50 Hz, feeds a 0.9 lagging power factor load, at rated terminal voltage and rated current. Each phase has a resistance ($R_a$) of 0.05 Ω; and a leakage reactance ($X_\sigma$) of 0.75 Ω.

We are required to express, in per-unit notation:

(1) line voltage, current, and power
(2) the voltages per phase
(3) the resistance and reactance values

*Solution*

(1) $U_{base\ L} = 6600$ V  $U_L = 6600$ V
$S_{base} = 2500$ kVA  $I_L = 219$ A
$I_{base\ L} = 219$ A  Pf $= 0.9$ lagging
Power, $P = 2250$ kW

$U_{L\ pu} = U_L/U_{base\ L} = 6600/6600 = 1.0$ pu
$I_{L\ pu} = I_L/I_{base\ L} = 219/219 = 1.0$ pu
$P_{pu} = P/S_{base} = 2250/2500 = 0.9$ pu*

* the per-unit power output of a generator, operating at rated conditions, is always the power factor value.

(2) $U_{base\ ph} = 3810$ V
$U_{ph\ pu} = U_{ph}/U_{base\ ph} = 3810/3810 = 1.0$ pu
$(I_L.R_a)_{pu} = I_L.R_a/U_{base\ ph} = 0.05 \times 219/3810 = 0.003$ pu
$(I_L.X_\sigma)_{pu} = I_L.X_\sigma/U_{base\ ph} = 0.75 \times 219/3810 = 0.052$ pu

(3) $Z_{base} = U_{base\ ph}/I_{base\ ph} = 3810/219 = 17.4\ \Omega$
$R_{a\ pu} = R_a/Z_{base} = 0.05/17.4 = 0.003$ pu
$X_{\sigma\ pu} = X_\sigma/Z_{base} = 0.75/17.4 = 0.043$ pu

Since the constants of machines lie within a reasonably narrow range when related to their output ratings, the per-unit notation affords a ready means of directly comparing machines of different voltages and ratings. Another advantage is its usefulness in simulating machine systems in computer analyses of transient and dynamic conditions.

# 5 Load considerations

**Contents**

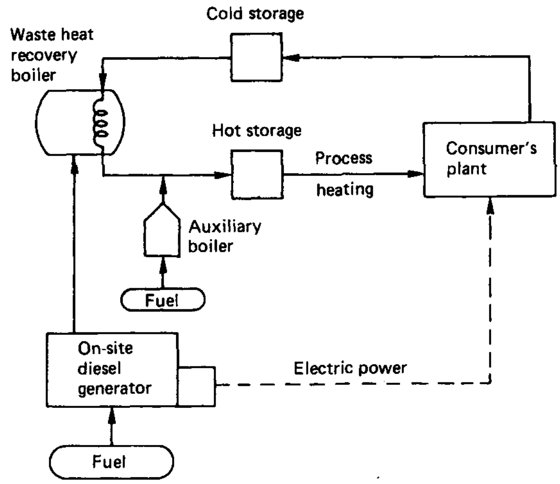
## 5.1 Introduction

Generating plants are employed in three main roles:

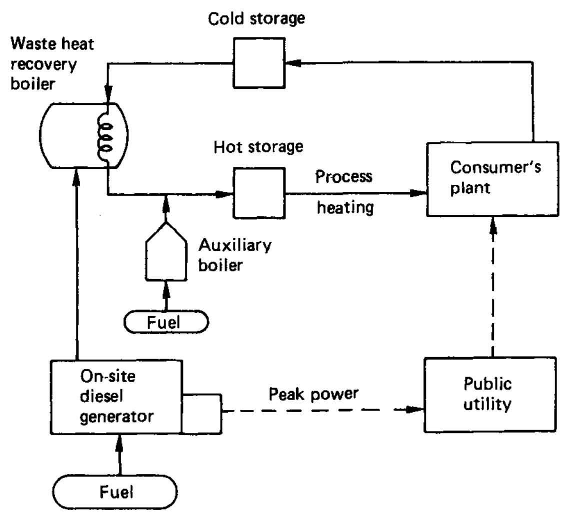
### *Primary or base-load duty*

1. Independent of utility supply:
   - to provide power in remote areas, where no public electricity supply system exists; or
   - to ensure security of supply, where a public supply system is available, but is unreliable.
2. Supplemented by utility supply: the utility supply may operate in parallel with the privately owned generators, or it may provide full or partial standby capacity.
3. In a *total energy system* (TES) mode: in which the power plant produces both electricity and heat for local needs, and is a self-sufficient energy source; or, in a *cogeneration* arrangement, producing heat (either as hot water or steam, or both) for local consumption, with any excess electrical power being exported to the regional utility. The cogeneration method, gives the best private energy-generating scheme, when the utility's *'purchase tariffs'* are attractive. The United Kingdom's 1983 Energy Act was designed to encourage such schemes. The schematic diagrams of Figure 5.1 (a) and (b) illustrate the basic differences between the two total-energy concepts.

   The description *combined heat and power* (CHP) is often applied to total-energy systems. See also Section 1.8 of Chapter 1.




(a) Total energy system mode: self-sufficient energy source




(b) Cogeneration mode: electrical excess power exported to utility

**Figure** 5.1 Schematic diagrams of total-energy and cogeneration schemes

### *Peak lopping operation*

The private plant is used in this mode to reduce the maximum-demand charges from the utility. Two arrangements are possible:

1. The peak-lopping plant does not not run in parallel with the utility supply. The consumer's power distribution network must be so arranged that a sizeable section of load can be switched to the on-site generator(s), during peak electricity consumption periods.
2. The on-site generators are operated in parallel with the utility supply. This is the more usual scheme; and offers the consumer the highest degree of reliability. Should the peak-lopping generators fail, the Utility supply provides immediate and uninterrupted standby.

### *Standby-to-utility mode*

Generating plants in this and the second category above are described in greater detail in Chapter 11.

Whatever the mode of operation, the first consideration must be to ascertain, or predict, the load requirements as accurately as possible. We shall be discussing some of the techniques used in load assessment and in determining the most suitable ways of combining and operating multiple power units. Those loads which have a direct bearing on the sizing of plant, and on the quality of the power supply, will then be reviewed. Finally, we shall examine the supply parameters demanded by high-technology, sensitive loads (e.g. computers, data processing, and communication systems).

## 5.2 **Load assessments**

Installations may be loosely categorized under three headings:

1. Domestic premises: including private dwellings or apartment-type buildings.
2. Non-residential buildings: in business and commercial centres.
3. Industrial premises: including factory plants and installations such as water-treatment and sewage works, and telecommunication centres.

Elements of all three categories will be found in small isolated communities and townships, shipboard installations, hospitals, and hotels. Loads commonly include:

- lighting;
- environmental conditioning (space heating, ventilating and cooling systems);
- water heating;
- small power appliances; and
- a variety of electric motor drives.

An increasing proportion of so-called technical loads (computers, processors, communication, and security systems, etc.) can now be found in all three categories.

### 5.2.1 Load prediction

The first consideration, in any application, must be to define the load requirements as accurately as possible. This is done by assessing tht various elements of the existing (or proposed) load in order to establish demand patterns, plant duty cycles, and realistic diversity factors.

Graphs are perhaps the best way of presenting the information. Figure 5.2 [1] shows a typical chronological curve for a process plant. It gives the variations of average load for process steam and electrical power, over a twelve month period. The areas under each load curve represent the total annual demands.

The chronological curve may be rearranged to give a load-duration characteristic, which shows the load demands in descending order of magnitude (Figure 5.3). It is of particular value to the plant designer, because it summarizes the demand from peak to minimum values and gives the durations of each intermediate demand level.

### 5.2.2 Definitions

Definitions follow of some of the factors and ratios used to describe load-demand patterns. They are illustrated in Figure 5.4 [1].

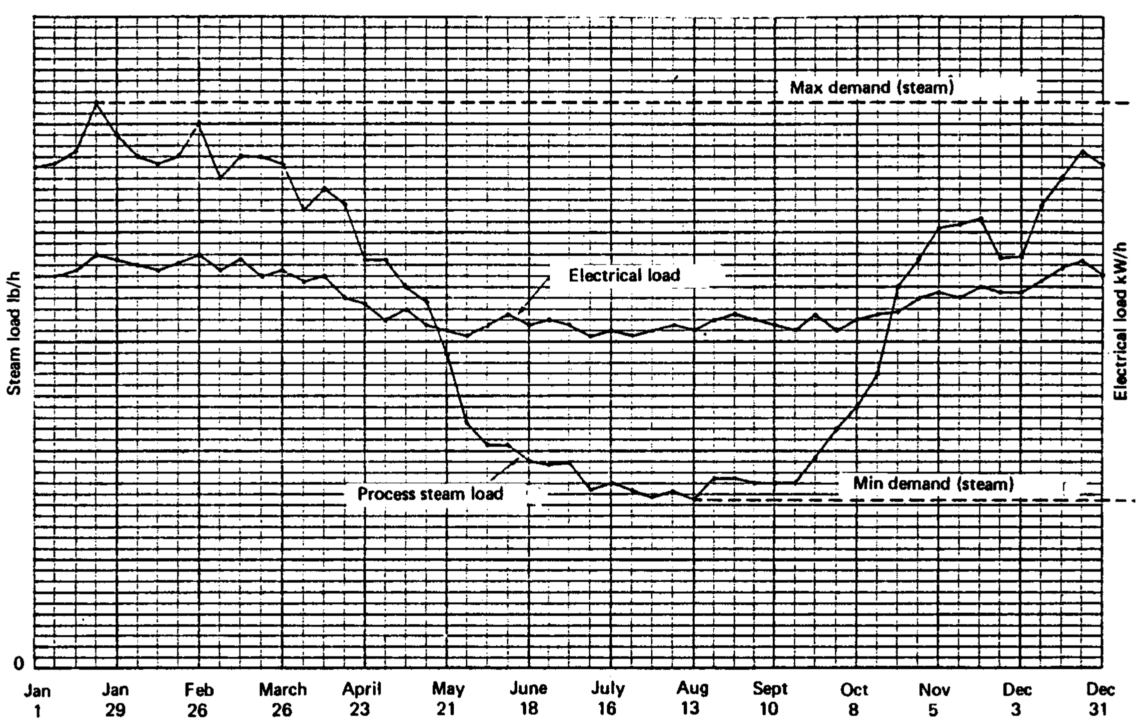



Figure 5.2 Chronological load curves for process heat and electrical power (Courtesy: NEI Allen Ltd)

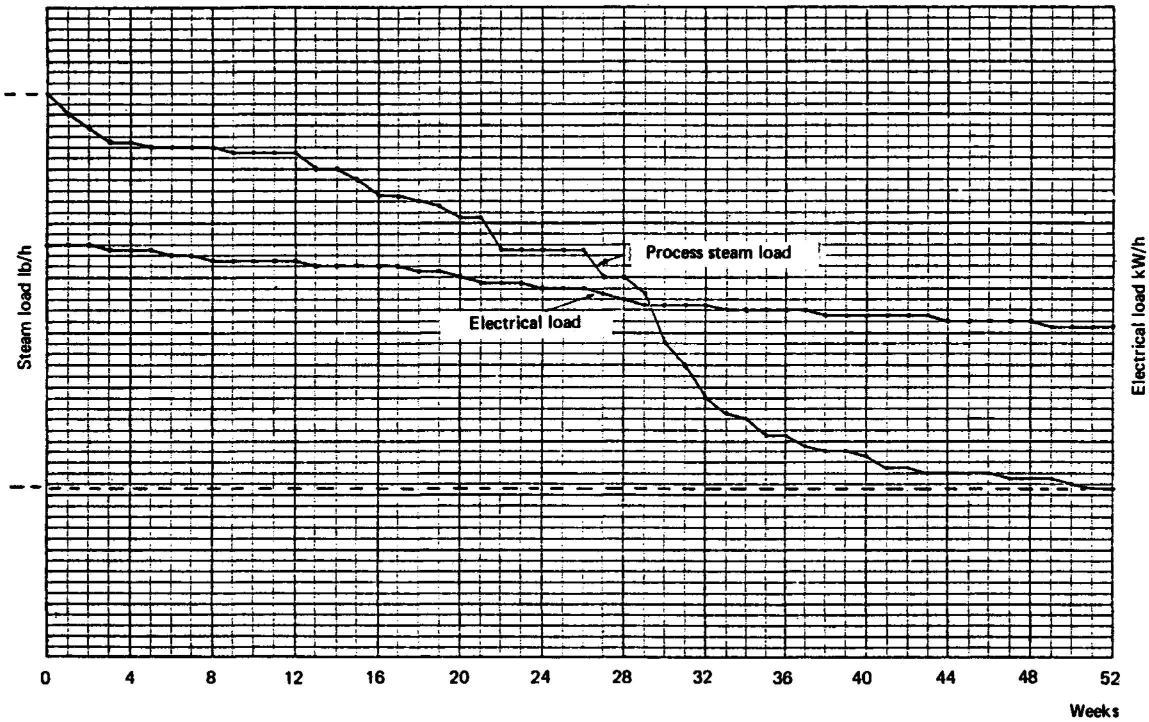



Figure 5.3 Load–duration curves derived from Figure 5.2 (Courtesy: NEI Allen Ltd)

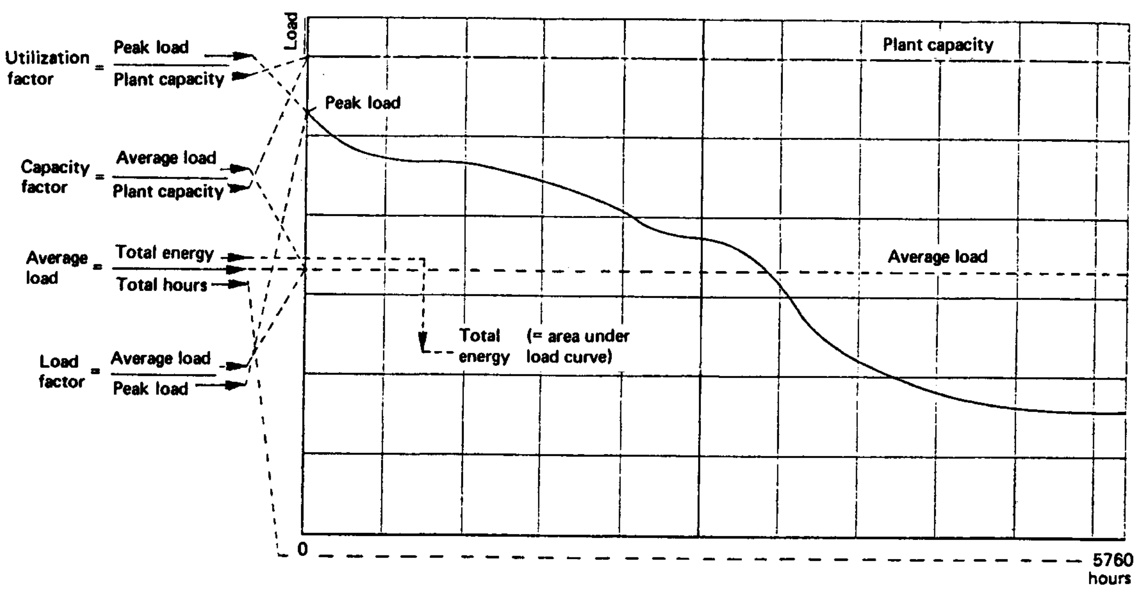



Figure 5.4 Factors and ratios applied to load-duration curves (Courtesy: NEI Allen Lld)

*Peak load* is the maximum load during the period reviewed. Electricity supply authorities customarily apply two-part tariffs to industrial consumers. One element is the *maximum demand* (or the highest demand) which a consumer places on the supply authority, within a specified period.

*Utilization factor* is the ratio of peak load to total plant capacity. It is the measure of the extent to which the plant is used to meet the peak demand.

*Average load* is the average height of the load curve, and is given by:

the total energy over a period

the total hours in the period

The total energy (or the total number of energy units consumed) is the area under the load curve. If the power plant were run at average load for the period, it would generate the same number of units as those represented by the area under the load curve.

*Capacity factor* is the ratio of the average load to the plant's total capaCity. It is a measure of the actual energy supplied, against the potential *capacity* of the plant. It is often confused with 'load factor' .

*Load factor* is a measure of the power plant's *utilization.* It is defined as the ratio of the number of energy units actually supplied in a given period, to the number of units that would have been supplied if the plant had been run at peak load for that period:

load factor = average load/peak load

It may apply to the consumer's total plant, or to a single item of equipment in the plant.

The more usual way of expressing load factor is to use the consumer's maximum demand (in kW or kVA) multiplied by the length of the period - in hours. The *annual load factor* (ALF) would then be given by:

$$\text{ALF}\ (\%) = \frac{\text{units* used in the period} \times 100}{\text{MD} \times 8760}$$

Similarly, the *monthly load factor* (MLF), for a 31 day month, would be expressed as:

$$\text{MLF}\ (\%) = \frac{\text{units* used in the period} \times 100}{\text{MD} \times 774}$$

* the units would be in kWh, if the MD is in kW

Any consumer contemplating private generation, and negotiating a special tariff with a utility, improves the chances of a favourable outcome if his annual load factor is higher than that of the utility. The ALFs of United Kingdom Area Boards are around 50 %; and are related to maximum demands occuring during the winter months [2].

The minimum ALF level for the economic viability of private generating plant is therefore considered to be of the order of 50 %, for the United Kingdom. Plants with a capacity greater than 3 MW seem to offer the best rate of return on capital invested - this in the context of electricity generation only.

A viewpoint often expressed is that, since load factor is an indicator of plant *availability,* too high a value would be undesirable because of plant overhaul requirements. Bolton [3] suggests that 'such a statement, made in respect of the annual load factor as a single entity, is meaningless; since the different components of the annual load factor are quite different in their effect upon overhaul facilities'. For example: one of its components, the daily load factor, has a cycle that is too short for overhaul purposes. He proposes that the ALF be analysed into a minimum of three components, corresponding to the three main cyclical fluctuations in human behaviour, and seasonal changes, i.e. daily, weekly, and annual.

His method treats the supply system as a whole and disregards any difference in peak time between generation and distribution equipment. It also assumes that the annual peak occurs on a single day (the *peak day)* during a week (the *peak week,* when consumption is higher than that in any other week in the year).

The three components are designated A, B, and C.

$$\text{daily load factor, A} = \frac{\text{kWh during peak day}}{\text{peak kW} \times 24}$$

and corresponds to the day-and-night cycle of human activity.

$$\text{week/day factor, B} = \frac{\text{kWh during peak weak}}{\text{kWh during peak day} \times 7}$$

which corresponds to the working-day and weekend cycle.

year/week factor,

$$\text{C} = \frac{\text{kWh during year}}{\text{kWh during peak week} \times 52}$$

and accounts for seasonal variations in daylight, temperature, trade, and holiday cycles.

All three are less than unity and their product gives the annual load factor. For example: assuming A = 0.69, B = 0.90 and C = 0.75, the annual load factor would be:

$$\begin{aligned}\text{ALF} &= \text{A x B x C} = 0.69 \text{ x } 0.90 \text{ x } 0.75\\ &= 0.466 \text{ or } 46.6\ \%\end{aligned}$$

In total-energy-system evaluation, the *heat balance* is a measure of the relationship between the

| | *For 260 days per year* | *For 105 days per year* |
|---|---|---|
| 12.00 pm to 8 am | 100 kVA at 0.8 pf lagging | 50 kVA at 0.9 pf lagging |
| 8 am to 4 pm | 500 kVA at 0.8 pf lagging | 100 kVA at 0.9 pf lagging |
| 4 pm to 12 pm | 200 kVA at 0.8 pf lagging | 50 kVA at unity pf |

waste heat and electricity requirements, on an hourly basis. It is expressed as:

$$\text{Heat balance} = \frac{\text{heat requirements (in kg steam per hour, equivalent)}}{\text{electricity requirements (in kWh)}}$$

*(Note:* the numerator and denominator of this expression must be in consistent units: kWh.)

The reader may encounter other terms such as *load form factor* and *loss factor.*

*Load form factor* is defined as the ratio of the Lm.S. value of the annual load curve, to the average value of that curve. The following example illustrates the method of calculation.

### Example

The annual load variations recorded for a small rural township are shown in the table at the top of this page.

We are required to calculate the annual load factor and the form factoL

### Solution

The load-duration curve for the township is shown in Figure 5.5.

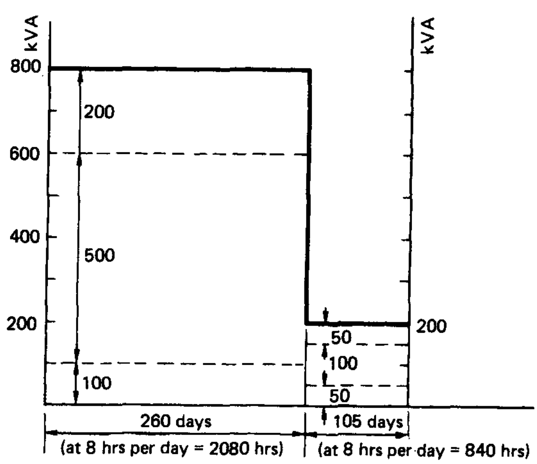



**Figure** 5.5 Load-duration curve for worked example

The average value of the load p.a. is

$$[(800 \times 2080) + (200 \times 840)] \div 8760 = 209\,\text{kVA}$$

Annual load factor,

$$k_l = \text{average load p.a./maximum demand} = 209/500 = 0.42$$

R.m.s. of annual load is given by

$$\{[(800^2 \times 2080) + (200^2 \times 840)]/8760\}^{1/2} = 394.7\,\text{kVA}$$

Form factor,

$$k_f = \frac{\text{Lm.s value of annual load-duration curve}}{\text{average value of annual load-duration curve}} = 394.7/209 = 1.89$$

These two factors are used in determining the most economical cross-sectional area for the transmission cable which is required to carry power from a generating source to the point(s) of distribution. The Lm.S. value of the current, corresponding to the maximum anticipated load demand, may be calculated by:

$$I_{r.m.s} = I_{max} \times k_f \times k_l$$

The following table [4] gives the corresponding values of $k_l$ and $k_f$ for typical UK annual load curves:

| $k_l$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| $k_f$ | 2.2 | 1.7 | 1.45 | 1.3 | 1.2 | 1.12 | 1.08 | 1.04 | 1.02 | 1.0 |

*Loss factor* is defined as the ratio:

$$\frac{\text{average losses (kWh) during a period}}{\text{maximum power losses (kWh) over the same period}}$$

It is applied to transmission systems only. It differs from the 'load factor', because copper losses vary as the square of the load current. The loss factor *(G)* is always less than the load factor, where copper losses only are considered. The overall loss factor is likely to rise above unity when iron losses in transformers and dielectric losses in cables are also included. The difference between the loss and load factors accounts for the variation in the costs of transmitting and generating electrical energy - for given loads.

The term *diversity factor* (see Section 5.2.1) is defined as the ratio:

It is very unlikely that individual consumers' MDs will coincide at anyone point in time. The maximum demand on the plant will always be less than the sum of the MDs of the individual consumers. *Diversity factor* is therefore always greater than 1.

Utilities offer tariff inducements to encourage consumers to use energy in off-peak periods (nights and week-ends). The objective is to reduce the level of maximum demand on their generating plants. Large numbers of machines and equipments operating concurrently within a factory will increase the demand placed on the supply source. The demand level may be reduced by rescheduling the use of some of the larger items, to off-peak periods. This will not reduce the energy consumed but it will even out the load, and reduce the peak demand on generating plant.

### 5.2.3 Some typical features of installations

*Non-residential buildings*

These have essentially flat energy-demand curves. Operations in commercial buildings begin and end an hour each side of the normal business day. Demand level in office buildings, shopping centres, and large retail stores varies above the base load set by lighting conditions almost directly with outside temperature conditions [5]. Loads consist primarily of lighting and environmental conditioning (space heating, air conditioning and refrigeration). Vertical transportation, cooking, and miscellaneous loads account for about 3 % of total demand.

Slattery ([5] Chapter 12) suggests that building services designers have tended to select equipment of sufficient capacity to offset the maximum heat loss, or heat gains, under the most extreme temperature conditions defined in standards prepared by authorities such as the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). These climatic conditions may, perhaps, only occur for a total of 8 months in 30 years (2.5 % of the time). The result has been that systems and equipments tend to be oversized for average conditions. Slattery cites as examples:

- the use of constant air circulation rates (as opposed to variable air volume systems) in air conditioning sytems;
- circulating water systems using constant rates, based on maximum conditions;
- the use of refrigeration compressors with capacities matching maximum load conditions despite the fact that they usually operate partially loaded - the result is lower efficiencies and lower power factors;
- the use of system controls whose primary purpose has been to increase (to unnecessarily fine degrees) the comfort level of building occupants, energy conservation being a secondary consideration.

Rising costs have forced system designers to introduce controls to improve the efficiency of energy use. Most large commercial installations now employ central energy-management systems. These are 'tuned' to optimize performance, against the prime need to minimize energy consumption.

*Industrial installations*

The nature and characteristics of loads must be established and supported by chronological data. If the installation is a new one, an overall assessment is necessary. Installed equipments should be listed, preferably for each main distribution board or substation. Their duty cycles should be known so that diversity factors may be estimated.

Diversity, particularly in larger installations, is invariably found to be greater than expected. This is also true of many continuously operating plants [6]. A useful check on estimates comes from knowledge of the electricity consumption per unit of product, or for each part of the process. The proposed method of plant operation (shiftwork, etc.) must be known so that the load factor may be assessed, and the demand deduced. Rolls [6] draws attention to the existence of published information for some industries, giving demand related to floor area. The Factory Buildings Studies Publication No. 10: *Electrical Supply and Distribution* by A. G. Aldersey-Williams (HMSO) is one useful data source.

Where loads of different power factor are being considered, the active (true) and reactive powers should be segregated, and added separately. More accurate predictions may also be obtained by applying diversity factors to both the active, and the reactive powers [6]. For example, a motor running unloaded for long periods will have little diversity with respect to reactive power but considerable diversity with respect to active power. Appendix 4 of the IEE Wiring Regulations for Electrical Installations (15th Edition, 1986) includes useful notes on the application of allowances for diversity.

It is necessary to know the mode of operation, when predicting the demand from groups of motors. Are some on standby to others? Do those on primary duty operate continuously or intermittently? These, and similar questions must be asked and answered, if an accurate demand pattern is to be established. Machine tool shops, for example, would be expected to have considerable diversity. This is because of setting-up and taking-down operations, and the infrequent use of certain machines.

It should never be assumed that driving motors will operate at their full-load (nameplate) rating. Machinery designers tend to use standard frame size motors in their equipments. They inevitably choose the next largest motor to meet their drive requirements. It would not be unreasonable to assume that every drive in an installation will be 'over-motored' in this way.

## 5.3 Planning capacity of generating plants

Generating capacity must be sufficient to meet peak power demand, even if the peak only occurs for a few hours a year. There must be some in-built margin for contingencies such as plant failures and abnormally high loads. Due allowance must also be made for routine maintenance.

Future load expansion should not be ignored. In certain applications there may well be a regular annual rise in energy requirements. An increase of 7 % per annum equates, when compounded, to an approximate doubling of load demand every 10 years ($E_{10} = E_0(1 + 0.07)^{10} = 1.96\ E_0$). This sort of growth rate would not be unreasonable for small communities in developing areas.

The timing of power plant additions must be carefully planned and expenditure on extra capacity should be deferred until the need arises. Designs must be flexible enough to allow for planned expansion with the minimum of disruption to existing plant. It is usual to provide, at the outset, a 10-20 % margin of capacity over and above that required by the annual peak demand. Where a number of small power stations feed individual communities, they may pool their generating resources (using tielines) to share power reserves between them. Tieline costs may be retrieved by levying direct (power-demand) charges, and the capital cost of any new plant added to the pool may be shared [7].

Where supplies have to be maintained after the loss of a generating unit, load shedding is inevitable unless some reserve capacity is available. This problem is not unique to the isolated power station. It applies wherever only part of a load demand can be met from available generating plant. One must, therefore, always consider the security or reliability of any proposed system.

Security of supply is defined by the ratio:

$$\frac{\text{(the total hours the supply is required)} - \text{(the hours of } \textit{unplanned} \text{ outage of the supply)}}{\text{to the total hours for which the supply is required}}$$

and is normally expressed on an annual basis. Public Utility supplies usually have excellent reliability. In the United Kingdom, for example, the National Grid has a reliability of better than 98 %. This means that consumers experience annual outages of less than 2 hours. If a private generating plant is to have reliability approaching this level, it must have a greater number of generators than that apparently required to meet the anticipated maximum demand. It would be quite unrealistic to expect full security of supply from a base-load system (or a peak-lopping system) which has only one generating unit.

All plant needs regular overhauling and maintenance. When this is being undertaken the remainder of the installation is at risk. More so where the annual load pattern is 'flat' and shows no marked seasonality in demand. A well-designed multiple generator plant is unlikely to experience total failure - since the units should fail individually. Outage durations will depend upon the nature of failures, the availability of spares, and the skill of repair staff. Evidence, from such sources as the *Annual Working Cost and Operational Reports* of the Institution of Diesel and Gas Turbine Engineers, indicates that it would be rash to expect any type of generating plant to have an availability greater than 98 %.

### 5.3.1 Multi-generator power plants

West [8] suggests that, in a multi-set installation of similar units, 'reliability may be calculated according to the laws of chance, bearing in mind that while one set is being maintained, the likelihood of outage for the remaining installation increases'. This likelihood may be expressed as the number of hours of anticipated outage in a year. Table 5.1 permits determination (for any assumption regarding maintenance hours) of the number of hours in a year when the number of sets available is at least one less than the number required to meet the maximum demand. The hours of risk will reduce if the load pattern contains periods when load is at a sustained lower level.

*Example*

The following example [8] shows how Table 5.1 may be used to determine the annual *hours of risk* for a 6-unit installation (where 4 are required to meet the maximum load demand). It is assumed that each unit requires 1000 hours of maintenance per year, therefore 5 sets only are available for 6000 hours each year, and all 6 sets are available for 2760 hours each year.

From Table 5.1:

for $N = 5$ and $r = 4$: the hours of risk, per year, are 33

for $N = 6$ and $r = 4$: the hours of risk, per year, are 2

Table 5.1 Non-availability of plant due to breakdown (Average number of hours each year when the number of sets available is less than the number required to meet the maximum demand)

| *No. of sets required (r)* | *No. of sets installed (N)* (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4 | * | * | * | * | * | * | * |
| 2 | 346 | 11 | * | * | * | * | * | * |
| 3 | | 515 | 20 | * | * | * | * | * |
| 4 | | | 680 | 33 | 2 | * | * | * |
| 5 | | | | 844 | 50 | 3 | * | * |
| 6 | | | | | 1000 | 69 | 4 | * |
| 7 | | | | | | 1155 | 90 | 5 |
| 8 | | | | | | | 1310 | 115 |
| 9 | | | | | | | | 1460 |

* = less than 1 hour

Therefore, total hours of risk is

$$(6000/8760) \times 33 + (2760/8760) \times 2$$
$$= 23 \text{ hours per year}$$

Using Table 5.1 and this method of calculation one can assess the effect of various maintenance outages.

Table 5.2 shows the average hours of risk for an installation in which 4 generators are required to meet the maximum demand. It considers the effect of maintenance periods varying from 100 to 1000 hours per annum and shows that, for all reasonable assumptions of maintenance outage, the minimum number of sets required for adequate reliability is 6.

Table 5.2 The effect of varying annual maintenance periods

| *Number of hours per year required for maintenance of each set installed* | *Average hours of risk p.a. for number of sets installed* 4 | 5 | 6 | 7 |
|---|---|---|---|---|
| 100 | 1049 | 70 | 4 | |
| 200 | 1418 | 107 | 6 | – |
| 500 | 2525 | 218 | 13 | 1 |
| 1000 | 4369 | 402 | 23 | 2 |

Diesel power stations playa very important role in the development of electricity supplies in rural areas. Indeed, they are often used to build up local demand in villages and small townships. They may start with just a single generator. Expansion to meet agricultural and industrial load growth is possible with very modest capital outlay. Load growth may eventually justify the construction of an interconnecting transmission grid - between regional generating centres and expanding load centres. If larger thermal or hydro power stations come to be installed at a much later stage, the diesel stations may be used for peak power or standby duty.

Figure 5.6 shows a typical layout for a small rudimentary power station consisting of self-contained, canopied diesel-generator sets (2) housed in a simple shed with a metal roof and fenced sides (5). Two of the three sets are on base-load duty and the third is on standby. The capacity of the fuel oil storage tanks (1) is governed not only by the specific fuel consumption of the sets but also by economic factors relating to fuel deliveries and bulk. purchase incentives. Item (3) is a low voltage distribution board, and the pole-mounted step-up transformers (4) are for two outgoing high-voltage lines (typically 11 kV).

Perry [9] gives an interesting description of the large-scale use of diesel generating plant in isolated areas. The total capacity of the diesel generator plant operated by the State Energy Commission in Western Australia had reached 170MW, by 1985. In certain areas, the annual load growth since 1976 had been between 10% and 33%.

Among the many points taken into consideration, when selecting sites for power stations, were:

- the ability to distribute power from a station through at least four outgoing feeders;
- the ability to initiate fuel-saving measures by utilizing engine waste to generate process steam or to be used in lithium-bromide chillers for air conditioning; and
- a site's potential for development over a period of not less than 25 years.

Stations are planned to form an integral part of the business and commercial centres of the future development towns of the north-west territories, the intention being to encourage total energy. schemes from the outset. Design philosophy has been to

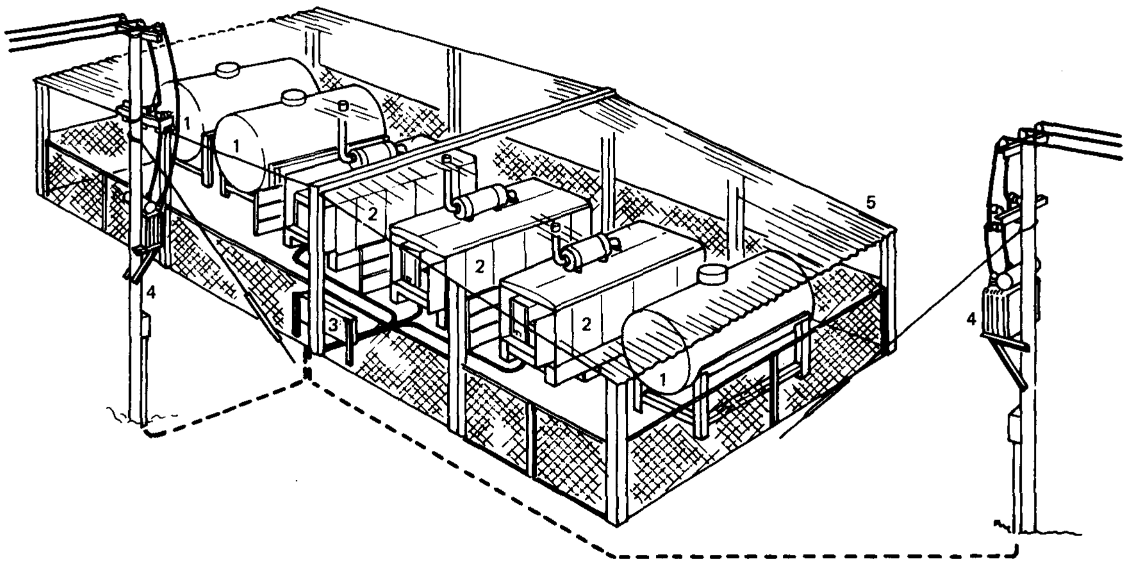



**Figure** 5.6 Example of the layout of a small diesel power station (Courtesy: ABB - Asea Brown Boveri Ltd)

'modularize equipment as much as possible to minimize *on-site* installation costs and to allow units, where required, to be removed and reinstalled in another location with a minimum loss of installation equipment and material'.

An eventual total of nine generating sets is envisaged for each station. Unit sizes are initially based on the need to supply off-peak load with no fewer than two sets. The nine units eventually installed will comprise:

- four of the original selected size; followed by
- five, whose individual capacity is approximately twice that of the original size.

For example: 4 x 1MW and 5 x 2MW.

A *'safe generating capacity'* (SGC) caters for system demand.

The SGC = (the installed capacity of the station) - (the capacity of the largest machine) - (a further margin of 15% of the remaining installed generating plant).

The latter margin allows for site derating due to high ambient temperatures and low atmospheric pressures. A typical 14MW station would have an SGC of:

(14) - (2) - (12 x 0.15) = 1O.2MW

Table 5.3 describes the Energy Commission's operating policy for the stations. The objectives are to ensure that:

1. a minimum of two units are in service at all times - to guarantee integrity of supply;
2. when more than two units are in service, the load that each carries is restricted to 85 % of its capacity at normal ambient conditions;
3. when three units of equal size are loaded to more than 85 % of their nameplate rating, a fourth machine, of twice the rating of the running machines, is introduced. The load carried by the incoming machine should not then exceed 40 % of the total system load.

The *spinning reserve* in Table 5.3 is defined as the capacity of the station to pick up the immediate loss of the largest unit in service. It is calculated as:

$$\frac{\text{the spinning reserve capability of all but the largest unit in service}}{\text{the load on the largest unit in service}}$$

The spinning reserve has a twofold purpose:

1. to cover such incidents as significant generating loss; and
2. to ensure that any subsequent fall in system frequency is sufficiently slow as to allow the automatic load-shedding controls time to operate, and thus minimize disturbance to the station and to the loads it serves.

### 5.3.2 Programming expansion of power plants

We have mentioned the prudence of planning for future expansion when designing a power station. Expansion may take the form of:

- a larger generator to replace the original, in a single-set standby installation; or

**Table** 5.3 Operating policy for diesel stations in Western Australia

| *Machines in service* x *rating* (MW) | *System load* (kW) | *Spinning reserve* (%) | (kW) | *% load on units* (1MW) | (2MW) | *System load on largest set* (%) |
|---|---|---|---|---|---|---|
| 2 x 1 | 1700 | 29 | 250 | 85 | – | |
| 3 x 1 | 1800 | 157 | 1000 | 60 | | |
| 3 x 1 | 2550 | 59 | 500 | 85 | | – |
| 4 x 1 | 2600 | 208 | 1350 | 65 | | |
| 2 x 1<br>1 x 2 | 2800 | 46 | 520 | 84 | 56 | 40 |
| 4 x 1 | 3400 | 88 | 750 | 85 | | |
| 3 x 1<br>1 x 2 | 4000 | 56 | 900 | 80 | 80 | 40 |
| 3 x 1<br>1 x 2 | 4200 | 46 | 780 | 84 | 84 | 40 |
| 4 x 1<br>1 x 2 | 5100 | 59 | 1000 | 85 | 85 | 33 |
| 4 x 1<br>2 x 2 | 6800 | 88 | 1500 | 85 | 85 | 25 |
| 4 x 1<br>3 x 2 | 8500 | 118 | 2000 | 85 | 85 | 20 |
| 4 x 1<br>4 x 2 | 10200 | 147 | 2500 | 85 | 85 | 17 |
| 4 x 1<br>5 x 2 | 11900 | 177 | 3000 | 85 | 85 | 14 |

- additional units, to cater for anticipated load demand increases, in multiple generator stations. (The timing of these additions is important, as one would not wish to commit capital resources too early in any programme.)

We have seen that most loads have repetitive chronological patterns. These patterns must be carefully analysed, in order to predict future trends. The collection of historic load data must, therefore, always be the starting point.

Many techniques are used in load prediction. (The IEE publication [10] Chapter 4 will give the reader a good introduction to the subject.) Dale [7] describes a dynamic-programming technique for the economic selection and timing of generator-plant additions. He uses a *minimum-percentage-reserve* concept to determine the date at which generating plant should be added to a power system. Although he deals with large systems, the principles apply to any scale of operation. The diagrams that follow have been adapted to show load and capacity ordinates of reduced scale.

Figure 5.7 shows the peak-load trend forecast for a utility system (curve I). It is obtained by extrapolating the curve through the actual annual peaks for the preceding few years. The system is assumed to have had 8 generator units, initially (at year 0):

- two of 2.5 MW capacity;
- two of 2.0 MW capacity; and
- four of 1.25 MW capacity.

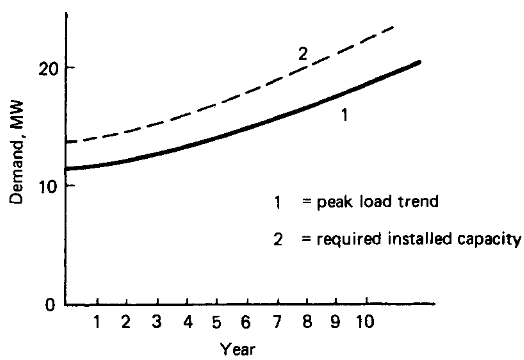



**Figure** 5.7 Predicted load growth, and related future installed-capacity requirements [7]

The annual installed-capacity curve (shown dotted in Figure 5.7) is derived by adding the required percentage reserve (20 %), to the peak-load trend line.

Figure 5.8 shows two alternative ways of adding generating capacity. In each case, the installed capacity is never less than the required level established in Figure 5.7. Plan 1 proposes large units installed at three-yearly intervals, whereas Plan 2 advocates a smaller-sized unit being added each year. Relative capital and running costs will determine which is the more economically attractive proposition.

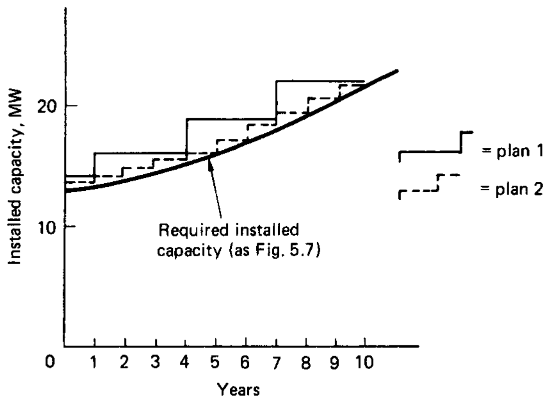



**Figure** 5.8 Alternative generator-expansion plans [71

If choice of unit size was confined to these two options (very unlikely, in practice), the number of ways in which they could be combined assumes very large proportions - as shown in Figure 5.9. L represents a large-unit addition sufficient for two years; and S a small-unit addition sufficient for one year.

Very probably, one of the many paths shown in Figure 5.9 will be more economical than either Plan 1 or Plan 2. Dale goes on to explain that 'previous methods of trying to find the optimum generation-expansion plan have been based, almost without exception, on procedures or computer programs that evaluate the total cost of following one particular path, or plan, over a long-range study. By running through this program for each of, say, 10 or 20 different plans, the so-called optimum plan can be found. Using the procedure he describes, the best

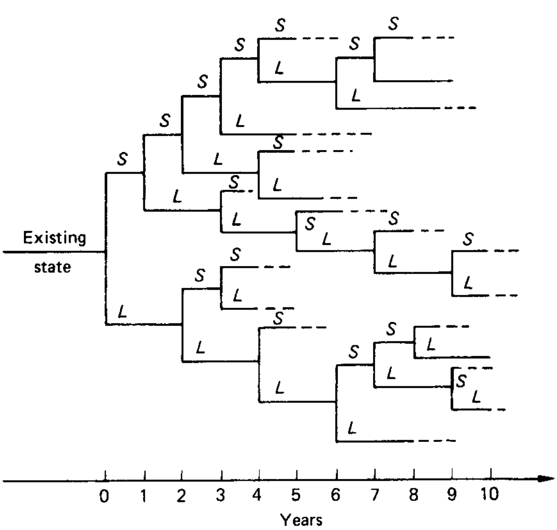



**Figure 5.9** Some possible ways of increasing installed capacity, with two available unit sizes [7]

of many thousand possible paths may be determined, by just one run through the program.

## 5.4 Load elements affecting plant size and performance

The type and rating of any generating plant must depend upon the nature and size of the load it is required to serve. When considering the characteristics of a particular load, it is necessary to identify:

1. those elements which demand close-tolerance power parameters (e.g. *technical loads* such as computer and telecommunication systems); and
2. those elements likely to impinge upon these demands by adversely affecting generator steady-state and/or transient performance. These might include:
   - step-change loads (induction motor starting);
   - non-linear loads (rectifiers and switched-mode power supplies - SMPS);
   - cyclically varying loads; and
   - regenerative loads.

We shall now examine the characteristics and effects of some of these load elements.

### 5.4.1 Motor loads

Perhaps the most common problem associated with the correct sizing of synchronous generators is that related to the starting of induction motors.
Industrial installations inevitably contain numbers of induction motors. These are often of sufficiently large size as to dictate the capacity of the generating plant required to meet the 'impact' loads imposed during their starting. Nowhere is the problem more acute than in marine electrical systems, where loads are essentially concentrated, and contain a high proportion of induction motors; and where generators are operated near to full capacity. Also, the operational and economic advantages offered by 3-phase systems are exploited to the full, by the almost universal use of the more robust direct-on-line started squirrel-cage motor. Applications include: pump, fan, and separator drives; deck auxiliaries such as cargo winches and windlasses; and oil transfer pumps on tankers.

The problem is that of limiting voltage variations to a minimum while coping with the transient currents and torques imposed by the ship's system. Careful consideration must be given to the resulting reactive and active power demands, and to equating these with the required generator reactance and prime mover output, respectively. Marine classification societies also require that, with one generator out of action, the remaining plant shall have sufficient reserve capacity to permit starting of the largest motor in the ship. This must be achieved without causing any motor to stall or any devices, such as contactors, to fail due to excessive voltage drop in the system.

## *Motor characteristics*

The equivalent circuit of a single-squirrel-cage induction motor is shown, in its simplest form, in Figure 5.10. Here, *Rl* and *XL* are the combined rotor and stator resistance and leakage reactance values, respectively, expressed in stator terms. $X_M$ is the magnetizing reactance across the supply voltage *V*. The 'added' resistance, given by the term *Rz* ((1 - 5)/5), is zero when 5 = 1, and infinity when 5 = 0. The internal mechanical power per stator phase is equal to the power absorbed by this resistance [11].

An induction motor must run at a speed less than synchronous speed in order to produce a driving torque. 5 is a ratio known as the *fractional slip* or, more usually, as the *slip.* It determines the amount by which the rotor 'slips backwards' relative to the rotating stator field to give the induced rotor e.m.f., and hence the current, required to produce driving torque.

$$\text{Slip, } S = \frac{(\text{synchronous speed} - \text{rotor speed})}{\text{synchronous speed}}$$

At rotor standstill, 5 = 1; and at synchronous speed, 5 = 0. At no-load when the motor is running freely the slip is very small and usually of the order of 0.5 % (0.005). When the rotor shaft is connected to a mechanical load the torque required to drive the load necessitates an increase in rotor current above the no-load condition. This can only be achieved by an increased rate of cutting of the rotating (stator) field by the rotor conductors - to give a greater induced e.m.f. and, hence, more rotor current. There is, therefore, a speed corresponding to each value of load torque at which the rotor current is just sufficient to produce the required torque. Rotor speed falls (the slip increases) as load torque increases. One expects the slip to be between 0.03 and 0.05 at normal load. The magnetizing current through the parallel branch $X_M$ may be of the order 25 % to 50 % of the full-load current.

Where a motor obtains its supply from a constant voltage source, such as a very 'rigid' public utility, the relationship between electrical input and torque output is as shown in the performance curves of Figure 5.11. These curves have the following features:

The *current,* and therefore the kVA demand (since a constant voltage supply has been assumed), has a maximum value at standstill. It falls almost linearly, and gradually, until the motor reaches about half speed. Thereafter, it drops more rapidly as synchronous speed is approached.

The value of the 'added' resistance, *R'z* [1 - *5)/S]* in the equivalent circuit of Figure 5.10, is zero **at** motor standstill. The secondary circuit is closed and the machine is equivalent to a transformer whose secondary winding is short-circuited. A very large current is therefore demanded from the power source during starting. Whilst this is, effectively, a short-circuit current (hence the term *locked-rotor* current), it is not as high as it would be in a short-circuited transformer. This is because the leakage reactance of the motor is so much greater than that of an equivalent transformer. Nevertheless, starting currents of the order of 5 to 6 times full-load value are not unusual for most 3-phase induction motors. Actual ratios of starting-to-rated current will vary with motor size and design, and may be as low as 4, and as high as 10. The magnitude of the starting current is independent of applied load torque and is the same value whether the motor is started with or without load. As rotor speed

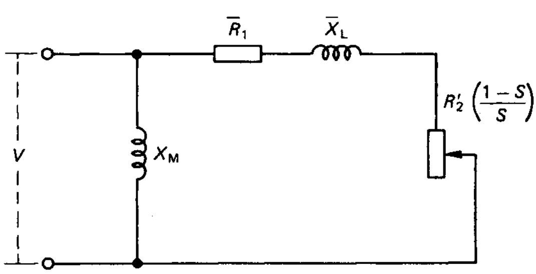



**Figure 5.10** Simplified equivalent circuit for a squirrel-cage induction motor

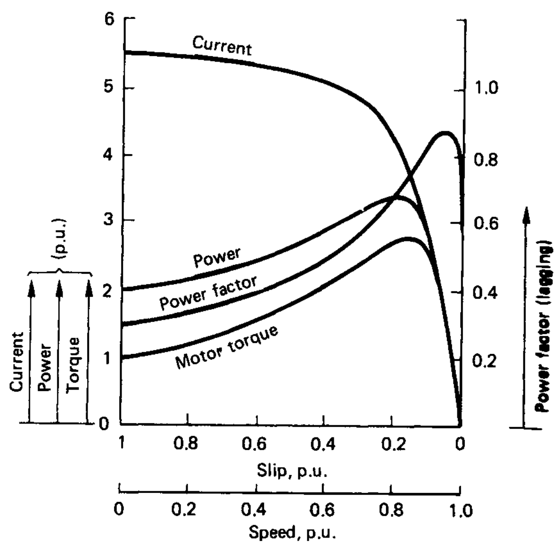



**Figure 5.11** Typical single-squirrel-cage induction machine performance characteristics

increases, the secondary induced e.mJ. decreases. This results in less current demand until, at synchronous speed, there is no e.m.f. and no current drawn.

The starting *power factor* is very low (of the order of 0.3 to 0.4) and increases during the run-up period, to reach its peak just before nominal operating speed. Thereafter, it drops very rapidly to zero at synchronous speed. Full-load power factor is of the order of 0.8 to 0.9 and, of course, is always lagging. When the load on a motor is reduced its power factor falls.

The active *power* requirement during run-up is the product of kVA (which follows the current curve) and the power factor. The rising power factor during the run-up means that the peak power occurs at approximately to 80% speed and is of the order of 3 to 3.5 times the nameplate rating of the motor. When the motor is supplied from a generator, this instantaneous peak power has to be provided by the generator's prime mover.

The motor *torque* characteristic is generally of the same shape as the power curve but its peak value, known as the *pull-out torque* or *stalling torque,* is slightly displaced from it. At higher values of slip (5 approaching 1), the torque is seen to decrease. This is because the rotor power factor decreases at a greater rate than that at which the rotor current increases.

## *The dynamics of starting*

The relatively large currents during the starting cycle place heavy mechanical and thermal stresses on windings - conditions which are tolerable for limited periods only. It is important, therefore, that the motor is driven up to its normal operating speed as quickly as possible, consistent with the requirements of its driven machinery. Run-up time is significantly influenced by the inertia and the dynamic characteristics of the driven load. The torque/speed characteristic of the driving motor must be matched to the requirements of the driven load. Among the features of particular interest to the machinery designer are the starting, and maximum, torque capability of the motor. During the run-up period the difference in torque between that produced by the motor and that required to turn the load is available to accelerate the combined rotating masses of motor and load (see Figure 5.12). This *accelerating torque* may be expressed as a function of the speed:

$$T_{acc} = T_{mot} - T_{load}$$
$$= J.\ d\omega_0/dt$$

where $J$ is the combined moment of inertia of the motor and the load coupled to it and Wo is the motor speed, in mechanical radians per second. Also

$$T_{acc} = J[(2\pi/60) \times (dN/dt)]$$

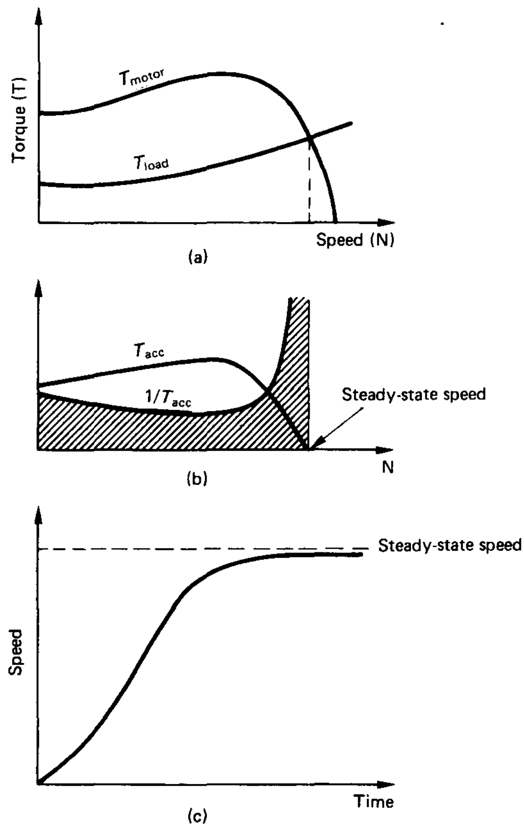



**Figure** 5.12 A graphical procedure for determining run-up speed as a function of time

where $N$ is the speed, in revolutions per minute (rpm).

The time required to attain any speed, $\omega_0$, is therefore given by:

$$t = J f [(1/T_{acc})d\omega_0]$$

Simple graphical solutions of this equation are contained in [11] and [12]. Figure 5.12 illustrates the steps employed in determining the run-up time to steady-state speed.

Figure 5.12(a) shows the torque available for acceleration of both motor and load. The next step in the procedure is to plot the accelerating torque ($T_{acc}$) and its reciprocal ($1/T_{acc}$) against the speed – see Figure 5.12(b). Integrating the reciprocal function (by finding the areas between the curve and the speed axis for all intermediate points from zero up to steady-state speed, and multiplying the results by $J(2\pi/60)$) yields the function $t$ $N$ (Figure 5.12(c)).

Note that the curve for the reciprocal of accelerating torque ($1/T_{acc}$) tends towards infinity, as speed approaches the steady state, i.e. steady-state is always reached asymptotically.

Run-up times are largely governed by the combined inertia of motor and load, and by the operating speed. They need to be determined for each specific application - using, perhaps, the graphical integration procedure described above. Start times on loaded machines rarely exceed 5 seconds and are likely to be within the range of 0.5 to 2.5 s, for motors up to 100 kW.

On certain machinery, it is possible to employ control devices, such as unloading or bypass valves, to reduce the starting torque required. For example, it is usual, on marine tankers, to start cargo oil pumps with their valves closed; the valves are only opened when the pumps have run up to full speed.

It is possible to have transient starting torques which may persist for several periods of the power supply frequency. They are affected by:

- the instant at which the first phase closes, and the delay, if any, in closure of the other two phases; and by
- the residual flux from a previous duty cycle [13].

Pulsations may be superimposed on the steady-state torque/speed characteristic during fast-run-up conditions. The torque reversals that may be produced form 'loops' of the type shown in Figure 5.13. These reduce the accelerating torque available from the motor and prolong the machinery run-up time. Their effects may not be too disturbing on slow-start applications involving high-inertia machinery as they may die away before the machine has gathered speed.

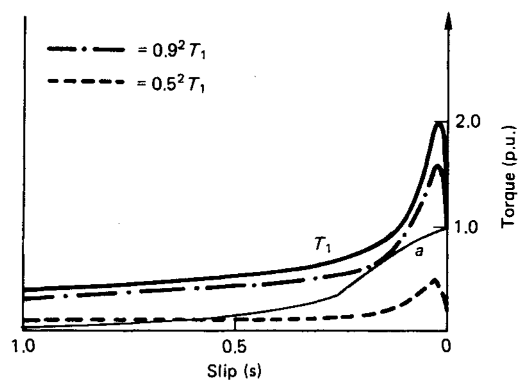
## *Voltage reduction effects*

Referring to the equivalent circuit of Figure 5.10, it can be shown that:

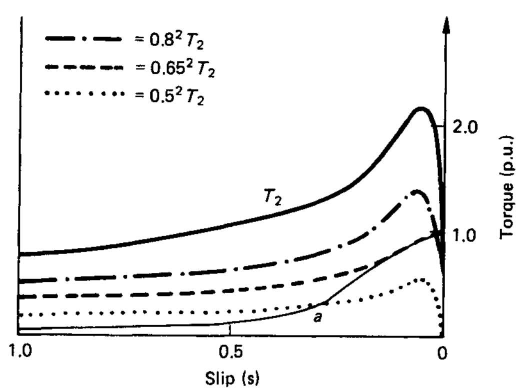
1. at a given slip, and neglecting magnetizing current, motor current varies directly as voltage; and
2. input power and motor torque both vary as the square of the voltage.

A fall in voltage to 50 % of nominal would thus mean that the available torque is reduced to 25 % of nominal. Figure 5.14 [14] shows a typical torque/speed curve for a pump (curve a), superimposed on the torque/speed curves of alternative designs of induction motor, at various values of reduced voltage. If the pump were coupled to the first motor (Figure 5.14(a», it would not accelerate to full speed unless the supply voltage is restored to a level above 90 % of nominal. Similarly, the lowest permissible voltage level for a successful start with the second motor (Figure 5.14(b», would be approximately 70 % of nominal.

Input power to a motor varies as the square of the voltage. If the supply for this second motor was obtained from a generator of comparable rating, and the voltage depression on starting was 30 %, the active power required at the instant of start is 49 % of that which would have been required had system



(a) Motor with torque characteristic $T_1$ and load curve *a*



(b) Motor with torque characteristic $T_2$ and load curve *a*

**Figure 5.14** Torque/speed curves for alternative designs of induction motor, at full and reduced voltage

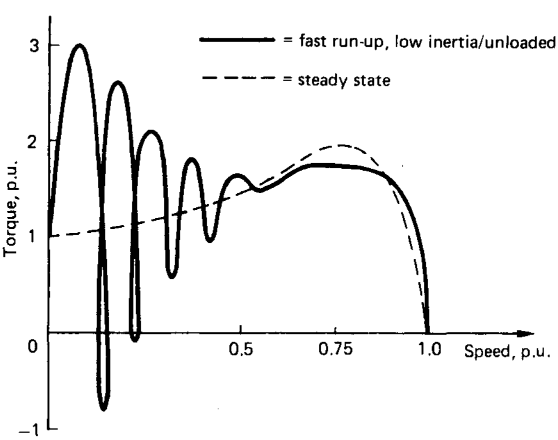


**Figure 5.13** Starting-torque transients

voltage been 100 %. Using the efficiency of the generator, the *momentary* active power required from the prime mover may then be determined. As a corollary to this, the less the allowable voltage depression on starting, the more the momentary power that is required from the prime mover.

An induction motor may behave in one of several ways during a voltage depression, and behaviour is directly related to the driven-load requirements [14]:

1. it may stall completely and fail to restart because the voltage cannot recover as a result of the current drawn by the motor, and by others connected to the same point in the system;
2. it may stall momentarily before recovering to a reduced speed level as the voltage is restored to a value lower than normal;
3. it may stall or lose speed and then run up to normal speed.

If the selected motor is designed to respond as in 3, to anticipated voltage depressions, it is more than likely to behave as in 1 or 2 under abnormal conditions.

For any given motor and load characteristics, there is a minimum voltage at which the motor can run up to speed from a particular slip. Figure 5.15 shows this voltage for a motor operating against two load characteristics [15]. Motor reswitching characteristics are discussed later in this section.

We have already established (in Sub-section 4.3.2 of Chapter 4) that generating sets represent a high-impedance power supply source and that, when relatively large wattless loads are switched on to them, instantaneous voltage dips will occur. A typical voltage response characteristic was shown in Figure 4.38 and its features discussed in the accompanying text. Figure 5.16 [16 and 17] shows the current and speed characteristics for a typical motor switched to a constant voltage, zero impedance supply source such as the 'infinite busbar' of a public utility (solid line curves). The dotted curves show the effect of switching the same motor to a higher-impedance generator, whose voltage recovery response is similar to that of Figure 4.38. The run-up period is approximately extended by the response time of the generator's excitation control system. The faster this response is, the less significant are the effects of the voltage dip on the motor's starting performance.

Transient voltage disturbances can be a source of particular trouble in two areas: lighting and contactor switchgear. The light output of lamps depend, very much, upon the supply voltage. Filament lamps are inherently more sensitive than fluorescent lamps to fluctuations of voltage at frequencies causing flicker. It is therefore common practice to install fluorescent lamps in ship's accommodation spaces because they will accept two to three times as much voltage fluctuation as filament lamps, for the same visible flicker.

High-pressure mercury vapour and high-pressure sodium lamps are installed on deck and in areas where a higher level of flicker may be tolerated. Both types are more sensitive to rapid voltage fluctuations than filament lamps. One solution is to employ a combination of fluorescent and vapour lamps. Ordinary sodium lamps are insensitive to flicker but their use will be more often limited by their colour characteristics [18].

BS 5424: Part 1 (IEC 158 - 1) requires contactors to close satisfactorily at 85 %, and drop-out between 75 % and 10 % of rated voltage. Some thought must therefore be given to the supplies for contactor coils in systems where voltage dips greater than 25 % are possible. Unless suitable measures are taken, there is a risk that contacts will chatter, arc and, finally,

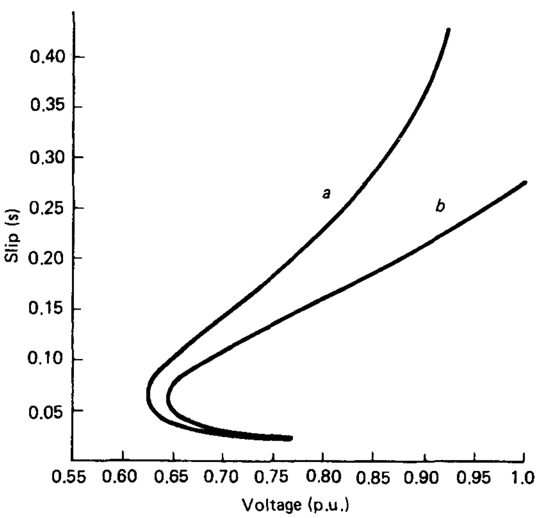



**Figure** 5.15 Minimum voltage required for re-acceleration of a motor against (a) linear load and (b) constant load torque characteristics

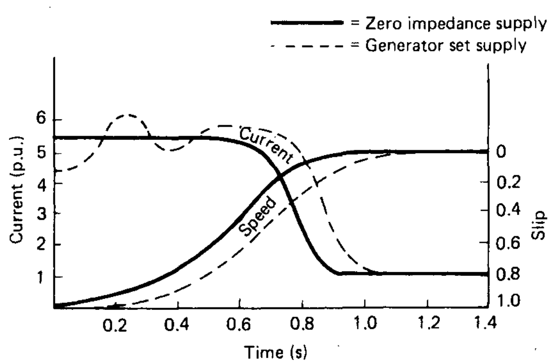



**Figure** 5.16 Effect of voltage depression on motor run-up characteristics weld-on. One possible solution is to isolate the coils of contactors in essential circuits through small constant voltage transformers. Contactor coils operated from a d.c source are another possibility. More severe difficulties are likely to be experienced when large voltage dips coincide with contactor closing operations. The closing force may be reduced to such an extent that it is unable to overcome contact spring pressures.

### *Estimating the voltage dip*

The magnitude of the voltage dip at a generator's terminals, following load switching, is a direct function of the subtransient and transient reactances of the machine.

$$\text{dip}, \Delta V \equiv X'_{du}/(X'_{du} + c)$$

where $X'_{du}$ is the per-unit unsaturated transient reactance and $c$ is the ratio:

$$\frac{\text{generator rating (kVA or current)}}{\text{impact load (kVA or current)}}$$

The expression only gives an approximation because most modern excitation control systems are sufficiently fast-acting to lop-off the bottom of the transient voltage 'trough' (point B in Figure 4.38) [19].

Generator manufacturers supply performance data (usually in the form of curves supported by application notes) enabling determination of voltage dips for given impact loads. Examples of such data are given in Figures 5.17 and 5.18.

Figure 5.17 shows typical 3-phase voltage dip characteristics, based on results using ultraviolet recorder measurements. The performance curves are for a specific frame size. The terms 'minimum' and 'maximum' voltage refer to the bottom and top ends of the standard range of voltages available from the particular winding applied to the machine. Typically, these may be 346 volts and 480 volts, respectively. The 'maximum rated kVA of the frame' is its standard (industrial) continuous maximum rating. In all instances, the impact current must never exceed the machine's declared overload capability. The overload ratings may vary between those equivalent to 1.5 pu and 4.5 pu full-load impedance at zero power factor for periods of up to 15 seconds.

BS 2949 (the specification for rotating electrical machines for use in ships) requires generators to accept 50 % excess current for 15 s, at the approximate rated voltage. Marine Classification Societies' rules generally call for a 50 % overload, at 0.6 to 0.8 pf, for periods up to 2 minutes. This is one of the reasons why industrial machines are derated for marine use. Because of this derating the per-unit overload capability of marine generators may appear to be better than their industrial equivalents. The actual overload performance (in terms of current or kVA) is the same in both cases.

Figure 5.18 illustrates yet another approach to the presentation of impact performance data. The curves relate to the full range of 4-pole low voltage machines available from the manufacturer. $\Delta S$ (in kVA) is the impact load, assuming connection to an infinite busbar system. $S_{type}$ is the maximum rating (kVA) listed in the manufacturer's technical data for the generator type and frame size. Figure 5.18(a) gives the voltage dip ($\Delta V$) related to per-unit applied load, at 0.8 power factor lagging, for so-called 'short' and 'long' generators. The manufacturer uses the ratio:

$$\frac{\text{rotor length}}{\text{rotor diameter}}$$

to define the two types.

'Short' refers to a low ratio; and signifies the first machine listed in the series, for a given diameter. The high ratio 'long' machine is the last machine listed in the manufacturer's series, for a given diameter.

The graph of Figure 5.18(b) is used to convert the value for $\Delta V$ to that to be expected at the power factor of the impacting load by applying a correctioD factor *k*. For example, for an applied load of 1.1 pu, the voltage dip at 0.8 power factor for a 'long' generator would be approximately 17 % (curve a). Assuming the power factor of the switched motor is 0.35 at starting, the correction factor would be 1.16 (from curve b), giving an anticipated voltage dip of 19.7 %. For this manufacturer's machines, peak kVA (defined as existing load plus impacting load) should not exceed 1.7 x rated kVA.

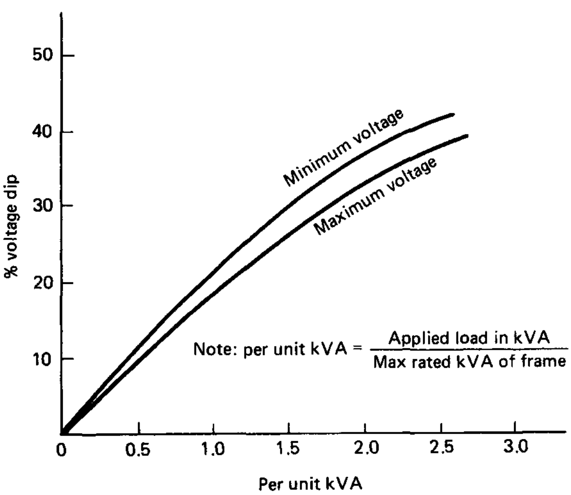



Figure 5.17 Voltage dips related to impact load at low, lagging power factors (Courtesy: Newage International Ltd)

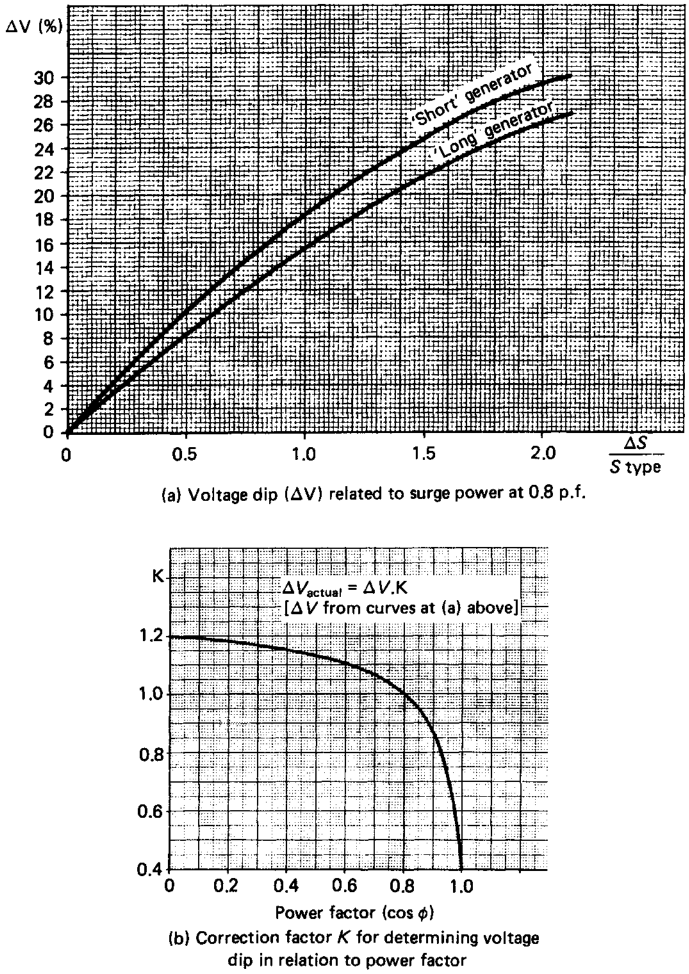



**Figure 5.18** Manufacturer's typical curves for determining voltage dip on a range of 3-phase, 4-pole, low voltage generators (Courtesy: A van Kaick Neu-Isenburg GmbH

Voltage dip is largely independent of the load already carried by a generator, particularly if this is a mixed *passive load,* e.g. lighting and heating. But any motors running on the system at the time will experience a speed change, which will cause them to draw more current. This increased load current, when added to the starting current of the incoming motor(s), causes the voltage dip to exceed its expected value. An allowance may therefore have to be made for any *dynamic preloading* when estimating the voltage dip - especially in borderline cases. A dynamic (motor) preload of 50 % of the generator rating will increase the voltage dip by some 10 % [16].

A few words of caution on methods of measuring voltage dip are apposite at this stage. Perhaps the most versatile instrument for monitoring and displaying time-varying phenomena is the cathode-ray oscilloscope. Available in either analogue or digital reading forms, it offers the possibility of storing fast transient data for retrieval at a later date. This data may then be permanently recorded on either slow-speed pen or galvanometer-type X-Y recorders. Utraviolet (uv) recorders may also be employed to provide time-domain records, but their response to step functions is largely governed by the damping of the galvanometers they use. With underdamping, the response is fast but contains an overshoot and a decaying oscillation. With overdamping, the time to reach a final deflection is excessive. A damping factor of 0.64 is usually suitable for a.c. signals [20]. Pen recorders are, generally, not fast enough for directly recording the magnitude of short-time transients. Similarly, most digital voltmeters are unsuitable for measuring transient conditions. Much depends upon the measurement systems they employ; and the intervals at which signals are sampled. Remember that one could be dealing with generator voltage response times as low as 80 ms (and certainly below 1 s), with most modern machines. The use of conventional switchboard-type moving-iron, induction, and moving-coil rectifier instruments should never be entertained. It is surprising how often one is still asked to accept their evidence, on site performance tests. When faced with no other alternative, apply a 'correction factor' of between three and three and a half times the observed voltmeter reading.

### *Limiting voltage dip*

Several lines of approach are possible:

1. Where the installation contains a number of motors (and particularly where one or two relatively large motors constitute the major part of the load), it may be feasible to rearrange starting sequences so as to minimize impact currents on the generators. The motors with the largest starting currents should be run-up first. See the case study, Appendix 5.1.
2. Use a generator of lower transient reactance. One way of achieving this is by using a larger frame size machine. Alternatively, order a low reactance machine, specifically designed for the starting duties proposed. A machine of this type may suffer from the disadvantage of having a lower than normal continuous rating for its frame size. The economics of either solution must be compared with the additional costs of (3) below.
3. Use one of the reduced-voltage starting systems described later in this chapter. A careful assessment of each application will be necessary. While starting current may be reduced, the starting torque is, unfortunately, also reduced in the same proportion. This could be a serious limitation with heavy-start, high inertia loads.
4. Replace some, if not all, of the squirrel cage motors in the system with those of the slip-ring type, which can provide large starting torques, without drawing excessive starting current. This is not quite the panacea it may seem, at first sight. First, there is the economic penalty of added cost. Then there is the possibility that the prime mover rating may have to be increased to cater for the higher active power demand resulting from the higher starting power factors (see the sub-section on prime mover sizing later in this chapter).

### *Motor types*

Induction motors are subdivided into two groups: cage motors, and wound-rotor (or slip-ring) motors.

1. *Cage motors* are highly robust, reliable machines offering simplicity of operation in their single speed direct-on-line started forms. Rotor construction varies from the diecast aluminium single-cage arrangement used on small motors, through the various forms of deep-bar rotor used on medium and large machines, to double-cage versions (and even 3-slot arrangements) employing bars of copper, cuprous alloys, or nickel alloys.
2. *Slip-ring motors* were the forerunners of cage machines. As their description implies, they have rotor windings which are similar to the stator (or primary) winding. Access to the rotor windings, through shaft-mounted slip rings, means that starting performance can be controlled by external resistance. The external resistance permits repeated starting against high inertia loads, besides giving a limited amount of speed control. Any losses and heat dissipation during starting are confined to the external resistance.

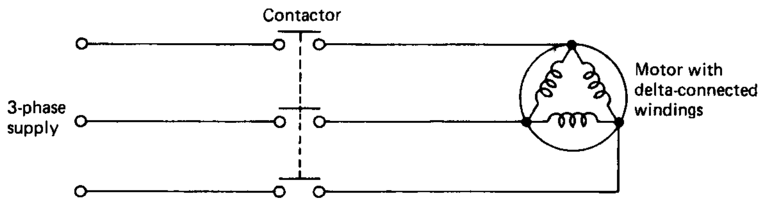
### *Conventional methods of starting*

Discussion is limited to 3-phase machines. Motor protection devices are omitted from the diagrams that follow, for convenience of presentation. Starters may be classified in one of two categories:

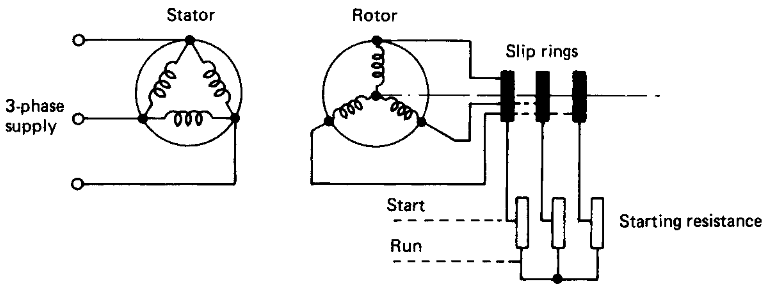
1. those in which full line voltage is applied to the motor windings - known as *full-voltage starters*
2. *reduced voltage starters,* in which the voltage applied to the windings is some fraction of the line voltage. This gives a corresponding reduction in starting current, but at the expense of greatly reduced starting torque (which is proportional to the square of the voltage applied).

#### *Full voltage starters*

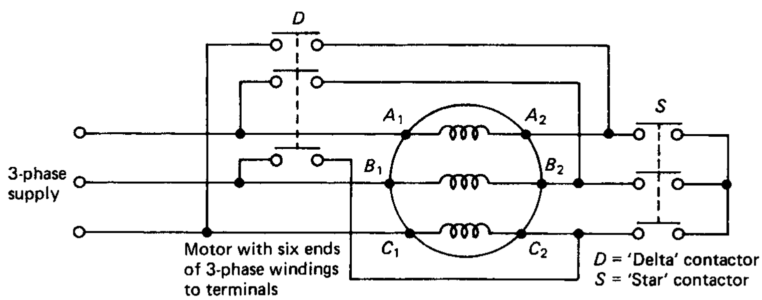
*Direct-an-line (d.a.l.) starting.* This is the simplest method of starting a cage induction motor. A contactor is used to switch full line voltage directly to the motor terminals (see Figure 5.19(a)). The motor stator windings are normally connected in delta. It is of course possible to start slip-ring motors in this way. The method is seldom, if ever, used since no advantage is gained over the cheaper cage machine. Starting torques are of the order of 0.75 to 1.0 times full-load torque and inrush currents are between 4 and 6 times full-load current. Typical values of the starting kVA/rated kW ratio are given in Table 5.4. Direct-on-line starting is customarily applied to small and medium power drives, but it is not unusual to have LV motors of up to 350 kW rating started in this way.



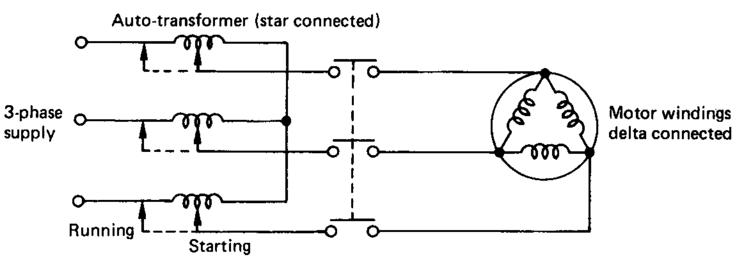

(a) Direct-on-line (D.O.L.) starting




(b) Rotor resistance starting




(c) Star-delta starting




(d) Auto-transformer starting

**Figure 5.19** Simplified diagrams for conventional motor starters

**Table** 5.4 Variation of the ratio: starting kVA/rated output power for simple cage motors

| *Motor rating (kW)* | *Ratio start kVA rated kW (for d.o./. starting)* | *Maximum starting kVA d.o./.* | *star-delta* |
|---|---|---|---|
| 2 | 10.5 | 21 | 7 |
| 5 | 9.8 | 49 | 16.3 |
| 15 | 9.2 | 138 | 46 |
| 40 | 8.7 | 348 | 116 |
| 100 | 8.2 | 820 | 273 |
| 250 | 7.8 | 1950 | 650 |
| 500 | 7.6 | 3800 | 1267 |

*Solid-state starting.* This is primarily employed on loads with a rising torque/speed characteristic. These starters give a 'soft' and stepless start by controlling stator voltage through anti-parallel thyristors fitted in each supply line, and phase-controlled by appropriate triggering. An alternative method is to connect the thyristors across the secondary of a gapped-core inductor whose primary is in the supply line. This gives variable-impedance contro!. Voltage reductions of between 25 % and 70 % rated value, with corresponding torques of between 6 % and 50 % of the d.o.!. value, can be achieved. Extended run-up times may be arranged to give smooth starting with low inrush currents. First costs are higher than the electromechanical d.o.!. starter, but may be justified where very frequent starting is necessary.

*Rotor resistance starting.* This method is confined to wound rotor machines. Resistors are connected in series with the rotor windings (see Figure 5.19(b)). They are graded in sections, or steps, whose values follow a geometric progression - similar to the pattern employed on d.c. shunt motor starters. The motor is started with all steps in circuit. As it runs up, the external resistance is reduced, step by step, in a controlled sequence, until, at normal speed, the rotor winding is short-circuited at the slip rings. The series resistance limits the starting current and improves the starting torque. Where a machine is required to start against full-load torque, the resistance is arranged to give about 1.5 times full-load torque with about 1.5 times full-load current. Points to note are: the starting power factor is high (typically 0.9); peak power demand usually occurs at switch-on. This will influence the rating of a generator's prime mover. Alternative forms of wound-rotor starter use liquid resistors, or star-connected choke coils of low resistance and fairly high inductance, chosen to suit the given rotor.

*Reduced voltage starting*

*Primary resistance starting.* This system is mainly used for small drives and is much favoured in Amencan practice. A resIstance, usually graded in two steps and controlled by contactors, is inserted in each line to the stator terminals of the machine. It is designed to reduce the stator current by a fraction *(x)* of its direct-on-line value, as the motor drives up to normal speed $x$ approaches unity. The starting torque is $x^2$ of that obtainable with direct-on-line switching.

*Star-delta starting.* This is the most widely applied method of starting cage motors on reduced voltage (Figure 5.19(c». The system requires that all six ends of the three phase windings are brought out to the motor terminals. The starter circuit is arranged so that the stator windings are first connected in *star* (where the phase impedance is three times that in the delta condition) until either a steady speed is attained or a preset time has expired. The windings are then connected in *delta* for motor running. Motor acceleration should proceed as far as possible before the transition is made so as to minimize the transient current peaks during changeover to the delta mode. Starters for small motors may employ hand-operated changeover switches. Where contactors are used, some form of interlocking is necessary in order to give the proper starting sequence.

In the initial star connection, each phase of the motor receives a reduced voltage, $1/\sqrt{3}$ (i.e. 58 %) of the line voltage. The starting current is also reduced to $1/\sqrt{3}$ of the direct-on-line value (since $I \propto V_{line}$). Starting torque and kVA demand are 1/3 of their d.o.!. values since both are proportional to the square of the line voltage. The torque reduction usually limits this method of starting to applications with low starting loads, e.g. fans.

Star-delta starting is less effective in reducing the peak kW demand, particularly if the changeover occurs at relatively low speed. The power requirement is then of the same order as the maximum that would occur if the motor were switched direct to the supply in delta (see Figure 5.11).

An interesting variant of the star-delta system is the 'closed transition' Wauchope type starter. This improves the motor's starting characteristic by inserting resistances in series with the windings, when these are in 'transition' to the delta stage. The resistances are short-circuited before the motor runs up to full speed, in delta. They not only reduce the high peak current demanded by the motor during the transition from star to delta (see Figure 5.20), but they also give smoother acceleration [21].

*Auto-transformer starting.* An auto-transformer, which has fixed tappings along its windings, is interposed between the supply and the motor terminals (see Figure 5.19(c)). Usually, no more than three tappings are necessary - typically, at 50 %, 70 % and 80 %. The lowest voltage tap is used to feed the motor at standstill. As it speeds up, the tap position is changed to the next highest level until full

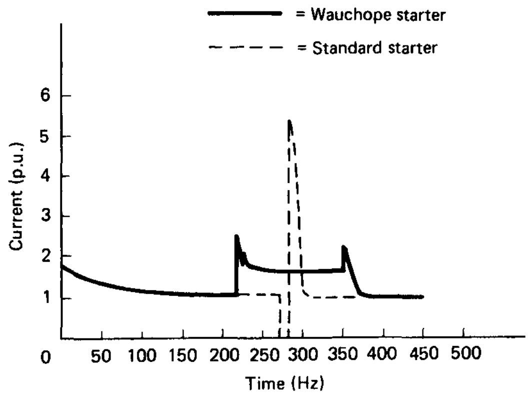



**Figure** 5.20 Variation of line current during star-delta starting

line voltage is eventually applied to the motor terminals. The auto-transformer is then switched-out. The transformer need only have a short-time rating, but its leakage impedance should be small enough to avoid undue limitation of the starting current [13]. Hand-operated air-break switches may be used. Fully automatic control is achieved by means of contactors and timing relays. In the *Korndorfer* variant of this starting system a part of the transformer winding is arranged to remain temporarily in series with the motor windings at the changeover to full voltage. Thus, the supply to the motor is not interrupted in the transition from reduced to full voltage. The lowest tapped-voltage provided must be consistent with the starting torque requirement of the load. If this tap provides a fraction $x$ of nQrmal voltage, the starting torque and current are each $x^2$ times that obtainable with direct switching. For example, 25 % of the direct-switching values would be obtained for a 50 % tap. Auto-transformer starters may be more expensive and bulky than their star-delta alternatives but they do provide higher starting torque.

Table 5.5 [17] gives a comparison of typical starting characteristics for various forms of starting.

## *Generator and prime mover sizing*

The kVA elements of system load must be supplied by the generator. It should be rated to cope with the steady-state and transient demands made upon it without exceeding its designed overload capacity or the permissible voltage dip for the application. The active power demand is met by the prime mover, which should be matched to the continuous maximum rating of the generator, and should be capable of meeting the peak kW demands of all impacting loads without excessive and intolerable speed droop.

Assessment of the generating set's capacity must be based upon load analyses which take account of the steady-state and transient conditions relating to every stage of the installation's operations. The case study in Appendix 5.1 of this chapter shows how a typical assessment is made. Figure 5.21 illustrates the stages in such an exercise.

1. Phasor OA represents the standing load (in kVA, at 0.95 power factor) on the generator, when a motor is started.
2. AB is the transient kVA demand. Its magnitude, and the angle it subtends above the x-axis (determined by the power factor), will vary with the type of motor and the starting method used. Different values for AB may apply when sizing the generator and when sizing the prime mover. For example, the starting characteristics in Figure 5.11 show that the maximum kVA (5.5 pu) occurs at starting, with a corresponding power factor of about 0.3. The maximum power occurs at about 80 % synchronous speed and corresponds, approximately, with 4 pu kVA at 0.65 power factor. The latter values should be used for plotting AB when prime mover selection is being considered. Figure 5.21 is therefore presented in two constructions: (a) for generator assessment, and (b) for prime mover assessment. Diagram constructions for generator and prime mover assessments will be one and the same when considering slip-ring motor starting because the peak power demand is likely to be at starting (see the sub-section detailing auto-transformer starting p. 156).

**Table** 5.5 Comparison of typical starting characteristics (per unit values)

| *Starting method* | *DOL* | *Star-delta* | *A uta-transformer* | *Slip ring* |
|---|---|---|---|---|
| Starting kYA | 5.5-6.5 | 1.7-2.2 | 2.5-3.5 | 1.3-1.5 |
| Peak kY A | 5.5-6.5 | 3.0 | 3.5 | 1.5 |
| Starting torque | 1.5-2.5 | 0.4-0.6 | 0.6-1.0 | 1.0 |
| Peak kW | 3-3.5 | 2.5-3.0 | 2.5 | 1.5 |

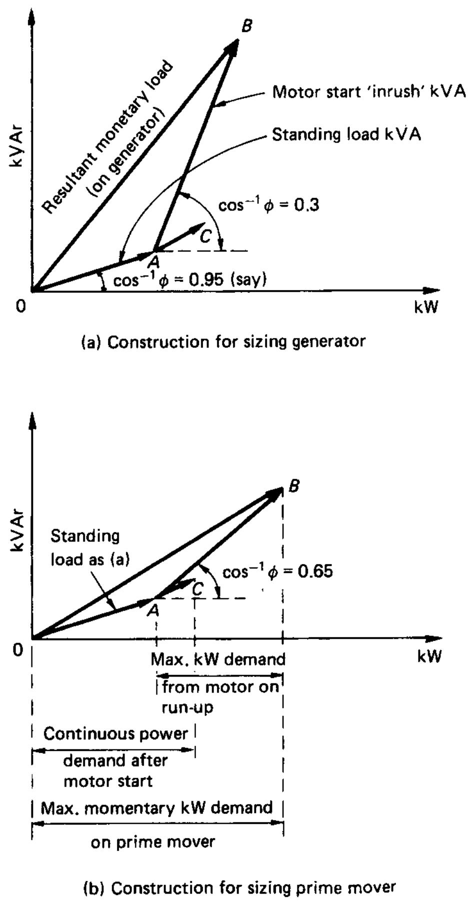



**Figure** 5.21 Assessment of generating plant sizes for impact loadings

3. OB is the 'vectorial' addition of OA and AB, and represents the resultant transient load imposed on the generating unit during the motor run-up period. Its magnitude (see Figure 5.21(a» must be within the rated overload capability of the generator .
4. Phasor AC is the running load of the motor (1 pu kVA). The angle it subtends above the abscissa (the x-axis) corresponds to the motor's designed, full-load power factor.
5. Projection of OB (in Figure 5.21(b» onto the abscissa gives the transient output required from the prime mover. This 'momentary' demand should not exceed the engine's declared overload capacity - which is usually 10% of its ISO continuous rating. If the demand marginally exceeds the overload rating the inertia stored in the system's rotating masses is generally sufficient to cover the deficit with only a minimal reduction in speed. The speed reduction ($\Delta N$) is given by the expression:

   $\Delta N \neq (P_d/J)^{1/2}$, in consistent units

   where $P_d$ is the shortfall in engine capacity, or the power deficit and $J$ is the polar inertia of the system's rotating masses (combined engine and generator).
6. The projection of OC onto the abscissa (in either diagram) represents the continuous output required from the engine, once the motor is running at normal speed on designed load.

## *Motor reswitching transients*

Situations may arise, such as on board ship, where essential services are provided with a maintained supply. This supply may be derived from two separate sources, feeding into a sectionalized duplicate busbar system incorporating 'main' and 'reserve' busbars, which may not necessarily be synchronized. Changeover conditions are classified as an *intentional supply interruption.* There may, however, also be quite unintentional interruptions to a running motor's supply, e.g. physical shock or excessive vibration, causing a starter's contactor contacts to open momentarily [22]. Any motor so disconnected from its supply source immediately loses its driving torque and begins to decelerate. The rate of deceleration is inversely proportional to the combined polar inertia of the motor and its driven machinery, and to the load torque. The motor behaves as a generator producing a voltage at its open-circuited terminals. If it is then reswitched to a supply source, surge torques and currents will result - after even the shortest interruption. The magnitude of the peak current is governed by:

- the motor load;
- the supply disconnection period; and
- the difference, in both phase and magnitude. between the residual stator e.m.f. and the supply voltage at the instant of supply reconnection. The greater the phase, and magnitude differences between the two voltages, the greater the reswitching transient will be.

Shoesmith [22] has reported on a series of motor reswitching tests conducted at the Admiralty Engineering Laboratory. The tests led to the following conclusions:

1. Provided contactor contact disturbance does not exceed three cycles of the nominal system frequency, the reswitching inrush currents will not greatly exceed the full-voltage starting current peaks.
2. After short-term supply interruptions, such as switch contact opening, current peaks on recla-

sure are unlikely to exceed 2 to 3 times existing load current.

3. Conditions will be more severe on supply changeover schemes - particularly where rapid changeover is attempted; peaks of the order of 13 times full-load current may be experienced on reconnection, at rated voltage.

Other examples of fast reswitching are the various electrical braking methods employed to stop motors or to reduce their speed. Current surges of the order of 16 to 20p.u. may be experienced. See Figure 5.22. Some plugging systems insert resistances in the lines to the motor terminals when reconnecting the reversed supply. Their purpose is to reduce the current peaks to predetermined limits.

Transient conditions in *dynamic* or *d.c. injection braking* are not likely to be very severe. Current peaks of the order of 4 to 5 p.u. may be expected. They are mainly caused by the injected direct voltage, rather than by the short-circuiting effect of the d.c. [23]. The longer the duration of supply disconnection, the less significant the transients are likely to be.

*Capacitor braking* - where the motor is disconnected from the supply and reconnected to a bank of capacitors, is generally used to reduce speed to some predetermined level. Where braking to standstill is required, a combination of capacitor and d.c. injection braking may be employed. In either event, the effect of the capacitors across the terminals is to maintain the air gap flux, and the stator voltage may build up to an overvoltage condition - in spite of the drop in rotor speed. Current transients may be very severe on reconnection to the supply since out-of-phase conditions are likely. The same effects obtain when terminal capacitors are used for power-factor correction [13].

Figure 5.23 [23] shows the typical transients which occur when reconnecting a motor at full-load torque

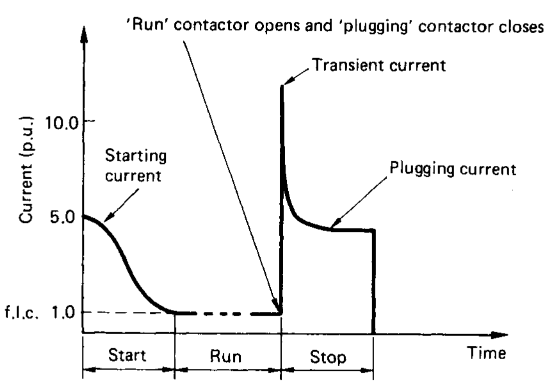



**Figure 5.22** Typical current characteristic for plug braking

and rated voltage. In this case the interruption period was 93 ms.

## *Regenerative loads*

When braking certain equipment, such as cranes and lifts, mechanical energy may be fed back to the power source in the form of electrical energy. This energy may also be absorbed by other equipment operating in the installation. The surplus (or reverse) power will cause any generator supplying the equipment to act as a motor, tending to drive its prime mover. The generating set's speed will increase and the natural response of the prime mover's governor will be to reduce the fuel supply. If the speed continues to rise the governor may become ineffective. A runaway condition is only avoided if the *reverse power* is totally absorbed by the prime mover's mechanical losses and by the generator's electrical losses. Reverse power in excess of 10% of a diesel-generator's rating constitutes a dangerous condition. Runaway will almost certainly occur if fed back power exceeds 25% - 30% of the rating. If regenerative load is connected to a generator, the total of the other load elements should, at least, be equal to the regenerated power. Failing this, it may be necessary to connect a continuously-rated resistive load to absorb the regenerated power [24].

## *Voltage unbalance*

The performance of a 3-phase induction motor is adversely affected if its stator phase voltages differ in magnitude or phase displacement [13]. The limiting criterion for voltage imbalance in an installation may well be the amount of unbalance that the motors in the system can tolerate. BS 4999: Part 101 (IEC 34-1) requires motors to be designed to operate under 'virtually balanced' voltage conditions. Any asymmetry exceeding 2% could lead to increased motor losses and overheating. Asymmetry in this context means that the negative phase sequence (n.p.s.) component of voltage does not exceed 2% of the positive sequence component. See Sub-section 10.4.6 of Chapter 10 for an explanation of n.p.s. (The reader's attention is directed to the review by Roper and Leedham (Bibliography [15]) for a detailed treatment of the topic of 3-phase unbalanced systems.)

## *Harmonic voltages*

A full discussion on the effects of harmonics on induction motor performance is outside the scope of this chapter. The increasing application of non-linear loads makes it necessary to appreciate the distorting effect they may have on the voltage

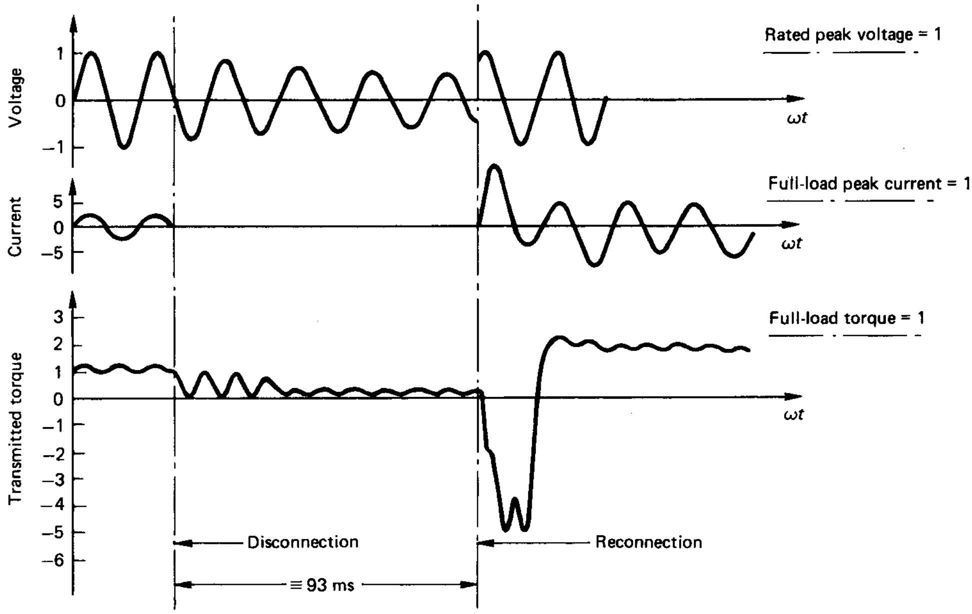
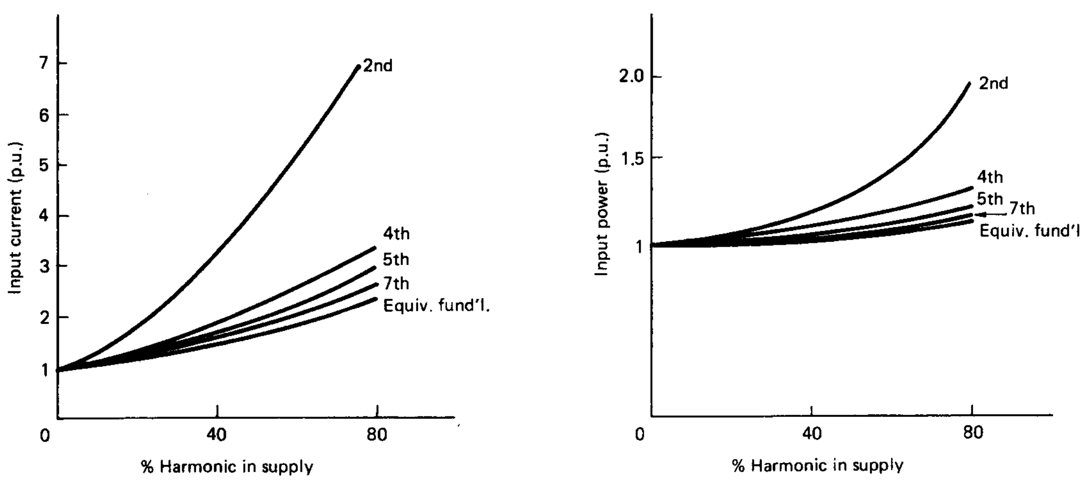



**Figure 5.23** Typical motor reswitching transients [23]




*Note*: Experimental motor operated at constant full-load torque. Single harmonics were added to a chosen fundamental using a waveform synthesizer.

**Figure** 5.24 Effect of voltage harmonics on input current and power to a motor [25] waveform of high impedance generators (see Section 5.4.3). The effects can be reflected into the performance of motors in the system. Figure 5.24 (adapted from [25]) shows the typical effect of varying the amount of harmonic voltage in the supply to a motor. Whilst the 2 nd harmonic is not likely to be present in any significant amount, 5 th and 7 th orders may be very evident on convertor loads. Perhaps the most important effect on performance is the increase in harmonic copper losses within the motor; resulting in increased local heating [25].

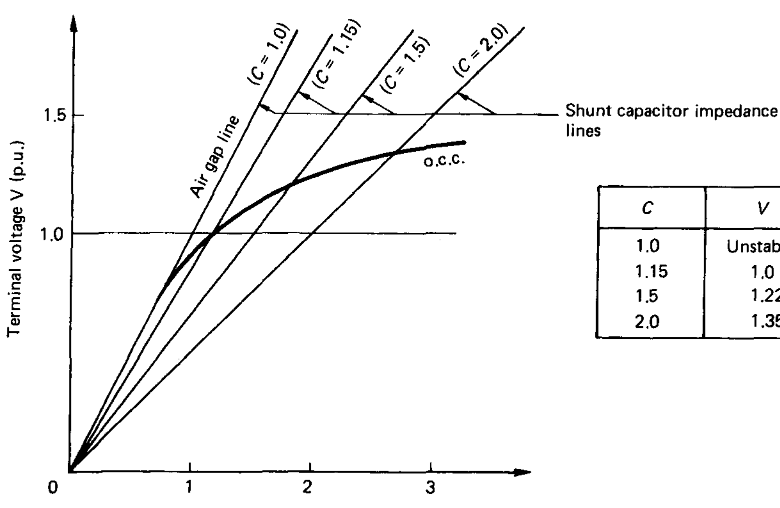
### 5.4.2 Capacitive loads

In discussing the concept of synchronous reactance (Sub-section 4.2.6 of Chapter 4), we established that the effect of armature reaction was to demagnetize the main field at zero power factor lagging (inductive) loads and to directly magnetize the main field at zero power factor leading (capacitive) loads. There will be a tendency to over-excite the generator, as the proportion of capacitive load increases unless the main field current can be *'reversed'* by the action of the machine's excitation control system. This is not possible with an ordinary brushless generator. There is also little chance of controlling the over-excitation on compounded machines (of the type described in Sub-section 3.3.4 of Chapter 3), which use the automatic voltage regulator to 'buck' the a.c. exciter field through a separate winding; more so, if the compounding circuit is not phase-compensated, i.e. if it is not directly related to load power factor.

The self-exciting effect of purely capacitive loads is, therefore, to produce a high terminal voltage, limited only by the magnetic saturation of the machine. The terminal voltage is determined by the intersection of an impedance line (whose slope corresponds to the amount of load capacitance), with the open-circuit magnetization characteristic of the generator. Figure 5.25 [26] shows typical terminal voltages to be expected when a generator is self-excited by various amounts of capacitive load.

There must be a limit to the amount of capacitance that can be switched on to a given generator if voltage stability is to be maintained. Modern 4-pole and 6-pole machines, having synchronous reactance values varying between 2 p.u. and 4 p.u. for ratings between 20kVA and 1750kVA, can seldom be safely exposed to more than about 25 %-30 % purely capacitive load [26]. The presence of active load (kW) will alleviate the situation. This is because such loads will tend to increase the main and exciter field currents and oppose the self-excitation effects of the capacitive load element.

The limitation on capacitive load level is confirmed by the characteristic in Figure 5.26 [27] since the lowest practical 'working' level of excitation should be of the order of 0.75p.u .. The characteristic illustrates the effect of self-excitation. It shows the excitation required to maintain constant voltage as reactive load is varied from inductive (lagging) to capacitive (leading). It should be noted that the field excitation becomes negative at point A, and is positive again at point B. Point A is that at which the load's capacitive reactance is equal and opposite to




| C | V |
|---|---|
| 1.0 | Unstable |
| 1.15 | 1.0 |
| 1.5 | 1.22 |
| 2.0 | 1.35 |

**Figure 5.25** Terminal voltages to be expected for different values of capacitive load [26]

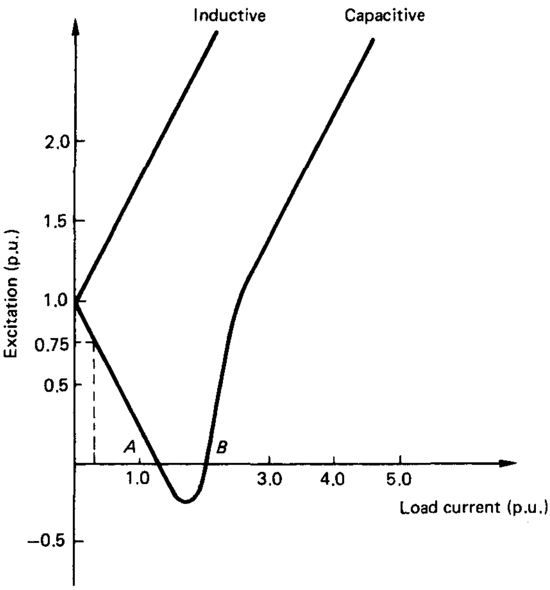



**Figure** 5.26 Excitation required to maintain constant voltage, with increasing load [27]

the generator's direct-axis synchronous reactance $(X_{sd})$. *B* is that point where the load reactance is equal and opposite to the generator's quadrature-axis synchronous reactance $(X_{sq})$.

Two of the major problems encountered, in practice, are:

- the capacitance of long transmission lines, in isolated areas;
- the capacitors of bulk power factor correction schemes, applied to main distribution boards.

Not only are high steady-state voltages possible at switch-on, but excessively high transient terminal voltages will also occur if sufficient purely capacitive load is present without any appreciable level of active (kW) load. Dinsley and Glover [27] cite some of the transient voltage problems associated with the switching of capacitive loads. The power factor correction capacitors of fluorescent lamp installations (such as those in departmental stores, where this type of lighting may constitute the bulk of the essential load fed from a standby generator) can have the effect of imposing high transient stresses on the rotating diodes of brush less generators. A non-inductive and matched resistance in parallel with the main field offers a simple and economic solution to the problem [28]. See Figure 3.8 in Chapter 3.

Large installations of mercury or sodium metallized vapour discharge lamps are often found in the industrial, horticultural, building construction and public lighting sectors. These lamps require control gear to provide a high voltage across them to cause them to strike. Equipment used for this purpose may include inductive chokes, high-reactance transformers, and electronic devices giving high-voltage starting pulses. The lamps may draw high currents at low power factor during run-up - which may be anything up to 15 minutes in some cases. (See the characteristics of Figure 5.27.) They also have the habit of extinguishing if their supply is interrupted. Unless special circuits are used, the pressure in the lamp then remains too high for the arc to 'restrike'. The lamp has to cool down before this happens and it could take up to 3 minutes to cool.

Lamp control gear usually incorporates power factor correction capacitors. Problems can arise with small standby generators supplying banks of these lamps. The generator is 'confronted' with a large capacitive load at switch-on while the lamps are cooling.

It is advisable to consult both lamp manufacturer and generator supplier if the principal role of a standby generator is to supply banks of discharge lamps. In practice, disconnection of as many as half of the power factor capacitors is possible without any significant deterioration in lamp performance [26].

### 5.4.3 Non-linear loads

In recent years, industrial plants and domestic equipment have made increasing use of solid-state power devices such as thyristors, in industrial convertor systems, and triacs (bidirectional thyristors). in household appliances. Loads using this form of control are the major sources of harmonic distortion in supply networks. The non-linear load currents that characterize such equipment may well be accommodated, within acceptable limits, where the power source is a low impedance public utility supply. But, where the source is a smaller capacity higher impedance generator, deleterious distortion of supply wave-form may be difficult to contain. **In** the following sub-sections we shall briefly review some applications of these control devices; and examine the distortion effects likely to be induced in network supplies.

#### *Domestic loads*

Domestic loads are mentioned because they may be a significant portion of the load on generating plant which supplies isolated communities and townships in developing territories. The two basic systems of power control applied to household appliances are those using *phase control,* and those using *burst-firing* techniques.

In the *phase-control* method, power is regulated by varying the point on the applied voltage wave-form at which a thryistor's conduction begins. The supply to the controlled equipment is then switched-off every time the voltage passes through zero.

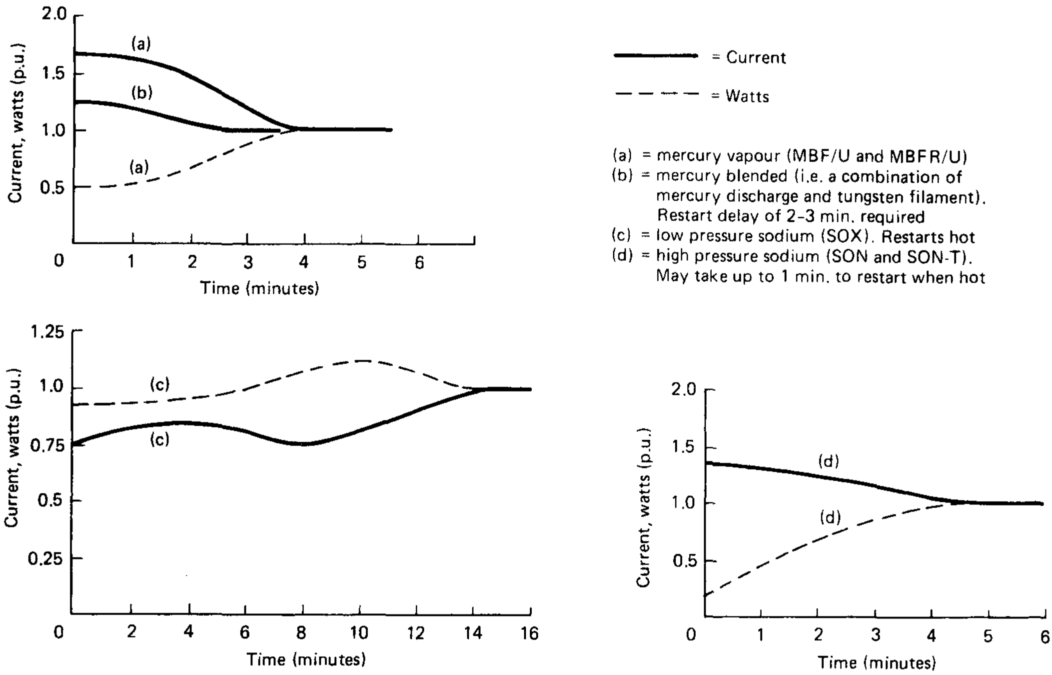



**Figure** 5.27 Typical run-up characteristics for discharge lamps (Courtesy: Crompton Parkinson Ltd)

In *burst-firing* control (also variously referred to as *integral-cycling, fast cycling,* and *cycle selection),* load current is switched on and off in blocks or chains of complete cycles. Switching is arranged so that each 'on' pulse is triggered at zero voltage - for resistive loads, and at zero current - for inductive loads. The required proportion of full-load power is obtained by varying the number of cycles in the 'on' and 'off' periods - for example, the on/off periods must be equal for 0.5 p.u. load.

Analyses of the load voltage wave-forms of both types of regulator would show that, for a given degree of power transfer, there are more significant harmonics present in integral-cycle control than in phase-control [30].

The disturbance caused by any domestic appliance depends not only upon the characteristics of the appliance itself, but also upon the characteristics of the supply network and on the connection point of the appliance to the network. Where the supply is obtained from a local generator (of finite impedance and producing, in itself, a distorted voltage waveform), the possibility exists for harmonic instability or harmonic magnification, extending into the appliance controls, causing firing-pulse irregularity and exacerbating the total system disturbance.

Joint studies were undertaken by electric utilities and manufacturers in the Common Market countries to set limits to the disturbances originating from domestic appliances. That work led to the issue, by CENELEC (the European Committee for Electrotechnical Standardization), of a harmonizing document (European Standard EN 50 006 (BS 5406 and IEC 555-2) : *Limitation of disturbances in electricity supply networks caused by domestic and similar appliances equipped with electronic devices,* 1975). Its objectives are not only to limit the quantity of 'generated' harmonics, but also to lay down requirements related to the use of phase-control systems for thyristors [31]. Its scope is restricted to non-professional equipment. (See also the following sub-section dealing with industrial loads.)

Colour television receivers frequently use half-wave rectifiers. Where there are large populations of sets, all simultaneously notching into the same half-cycle of supply, their combined effect can be significant [32]. Table 5.6 (taken from Kidd and Duke [33]) shows the harmonic phase currents recorded at substations feeding housing estates in the United Kingdom. The 2nd and 3rd harmonics were largely attributed to television and radio receivers operating at peak times.

It was found that distortion was mostly due to 2nd, 3rd, 4th, and 5th harmonics. Current magnitudes varied cyclically with television viewing times and, to a lesser extent, with other household activities. Phase angles of the 2nd, 3rd, and 4th harmonics often followed a regular pattern - similar to the harmonic magnitude, but could differ appreciably at distribution substations fed from the same primary

**Table** 5.6 Maximum harmonic currents recorded on a domestic estate

| *Supply* | *Time (May)* | *Fundamental (A)* | *Harmonic number* 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 500 kVA transformer | 22.30-Fri, Sat, Sun | 90 | 3.5A | 7.9A | 3.6A | 2.9A |
| 11/0.415 kV 3ph | 09.30-Mon | 140 | * | 3.2A | * | 0.9A |

, = less than O.4A

network. Most significantly, appreciable levels of d.c. current were present in the neutral, and values as high as 45 A were recorded [33].

## *Industrial loads*

The effects of non-linear loads on generators feeding industrial sites are more significant and less predictable. The common element in all industrial solid-state power supplies is the *convertor.* It may be defined as a device or circuit by which a.c. is converted to d.c.; or vice versa. The term is usually used to describe a rectifier, but the inverter, which converts d.c. to a.c., is also grouped under this generic description. Convertors are to be found in variable speed motor drives, chemical and materials processing plants, battery charging, switched mode power supplies (SMPS) to computers and other technical loads, and in the uninterrupted power supplies (UPS) often associated with such loads.

Switched mode power supplies are to be found in personal computers, computer terminals, small main frames, video display units, and in printers and other computer peripherals. Medium sized telecommunication loads are also becoming predominantly SPMS. Switched mode supplies employ capacitors connected to the mains supply through a single-phase diode bridge. The capacitors, being high voltage, high capacitance units, require high peak charging currents. SPMS current wave-forms contain very high third harmonics, and multiples of the third harmonic (45 % third harmonics are not unusual on high crest factor loads).

On 3-phase supplies SPMSs will be connected between line and neutral on all three phases. This means that the third harmonic currents generated in each phase add together in the neutral conductor to give a very high Lm.S. neutral current (it may be as high as 1.7 times line current for crest factors of 3 [34]). The following problems may then arise [34]:

1. High voltage drop along the neutral conductoL This effectively reduces the supply voltage at the load, accentuating the SPMS drop-out problem (described in more detail later).
2. Neutral-to-earth voltages are generated. This would cause the neutral terminal at the load equipment to float at a potential of a few volts above earth.
3. Overheating of the neutral conductor, leading, perhaps, to burn-out - especially on those older installations where the neutral is not fully rated.

Power distribution systems should be designed to handle full-loads at a crest factor of 3:1.

Where generators are used for standby to a mains supply on UPS installations they are likely to be confronted with non-linear loads with crest factors as high as 2.8 when the the UPS system goes into a bypass mode. See Suh-section 11.4.4 of Chapter 11. Crest factor is defined as the ratio of peak current to Lm.S. current. A linear load with a sine wave current wave-form has a crest factor of 1.41 (see Sub-section 4.2.4 of Chapter 4).

If a standby generator cannot supply the peak current of a high crest factor (HCF) load, its output voltage wave-form may become flat-topped. This can have a marked effect on the SPMS load. The capacitor of the switched mode supply is charged up to the peak of the supply voltage wave-form. If this is reduced by flat-topping, the d.c. voltage switched in the SPMS is also reduced. This, in turn, will reduce the low voltage operating margin of the computer equipment, and may cause power supply drop-out when transient load steps are applied [34].

A convertor is a source of harmonic currents which produce voltage drops at harmonic frequencies across the supply system impedances. The harmonic currents generated will depend upon the type of convertor used, whereas the resulting voltage harmonics will relate to the properties of the supply network. The harmonic voltage drops combine vectorially with the supply voltage to give a distorted wave-form at all points in the network. The effect on the converting equipment itself, and on other items of plant in the network, depends upon the degree of distortion, and the sensitivity of plant to it. The effects on public supplies are limited in the UK by application of the Electricity Council Engineering Recommendation G 5/3 - *Limits for harmonics in the UK electricity supply system.* This tabulates the maximum permissible kVA ratings for single-convertor and single-regulator installations, against listed harmonic currents, for the point of common coupling (PCC) with other users.

Reference was made in the previous Sub-section to the CENELEC standard EN 5~6 (based on IEC 555-2) which restricts the current harmonic components taken from the mains supply by household electrical appliances. IEC Sub-Committee 77A is now working on an extension of IEC 555-2 to widen its scope to cover all equipments with load currents up to 16 A per phase, and proposes a further extension to deal with equipment with load currents above 16A per phase. When issued, the new standards are likely to become mandatory under the Electromagnetic Compatibility (EMC) Directive of the EEC. Meanwhile, the European Commission have drawn up a mandate for CENELEC to amend existing European Standards and to initiate the other standards required by the Directive (89/336/EEC). This is to be on a phased timetable to 31 December 1992.

When a synchronous generator is loaded by a convertor, severity of voltage wave-form distortion will depend upon several factors, such as the ratio of machine-to-convertor ratings, the characteristics of the machine, and the performance parameters of the convertor itself. We shall examine some of these factors, and the salient characteristics of convertors.

*Rectifiers.* Bonwick and Jones [35, 36 and 37] have considered the characteristics of three-phase bridge rectifiers operating with synchronous generators, and against complex source impedances. They have derived theoretical wave-forms for three classes of generator coupled to both controlled and uncontrolled bridge-rectifier loads. The composite, Figure 5.28 [35], illustrates the comparison of the (theoretical) wave-form distortions to be expected for various combinations of generator class and

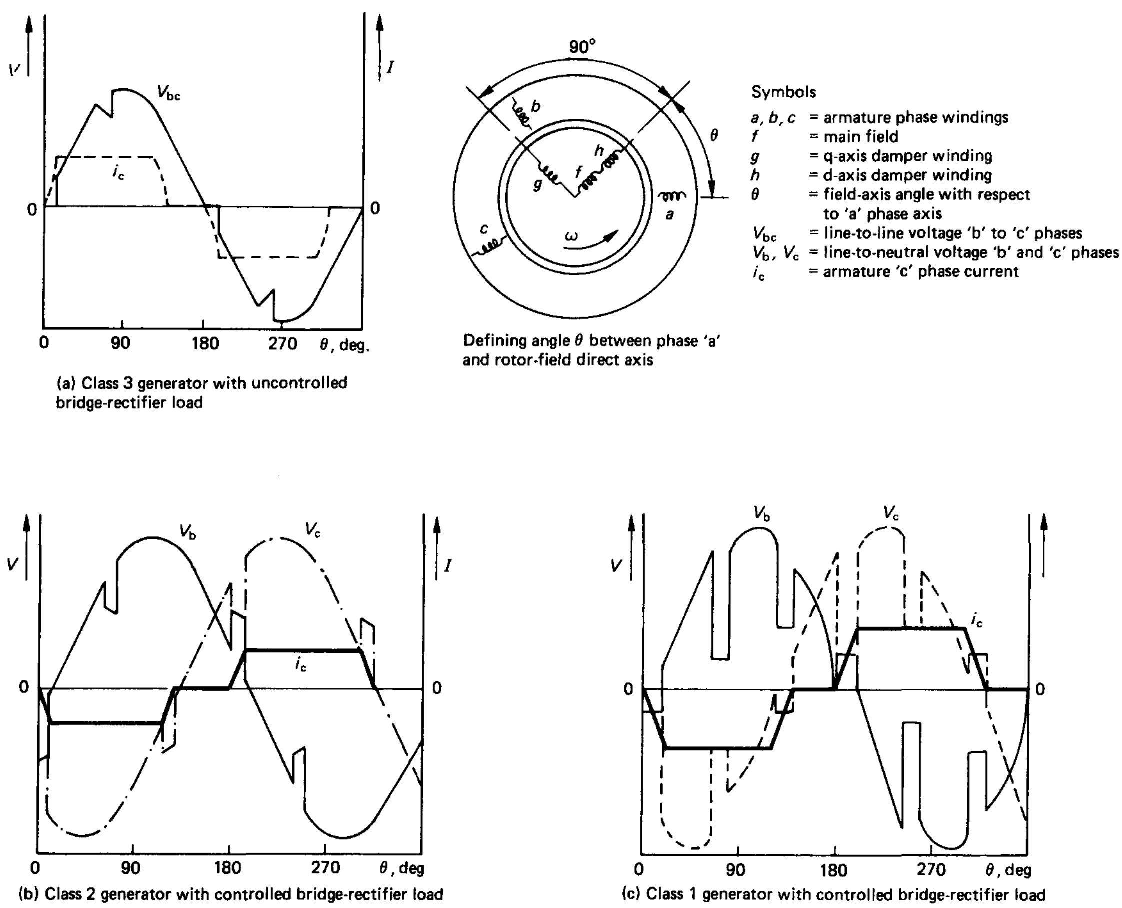



**Figure 5.28** Theoretical voltage wave-forms for generators with bridge-rectifier loads

rectifier bridge. Generators were classified as follows:

Class 1 no damper windings; substantial transient saliency
Class 2 no direct-axis damper winding; quadrature-axis damper with identical properties to the field windings; no transient saliency
Class 3 direct-axis and quadrature-axis damper windings; subtransient saliency

See Chapter 4 for an explanation of these machine features.

Oscillograms from experimental tests corresponded very closely with the theoretically derived wave-forms. Non-sinusoidal and notched waveshapes of the type shown in Figure 5.28 can be resolved by Fourier analysis into a system of sine waves, each consisting of a fundamental frequency and a number of higher-order harmonics.

Convertors may be considered to be ideal current harmonic sources. The orders of the harmonics injected into the supply are directly related to the 'pulse number' of the thyristor convertor; and are given by the expression:

where $n$ = the order of the harmonic
$p$ = the pulse number, i.e. the number of thyristors which successively begin to conduct during one cycle of the supply frequency; alternatively, the ratio of the ripple on the d.c. voltage to the fundamental frequency on the a.c. side of the convertor.
$k$ = an integer: 1, 2, 3, etc.

Typically, half-controlled and fully-controlled 3-phase thyristor bridge convertors give six pulses per cycle. The harmonics present on their a.c. side would therefore be the 5th, 7th, 11th, 13th, 17th, 19th, etc., orders of the fundamental load current. Whilst this is true of the line currents, it is also possible for 3rdharmonic currents to be present in the phase current. The latter condition may be avoided by making the thyristor commutations unequally spaced in time, but this causes asymmetrical currents to flow and even-order harmonics are introduced into the current wave-form [38].

In industrial installations it is usual to employ filters to suppress the generated harmonics. Their design requires careful consideration of the load duty cycle and accurate knowledge of system impedance - to avoid them acting as 'sinks' for harmonic currents generated elsewhere in the network [39]. With regard to system impedance, Ainsworth [40] concludes that:

1. Controlled convertors fed from a high-impedance a.c. system (such as an independent generator) may magnify abnormal harmonics originating in the a.c. system and also magnify similar harmonics caused by thyristor control-system errors or impedance unbalance.
2. Where system harmonic impedance is above a certain value, the convertor may exhibit harmonic instability.
3. Instability arising from high harmonic impedance may occur in a.c supply systems of low *short-circuit level,* and also in those of moderate short-circuit level if there is resonance. Behaviour largely depends on the type of control system used. Short-circuit level is defined by the ratio:

Any harmonic order is likely under non-ideal conditions. Because resonance can also occur at any order it becomes necessary to predict and calculate the whole spectrum of frequencies possible in all circumstances. Yacamini and de Oliveira [41] describe a computational method for finding the harmonics in convertor systems. All interactive effects are considered, at the design stage. These may include:

- unbalanced a.c. system voltages and impedances;
- any type of convertor/transformer arrangement;
- virtually any pulse number;
- a non-infinite a.c system representation;
- system resonances in both the a.c. and the d.c. system;
- no assumption of smooth d.c side current;
- harmonic filters.

The effects of features within the convertor itself, such as control methods, unequal commutation overlaps, and firing balance, may also be modelled.

Harmonic suppression measures may include:

1. The use of input filter banks, tuned to the 5th harmonic. They also have the advantage of improving the input power factor, thus reducing the input kVA demand; the p.t. at no-load becomes leading as a consequence. The no-load kVAr is normally about 30% of full-load kVA. It is necessary to ensure that the filter input kVAr is not excessively high, since some standby generators may over-excite with leading power factor loads [44]. See Sub-section 5.4.2.
2. Increasing the pulse number of the convertor. Several convertors may be arranged in groups to form a single convertor unit. They are connected in parallel on the a.c. side, and in series or parallel on the d.c. side. Complementary 6-pulse groups, arranged in this way, can give 'unit systems' corresponding to 12- and 24-pulse convertors. Harmonics are of the order $n = 12K \pm 1$ and $n = 24K \pm 1$, respectively.
3. Phase-shifting - achieved with the use of special rectifier transformers which alter the phasing of

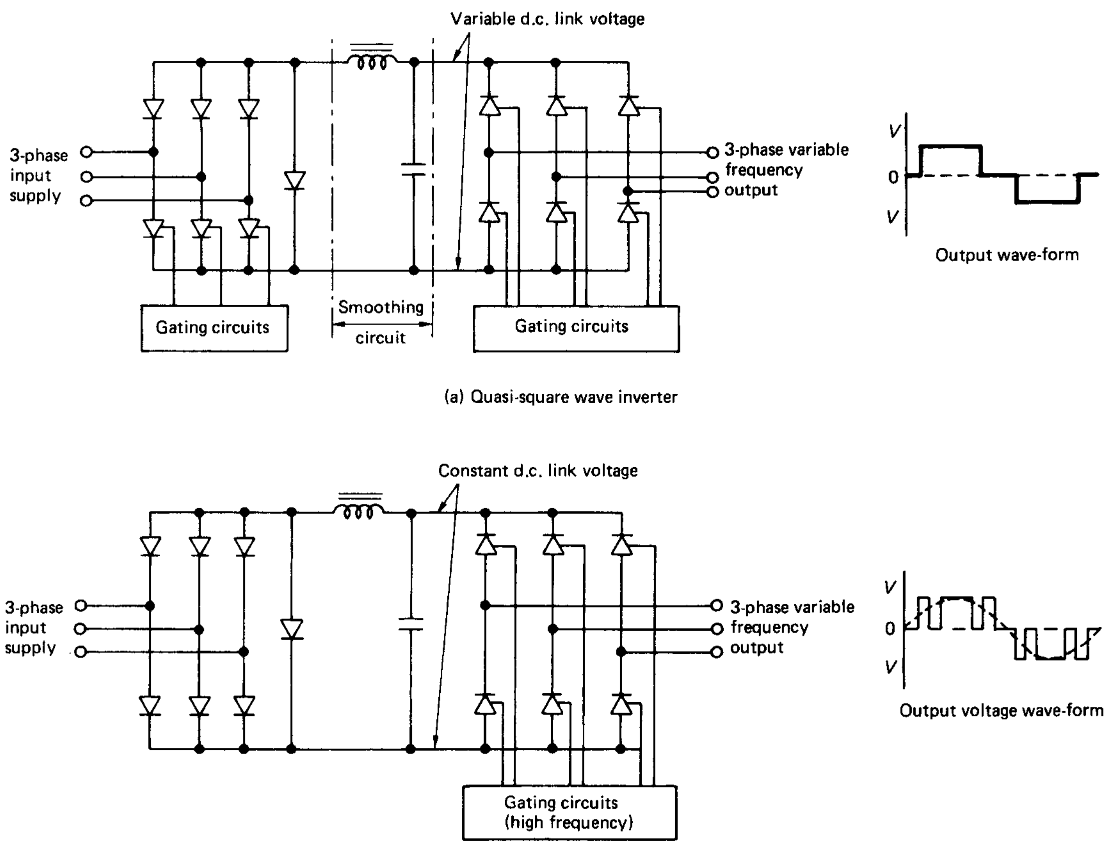
the secondary winding with respect to the primary. As a consequence, the angle at which the harmonics are produced (and thus the wave shape) is altered although the harmonic magnitudes are unchanged [44].

4. Reduction of the supply system impedance, either by increasing the generator frame size or by using a specially designed low-reactance machine.

*Inverters.* The inverter form most widely used in a.c. motor drive schemes and in fixed-frequency changers is that known as the *d.c. link inverter.* The a.c. supply to it is first rectified to give a direct voltage. This may be either at variable magnitude (see Figure 5.29(a» or at constant level (Figure 5.29(b». A three-phase inverter then converts this d.c. into a.c..

D.C. link inverters are classified by the output wave-form generated. This may be *quasi-square* shaped (Figure 5.29(a», or a synthesized sinusoidal waveshape (Figure 5.29(b». The latter is obtained from a constant d.c. link voltage by switching the inverter section thyristors at high frequency. This gives a constant-magnitude, variable-width, output voltage pulse simulating a sine wave-shape. A constant output voltage/frequency ratio is then obtained by varying the thyristors' switching speed and the mark/space ratio of the voltage pulse. Equipment giving this type of output is known as *pulse-width-modulated* (PWM) inverters.

One of two configurations may be employed in the quasi-square wave inverter. The first uses a half-controlled, or fully-controlled, rectifier to give a variable d.c link voltage. The output frequency is then controlled by varying the timing of the inverter-stage thyristor timing pulses. The firing circuits of the rectifier thyristors may also be coupled with those of the inverter section to give a constant volts-per-cycle ratio. The second configuration




(b) Pulse-width-modulated inverter

**Figure 5.29** Elementary arrangements of d.c. link inverters employs an uncontrolled diode-bridge rectifier in the input stage. The variable voltage for the d.c. link is obtained by using a d.c. chopper.

As far as generated harmonics are concerned, what applies to rectifiers also holds good for these types of inverter. The independent generator, feeding this type of equipment will 'see' the harmonic currents expected from a 6-pulse converting device.

The second type of inverter is a frequency changer, which has no intermediate d.c. stage, and is known as the *cycloconvertor.* The fixed supply frequency is 'chopped' directly by means of thyristors, arranged to conduct alternately in two inversely-connected convertors for each phase. An approximately sinusoidal wave-form is attainable. The main limitation with this type of inverter is that its output is at low frequency - less than the supply frequency. It is best employed for drive speeds corresponding to about one-third supply frequency and has inherent regenerative capabilities. In the latter context, it should be appreciated that d.c. link inverter drives of the type shown in Figure 5.29 are often fitted with regenerative convertors when they are used in reversing-drive applications. These regenerative capabilities are of particular significance to consumers using independent generators as a power supply source. The comments made in Sub-section 5.4.1 with regard to regenerative loads will equally apply here.

*Convertor power factor.* We have established (in Sub-section 4.2.3 of Chapter 4) that the expression:

power factor = true power (watts)/apparent power (volt-amperes)

always holds good as a definition for power factor. The alternative definition:

p.t. = *IR/V*

is only valid when both the voltage and the current wave-forms are sinusoidal.

As we have seen, the harmonic currents in the input to a thyristor convertor distort the line current wave-form. The *distortion factor* would be unity if no harmonics existed. A further consideration is that there is a *phase displacement* of the fundamental a.c. line current with respect to the a.c supply line voltage (see Figure 5.28(c». The extent of this displacement is affected by operating characteristics such as convertor phase control and 'system' reactance. Because phase control is not possible in an uncontrolled diode bridge rectifier, it would have a fairly high and constant power factor. On the other hand, one expects a thyristor convertor to have a lower, and variable, power factor.

The power factor is a product of *distortion* and *displacement* [41]. The displacement power factor, which satisfies the ever-valid definition of power factor (i.e. the ratio: input watts/input volt-amperes) is approximately equal to the ratio of *Eo/Eoo* [41].

Figure 5.30 (curve (a» illustrates the relationship between power factor and phase control delay angle o'. Curve (b) shows the effects of reduced power factor due to commutating reactance. The mode of operation changes from rectification to inversion at the point where the curves intersect the abscissa. The symbols used in Figure 5.30 are defined as follows:

*ED* = output voltage
*Eoo* = d.c. no-load voltage
Ie = commutating current
*Xc* = commutating reactance (which is the sum of source reactance and transformer leakage reactance - where the latter is applicable)
*Es* = source voltage (this could be the rated secondary voltage of a transformer - where applicable)
o' = controlled-bridge delay angle, or firing angle

During commutation, current *Ie* is, effectively, a 2-phase short-circuit current. It is only limited by the instantaneous voltage difference between source phase voltages and source (commutating) reactance.

The following example [34] typifies the effect of HCF loads with regard to system power factor.

*Example*

The harmonic analysis of a 2.6 crest factor balanced current wave-form gave these results:

| | r.m.s. | 50 Hz | 3rd | 5th | 7th | 9th | 11th |
|---|---|---|---|---|---|---|---|
| % | 120 | 100 | 45 | 36 | 24 | 14 | 14 |

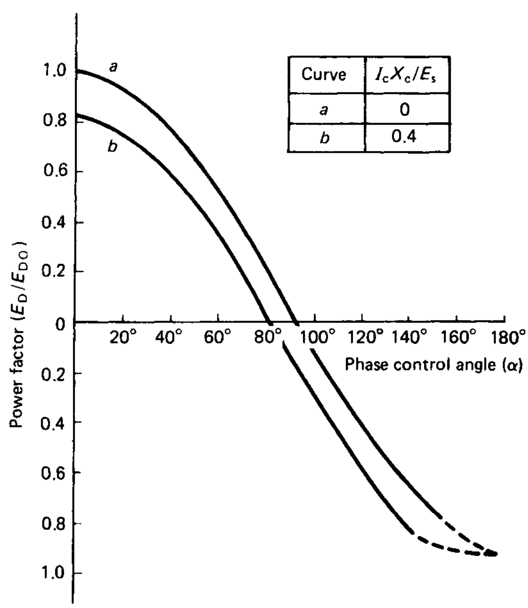



**Figure 5.30** Power factor/delay angle curves for a thyristor convertor

The total harmonic distortion (THD) (see also Appendix 5.2) is given by:

$$\text{THD} = \sqrt{(f_3^2 + f_5^2 + f_7^2 + \ldots \text{ etc.})}$$
$$= 0.65\ (65\,\%)$$
$$\text{r.m.s. value} = \sqrt{(1 + \text{THD}^2)}$$
$$= 1.2$$

This distortion factor is given by fundamental/r.m.s.
= 100/120
= 0.83

Generally, the displacement factor of HCF loads is less than 1 and, consequently, very low power factors obtain. McLennan [34] cites a typical value of 0.63 for a computer load.

It should be appreciated that the power taken from the supply source is a function of the fundamental current *only,* i.e. harmonics have the effect of increasing the r.m.s. current, without increasing the power demand. Discrepancies may therefore arise between r.m.s. current readings and the wattmeters connected to the system. Also, harmonics may cause errors in power factor meters, where these only measure the displacement factor and do not compensate for the distortion factor. A p.f. meter may indicate unity power factor when, in fact, it may be as low as 0.7 [34].

## *Currents in the neutral conductor*

In large lighting installations, as with HCF loads, the distortion of the supply current wave-form can be considerable. Contributory factors are the discharge tubes themselves and the inductive chokes forming part of their control gear. BS 2818 *(Ballasts for tubular fluorescent lamps)* effectively permits a 30 % third harmonic current to be 'generated' by lamps. This limit relates to a test source having a harmonic voltage content not exceeding 3 % (this compares with the 5 % to 10 % permitted by BS 4999 Part 101, for a generator). In practice, some generators are likely to have open-circuit voltage wave-forms with a harmonic content greater than 3 %. Some may even generate significant third harmonic voltages and their wave-form may worsen with load. See Appendix 5.2 for the wave-form analysis of a typical proprietary machine.

Even in well-designed lighting installations, where the load may be equally balanced between phases, third harmonic (or triplen) currents will be additive in the neutral conductor. If each of the three phase banks of the lighting gives a third harmonic current of 20 % (which is not untypical), the result would be 60 % r.m.s. current flowing in the neutral. If the load imbalance were such that there was full-load current in two phases, and none in the third, the 20 % harmonic would produce over 100 % current in the neutral [43].

Griffin [43] cites problems associated with standby generators. For example: the carefully balanced 250 kVA fluorescent lighting load in a warehouse was said to have had 13 % of full-load line current in its neutral when fed from the public electricity supply. When the same load was fed from a 320 kVA standby generator, the neutral current rose to 250 A (72 % f.l.c.). The presence of a high third harmonic content in the generator's output waveform was exacerbating the situation. The solution was to replace the generator's *11/12* pitch stator winding with one having a *2/3* pitch. The latter coil has the advantage of covering two harmonic pole-pitches and links zero third harmonic flux so that, in theory, third harmonic e.m.fs disappear from the phase e.m.f.. If a coil is short- or long-pitched by *-rrln, 3-rrln,* etc., no harmonic of order *n* will survive in the phase e.m.f. [13]. In the warehouse problem, the replacement winding resulted in the neutral current falling 'to less than it had been on the mains'.

A similar situation arises on convertors which have fully-controlled thyristor rectifiers fed from a three-phase supply. As the firing angle of the thyristors approaches 90°, the r.m.s. current in the neutral reaches a maximum value equal to the full-load line current. It falls away towards zero at full power as the firing angle approaches 180°, The maximum neutral current consists entirely of 3rd, 9th, 15th, ... , etc. harmonics [44].

The generator manufacturer should be consulted for those applications where third harmonic load currents are likely to exceed 15 %. Fortunately, modern high-speed generators in the range 50 to 500 kVA usually have *2/3* pitch stator windings. These windings are also available at outputs up to 1500 kVA, but with, perhaps, some sacrifice in output or voltage range [43].

## *Sizing of generators for non-linear loads*

It is difficult to generalize on the capabilities of standard generators, as far as convertor loads are concerned. Rules of thumb, which involve the oversizing of generating plant, are usually too rigid and overly simplistic. Opinions differ as to the capabilities of 'standard' machines in coping with non-linear loads. Some would place the limit as high as 70 % of rating, whereas others are more conservative in suggesting a limit at nearer 50 %. In any event, by far the best approach is to pass all available information on the proposed load to the generator manufacturers and give them the opportunity of selecting the right machine for the application - consistent with any limits imposed on wave-form distortion.

Machine manufacturers use general factors, based on experience, to estimate the generator size for non-linear loads. The crux of the problem is one of generator impendance. The current harmonics produced by non-linear loads are constant, regardless ofthe power source. The voltage distortion, however, is a direct function of the generator impedance. *(Note:* There is no one value of impedance which can be used for all harmonic orders. The stator winding, being of pitched configuration, has varying reactance for each harmonic order. Therefore, a true theoretical approach to evaluating the voltage distortion would need to examine all orders individually. Whilst this may be a simple mathematical analysis, evaluation of the generator reactance at all orders of harmonics is complex and subject to significant inaccuracies [45]).

The main concern is the effect of the distorted voltage wave-form on automatic voltage regulators (A VRs), as this could influence stability. Those A VRs which are fed from the main generator windings could be disturbed by heavy distortion interrupting their power circuits (and causing misfiring of their output device) or by changing peak values in their sensing circuits. The generator excitation system is just one of several 'closed loops' within a power network supplying non-linear loads. Compatibility of these closed loop systems is essential for stable network operation. (See Sub-section 5.4.4.)

The development of excitation control systems employing permanent magnet auxiliary exciters (see Chapter 7) has done much to minimize the effects of voltage distortion. The power of the A VR remains constant, irrespective of generator output voltage wave-form. Only the sensing circuits are subjected to the voltage distortion. Improvements in this area, as a result of *average* (rather than *peak)* and 3-phase (rather than single-phase) sensing, gives the best possible signal to the A VR, and better overall regulation and stability. The isolation and filtration techniques used in modern A VRs appear to provide tolerable performance in all but the most extreme circumstances [19].

It is feasible to design generators with specific winding pitches and low reactance in order to minimize distortion levels. But, for sound commercial reasons, derating of *standard* industrial generators is the only practical solution. Fundamental machine design changes for specific applications are not viable options. Generator sizing is derived from the manufacturer's past practical experience, and the synchronous $(X_s)$ or subtransient $(X'd)$ reactance values are usually used as the yardstick [45]. (See Sub-sections 4.2.6 and 4.3.1 of Chapter 4.) Newage International, for example, have selected a 0.12 p.u. subtransient reactance as a good practical figure (on the basis of a 6-pulse, variable speed, motor drive, having 26 % current distortion, giving 20 % voltage distortion at approximately 80 % of the generator rating).

The following example [45] illustrates how a generator would then be sized to power a 6-pulse, 200 kV A input, uninterrupted power supply (UPS) system, plus a 30 kV A linear load. Because the UPS rating should not exceed 80 % of generator rating, at 0.12 p. u. subtransient reactance, the generator rating (at 0.12 $X'd$) must be (200/0.8)kVA = 250kVA. The maximum total load is (200 + 30) kV A = 230 kV A. The generator may then be sized on 250kVA - at 0.12p.u. $X'd'$

If the nearest standard generator has an industrial rating of 275kVA at O.13p.u. $X''d$, its rating at 0.12p.u. $X'd$ would be:

275 x (12/13) = 254 kV A

It would therefore be suitable for the proposed duty.

## *Sensitive equipments*

We shall now consider the effects that wave-form distortion can have on equipment connected to the network.

*On-site generators.* We have established that wave-form distortion will affect, not only the sensing and firing circuits of the A VRs associated with machine excitation systems, but also (where a machine is self-excited) the excitation power available from the main output winding. Furthermore, if the firing angle of the thyristor load approaches that of any thyristor in the generator's automatic controls, the two systems may interact to give overall system instability. Separate pilot excitation will be an advantage.

The presence of any 2 nd harmonics (and multiples thereof) will induce pole-face currents in generators. This could lead to local overheating.

*Capacitors.* BS 1650 *(Capacitors for connection to power frequency systems)* limits the harmonic overloads permissible on capacitors. Because the reactance of a capacitor is inversely proportional to frequency, it is particularly sensitive to high frequency harmonics. The presence of any resonance conditions in a power factor correction network will not help either. A series inductor in the power factor correction circuit will prevent this happening. The inductor must have a reactance about 1/10 th that of the capacitor bank at fundamental frequency.

*Technical loads*. These may include computers. communications, signals and radar installations, and electronic office equipment. All are sensitive, in varying degrees, to wave-form distortion. Typical limits on total harmonic content are set at between 3 % and 5 %. Electronic office equipment (such as microcomputers, and associated laser and ink-jet printers) usually form a small, but critical, proportion of the total load in many commercial installations. The load attributable to these machines is of the order of 10 to 20 watts per square metre of office area. It is customary to provide larger installations with some form of standby supply, based on engine-driven generators and/or UPS systems. (See Chapter 11.)

Convertors operating under fully-controlled conditions tend to produce low power, high frequency, signals in the range 150 kHz to 30 MHz. These signals are likely to cause disturbance to nearby radio receiver and transmission equipment either by direct radiation from the convertor housing itself, or by being carried on the incoming and outgoing power conductors to radiate elsewhere. Direct radiation from within the converter itself may be suppressed by simply earthing its housing cubicle. Signals carried along the external cables require the use of special filter, or suppression, networks to prevent them radiating elsewhere. The technology is described as *radio interference suppression* or *radio frequency interference (RFI) suppression.*

Radio interference limits are defined in several standards, notably:

- BS 800, for industrial and household equipment;
- BS 1597, and its associated Code of Practice BS 5260, for marine installations;
- the Federal German Republic's VDE 0875 – whose Grade G is very similar to BS 800 Part 3; and
- military specifications and defence standards such as those whose curves are compared in Figure 5.31, where the ordinate scale of dB(μV) is based on 0 dB(μV) being equivalent to 1 μV. The dotted curves show the RFI levels recorded on a typical machine, in tests before and after suppression.

Many drive systems are required to operate in a fully automated mode, controlled by telemetry links. It is important that both convertor equipment and power source are adequately suppressed against interference in the signal frequency range used for the telemetry link.

*Motors and transformers.* Motors, like generators, are particularly affected by 2 nd order harmonics and multiples thereof. The effects are increased losses and localized heating.

The presence of third harmonic currents in transformers will lead to increased iron loss and overheating of windings. Third harmonic voltages may overstress insulation and could give rise to resonance, at third harmonic frequency, between transformer windings and network capacitance.

*Cables.* Cables should be capable of withstanding the effects of a total voltage distortion of 10% without damage. Harmonic currents may reduce ratings due to: *PR*, eddy current, and skin and proximity effects. A current distortion limit of 10% is recommended if reduction in rating is to be avoided (33].

*Control and protection devices.* Unwanted harmonics are likely to affect generator excitation, convertor firing controls, and electronic devices in

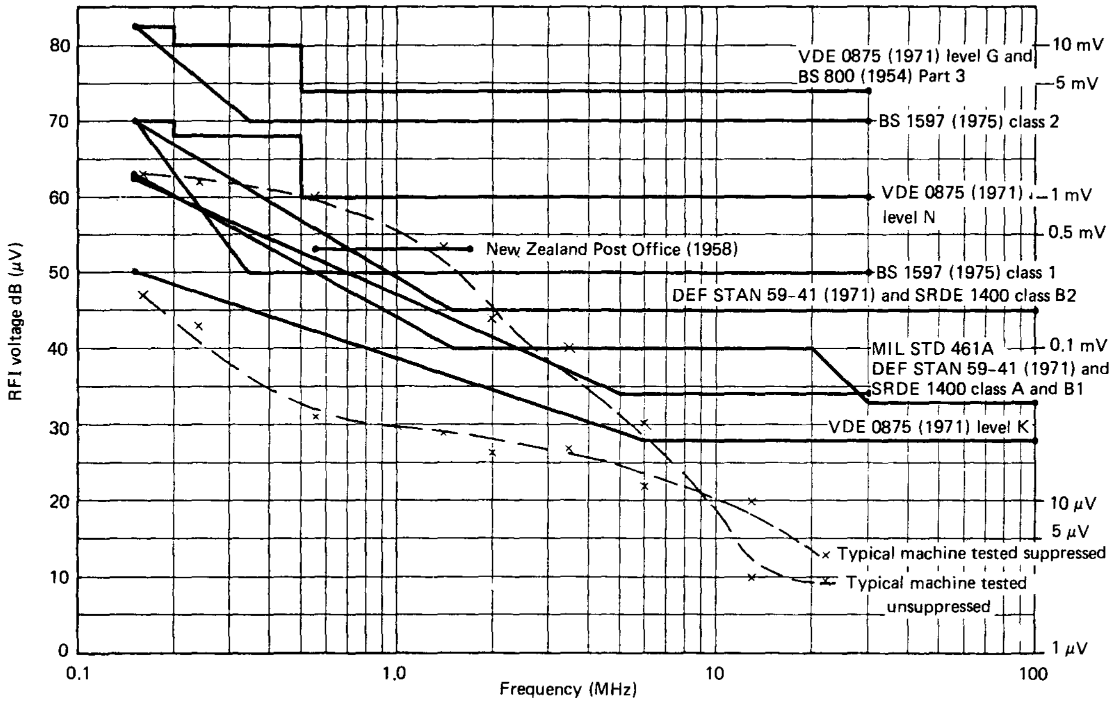



**Figure 5.31** Limits of radio frequency interference set by various standards (Courtesy: Newage International Ltd)

systems concerned with monitoring, alarm and protection functions. For example, 'notches' in voltage wave-forms could cause incorrect operation of voltage and frequency monitors unless they are adequately filtered; overload protection relays fed by current transformers may trip at low current levels, when harmonic currents are present.

### 5.4.4 Cyclic loads

Certain loads, such as radio identification beacons or transmitters, vary cyclically at a regular rate, with periodic times between 0.3 and 5 seconds. Where regular load-pulse intervals interact with the prime mover governor's response characteristics, speed (and therefore frequency) oscillations are likely. Improving engine speed response, by fitting, for example, a fast-acting governor, may merely introduce instability and, possibly, excessive wear on the governor's precision parts and linkages. Conversely, reducing governor response should alleviate a hunting problem, but at the risk of putting normal speed recovery outside acceptable limits. Therefore, where regular load pulses are expected, a compromise must always be sought in selecting the correct generator shaft system inertia and the correct governor response characteristics for the proposed duty cycle. Sufficient rotating energy, in the form of inertia mass, should be built into the generating unit(s) to minimize the momentary speed changes that will be outside the control response of governor and turbo-charger (where one is fitted). To this end, the largest standard flywheel capable of being fitted to the diesel engine should be considered. The additional rotor inertia of a larger frame generator will also assist in this respect.

Manning [46] gives an example of typical cyclic load conditions relating to a radio relay station. The installation was for the External Radio Service of the British Broadcasting Corporation (BBe). The input power demand from the HV rectifiers feeding each of the four anode-modulated transmitters varies rapidly with the degree of transmitter modulation and is dependent upon the programme material being broadcast from the station.

(Koeppen [47] gives the following formula for calculating the power required for a transmitter:

$$S_A = \frac{P_0(1 + m^2/2)}{\cos\phi . n}$$

where $S_A$ = power input in kVA
$P_0$ = power transmitter output in kW
$m$ = degree of modulation
$\cos\phi$ = 0.7 to 0.9
$n$ = 0.55 to 0.7
$1 + m^2/2$ = 1.08 for programme operation with 40% modulation)
= 1.50 for 100% sine-wave modulation)

For the example cited [46], in worst-case conditions, all four transmitters are operated on the same programme and their modulation level varies between zero and 100%. The transmitter load fluctuates rapidly (at syllabic or tonic frequencies) between 1920kW and 3020kW (approximately 60% load step changes). Generator voltage controls and engine governors were designed to take account of these load fluctuations in the frequency range 3 Hz to 15 Hz.

The three basic interactive control loops that would have had to be considered in a design exercise of this type are shown, in simplified form, in Figure 5.32 [48]. The schematic shows the mutual interactions between the three automatic-control loops of engine governor, generator control, and rectifier control. The characteristics within the functional blocks of each loop give an indication of their individual step responses. The d.c. current from the rectifier to the anode-modulated transmitter is the final loop output in the schematic and has a direct influence on the prime mover speed - the parameter controlled in the first of the three loops.

When the BBC broadcasts its signature tune and time signals, using all four transmitters, rapid and substantial load changes occur. Their nature is illustrated in Figure 5.33, which reproduces traces taken during engine performance tests. These tests were designed to simulate the hourly time-signal load changes.

## 5.5 Related standards

Specific reference has been made to the following British Standards in this chapter. Entries in brackets contain reference to corresponding and/or technically equivalent international or world regional standards.

BS5424: Part 1 (IEC 158-1 and lA) - *Contactors*
BS 2949 (lEC 92-5) - *Rotating electrical machines for use in ships*
BS 5406 (EN 50006) - *The limitation of disturbances in electricity supply networks caused by domestic and similar appliances equipped with electronic devices*
BS 2818 (IEC 82) - *Specification for ballasts for tubular fluorescent lamps*
BS 4999 - *General requirements for rotating electrical machines* Part 101 (lEC34-1) - *Specification for rating and performance*
BS 1650 (IEC70) - *Capacitors for connection to power-frequency systems*
BS 800 (VDE 0975 Grade N) - *Specification for radio interference limits and measuremenlS for equipment embodying small motors, contacts, control and other devices causing similar interference*

Schematic legend

1. Engine speed control
   - 1.1 Generator set inertia
   - 1.2 Speed governor
   - 1.3 Fuel injection system
   - 1.4 Deviation produced by load torque
2. Generator voltage control
   - 2.1 Excitation circuit
   - 2.2 Automatic voltage regulator
   - 2.3 Deviation of frequency (rotary speed)
   - 2.4 Deviation of load current $I_L$
3. Rectifier control
   - 3.1 Thyristor circuit
   - 3.2 Automatic voltage control (inc. triggering circuits)
   - 3.3 Deviation of a.c. input voltage
   - 3.4 Time-delay of voltage increase (by filters)
4. D.c. load current response determined by load changes (e.g. modulated-transmitter as Figure 5.33)

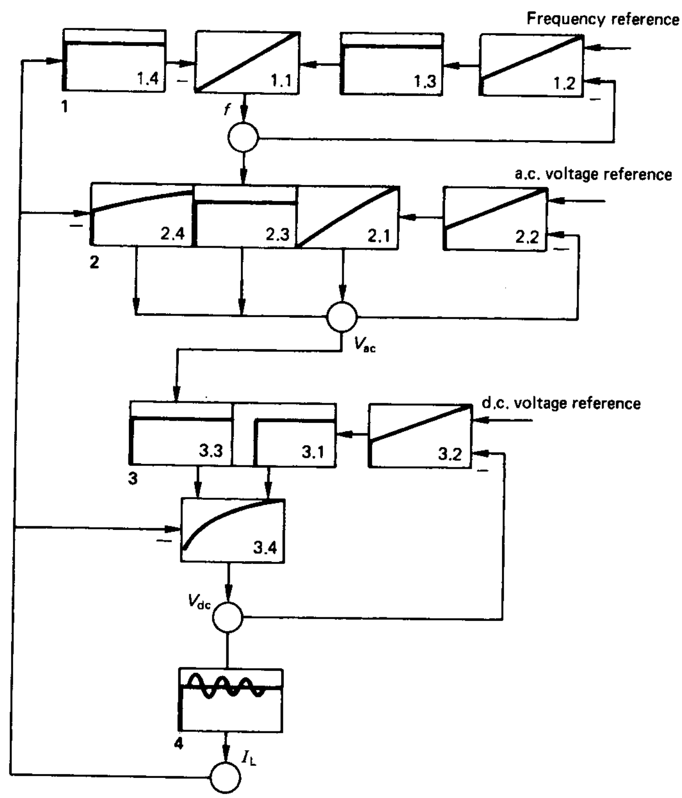



**Figure 5.32** Typical schematic of the control loops in a diesel generator/controlled convertor system (Courtesy: AEG)

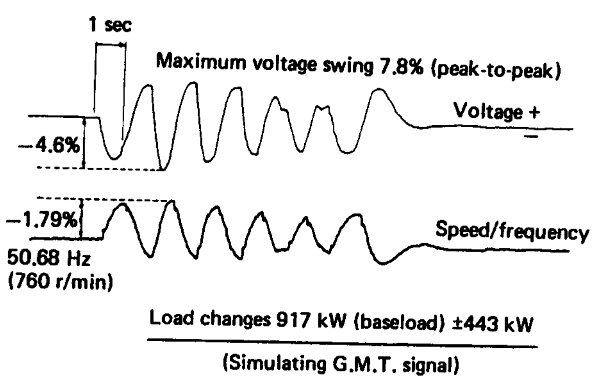



**Figure 5.33** Oscillograms showing variations of voltage and speed/frequency during load changes imposed by hourly transmitter time signals (Courtesy: NEI Allen Ltd)

BS 1597 - *Radio interference suppression on marine installations*
BS 5260 - *Code of practice for radio interference suppression on marine installations*

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### 5.6.2 Bibliography

The references listed above contain, within themselves, useful cross-references to related papers on the topics covered. Additionally, the lEE Conference publications mentioned in [15], [22], [24] and [48] also contain a significant number of contributions which may be of help to the reader who is researching this chapter's subject matter.

**In** this context, the lEE Conference publication No. 272 covering the first *International Conference on Industrial Power Engineering,* organized by the lEE in London in December 1986, also includes helpful and informative papers on electrical power system design and the nature of loads in industrial systems.

The following literature, reports and papers also cover the various topics of this chapter, in some detail.

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## Appendix 5.1 - Selection of power plant for load conditions

The following example has been devised to demonstrate the practical methods used for assessing the sizes of a.c. generator and prime mover required for a given installation.

### Example

A standby generator is required to supply the following essential loads within a manufacturer's premises with 415 volts 3-phase 50 Hz, in the event of a utility supply failure.

#### Load details

*Single phase - 240 V*

1. Fifteen high-pressure mercury vapour, highbay luminaires (400 W nominal each) and 60 fluorescent fittings (100 W nominal each), all corrected to 0.95 power factor lagging.
2. 10 space heaters (5 kW each) at unity power factor.

*Single phase - 415 V*

3. Seven welding machines each rated at 12 A primary current at 0.4 power factor lagging

*Three-phase - 415 V*

4. A process control system rated at 10 kW at 0.85 power factor lagging.
5. A series of motors driving process line equipment, as follows:

   1 kW (7 number)
   3kW (3 number), all d.o.!. started

6. One motor, 30kW d.o.!. started;
   One motor, 80kW star/delta started.

#### Governing conditions

1. For safety and operational reasons, the essential lighting (load element 1), the process control system (load element 4), five 1 kW motors and one 3 kW motor (load element 5) must be restored as soon as possible, after utility supply failure.
2. The 80 kW motor (load element 6) may not be started until all other motors are on-line.

3. The process control equipment is sensitive to any voltage dips of more than 10 % magnitude.
4. The remainder of the site's plant will tolerate a 20 % voltage dip.

## Load application stages

Based on these governing conditions, the following stages of load restoration were agreed with site management.

| *Stage* | *Load element* | *Description* |
|---|---|---|
| 1 | i | Lighting |
| | 4 | Process controller |
| | 5a | 1 No. - 3 kW motor d.D.!. |
| | | 5 No. - 1 kW motors d.o.!. |
| 2 | 6a | 1 No. - 30kW motor d.o.!. |
| | 5b | 2 No. - 3 kW motors d.o.!. |
| | | 2 No. - 1 kW motors d.o.!. |
| 3 | 6b | 1 No. - 80 kW motor star/delta |
| | 3 | 7 No. - welding machines |
| | 2 | 10 No. - space heaters |

## Procedure

The running (steady-state) and starting (transient) kVA and kW requirements of each load element must first be analysed, before being tabulated for each of the load-application stages proposed.

Motor nameplates, or manufacturers' literature will provide details such as:

full-load power
efficiency
power factor
starting current
starting torque
peak (or pull-out) torque

Given such data it is possible to calculate:

1. the starting kVA, which may be obtained directly from the starting current;
2. the running kW requirement: this from the ratio of operating load divided by the motor efficiency. If the operating load is not known, assume the worst case, i.e. the motor is running on full load;
3. the running kVA: this is given by the running power, as at 2 above, divided by the power factor. It should be appreciated that power factor will vary considerably with the operating load. Typical values for the sizes of motor considered in this example are tabled below;
4. the maximum kW demand at starting: since information on the maximum power factor during starting is seldom available, a reasonable

| *kW* | *Full load* | 75 % *f.l.* | *50 % f.l.* |
|---|---|---|---|
| 80 | 0.92 | 0.91 | 0.88 |
| 30 | 0.90 | 0.88 | 0.83 |
| 3 | 0.85 | 0.81 | 0.73 |
| 1 | 0.80 | 0.75 | 0.65 |

estimate of the peak starting power requirement can be obtained from the expression [17]:

peak power = [rated power x peak torque (p.u.)]/motor efficiency

Peak or pull-out torque is usually between 2 and 2.8 times rated torque. For this example, we shall assume 2.5 p.u.

## Load analysis

### *Single phase loads*

*Lighting* (load element 1) The 15 mercury vapour and 60 fluorescent lamps may be balanced over the three phases. The load per phase would then be as indicated in Table 5A.

*Space heating* (load element 2) Since there ate ten space heaters over three phases, one phase must supply four heaters; the loads are therefore as detailed in Table 5B.

*Welding machines* (load element 3) With each of the seven welding sets across one pair of 415 V line conductors there is a 'worst-case' condition of three sets across a particular pair of lines.
This gives the loading conditions shown in Table 5C.

### *Three-phase loads*

*Process controls* The load is:

| *Running* | *Starting* |
|---|---|
| lOkW | Typically, 47 kYA |
| *10/0.85* = 11.8kYA | 47 x 0.5 = 23.5 kW |

*Induction motors* The loads are listed in Table 5D.

## Load demand at each stage

Strictly speaking (as discussed in Section 5.4.1 and illustrated in Figure 5.21), the effect of power factor in transient load switching should be considered by a vectoral summation of existing and incoming loads at each stage. However, for the purpose of this exercise, we shall ignore that requirement and make an arithmetical addition instead. This is normally

**Table 5A**

| | Running | Starting |
|---|---|---|
| Mercury vapour | 5 × 400 × 1.8 = 3.6kVA<br>and 3.6 × 0.95 = 3.4 kW | 5.8 kVA<br>1.7 kW<br>(see Figure 5.27) |
| Fluorescent | 20 × 100 × 1.8 = 3.6 kVA<br>and 3.6 × 0.95 = 3.4 kW | Typically, 4.7 kVA<br>and 2.3 kW |
| Total equivalent 3-phase load | 20.4 kW<br>21.6 kVA | 12.0 kW<br>31.5 kVA |

**Table 5B**

| | Running | Starting |
|---|---|---|
| Maximum single-phase load | 4 × 5 = 20 kW<br>20 kVA | as running |
| Equivalent 3-phase load | 60 kW<br>60 kVA | 60 kW<br>60 kVA |

**Table 5C**

| | Running | Starting |
|---|---|---|
| Maximum single-phase load | (3 × 415 × 12)/<br>1000<br>= 14.9 kVA<br>14.9 × 0.4 = 6 kW | 37.3 kVA<br><br><br>18.6 kW |
| Equivalent 3-phase load | 18 kW<br>44.7 kVA | 55.8 kW<br>111.9 kVA |

**Table 5D**

| *Rating* (kW) | *Efficiency at rated power* | *Power factor at rated load* | *Power requirements* | | | |
|---|---|---|---|---|---|---|
| | | | *Running* | | *Starting* | |
| | | | kW | kVA | kW | kVA |
| 1 | 0.75 | 0.8 | 1.3 | 1.6 | 3.3 | 10.5 |
| 3 | 0.80 | 0.85 | 3.8 | 4.5 | 10.5 | 29.4 |
| 30 | 0.90 | 0.90 | 33.3 | 37.0 | 83.3 | 261.0 |
| 80 (Y-Δ) | 0.92 | 0.92 | 87.0 | 94.6 | 217.4 | 219.0 |

acceptable for sizing exercises of this type as the arithmetic addition always gives a larger kYA load demand figure than the vectorial addition.

The three-phase starting and running (kYA and kW) requirements are summarized in the following tables and are based on the stage load elements listed earlier in this Appendix.

The voltage dip experienced by the generator is related to the highest applied kYA at any of the three load stages (column 1 of Table 5 E). From Table 5.E it will be seen that the maximum is 390.9 kYA; and occurs at stage 3.

Referring back to the governing conditions, we see that a critical factor is the voltage dip limit of 10% imposed by the process control equipment. Assuming that the generator voltage dip characteristic of Figure 5.17 applies in this case, it becomes necessary to restrict the applied kYA to no more than about 0.5 times the maximum rating of a generator frame if the voltage dip is to be limited to

**Table 5E** Starting and running kVA requirements

| *Stage* | *Starting kVA* | | | *Running kVA* | | |
|---|---|---|---|---|---|---|
| | *kVA applied this stage* | *Running kVA existing* | *Peak kVA* | *kVA this stage* | *kVA from previous stage* | *Total kVA running* |
| | (1) | (2) | (3)=(1)+(2) | (4) | (5) | (6)=(4)+(5) |
| 1 | 160.4 | Nil | 160.4 | 45.9 | Nil | 45.9 |
| 2 | 361.8 | 45.9 | 407.7 | 49.2 | 45.9 | 95.1 |
| 3 | 390.9 | 95.1 | 486.0 | 199.3 | 95.1 | 294.4 |

10 %. This means that we would need to select a generator rated for 782kVA (= 390.9 -:- 0.5), i.e. 2.7 times the steady-state kVA requirement (294.4 kVA) of our essential load. Obviously, this is not an economical proposition. We are faced with two practical alternatives:

1. The first is to 'remove' the performance restriction imposed by the process controller, by supplying it from a dedicated inverter, thus isolating it from all disturbances in the standby generator supply (see Chapter 11). This means that we could work to the wider (20 %) voltage dip tolerance applicable to the remainder of the consumer's essentialloads (governing condition 4). This being so, we can select a generator frame with a maximum rating of 390.9 kVA to meet the less arduous 20 % voltage dip tolerance (see Figure 5.17). The selected generator is now only some 1.3 times the capacity required by our steady-state load. This is not unreasonable, economically, and it does allow for the 'accommodation' of further essential loads, either now or at some future date when the site is expanded.
2. The alternative is to rearrange the load switching sequences - provided, this is acceptable to the user. So that, for example, an intermediate load-restoration stage is introduced between stages 2 and 3. The revised load-switching pattern could then be:

The revised start/run kVA requirements would then be as shown in Table 5 F. This now gives us a maximum applied kVA, at any stage, of 361.8 (as opposed to the 390.9 kVA of our original loading pattern). This means that, if we are to meet the 10% voltage dip limitation imposed by the process controller, the selected generator frame now needs to be rated for 723.6kVA (= 361.8 -:- 0.5) i.e. 2.5 times the required steady-state rating - still not an economical proposition .•

Perhaps the best compromise would be to provide the process controller with a separate and 'buffering' inverter and, at the same time, revise the loading stages as Table 5 F above. If this is done, the maximum rating of the generator frame needs to be at least 361.8 kVA, in order to meet the 20 % voltage dip limitation.

As explained in Section 5.4.1 the selected machine must have an overload capability greater than the largest peak kVA figure given in column 4 of Tables 5 E and 5 F. In this example these maxima are 486 and 407.7kVA; and equate to per-unit overload requirements of 1.24 (486/390.9) and 1.38 (407.7/294.4), respectively. Both are well within the 2.0p.u. capacity, for 10 seconds, associated with generators of this size. Generally speaking, in order to achieve the minimum size of generator based on overload performance, it is desirable to apply starting loads (column 2) in descending order of magnitude, i.e. the largest starting load should be switched-on first, and the smallest last. Whilst this is the ideal, it is seldom achieved in practice.

Having considered the optimum sizing of the generator (against kVA requirements), it is now necessary to analyse the kW requirements. It is these that will determine the rating of the prime mover to be used. Table 5 G gives the starting and running kW demands at the three stages corresponding to those of Table 5 E.

The first conclusion to be drawn, when comparing the total running kW (249.2) from this table with the corresponding total kVA (294.4) in Table 5 E, is that the essential load's power factor is of the order of 0.85 (249.2/294.4). This implies that the selected generator should not have to be derated for power factor (see Chapter 3, Section 3.7.2).

The next point to be noted is that the peak starting demand is 417.4kW. When the generator losses are taken into account (the efficiency of a machine of this size is approximately 93 %), this demand equates to 449kW, and is the output required from the prime mover during the load

**Table 5F** Starting and running kVA requirements for revised stages

| *Stage* | *kVA applied this stage* | *Starting kVA Running kVA existing* | *Peak kVA* | *kVA this stage* | *Running kVA kVA from previous stage* | *Total kVA running* |
|---|---|---|---|---|---|---|
| 1 | 160.4 | Nil | 160.4 | 45.9 | Nil | 45.9 |
| 2 | 361.8 | 45.9 | 407.7 | 49.2 | 45.9 | 95.1 |
| 2a | 219.0 | 95.1 | 314.1 | 94.6 | 95.1 | 189.7 |
| 3 | 171.9 | 189.7 | 361.6 | 104.7 | 189.7 | 294.4 |

**Table 5G** Starting and running kW requirements

| *Stage* | *kWapplied this stage* | *Starting kW Running kW existing* | *Peak kW* | *kW this stage* | *Running kW kW from previous stage* | *Total kW running* |
|---|---|---|---|---|---|---|
| 1 | 62.5 | Nil | 62.5 | 40.7 | Nil | 40.7 |
| 2 | 110.9 | 40.7 | 151.6 | 43.5 | 40.7 | 84.2 |
| 3 | 333.2 | 84.2 | 417.4 | 165.0 | 84.2 | 249.2 |

changes in stage 3. This means that the prime mover need only be continuously rated for about 408 kW, at site conditions since advantage can be taken of its 10% overload capacity to meet the momentary 449 kW demand. A prime mover of this capacity would normally be coupled to a generator of some 475 kVA rating. Were our generating set to be so rated, we would expect a voltage dip of the order of 17% when switching the 390.9 kVA required in stage 3 of Table 5 E. This is still an unacceptable performance as far as the process controller is concerned. Furthermore, a 475 kVA machine is 1.6 times the capacity required by the total steady-state load.

We shall now analyse the kW requirements of the 4-stage load restoration pattern of Table 5 F to determine if any reduction in peak demand results. The analysis is presented in Table 5 H.

Clearly, this has had the desired effect of reducing the peak starting requirement (from the 417.4 kW of Table 5 G to 301.6 kW). Taking generator efficiency into account, this revised demand means that the prime mover need only have a momentary capacity of about 325 kW with a corresponding continuous rating of about 295 kW. This size of prime mover would normally be equipped with a generator of some 340 kVA. This rating is only 15% higher than the total steady-state load requirement of 294.4 kVA and would be quite acceptable in our case. Unfortunately, unless the selected generator frame is capable of a maximum rating of 361.8 kVA we shall have voltage dip problems - the dip will exceed our permissible limit of 20%.

## Conclusions

To meet the conditions set by the consumer, it is necessary to use a generator with a minimum capacity of 361.8 kVA; and a prime mover with a minimum continuous output of295 kW.

**Table 5H** Starting and running kW requirements for 4-stage switching

| *Stage* | *kWapplied this stage* | *Starting kW Running kW existing* | *Peak kW* | *kW this stage* | *Running kW kW from previous stage* | *Total kW running* |
|---|---|---|---|---|---|---|
| 1 | 62.5 | Nil | 62.5 | 40.7 | Nil | 40.7 |
| 2 | 110.9 | 40.7 | 151.6 | 43.5 | 40.7 | 84.2 |
| 2a | 217.4 | 84.2 | 301.6 | 87.0 | 84.2 | 171.2 |
| 3 | 115.8 | 171.2 | 287.0 | 78.0 | 171.2 | 249.2 |

One option is to install a generating unit employing a 295 kW prime mover coupled to a generator, whose frame is capable of a maximum rating of 362 kVA, but would be nameplate-rated for 340kVA (to match the prime mover output). This would not only result in a 'non-standard' generating set, but it would also restrict the potential to accommodate non-essential, but desirable, loads, and any future essential loads resulting from expansion of the consumer's site operations.

Provided adequate funds are available, it would be prudent to install, initially, a 'standard' unit using a prime mover rated 20% higher than that now required. This would give a generator output of about 360 kVA. Much will depend upon where this rating falls within a machine manufacturer's range. For example, it is possible that the 360kV A rating is obtainable from a generator frame whose maximum output is 420 kVA, giving increased potential for coping with inrush kVA loads.

It should be appreciated that, unless some form of auto-recloser is used on the contactor switchgear controlling the lighting, heating, process controller and d.o.!. motors, it is unlikely that the standby generator will experience simultaneous switching of the load elements at each stage. The load steps calculated in this example, therefore, represent 'worst-case' emergency conditions.

These conclusions are, of course, based on the assumption that an inverter will be installed to give a dedicated supply to the process control equipment. Again, capital permitting, it would be prudent to incorporate a battery energy store in the inverter equipment to provide the processor with an uninterruptible power supply. See Chapter 11.

## Appendix 5.2 - Wave-form analysis of a typical generator

The table below gives the wave-form analysis of one of a range of generators manufactured by Newage International of Stamford, England. The machine has a 3-phase, 50Hz continuous rating of 160kW. Results were obtained using a Camille-Bauer wave analyser.

| *Harmonic* | *Frequency* | *L to L No load* | *L to L Full load unity p.f.* | *L to L Full load 0.8 p.f.* | *L to N No load* | *L to N Full load unity p.f.* | *LtoN Full load 0.8 p.f.* |
|---|---|---|---|---|---|---|---|
| Fundamental | 50 | 100% | 100% | 100% | 100% | 100% | 100% |
| 3 | 150 | 0.20 | 0.11 | 0.19 | 0.30 | 0.28 | 0.21 |
| 5 | 250 | 0.64 | 0.32 | 1.7 | 0.74 | 3.2 | 1.6 |
| 7 | 350 | 0.64 | 0.72 | 0.48 | 0.52 | 0.90 | 0.53 |
| 9 | 450 | 0.12 | 0.07 | 0.14 | 0.16 | 0.09 | 0.14 |
| 11 | 550 | 0.72 | 0.32 | 0.70 | 0.70 | 0.34 | 0.78 |
| 13 | 650 | 0.35 | 0.18 | 0.29 | 0.40 | 0.16 | 0.25 |
| 15 | 750 | 0.13 | 0.11 | 0·07 | 0.11 | 0.10 | 0.09 |
| 17 | 850 | 0.23 | 0.27 | 0.23 | 0.24 | 0.19 | 0.21 |
| 19 | 950 | 0.20 | 0.18 | 0.02 | 0.06 | 0.20 | 0.07 |
| 21 | 1050 | 0.10 | 0.09 | 0.03 | 0.05 | 0.04 | 0.02 |
| 23 | 1150 | 0.08 | 0.14 | 0.04 | 0.05 | 0.02 | 0.04 |
| 25 | 1250 | 0.07 | 0.10 | 0.07 | 0.03 | 0.08 | 0.09 |
| Total % distortion | | 1.28 | 3.33 | 1.95 | 1.29 | 3.37 | 1.94 |

$$\% \text{ distortion} = \sqrt[2]{\Sigma(a_3^2 + a_5^2 \ldots\ldots a_n^2)}$$

taking values for $a_3$, $a_5$ etc from each column

# 6

# Engine governing

**Contents**

## 6.1 Introduction

In this chapter we shall consider the principles behind the many forms of speed governor used in the control of diesel engines in generating plant. First, the meanings of commonly used governing terms will be explained and, then, the factors that influence the selection of governors will be examined. This will be followed by a discussion of the fundamental operating principles of the various governor types, before a more detailed study is made of the constructions and actions of some commercial examples.

The reason for the complex mechanical solutions offered is that any engine system is inherently unstable. This is due to the time lag between modification of the fuel position and a resulting new value of torque produced at the crankshaft. For example, if a 4-stroke engine runs at 1200 rpm it must complete two revolutions before any change in fuelling rate has an effect. This will take 60/1200 s or 50 ms. If the natural acceleration of the engine is 60 % per second (a fairly normal figure), the result would be a 3 % excursion from set speed, and the fuel pump/governor/engine combination would oscillate continuously to correct this condition - a phenomenon known as *hunting*. Therefore, in addition to providing a precise *regulation of speed*, a governor must include some compensating system to control this instability.

## 6.2 Basic terminology

The definitions that follow are not necessarily precisely those given in any national standards, rather, they are largely based on glossaries of terms contained in [1] to [7], and in the British Standard Specification BS 5514 - *Reciprocating internal combustion engines:* Part 4. *Speed governing.* The intention here is to convey, in as simple a form as possible, the meanings of those terms that are in most common use.

*Actuator:* A device in a governing system which provides the final control output, usually to the fuel pump rack(s)

*All-speed governor:* Is one which may be adjusted to control an engine's speed at any selected value within a predetermined range. It is also referred to as a *variable speed* governor. It differs therefore from a *single speed* governor, which is intended to control an engine required to operate at one predetermined speed, and from a *multiple speed* governor, which may be adjusted to control the speed of a prime mover at two, or more, predetermined speeds.

*Control action:* This is usually defined under three headings:

1. *Proportional,* which implies engine control proportional to the difference between actual speed and the reference speed setting (this difference is sometimes referred to as the 'offspeed' value). Proportional control gives a continuous linear relationship between the output from, and the input to, the governor.
2. *Integral* control wherein the governor's output is proportional to the *time integral* of the input, i.e. the time of the offspeed.
3. *Derivative* control, where the output is proportional to the *rate of change* of the input or, in other words, the rate of change of the offspeed.

*Dead band or dead zone:* Is the range of speed (usually very small), expressed as a percentage of the nominal rotational speed, through which the governor will operate before it responds to an input and makes a corrective movement of the fuel rack actuator. The related term is *sensitivity,* which is defined as the smallest speed change for which a governor will affect a movement of the fuel controlling actuator.

*Dead time:* Is the time interval between initiation of an input change signal to a governor and the response of the engine to this signal. The delay in response is due to several factors, which are discussed in Section 6.3.

*Governor:* A device or mechanism that senses a parameter and automatically controls and maintains it at a desired level. In the context of a.c. generation, the regulated parameter is engine speed, and the governor's purpose is to keep the speed constant under all conditions of loading. It does this by controlling the fuel consumption, so that a rise in speed is arranged to reduce the fuel intake and a fall in speed to increase it. Definitions have been given for all-speed, single speed and multiple speed governors. We shall be considering other types, such as load-sensing governors, later in the chapter.

*Hunting:* Also called 'cycling' is a rhythmic and repeated variation of speed, sometimes due to overcontrol by the governor but not always necessarily so. If the governor is responsible, manually and momentarily 'blocking' the fuel control actuator will eliminate the condition. If speed surging persists, the governor is not the cause. Also see 'stability' below.

*Hysteresis:* The speed 'difference', at a given load, between conditions of increasing and decreasing load. It is expressed as a percentage of rated speed.

*Isochronous speed governing:* Implies constant speed operation, regardless of load, within the rated capacity of the engine controlled. It equates to zero percentage speed regulation or zero permanent speed droop (see later definitions).

*Pilot valve:* One which is used to regulate hydraulic pressure to the piston and cylinder of a *servomotor*, which, in turn, may be employed to act directly into the fuel control mechanism.

*Recovery time:* Also referred to as 'settling time', is the time interval (expressed in seconds) between the instant when the speed departs from its steady-state band value after a load change, and the instant of return to speed control within the specified steady-state band associated with the new load. See Figure 6.1(a).

*Response time:* In governor parlance, this refers to the time required for its output to affect a speed change from its initial value to a large specified percentage of the steady-state. See Figure 6.1(b). Kates and Luck [3] use the term *promptness* to convey this idea of speed of action by the governor. Much will depend upon the power of the governor relative to the work it must do. The greater the power the shorter the response time. See also *work capacity,* explained below. The governor system's *dead band* will determine the time delay before corrective action is taken. Its *promptness* will determine how rapidly the corrective action is completed.

*Sensitivity:* See 'dead band'.

*Speed band:* The width of the speed/time envelope (i.e. the difference between upper and lower speed instantaneous values) expressed as a percentage of the declared speed. Thus the width of the envelope under steady-state conditions would be called the *steady-state speed band.* See Figure 6.1(c)

*Speed drift:* Gradual deviation from the desired governed speed.

*Speed droop:* Is the percentage change in speed corresponding to full travel of the governor output shaft (i.e from its full speed to its zero speed position). It is a characteristic of governor operation that provides 'stability', and one that is necessary when two or more engines fitted with speed-sensing governors are operating in parallel, mechanically or electrically, to share load proportionally [2]. See also Chapter 8: *Parallel operation of generator sets.*

*Speed regulation* or *steady-state speed regulation:* Is the speed increase from full to zero power output of the engine, without adjusting the governor. It is expressed as a percentage of the declared speed at rated power.

$$\text{speed regulation} = \frac{(\text{no-load speed} - \text{full-load speed})}{\text{rated full-load speed}} \times 100\,\%$$

Given the speed regulation, it is possible to compute the change of speed that will occur for partial changes of load. See Figure 6.2.

The terms speed droop and steady-state speed regulation are often used synonymously, but they have different connotations. The speed droop is a measure of the speed change necessary to cause the governor's control shaft (or servo) to travel through its full working range. See Figure 6.3. It is simply the

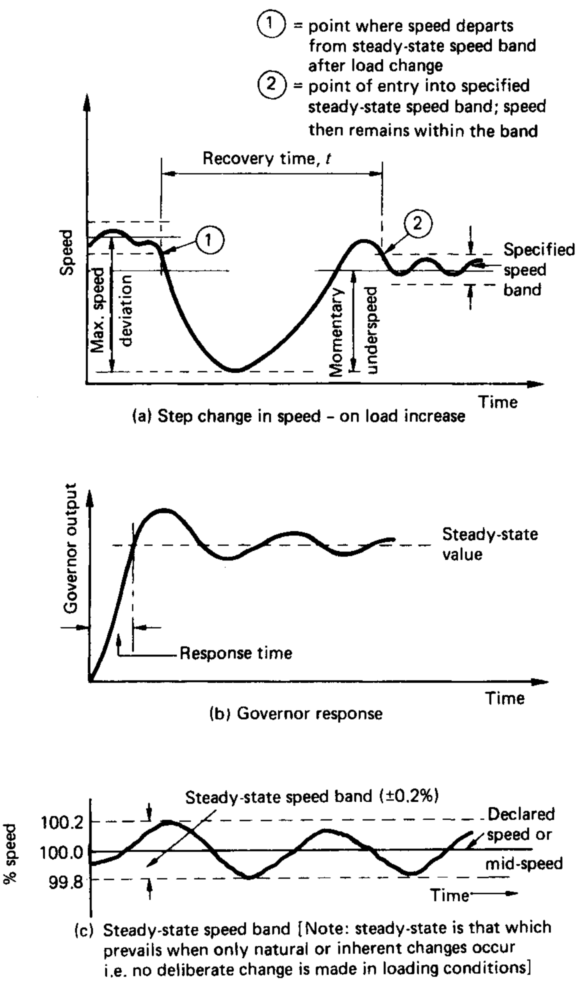



**Figure 6.1** Transient performance characteristics

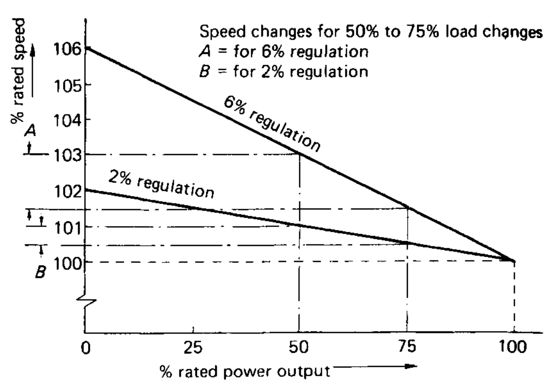



**Figure 6.2** Speed regulation characteristics

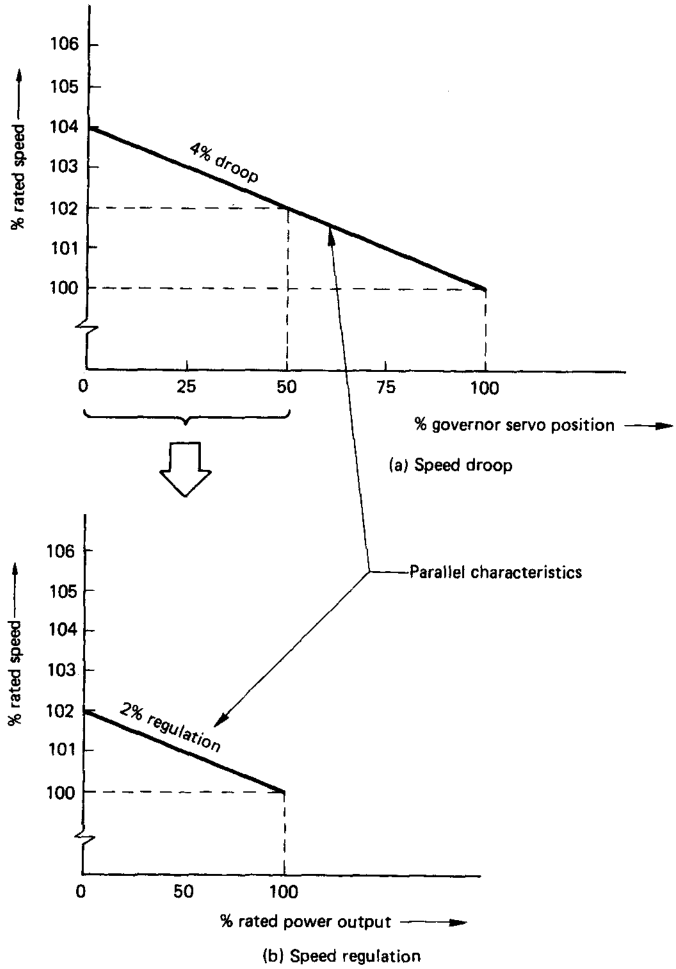



**Figure** 6.3 The relationship of 'droop' to 'regulation' for a given governor

governor characteristic which requires a decrease in speed to produce an increase in fuel supply to the engine. Since an increase in fuel is required if the engine is to carry more load, it follows that increased load means decreased speed. Speed droop is a function of governor design and adjustment only [5].

Regulation, on the other hand, is dependent not only upon the speed droop setting, but also upon the percentage of governor output shaft movement (or servo stroke) which is required to move the fuel rack between its no-load and rated-load positions. If the governor, whose speed-droop characteristic is shown in Figure 6.3, were so connected to the engine's fuel rack that only 50 % of its servo travel was required to move the rack between no-load and rated-load, the regulation would be 2 % although the speed droop is 4 % [5].

Unlike speed regulation, the engine's speed droop may be either permanent or temporary. If the speed droop is permanent, the governor's output shaft will come to rest in a different position for each speed. This would affect the speed regulation because the engine's final speed (as we see from Figure 6.2) is different for each level of loading. If the speed droop is temporary, the governor's output shaft will always come to rest at the same speed, so that the engine's final steady speed remains constant regardless of load [3]. The temporary speed-droop feature (then described as *compensation)* is normally designed into the servo movements of isochronous hydraulic governors to give stability in operation.

*Stability:* The capacity of a governor to maintain system speed equilibrium within specified limits (with constant or varying loads) without hunting. It represents the governor's ability to attain a pre-selected running speed and to settle down quickly. Every governor has a definite response time. One with poor stability will oscillate above and below the required speed (i.e. it will *hunt)* or take an excessive time to cease oscillating .

*Surging:* This is the same as *hunting* but the periodic speed swings are always of large magnitude.

*Time constant:* Gives a measure of the response of the 'governing system' to a step change. It determines the speed of the system reponse to the change. The typical step response of Figure 6.1(b) is reproduced in Figure 6.4 with the tangential speed *decay curve* shown by a dotted line. The time constant of this exponentially decaying characteristic is defined as the time taken *(T* seconds) to complete 63.2 % of the total decay.

*Transfer function:* Is the mathematical (or graphical) expression for the relationship between the input and the output of an electrical network, or of a mechanical element, in any closed loop control system. Expressed as the ratio of output/input for the particular element, it may be considered as 'that property of the circuit or element by which the input must be multiplied to give the output' [6]. Or again, it is defined as the ratio of the response produced by a system to a disturbance [7]. In its simplest form, the transfer function is a constant and is independent of time and, therefore, frequency. The 'form' of the output is identical to that of the input. It may be of greater or smaller amplitude depending on the value of the constant [6].

*Work capacity;* Of a governor, or an associated actuator, is a statement of the amount of work it can do at its output lever or shaft. It is expressed in joules (or in foot-pounds, inch-pounds). Selection for a particular application will also be influenced by available torque, given in Newton-metres (pound-feet) and by lever or shaft angular travel (in mechanical degrees).

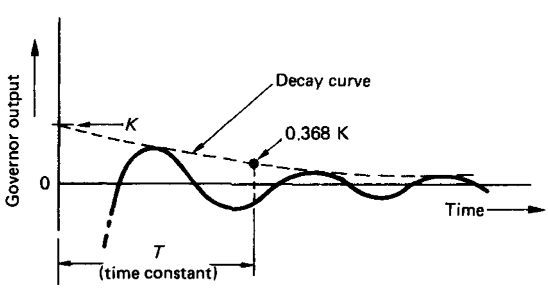



**Figure 6.4** Time constant of governor system to step change

## 6.3 Governor selection

Certain data are required if correct governor selection is to be made for the generator duty envisaged. National standards exist in most countries for engines applied to generators. Governor type will depend upon:

1. the specified standard of governing; and
2. the inertia of the combined engine-generator unit.

The applicable British Standard for the speed governing of reciprocating i.c. engines is BS 5514: Part 4. Its equivalent International Standard is ISO 3046: Part 4.

BS 5514 defines five classes of governing accuracy in its Table 2, and the parameters for the governing systems are given in Table 3. Those applicable to single speed operation, as on generator duty, are in the Class A category, and are defined as follows:

| *Class* | *Accuracy requirement* |
|---|---|
| Ao | Highest requirements of governing accuracy |
| Al | High requirements of governing accuracy |
| *Az* | Normal requirements of governing accuracy |

The British Standard does not give examples of installations for which each class is suited. Also, parameter values are not given in Table 3 for the highest accuracy (Ao) class. Those 'which are important in the context of a particular application should be subject to agreement between the manufacturer and the customer. Remaining values should conform to the next lower class.' Acceptable limits for the following parameters should be quoted by the customer, in the first instance:

- Speed droop.
- Steady-state speed band.
- Momentary overspeed and underspeed.
- Recovery time.

The customer should also declare any other special requirements such as parallel operation, etc. The importance of the combined inertia of engine, flywheel and generator in achieving specified governing will be discussed later.

It can be assumed that, for those applications where Class Ao governing or parallel operation is specified, some form of *external* (remote-mounted) governor, such as a mechanical-hydraulic or an electrically powered unit, will be required. This is in contrast to, say, the combined all-speed mechanical governor and block type fuel injection pump, used on high speed engines for Class *Az* governing (and, possibly, Class Al also). See Section 6.5.1 later in the chapter.

The moment of inertia $(mk^2)$ and the flywheel effect $(GD^2)$ of the combined engine and generator will have an important bearing on the choice of governor type.

When a load change takes place, the difference between the torque developed by the engine and that required by the load goes into accelerating or decelerating the engine. The amount of the acceleration or deceleration depends upon the inertia of the rotating parts. The basic laws of dynamics apply. Whenload is suddenly removed, the surplus power causes the machine to speed up. This power is converted into kinetic energy, which is directly proportional to the inertia of the machinery and the square of its rotating speed. It follows, therefore, that a generating set with high inertia will experience less increase in speed than one with low inertia. Conversely, as load is suddenly increased beyond the power developed by the engine, the rotating machinery gives out kinetic energy and slows down. The greater 'the flywheel effect' the easier it becomes to maintain steady running with smaller transient speed deviations.

Flywheels of the highest practicable inertia should therefore be used on generating sets where close-tolerance governing is required. It may then be possible to employ a relatively simple mechanical governor (in conjunction with a high inertia flywheel) to meet a tight governing specification in an economical manner without recourse to a more sophisticated and expensive governing system.

A flywheel then has the effect of supplementing the governor action by reducing engine speed deviations. The time required to correct the rate of fuel injection on sudden application or removal of load is a function of the governor. The governor's internal time intervals are so small as to be meaningless, and they are included in the total *time constant* of the governor (see the definition in Section 6.2). There will also be a further discrete interval in time before the engine will respond to any change in the rate of fuel injection. This *dead time* has at least two components in the case of diesel engines. The first is the time delay between the charging of a cylinder with fuel and its conversion to torque. The second is the interval then required for all the cylinders which simultaneously contribute to the developed torque to be firing at the new level. The latter time lag may amount to one-third of an engine revolution [5]. The extent of the dead time within the engine itself is influenced by the number of cylinders, the engine speed, and the type of fuel injection system used.

The instantaneous torque developed by an engine depends on the position of each piston and its connecting rod in relation to the crankshaft angular position. It will vary about a 'mean value', causing the crankshaft speed to fluctuate about a mean speed. This change of angular velocity gives rise to the effect known as *cyclic irregularity.* It is defined as the ratio of the total variation in speed during one engine cycle, to the mean speed when the engine is running at any load up to, and including, rated load and rated speed.

$$\text{Cyclic irregularity} = \frac{\text{maximum speed} - \text{minimum speed}}{\text{mean speed}}$$

It is important that the cyclic irregularity is not excessive on diesel generating plant, particularly on those required to operate in parallel. This topic is discussed in some detail in Chapter 8: *Parallel operation of a.c. generating sets.* Suffice it to say, at this point, that another purpose of a flywheel is to smooth out any cyclic speed variations.

In summary: the provision of higher inertia will allow the governor more time to take corrective action on sudden load change and will permit steadier running with less speed deviation.

Adding inertia to a generator rotor, or increasing the mass and diameter of an engine flywheel, costs money. Also, it should be appreciated that when large percentages of load are removed from an engine and the fuel injection rate is correspondingly reduced, the only retarding torque available for deceleration comes from that provided by windage and friction within the rotating machines themselves. If the inertia is high, it may take an appreciable (and unacceptable) time for the speed to return to specified limits. Some compromise is, therefore, always necessary between the limits specified for speed deviation and the time of return to rated speed. Choice of inertia may frequently be determined by which of these is more important in the given application [5].

## 6.4 Fundamental operating principles

### 6.4.1 The mechanical governor

Every speed governor must include at least two components: the first, to measure or *sense* the speed; and the second, to translate this measurement into a movement of the governor output shaft to control the device(s) that regulate the amount of fuel injected into the engine cylinders. In the simplest governors both functions may be combined in the one mechanism. Where any significanit force is required it is necessary to employ a servomechanism to *amplify* the low energy available from the speed sensing elemc;:nt. 'Servo' is derived from the Latin *servus* (a slave) thus expressing the idea that the output or controlled quantity is made to slavishly follow the input (or controlling) quantity [7].

The speed sensing element customarily applied to mechanical and mechanical-hydraulic engine governors is the *centrifugal bal/head.* The principle of its operation is illustrated by Figures 6.5 and 6.6 [5].

In the mechanism of Figure 6.5 spherical weights are fixed to the ends of arms pivoted near the axis of rotation of the governor *spindle. The* flyweights are able to move radially in a plane through the spindle's axis of rotation. Links are attached to the two arms and to a collar which forms a sleeve mounted on the governor spindle. When the weights are moved outwards, the collar travels up the spindle.

The spindle is rotated by the engine, possibly through a gear train. The spinning weights produce a centrifugal force, always acting at right angles to the axis of rotation. As speed increases, this force increases. The weights move further apart and raise the collar, which is connected, in the case of the direct-acting mechanical governor, to the *throttle. (Note:* This latter term is a convenient way of describing the fuel-control mechanism, whatever fuel injection system is used). The reverse action occurs when the speed decreases.

Because the centrifugal force is at right angles to the axis of rotation, it creates a torque about its pivot (see Figure 6.6). This torque is equal to the product of the force and the vertical distance *(A)* of the ball below the pivot. If no other forces are present, the torque is balanced, at equilibrium, by an opposing *gravity torque.* The latter is the product of the weight of the flyball and the horizontal distance *(B)* to the pivot.

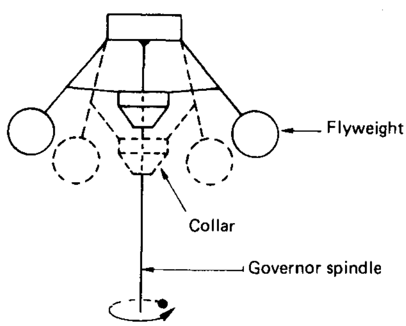



**Figure 6.5** Geometry of a centrifugal ballhead

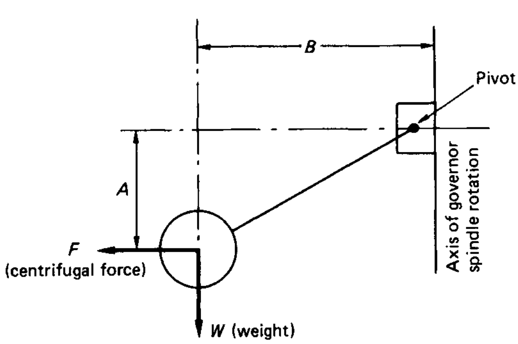



**Figure 6.6** Forces acting on the spinning flyweight

As speed increases, centrifugal force increases and the flyball moves outward. This movement reduces the torque arm *A* whilst increasing the arm *B* associated with the gravity torque until a point of equilibrium is reached when

$$FA = WB$$

There is a singular equilibrium position of weight and collar for each speed of rotation. This relationship will not exist if friction is added to the system. The torque equation on *speed increase* from an equilibrium position then becomes:

centrifugal force torque = gravity torque + friction torque

before any further movement occurs.

Conversely, on a *speed reduction* the equation must be:

centrifugal force torque = gravity torque - friction torque

before any further movement is possible.

There is therefore a speed range within which no corrective throttle motion (via the collar) is possible. This is the *dead band,* defined in Section 6.2.

To obtain the greatest sensitivity from a governor mechanism of this type, the ratio:

$$\frac{\text{force available from the ballhead for a small speed change}}{\text{the force required for throttle control}}$$

should be as large as possible.

One has two options in this regard:

1. To minimize both the friction and the magnitude of the force required for throttle control. This would entail careful construction to reduce friction and the use of a servomechanism to amplify the low-power ballhead output.
2. To increase the force available from the ballhead. This may be achieved either by increasing the size of the ballhead or by running a small ballhead at increased speed.

### 6.4.2 The mechanical-hydraulic governor

Otherwise referred to as the 'servo governor', this type still employs a ballhead as the speed sensing element, but, in order to provide a higher power level output to the engine's throttle control device, use is made of a servomechanism. Vane type hydraulic servos and hydraulic motors have been used, but the commonest form of servomechanism is the hydraulic power piston. The fluid medium is usually oil - supplied under pressure from a pump driven from the controlled engine. Lubrication is therefore inherent within the governing system. The possibilities of oil leaks, difficulties with flow at extremely low temperatures, and the necessity to maintain a clean oil supply may be considered disadvantages. These are far outweighed by the advantages of speed in operation, and in output power offered by the servomotors. By selecting the appropriate piston size and working oil pressure the power of the governor (or its *work capacity)* can be customed to suit the largest engines.

### *Servomechanisms*

The servomotor most commonly applied is the *reciprocating piston* type. Three variants are used and these are illustrated diagrammatically in Figure 6.7 [5].

The *double-acting* piston (Figure 6.7(a» requires a *pilot valve,* which has two control lands simultaneously regulating oil flow to and from opposite sides of the piston. The piston rod passes through a seal in the body and is connected to the throttle device. *(Note:* the *land* is defined as the enlarged diameter of the value plunger and is used to guide its movement or to control the flow of fluid through its ports. )

The *single acting, spring loaded* piston (Figure 6.7(b» uses a single land pilot valve to feed pressurised oil to it. In one direction of piston travel the hydraulic force overcomes spring and external load, and, in the other direction, the spring discharges the oil from the cylinder and overcomes the external load imposed by the throttle controls.

In the *differential* piston, the piston rod (connected to the external load) is sized to reduce the effective area on its side of the piston to about one-half of that of the other side. It will be seen from Figure 6.7(c) that oil is maintained at supply pressure in the piston rod area of the cylinder, and that oil flow in and out of the other side of the cylinder is controlled by a single land pilot valve.

### *A ballhead configuration*

Before we go on to consider elementary arrangements of *hydraulic* governors, we shall look at the ballhead design configuration used in the governors described in Figures 6.9 to 6.12. The weights (no longer 'balls') are arranged to swing about pivots located on opposite sides of a ballhead, which is rotated by the engine through gears (see Figure 6.8). The 'toes' on the ballarms, which are at right angles to the flyweights, convert the inwards and outwards movement of the flyweights (caused by changing centrifugal forces) into an axial movement of the speeder rod, through a thrust bearing. The centrifugal force is opposed and balanced by the force exerted by a compressed *speeder spring.*

The *speed adjusting device* consists of a plug into which the upper end of the speeder spring is fitted, and which is adjusted up or down to change the speeder spring force. Thus, raising the plug reduces the spring force and allows a lower engine speed for the same load condition. Conversely, lowering the plug compresses the spring, increasing its force and resulting in a higher engine speed for the same load. The conical spring gives better speed control

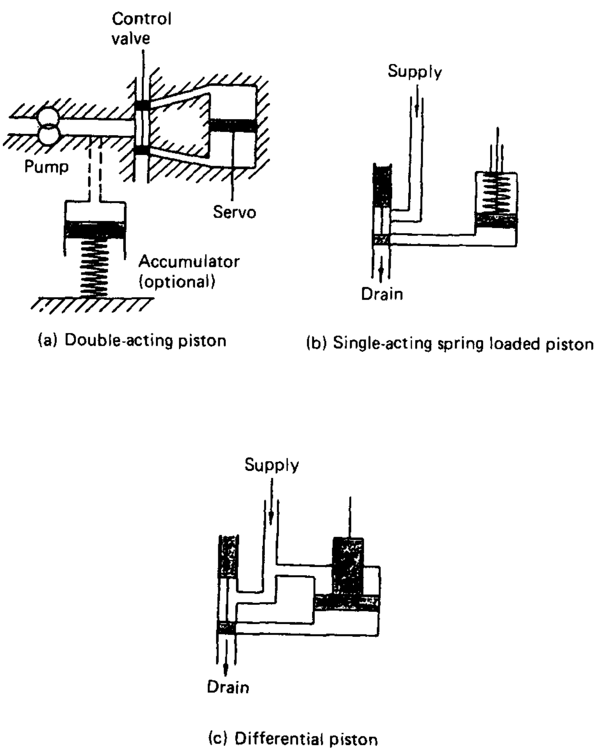



**Figure 6.7** Variants of reciprocating piston servos (a)

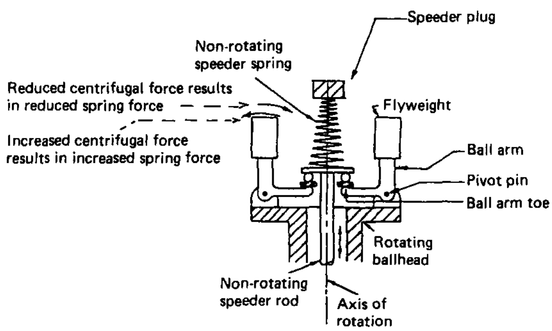



**Figure 6.8** A ballhead configuration (Courtesy: Woodward Governor Company)

through a wide range than an ordinary cylindrical spring would.

The speed adjusting screw on governors fitted to parallel running engine-generators may be operated through a small reversible, fractional horsepower, electric motor. The drive is through a friction clutch permitting overtravel without damage. The motor is controlled by speed *raise* and *lower* push buttons, located within the generator switchboard. (See also Chapter 8.)

## *The elementary hydraulic governor*

We shall now consider the very elementary hydraulic governor illustrated diagrammatically in Figure 6.9 [5]. A ballhead of the type just described operates in conjunction with a pilot valve to control a reciprocating piston servo. For this description we shall assume that an adequate oil supply is available. The ballhead, as we have established, is driven at a speed proportional to that of the controlled engine. The piston servo is connected to the engine throttle device. The ballhead and directly-connected pilot valve have only one equiblibrium position. This occurs when the valve is closed, and oil is neither admitted to, nor discharged from, the servo cylinder. For a given setting of the speeder plug (not shown at the top end of the speeder spring), the ballhead and pilot valve will be in this position at only one speed. The speed sensing element is, therefore, inherently 'isochronous'.

The one big disadvantage with this rudimentary system is its instability. Because of the inertia masses of engine and generator, engine speed does not instantly assume a value proportional to the fuel rack position. This means that if the engine speed is below the governor speed setting, the pilot valve takes up a position that allows the servo piston to move and 'open up' the throttle. Before the engine speed can increase to the set level (so that the pilot valve may centre and stop the servo), the fuel has already been increased too much and the engine continues to speed up past the setting point. This opens the pilot valve in the opposite direction and the throttle operates to decrease the fuel supply. Once again, by the time engine speed reaches its preset value, the throttle has overtravelled. The engine underspeeds and the cycle repeats itself. In other words, the throttle is continually moving in an endeavour to take corrective action - it *hunts*. Stabilizing controls must be added to the system, in order to ensure satisfactory operation.

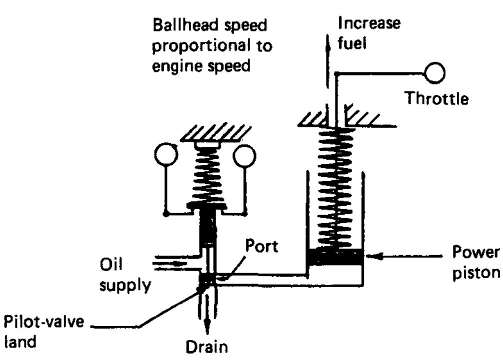



**Figure 6.9** Schematic of elementary hydraulic governor

## *The speed droop governor*

The simplest method of securing stability in the system just described is to provide *speed droop* within the governor [2]. It should be appreciated that the simple flyball mechanical governor (Figure 6.5) has inherent speed droop characteristics. This is because the only way in which the throttle opening can be increased, for instance, is by inwards movement of the flyweights, requiring a decrease in speed.

Speed droop gives stability because the throttle can only take up one position for anyone speed (see Figure 6.3). This means that when a load change calls for a speed change, the resulting governor action ceases at that *particular point* which gives the amount of fuel required for the new load. In this way, unnecessary governor movement and any tendency to over-correction (hunting) is avoided. It is of course important to ensure that the speed droop is large enough to cover any time delay while the engine itself is responding to the governor action. If the droop is insufficient, some hunting may still occur while the engine is returning to its steady speed after the first momentary speed change [3].

Permanent speed droop can be incorporated into the system illustrated in Figure 6.9 by employing a mechanical interconnection between the power servo and the governor speeder spring. Then, as fuel is increased the speed setting is decreased. As we have seen (when discussing the speed adjusting device of Figure 6.8), reducing the spring force reduces the engine speed and, conversely, increasing the spring force increases the engine speed. One such speed droop device consists of a lever of suitable ratio between servo rod and the top end of the speeder spring (see Figure 6.10, and Figure 6.21 later in the text) .

The equilibrium relationship between speed setting and servo position may then be represented by a line which slopes (or 'droops') downward to indicate decreased speed setting against movement of the servo in the 'increase fuel' position [5]. (See Figure 6.3.)

Obtaining speed droop by action on the speeder spring is not the only method used in hydraulic governors. An alternative is to change the flyweight position required to centre the pilot valve at its equilibrium position. This effectively changes the

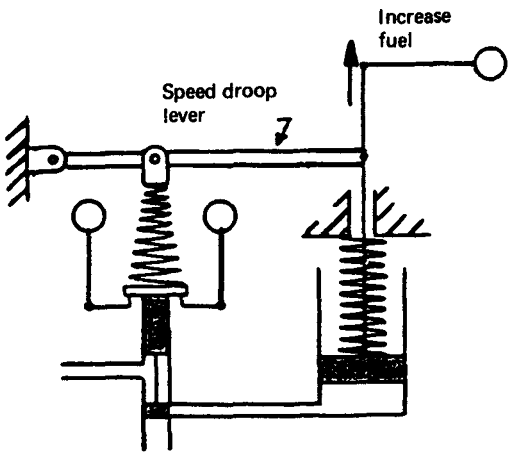



**Figure 6.10** Principle of speed droop lever

speed of the flyweights for a given speeder spring setting. One method uses a 'floating' lever connection between speeder rod, servo and pilot valve (see Figure 6.11, and Figure 6.27 later in the text).

### *The compensated isochronous governor*

While hydraulic governors of the type described have several commendable features (accuracy and sensitivity, and more power than mechanical governors of similar dimensions), they are not isochronous in operation and their speed droop setting is not conveniently adjustable. Since it is sometimes desirable to have an isolated engine-generator run isochronously, it is necessary to introduce *transient* or *temporary* speed droop (generally called *compensation)* to prevent any tendency of the governor to over-correct. This may be accomplished in a number of ways.

One system (see Figure 6.12) employing so-called *pressure compensation* consists of a buffer piston, two buffer springs, a needle valve, and a compensating land on the pilot valve plunger. It works on the principle of applying pressure to the pilot valve plunger, thereby adding to or subtracting from the speeder spring force to effect a temporary change in speed setting.

Pressurized oil actuating the servo piston is directed through the control port into a 'buffer' system which consists of a piston centred between two springs. Deflection of this piston produces a pressure differential across it. This, in turn, is transmitted to the area above and below the *compensating land* (or receiving piston) on the pilot valve plunger. The needle valve permits equalization of the pressure across this land and acts to restore the initial speed setting.

As oil flows to the servo the buffer piston is moved against the force of its centring spring. This gives a higher pressure on the lower side of the compensating land and produces an upward force on the pilot valve. The effect is a decrease in the force, which the flyweights must balance. The pilot valve then centres before the original speed is regained (i.e. at a lower speed) and provides speed droop. The differential pressure disappears as the displaced oil is permitted to leak across the needle valve. The temporary droop signal is, therefore, dissipated. The buffer piston returns to its equilibrium position and the speed setting reverts to its original value. The precise recentring of the buffer piston is not essential for exact return of the system to normal speed. Equalization of pressure is all that is required for this to happen.

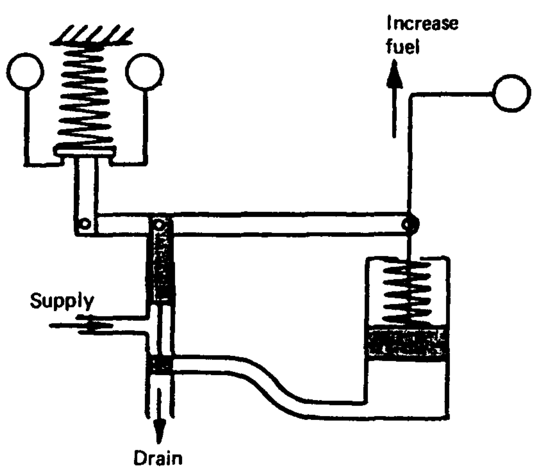



**Figure 6.11** Principle of the 'floating' speed droop lever

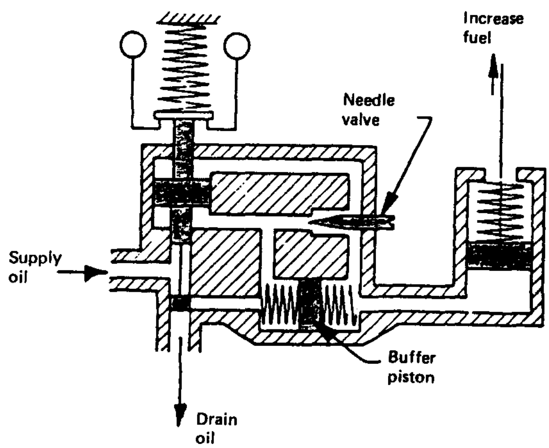



**Figure 6.12** An arrangement giving isochronous operation on a hydraulic governor (Courtesy: Woodward Governor Company)

*Applications summary*

The basic arrangement of Figure 6.9 is not used in generator applications because of its inherent instability. The speed droop types described under Figures 6.10 and 6.11 are extensively used on engine driven generators and are suitable for parallel operating units. The compensated isochronous type of Figure 6.12 has many applications. These include single running standby generators feeding 'technical' loads, where stability and constant frequency, regardless of load, are primary factors. It is possible to combine temporary and permanent droop in a single governor and this is a useful feature where parallel operation, requiring the proper division of load, is contemplated. The degree of accuracy of load sharing is improved by increasing droop. In pressure compensated isochronous governors the addition of droop provides only minimal improvement in stability. It should be appreciated that with 5 % droop, a speed setting error of 1 % between generating sets will give a load imbalance of 20 %. If speed droop is reduced to 2 %, the discrepancy would be 50 %, and with only 1 % droop, the imbalance could well be 100 %. (see Sub-section 8.6.4 of Chapter 8.) A 'compensated' isochronous governor may be set for 4 % permanent droop to give good load division, and with that amount of transient droop which is required for stable governing [5]. In most proprietary hydraulic governors speed droop adjustment is provided *inside* the governor, and is achieved by varying the ratio of the interconnecting lever between the throttle and speed setting elements.

### 6.4.3 The electric governor

In its very basic form (Figure 6.13) the electrically powered governor is a direct alternative to the simple mechanical governor. It comprises a speed sensing device, an electronic speed controller, and an actuator connected to the fuel control linkage. Only the actuator and the speed sensor need be installed on the engine. *(Note:* Some manufacturers offer integral injector pump mounted actuators which eliminate the need for an external fuel system control linkage and actuator support brackets.) The basic system can be expanded for a variety of control applications.

*Speed sensing*

It is possible to use the output power frequency as the *speed signal* in generating sets provided it is within the frequency range of the governor. Clearly this is only feasible for single unit, non-parallel, operation. Almost all proprietary electric governor systems use a magnetic pick-up (Figure 6.14), mounted in close proximity to a ferrous projection(s) driven by the engine, to detect prime mover speed. The flywheel *starter ring gear* is normally used because of ease of installation and the high frequency signal obtained, and because it is mounted on a nodal point of the shaft. See Figure 6.13. The magnetic pick-up (MPU) signals the number of gear teeth which passes its tip, or pole piece, per second - the signal being directly proportional to the engine's speed. The output from the sensor is determined by the peripheral speed of the teeth, their size, and their distance from the pick-up's tip. It is important that the governor manufacturer's installation instructions are closely followed. These would extend to the wire leads to be used. These may need to be of the *shielded* (and/or twisted pairs) type over their entire length up to the speed control unit.

*Speed control*

Basic control units compare the actual electrically measured speed from the sensor with the adjustable and preset *desired* (or *reference)* speed. The resultant error signal is amplified and fed to the actuator (Figure 6.15).

Failsafe circuitry in the controller senses MPU frequency and operates to move the actuator into the fuel shutoff (or minimum fuel) position.

*Fuel control actuators*

The actuator's purpose is to position the throttle controls which adjust the fuel supply to the engine. Actuators may be either electrohydraulic or electromechanical. Some electro hydraulic types may require an engine drive for an internal oil pump. Others may be driven by an electric motor (or an oil motor) if no drive pad is available on the engine.

Figure 6.16 [8] is the schematic diagram for a *Woodward* type EG-3P electrohydraulic actuator. Its essential element is a transducer which controls oil flow to and from a power piston through the action of a polarized solenoid. The position of the terminal (or output) shaft is proportional to the input current to this solenoid, which controls the movement of a hydraulic pilot valve plunger. The relationship between actuator position and input voltage is linear.

Very briefly, the mode of operation is as follows:

1. The movement of two opposing pistons (the loading and the power pistons) rotates the actuator terminal shaft to which the engine fuel linkage is attached.
2. Pressure oil from the pump is supplied directly to the underside of the loading piston and tends to turn the terminal shaft in the 'decrease fuel' direction.

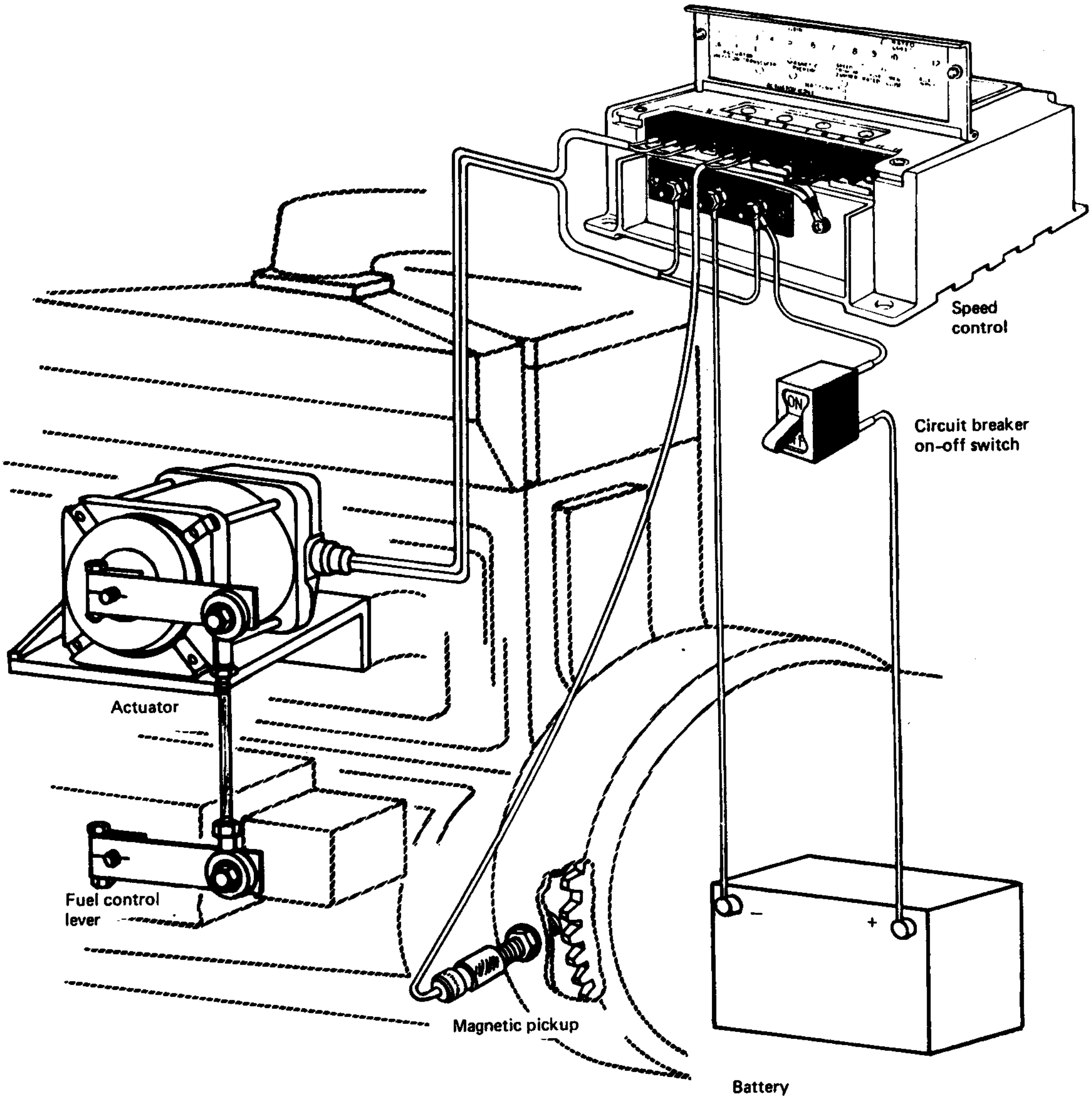



**Figure** 6.13 Basic electrically powered governor system (Courtesy: Woodward Governor Company)

3. The power piston can only move downwards when the oil trapped beneath it escapes to the sump. Oil flow to and from this piston is controlled by the pilot valve plunger.
4. The greater of two forces moves the pilot valve plunger up or down. The first, a downward force, is provided from a two-coil solenoid which is energized by the output signal from the governor speed controller. The pilot valve plunger is connected to a permanent magnet spring-suspended in the solenoid field. The second force is the resultant of (a) an upward force on the pilot valve plunger due to the action of a centring spring fitted above the solenoid core case, and (b) an opposing downward force due to the restoring spring. The magnitude of force (b) depends upon the position of the restoring lever. It reduces as the terminal shaft rotates in the 'increase fuel' direction and increases with rotation in the 'decrease fuel' direction.
5. The resultant force from the combined output of centring and restoring springs always acts to urge

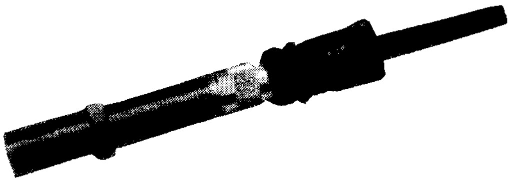


**Figure 6.14** A typical magnetic pick-up (Courtesy: Governors America Corp.)

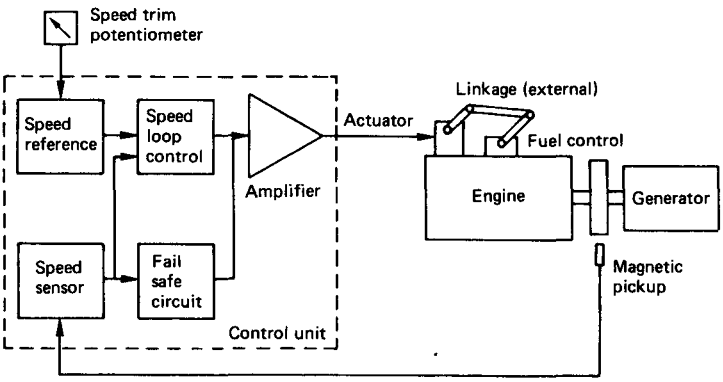



**Figure** 6.15 Simplified block diagram for an electronic governor

the pilot valve plunger upwards, and increases as the terminal shaft moves in the 'increase fuel' direction.

6. When the actuator is operating under steady-state speed conditions, this resultant force and that due to the current in the solenoid coils are equal, and in opposite directions to each other.
7. A decrease in solenoid coil voltage (brought about by a reduction either in speed setting or load) decreases the force tending to lower the pilot valve plunger. Because the force of the spring fitted below the permanent magnet is now greater, the pilot valve plunger lifts and allows oil to escape from below the power piston. This causes the terminal shaft to rotate in the 'decrease fuel' direction.
8. When it has rotated sufficiently to satisfy the new fuel requirement, the increase in restoring spring force equals the decrease in downward force from the solenoid and the pilot valve plunger is recentred by the equal and opposite forces acting upon it.
9. On any increase in speed or load, the voltage signal input to the solenoid coils is increased and similar but opposite reactions to those described in 7 and 8 above occur.

Electromechanical actuator form and design varies with individual manufacturers. Some proprietary configurations are described below.

Figure 6.17 shows the schematic arrangement of an actuator used in a Woodward EPG (electricallv powered governor) system. A shaft rotation of 30"~ provided for low mass, low friction, fuel controls. The magnetic circuit obtains its power supply from the governor speed controller and applies torque in the 'increase fuel' direction. A preloaded internal return spring supplies shaft torque in the 'decrease fuel' direction. The magnitude of this preloading can be reduced at the factory to compensate for some external fuel control linkage forces acting in the 'decrease fuel' direction.

The DYNA Plus series of actuators marketed by Barber Colman (Figure 6.18) are proportional sole~ oids with sliding armatures. Their magnetic force is proportional to input coil current. The armature is balanced between the force of a return spring and the magnetic force. Its linear motion is converted to an output shaft rotation, of up to 45°, by a beR crank.

### 6.4.4 Overspeed protection

It is essential that a separate overspeed device is used on engines fitted with independently mounted governors. This will protect against runaway o£ damage to the engine (and possible subsequent injury to personnel) caused by:

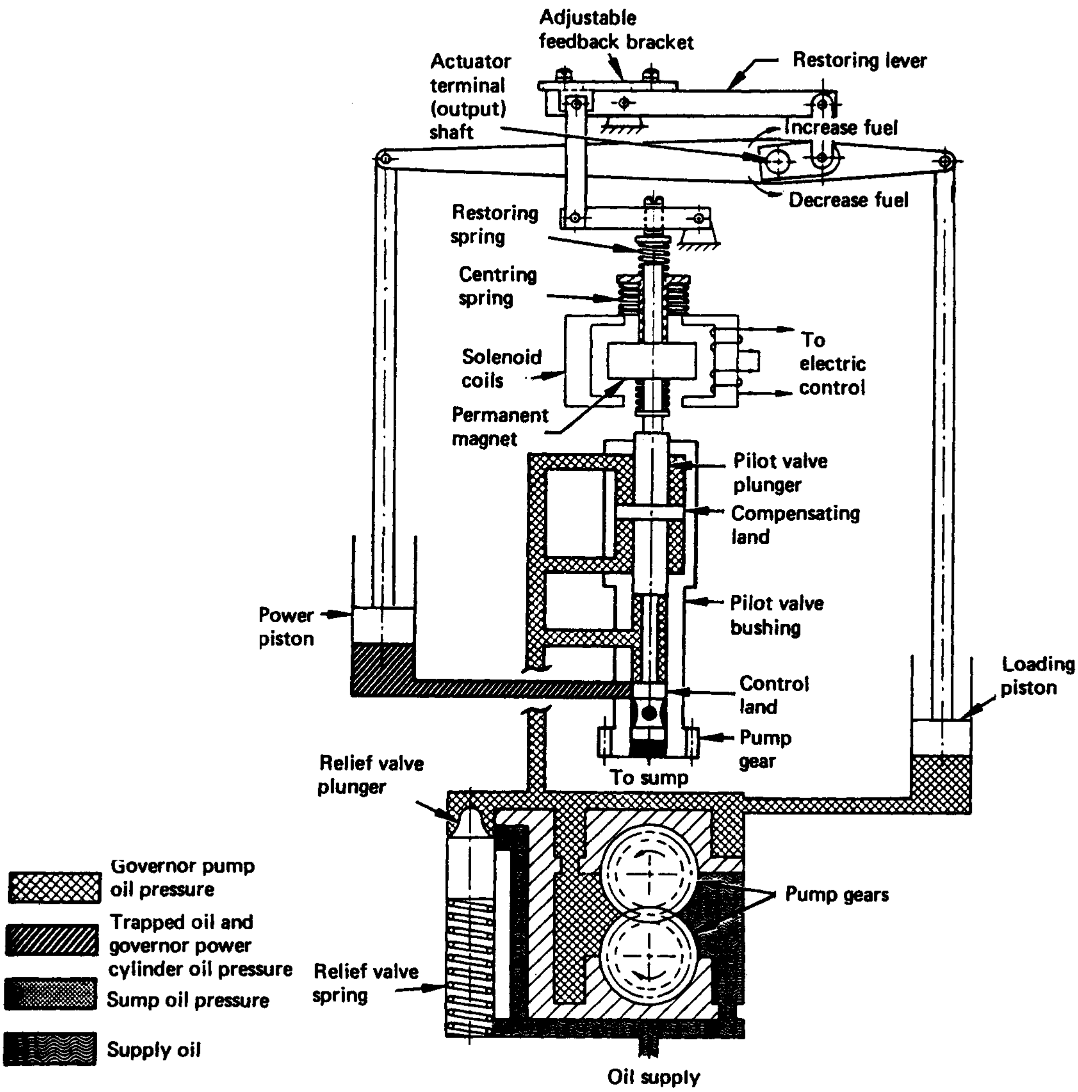



**Figure 6.16** Schematic diagram of EG–3P actuator (Courtesy: Woodward Governor Company)

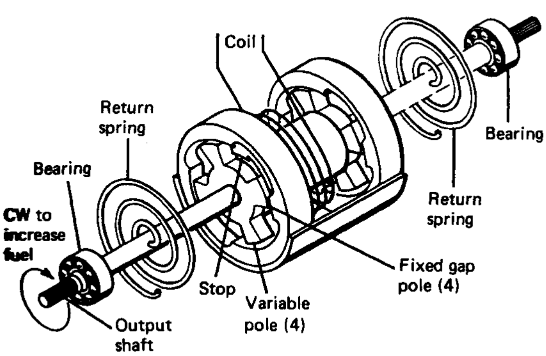



**Figure** 6.17 Schematic arrangement of a model EPG actuator (Courtesy: Woodward Governor Company)

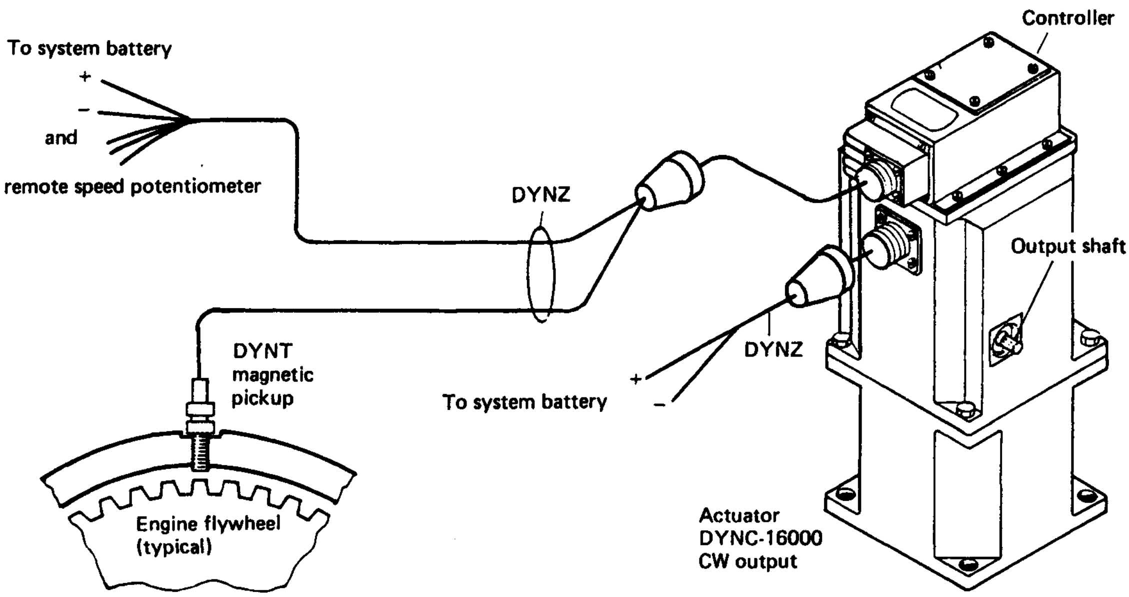



**Figure** 6.18 Typical wiring for DYNA Plus 6 actuator with surmounted controller unit (Courtesy: Barber Colman Company & SES Systems Ltd)

1. failure of the governor driving mechanism or the fuel control linkwork; or
2. failure of a controller or an actuator in the case of electrically powered governors.

Independent overspeed protection is not essential with injection pump-mounted mechanical governors because they do not use 'vulnerable' external fuel control linkages. The fuel injection pump rack is directly connected to the governor's speed sensing! speed adjusting elements.

Overspeed protection devices are. discussed in Section 10.1.3 of Chapter 10.

## 6.5 Typical governors

We shall now look at some proprietary treatments in the three categories of direct mechanical, mechanical-hydraulic, and electric governors.

### 6.5.1 Direct mechanical

Many governor constructions use the diagrammatic arrangement and ball-head principles illustrated in Figures 6.5 and 6.6. The weights may be pivoted in various ways and restoring force may be provided by springs - as shown in Figure 6.8.

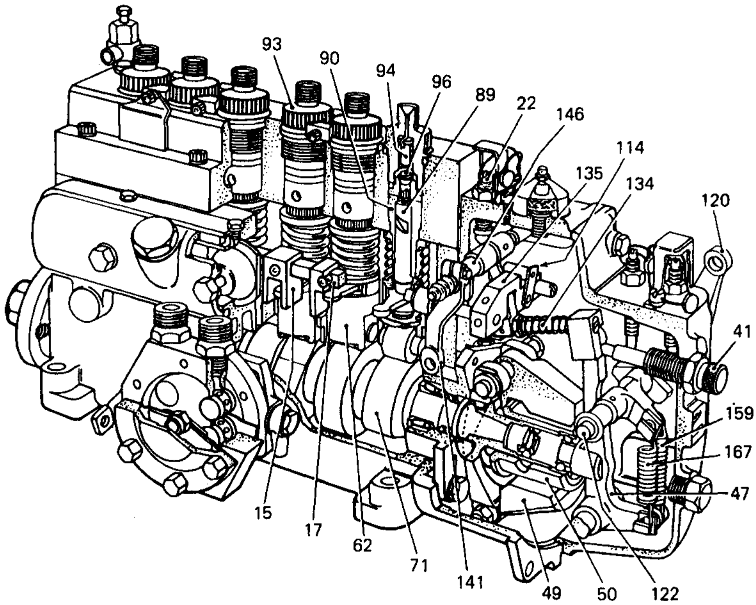
A good example of a direct mechanical governor is the Simms type GMV variable range unit, which is built onto the 'Majormec' fuel injection pump (see Figure 6.19). It offers a compact arrangement for use on high-speed diesel engines with a capacity of about $1\frac{1}{2}$ to $3\frac{1}{2}$ litres per cylinder [9].

The governor basically consists of two or four flyweights (Item 49 in Fig. 6.19) on a hub fitted on the end of the camshaft (71). The toes of the flyweights abut a sliding sleeve (50) on the hub. This sleeve has a fork which engages a pivoted crank lever (47). The fork is supported by a ball bearing **in** the sleeve. See the inset assembly in Figure 6.19.

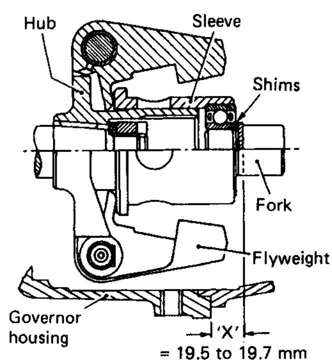
The longer arm of the crank lever is connected by a telescopic link (134) to a bridge link (135) on the end of the control rod (17). The shorter arm is connected by the governor springs (159 and 167) to the speed lever shaft (122). The engine speed is controlled by the spring tension applied through the operation of the speed lever (120).

When the speed lever is moved to a higher speed position the control rod moves towards the maximum fuel delivery position. At the same time, the sliding sleeve is moved against the toes of the flyweights to close them.

When engine speed increases just above the selected speed the centrifugal force of the flyweights acts on the crank lever and moves the control rod towards the minimum fuel position. Fuel delivery and engine speed are both reduced. Thereafter, as the setting of the speed lever remains unchanged, the tension in the governor springs moves the control rod to the selected speed position. This completes the cycle of operation.




15 Control fork
17 Control rod
22 Max. fuel stop screw
41 Damper
47 Crank lever
49 Governor flyweight
50 Governor sleeve
62 Tappet assy.
71 Camshaft
B9 Plunger
90 Barrel
93 Delivery valve holder
94 *Volume* reducer
96 Delivery valve
114 Trip lever
120 Speed control lever
122 Speed lever shaft
134 Telescopic link
135 Bridge link
141 Stop control lever
146 Excess fuel device
159 Governor idling spring
167 Governor main spring




**Agure** 6.19 Cutaway section of typical 6-cylinder MAJORMEC pump (Courtesy: Lucas Automotive Ltd)

### 6.5.2 Mechanical hydraulic

The first example of this type is the *Woodward PSG* (Pressure compensated Simple Governor), which is very widely applied to small and medium output plants using diesel, gas or dual-fuel engines. It is normally isochronous but is capable of adjustment to give speed droop operation.

Its elements are shown in the cutaway schematic of Figure 6.20. The governor normally uses engine lubricating oil. A foot valve should be used where an oil supply is obtained from a separate sump. The oil supply is pressurized in an oil pump which is by-passed by a relief valve. Four non-return valves (two of which are shown) permit rotation of the governor **in** either direction. Relief valve discharge is back to supply so that unused oil is recirculated within the governor.

Pressurized oil is supplied to the pilot valve system, which is a three-way spool valve. It applies oil to the power cylinder when an underspeed signal is received and it releases trapped oil from the cylinder on receipt of an overspeed signal.

The flyweights are attached to the pilot valve's rotating bushing by pivot pins. The bushing itself is driven by an external drive from the engine. A thrust bearing located under the speeder spring rides on the toes of the flyweights. This allows the fly-weights and pilot valve to rotate without extreme friction.

As the bushing rotates the centrifugal force increases and the flyweights pivot outward. This

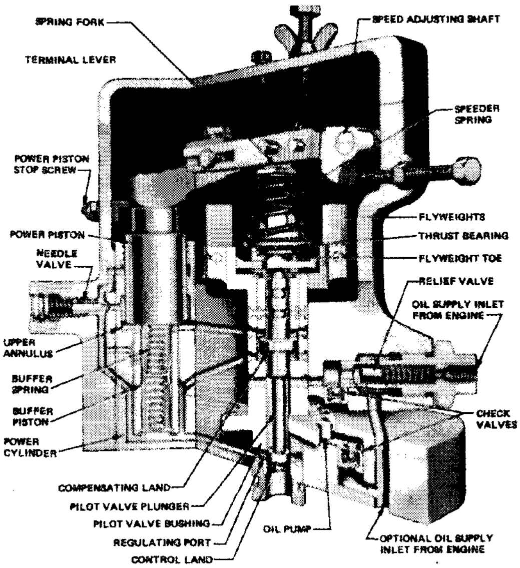



**Figure** 6.20 Cutaway schematic of basic PSG mechanical hydraulic governor (Courtesy: Woodward Governor Company)

force is opposed by the downward force of the speeder spring. Speeder spring compression, and therefore the speed at which the governor must run, is varied by positioning the speed adjusting shaft.

The methods used include:

1. a manual speed adjusting screw/lever; and
2. an electrical fractional h.p. motor - where remote speed control is required, from a generator switchboard

The centrifugal force of the flyweights balances the downward force of the speeder spring at setting speed. The flyweights are exactly vertical and the pilot valve plunger control land covers the control port of the rotating bushing.

The pressure compensating system, which provides the temporary speed droop necessary for stable operation, consists of a buffer piston, two buffer springs, a needle valve, and a compensating land on the pilot valve plunger. The operating principle has already been explained in the text associated with Figure 6.12.

The schematic diagram of Figure 6.21 will help to explain what happens within the governor on load increase, and on load decrease. Consider first the 'load increase' condition. The governor will increase fuel to the engine either on (a) an increase in governor speed setting or on (b) a decrease in engine speed due to an increase in load. The increase in the downward force of the speeder spring (associated with condition (a)) or the decrease in centrifugal force of the flyweights (due to condition (b)) allow the pilot valve plunger to move downward. Pressurized oil is then applied through the control port to the buffer system and into the power cylinder area.

The power piston has two concentric areas, both of which are exposed to the oil metered by the pilot valve. The lower (and smaller) diameter is acted upon directly, and the upper annulus is connected through the bore in the power piston - in which the buffer piston is carried.

Oil flow into the power cylinder forces the power piston upward against the force of the return spring. This spring may be fitted inside some models of the governor and is shown in Figure 6.21 only. It loads the power piston and terminal output lever in the 'decrease fuel' position. Pressurized oil displaces the buffer piston and is forced into the upper annulus. The oil flow into this annulus establishes a pressure differential across the buffer piston. This is because of the larger volume of oil being applied in the upper buffer piston area (as compared with the lower area).

The pressure differential is, in turn, transmitted to the area above and below the compensating land on the pilot valve plunger. The higher pressure on the lower side of this land acts in a direction to supplement the flyweight force causing the pilot valve to 'centre' before the original speed has been regained. As oil leaks across the needle valve the *temporary speed droop* signal is dissipated and the buffer piston recentres in its bore. Engine speed returns to normal.

The reverse actions occur under 'load decrease' conditions. On a decrease in speed setting, or on a decrease in load, the centrifugal force of the flyweights overcomes the speeder spring force and lifts the pilot valve plunger. Upward movement of this plunger opens the control port to 'drain'. The power piston is forced into the 'reduced fuel' direction by the return spring.

Simultaneous outflow of oil from the annular space between the two diameters of the power piston causes the buffer piston to move off-centre and in the downward direction. The pressure difference each side of the buffer piston again acts on the compensating land of the pilot valve and recentres that valve's plunger. As before, oil leaks past the needle valve to dissipate the pressure difference. When the engine returns to steady-state speed the centrifugal force of the flyweights is once again balanced with the downward force of the speeder spring.

Figure 6.22 illustrates speed adjusting and external speed droop adjustment arrangements on the PSG governor.

The cover-mounted motor rotates the speed adjusting lever and shaft, to change the governor speed setting in the following manner.

One end of the *floating lever* (294) is attached to the speed adjustment lever. Its other end pivots

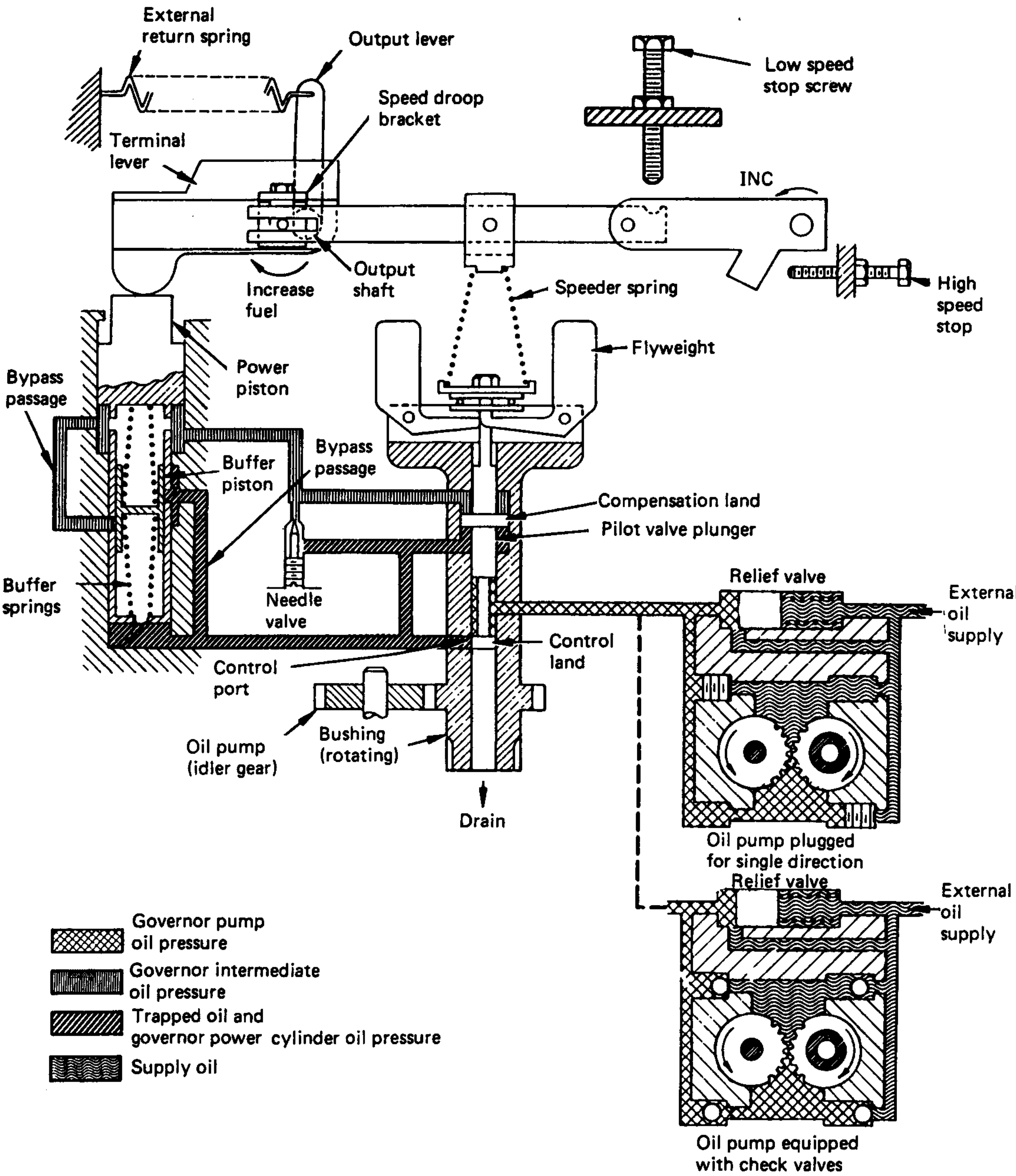



**Figure 6.21** Schematic diagram of PSG governor with external return spring (Courtesy: Woodward Governor Company)

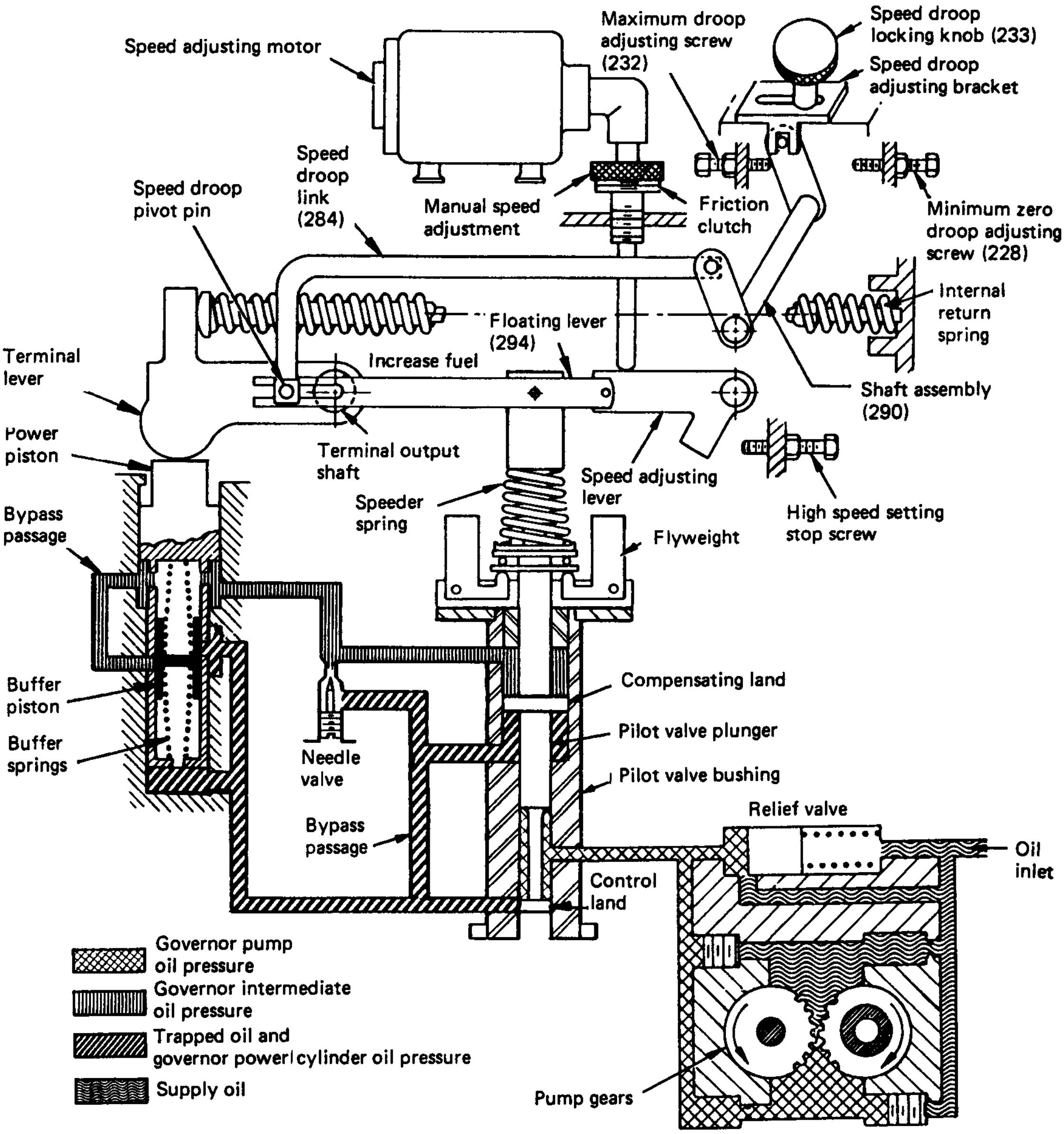



**Figure 6.22** Schematic diagram of PSG governor with horizontal internal return spring, externally adjustable droop, and electric speed setting (Courtesy: Woodward Governor Company)

about the *speed droop pivot pin.* The spring fork/speeder spring assembly connects to the floating lever. Rotating the speed-adjusting lever changes the compression of the speeder spring. This, as we have seen, changes the speed at which the governor must run in order to develop the flyweight force necessary to balance the spring force. Turning the speed-adjusting screw either manually (by turning the knurled friction cover) or 'electrically' (by means of the speed-adjusting motor) repositions the speed-adjusting lever. The motor drives the speed-adjusting screw through a friction clutch which protects the motor in the event of the lever reaching the top of its travel.

Turning now to the external speed droop feature: this provides adjustment between 0 and 7 %. The level of adjustment depends upon speed setting, speeder spring, flyweights, and terminal shaft travel. It allows two droop settings to be made, and for a rapid change between them if necessary. This is of particular value on multiple-generator installations where the droop may be set sufficiently high to prevent the undesirable interchange of load between the parallel-running units.

Where it is necessary to maintain a constant busbar frequency, one method of plant operation is to use a 'master' generator capable of absorbing the anticipated pattern of load changes, and set for isochronous operation. (See Chapter 8: *Parallel operation of generating sets.)*

The speed droop setting is positioned by means of the speed droop locking knob (233), the floating lever (294), and the two screws (228 and 232) on the outside of the governor casing. Screw 228 establishes the zero droop setting and is usually factory set. Screw 232 is used to adjust the maximum droop required on site. The bracket-mounted screw 233 locks the droop linkage at either of the two positions: zero or maximum droop.

The speed droop lever (identified in Figure 6.23 (c» is mounted on the speed droop shaft assembly, which is supported by the governor casing. The inner end of this shaft is connected to one end of the speed droop link (284). The other end of this linkage carries a pivot pin and is supported by the terminal lever. The pin's position can be adjusted from a point on the terminal shaft centreline to any point within a radius of about 12.5 mm from it (roughly as shown in Figure 6.22).

When the pin is at the terminal shaft centre, rotation of the shaft produces no vertical movement of the pivot pin and no movement of the speed droop lever. As the pivot pin is moved outwards from the shaft centre, shaft rotation produces increasing end movement in the speed droop link. This means that when the speed droop link moves it produces a speed setting which is a function of terminal shaft position. *Speed setting therefore decreases as fuel flow increases.* This is *speed droop.*

Speed droop is increased by moving the external lever forward (towards the maximum droop adjusting screw (232». It is reduced when the lever is moved back (by moving the speed droop pivot pin towards the terminal shaft centre). Speed droop is set by readjusting the screw on the side of the governor casing to obtain the desired speed change between full load and no load.

The external features of the basic PSG governor are shown in illustration (a) of Figure 6.23. Plate (b) shows the top-mounted electric speed-setting motor and the housing for the optional internal return spring (see the schematic diagram of Figure 6.21). The external speed droop adjustment option is illustrated in plate (c).

Before we leave the PSG governor and go on to consider an example of a higher work capacity unit, it is worth mentioning two important functional and installation aspects relating to it. These concern shutdown methods and recommended engine oil systems.

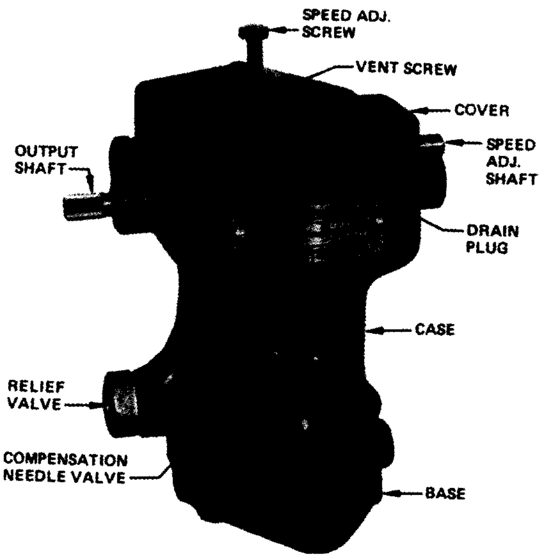
Since no governor mounted shutdown device is available for the unit, it is common practice to use external solenoid valves. Where engines are 'hydraulically' governed there is inherent danger in using cut-off valves in the *fuel system.* This is because valve operation may result in loss of governing and a possible runaway condition. This point is also stressed in Chapter 10: *Prime mover and generator protection.* The acknowledged shutdown method is to drain (or dump) the governor's control oil into the prime mover's lubricating oil sump. Solenoid valves may be arranged for 'energized-to-run' or 'energized-to-stop' operation. The former is the more usual configuration. Here, the dump valve is normally-open and is held in the closed position by the solenoid when the engine is running.

The Woodward Governor Company have published guidelines [10] on the application of external shutdown solenoids. Two factors have to be considered:

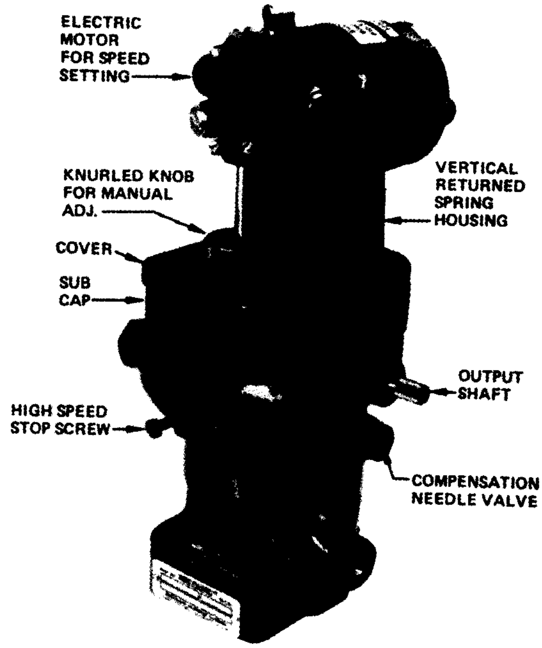
1. the location of the solenoid; and
2. solenoid size.

Regarding the first, Figure 6.24 shows the primary and optional shutdown connection points on the governor. Figure 6.25 shows typical installations using engine oil and separate sump arrangements. It is important that the solenoid is connected through the shortest possible tubing runs. Also, it should be mounted below the governor and oriented so that it does not fill with air. Air trapped in the solenoid or in the tubing will cause governor instability.

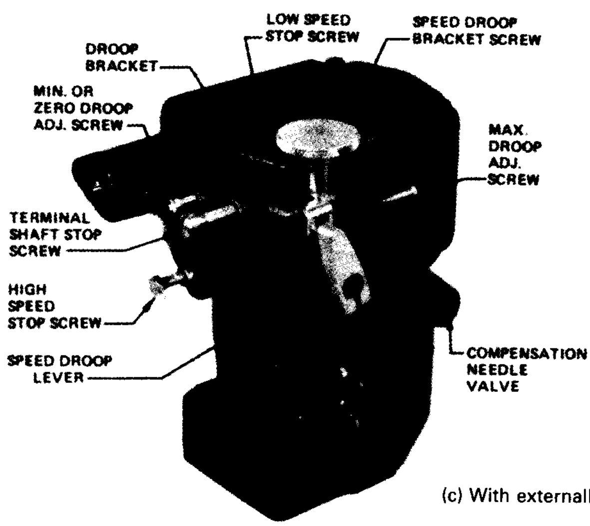
There is always the danger that the oil in the governor may drain back to the sump during extended shutdown periods. Then, because of the lack of an oil supply to the boost pump, the governor may not be able to open the fuel racks during cranking. This situation is most likely to occur on




(a) The basic governor




(b) With vertical return spring and electric speed setting motor




(c) With externally adjusted speed droop

**Figure 6.23** External features of the PSG mechanical hydraulic governor (Courtesy: Woodward Governor Company)

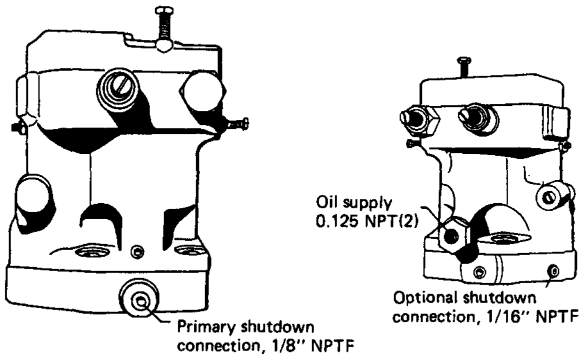



**Figure 6.24** Shutdown connection options for the PSG governor (Courtesy: Woodward Governor Company)

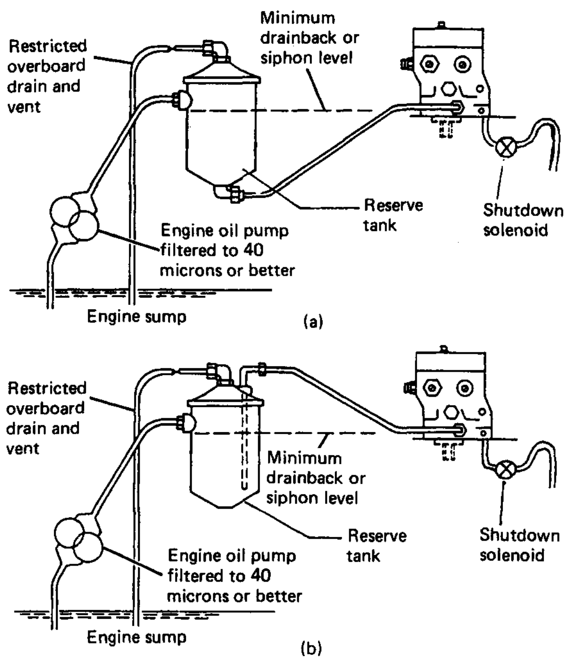



Figure 6.25 Recommended engine oil systems for the PSG governor (Courtesy: Woodward Governor Company)

engines in standby and emergency applications. To prevent this happening the engine oil system should conform to either of the options given in Figure 6.25 (a) and (b). Both arrangements ensure that oil remains in the reserve tank (even after long shutdown periods), and give a supply to the governor during engine start.

The 'restricted overboard drain and vent' permits the governor pump to draw oil before engine oil pressure is established and bleeds-off any air that has accumulated in the tank. A standard 1-2 Iitres fuel filter housing may be adapted for use as a reserve tank.

The solenoid (and its connected tubing) should be large enough to ensure that the governor moves to its minimum position and stays there. Shutdown is achieved by arranging for the solenoid to dump oil directly from the governor's power cylinder. The solenoid must therefore handle the full pump output. Different flow capabilities are required, depending upon rated governor speed - as shown in Figure 6.26.

The PSG governor has a rated work capacity in the range 0.9 to 1.75 Nm at operating pressures between 0.69 and 1.38N/mm$^2$. The larger type UG 8 (also manufactured by the Woodward Governor Company) has a maximum work output of 1O.9Nm (= 81bf ft; hence the designation Universal Governor 8). It is widely used on medium- and low-speed engines with rated outputs above 1 MW. Like the PSG, it has a single-acting power piston (i.e. it acts in one direction only). It uses continuous oil pressure instead of a spring to return the piston in its 'minimum fuel' direction. The schematic diagram for the basic design (Figure 6.27) illustrates the principles of its operation.

A brief description of the salient components will help towards an understanding of its operation. In the text that follows reference will be made to a *controlet* or a *controlet assembly.* The term defines the sub-assembly of pilot valve, power piston, compensation and accumulator parts.

*Oil pump:* The oil pump system is housed in the bottom of the controlet, which is mounted directly to the base. The system consists of two gears and four check valves. One gear is part of the rotating bushing and the other forms part of the laminated spring drive. The rotating bushing is driven by the governor shaft which, in turn, is driven by the prime mover. As the bushing rotates it spins the shaft of the laminated drive assembly. Oil flow is directed through the check valve system into the accumulators.

*Accumulator:* The accumulator consists of two cylinders, each containing a spring-loaded piston. Oil pumped into the cylinders is increased to a pressure of 0.83 N/mm by the accumulator springs. Should the pressure be exceeded, oil is released back to the sump through a pressure relief port in each cylinder. The oil is directed from the accumulator through passages to the top of the power piston and to the pilot valve system.

*Power piston:* This is of the *differential* type - with oil pressure on both the top and bottom of the piston. The upper end is connected to the governor's terminal shaft through a power lever and link assembly. Differential operation results from the difference in areas between the bottom and the top of the piston. Less oil pressure is required on the

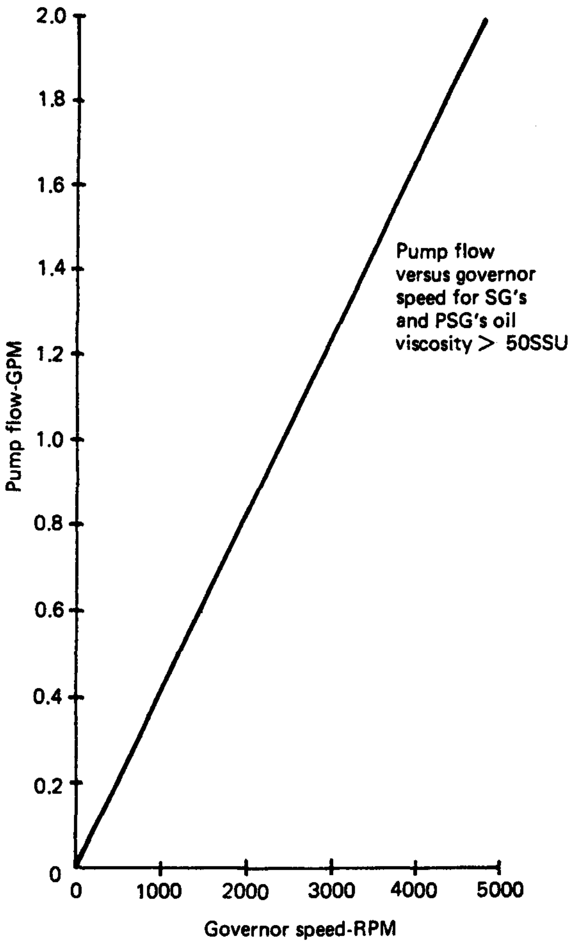



Figure 6.26 Governor pump flow rates versus governor speed relationship (Courtesy: Woodward Governor Company)

bottom of the piston than on the top, to keep the piston stationary. If the oil pressure is equal on both sides, the piston moves upward to rotate the terminal shaft in the 'increase fuel' direction. The piston only moves downward when oil is released to the sump. Oil flow to and from the bottom is regulated by the pilot valve system.

*Pilot valve system:* This comprises the rotating bushing and the pilot valve plunger (PVP). When the bushing is rotated by the drive shaft, the friction between it and the plunger reduces. The PVP has a control land that regulates oil flow through ports in the bushing. PVP movement is controlled by the ballhead. When the plunger is lowered, high pressure oil flows to the bottom of the power piston causing it to rise. Conversely, when the plunger is raised, oil from the bottom of the piston is released to the sump. The higher pressure on the top of the piston forces it downwards.

In its centred position, the PVP's control land covers the control port (as shown in Figure 6.27) and there is no movement of the power piston.

*Railhead system:* The ballhead assembly is very similar, in many respects, to that of the smaller PSG governor. It consists of a ballhead, flyweights, cooical speeder spring, thrust bearing, speeder plug, and speeder rod. The major difference is that the ballhead is driven, through gearing, by the laminated drive, and not by direct attachment to the rotating pilot valve bushing.

Speeder spring force (and therefore speed setting) is manually controlled through a *synchronizer* adjusting knob. As before, an optional feature is a cover-mounted synchronizer motor providing remote control of the governor's speed setting. The synchronizer knob is used to change engine speed on single-running engines. Where an engine is paralleled with others, the knob is used to change load on the controlled engine. (See Chapter 8 : *Parallel operation of generating sets.)* The upper right hand knob (marked 'synchronizer') on the governor's dial panel is the control knob. The 'syn indicator' knob indicates the number of revolutions of the synchronizer control knob.

*Compensation system:* This consists of an actuating and a receiving piston and a needle valve.

The larger actuating piston is linked to the terminal shaft by a compensation adjustment lever. Changing the position of the pivoted fulcrum allows the lever to control the amount of stroke available for the actuating piston. The receiving piston is connected through a floating lever to the pilot valve plunger and the speeder rod. Downward movement of the actuating piston forces oil under the receiving piston. As the latter is forced upward, it lifts the PVP to close-off the control port. This stops the flow of oil to the bottom of the power piston.

The needle valve controls the flow of oil between the oil sump, and the actuating and receiving pistons.

*Load limit control:* This consists of an indicator disc graduated 0 to 10, and geared to a load limit rack. The control knob (shown bottom left of the governor dial panel, in Figure 6.29(a)) is also attached to the load limit cam. When the load limit indicator reaches its preset point on the dial scale, PVP is lifted and stops any further increase of fuel. The engine may be stopped by turning the load limit control to zero. This also turns the cam and forces down both the load limit lever and the shutdown strap. As the right hand end of the load limit shutdown lever is forced downward, it pivots about its fulcrum and lifts PVP. This releases oil from under the power piston.

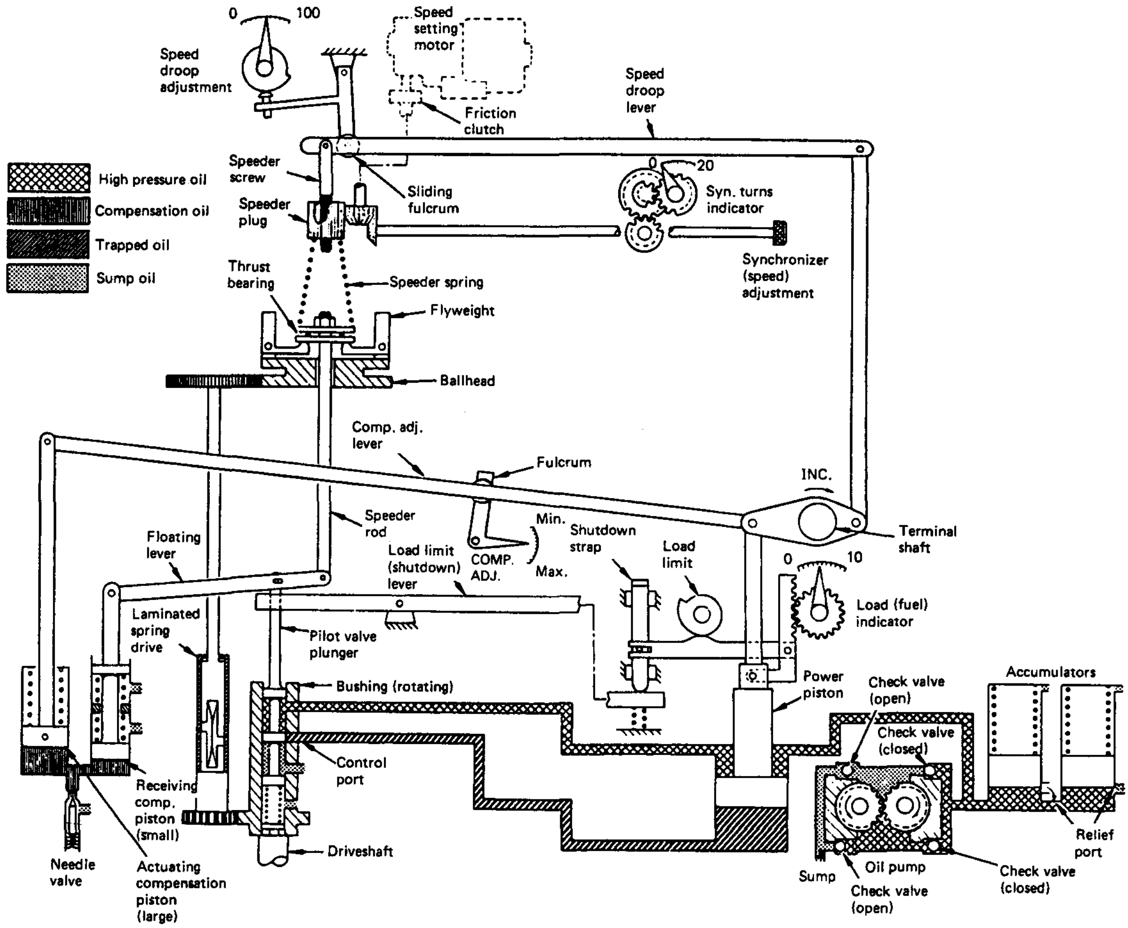



**Figure** 6.27 Schematic diagram of the UG8 dial speed setting governor (Courtesy: Woodward Governor Company)

The governor manufacturer cautions against the use of manual force on the throttle linkage to increase fuel. The load limit control knob must first be turned to its maximum position, i.e. mark 10 on the dial scale.

*Speed droop:* As with the PSG governor, pre-setting the speed droop adjustment has the effect of varying the compression of the speeder spring as the terminal shaft rotates. The speed droop 'kit' consists of a control knob (top left of the dial panel), a earn, and linkage.

*Governor operation:* It should be appreciated that changes in governor speed setting will produce the same governor movements as those induced by load changes on the engine.

Dealing first with 'load decrease' conditions, let us assume that the engine is running on set speed. In this situation the control land of the PVP is centred over the control port of the rotating bushing and the flyweights are in a vertical position - as for normal steady-state operation.

A load reduction creates an increase in speed. This increases the centrifugal force on the flyweights beyond the opposing speeder spring force. The flyweights tip outward raising the speeder rod, the right hand end of the floating lever, and the PVP. Oil is then dumped from under the power piston, which moves downward causing the terminal shaft to rotate in the 'decrease fuel' direction.

A downward movement of the power piston is associated with an upward movement of the actuating compensation piston (the two devices are linked by the compensation adjustment lever). Suction is then applied to the (smaller) receiving compensation piston, pulling it downward. The left hand end of the floating lever is also pulled down. This forces the PVP downward to close off its control port. The compensation system, therefore, anticipates the amount of fuel required to accept the new load change. We established in earlier discussion that the amount of movement (the *compensation)* of the actuating piston is controlled by the compensation adjustment and fulcrum.

Terminal shaft and power piston movement are both stopped in that 'decreased fuel' position which is required to run the engine at normal speed, following the decrease in load. As oil dissipates through the needle valve the receiving piston is returned to normal. It does so at the same rate as the speeder rod. This keeps the PVP in its centred position.

Operation on 'load increase' is the converse of that just described. The increase in load creates a decrease in speed. This results in both the speeder rod and the PVP being forced downwards. Pressurized oil is released through the control port into the lower cylinder of the power piston forcing it upward. The terminal shaft rotates in the 'increase fuel' direction. The compensation adjustment lever acts to push down the actuating piston. The oil, which is forced under the smaller receiving piston, raises the floating lever and, with it, the PVP. The latter recentres. Speeder spring and flyweight forces rebalance and the terminal shaft assumes the position necessary to provide the new fuel requirements.

*Auxiliary equipment:* Like the PSG governor, the UG 8 has a number of auxiliary features and devices. One of these is a direct-mounting shutdown solenoid. Two models are available. One provides shutdown when it is energized, and the other when de-energized. Both may be equipped with a latching device. Solenoids fitted with the device must be manually set to permit restarting when no supply voltage is available. Manual reset is not necessary on 'energize-to-run' solenoids if voltage is available.

The construction of an 'energize-to-run' solenoid is shown in the cross-sectional diagram of Figure 6.28.

The solenoid plunger must move upwards to allow the engine to run. When no supply current is available for the solenoid the plunger must be lifted manually using the shutdown latch knob. As the plunger approaches the top of its stroke the lock pin is depressed by hand. This latches the knob just below its upper position. It allows the engine to be started and run but no protection is provided.

When current is applied to the solenoid it moves to the fully upward position and unloads the lock pin. The pin is moved outward by the circular latch spring. When the supply to the solenoid is interrupted the load spring forces down the solenoid plunger. This lifts the governor pilOt valve and cuts off the fuel. A solenoid may be used without the latching feature on fully automatic plant.

Solenoids are mounted on special covers which mayor may not also accommodate electric (synchr~nizer) motors (See Figure 6.29(b». The motors give remote speed control, and operate into the speeder plugs - as illustrated in Figure 6.27. Microswitches mounted on the synchronizer indicator shaft are

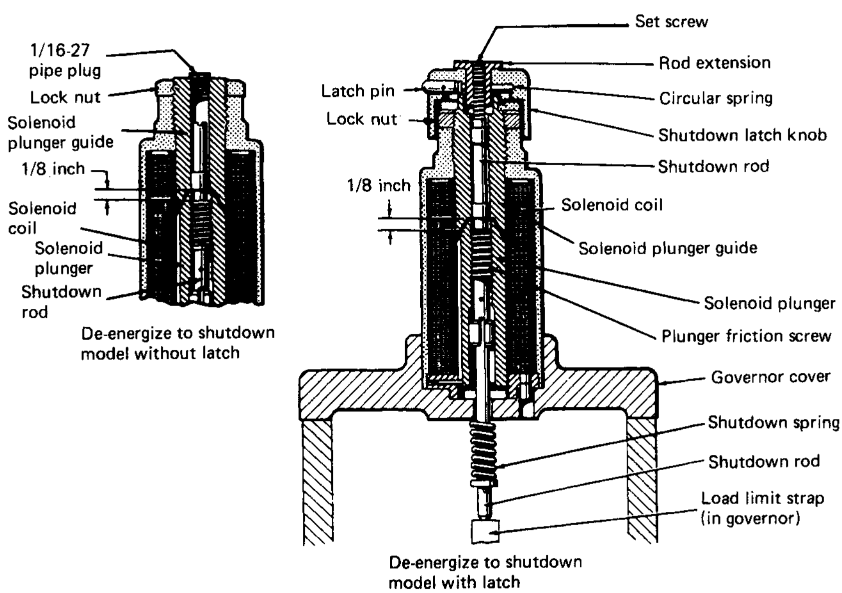
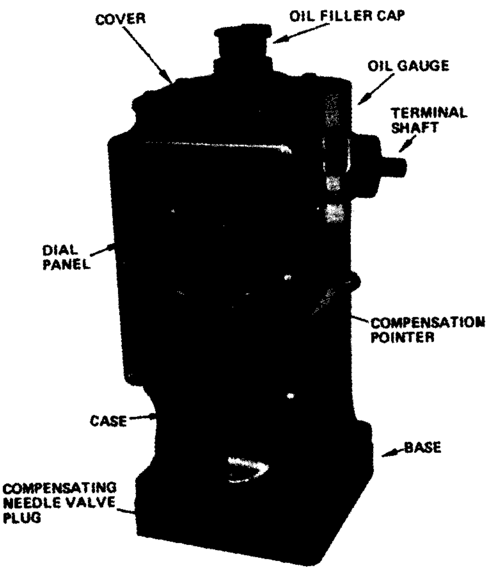
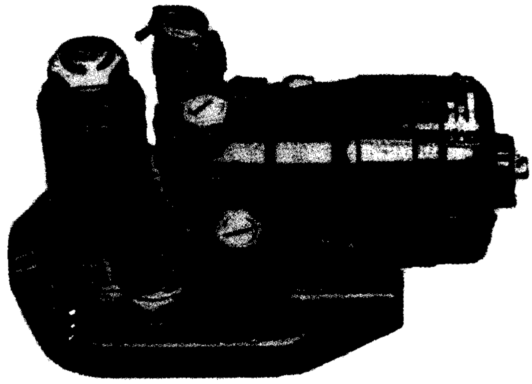


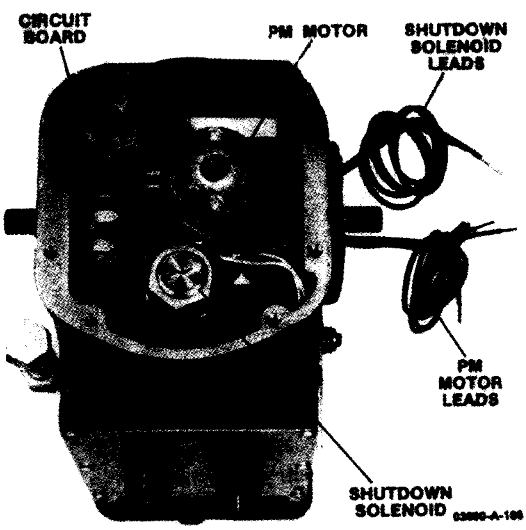

Figure 6.28 Cross-section of shutdown solenoid for the UG8 governor (Courtesy: Woodward Governor Company)




(a) The basic governor



(b) Cover equipped with shutdown solenoid and synchronizer motor




(c) Top view of a housing on the governor case with permanent magnet (PM) motor and shutdown solenoid


(d) Cover equipped with low lubricating oil pressure shutdown

**Figure** 6.29 External features of the UG8 mechanical hydraulic governor (Courtesy: Woodward Governor Company) used to energize a warning lamp or stop the motor when it has reached its maximum or minimum speed setting position.

A permanent magnet (PM) motor operating on d.c. power is another option. A top view of a housing accommodating PM motor and shutdown solenoid is illustrated in Figure 6.29(c). In every case, the motor is coupled to the governor's speed setting mechanism through a friction clutch. This provides the slip necessary to protect the motor, should the speed adjustment be run beyond its limit.

Another ancillary feature is a low lubricating oil pressure shutdown device which functions in much the same way as the solenoid shutdown. It requires no external linkage and is cover-mounted - as illustrated in Figure 6.29(d).

### 6.5.3 Electric

Electric governors give greater versatility in generating plant applications than either of the other types (direct mechanical or mechanical-hydraulic). Their appeal lies in the fact that they are most readily integrated into semi- or fully-automated power plants because of the range of ancillaries available. They also give more flexible mounting arrangements and are the only option when governor drives are not available on engines.

Where all the units in a multiple generator installation are fitted with electric governors the basic system advantages are [2]:

- smaller transient speed changes;
- isochronous operation;
- automatic load division; and
- convenient adaptability to complex control requirements

Module format and the range of available options will vary between manufacturers. The descriptions which follow are intended to convey some idea of the many proprietary forms available.

*Speed control units*

These are of solid-state design and give isochronous performance. They may be mounted off an engine and, within reason, in most positions on it. One treatment is that illustrated in Figure 6.18. Here, the controller is mounted on the actuator, which is located to give the most convenient connection to the fuel control linkage.

The controllers work (as described in Section 6.4.3) in conjunction with a speed sensor and a fuel control actuator to give basic speed governing. Among the standard features offered are:

- speed droop adjustment, for parallel operation with other engines fitted with speed-sensing governors;
- remote speed trim through a potentiometer;
- gain controls, to increase or decrease governor response sensitivity;
- stability control, to match the time constant of the governor to the response time of the engine.

The Governors America ESD 5221 speed control unit, whose connection diagram is shown in Figure 6.30, is typical of those which provide the above features.

The speed signal is usually obtained from a magnetic pick-up mounted in close proximity to the teeth of a ferrous gear driven by the engine. In most cases the flywheel gear ring is used since it provides a high frequency signal. The signal is amplified and shaped by a circuit to provide an analogue speed signal. If the speed monitor does not detect a speed signal within a period of 0.1 s, the output to the actuator is switched off.

A summing circuit which receives signals from the speed sensor and the the speed set point provides an input to the 'dynamic control' section of the speed control unit. This latter circuit (which contains the gain and stability adjustments) gives a dynamic control function, in that it provides isochronous and stable performance for most engine types and fuel systems.

In standard operation control unit performance is isochronous. Droop governing may be selected by connecting terminals K and L, while the droop range may be adjusted by means of the integral

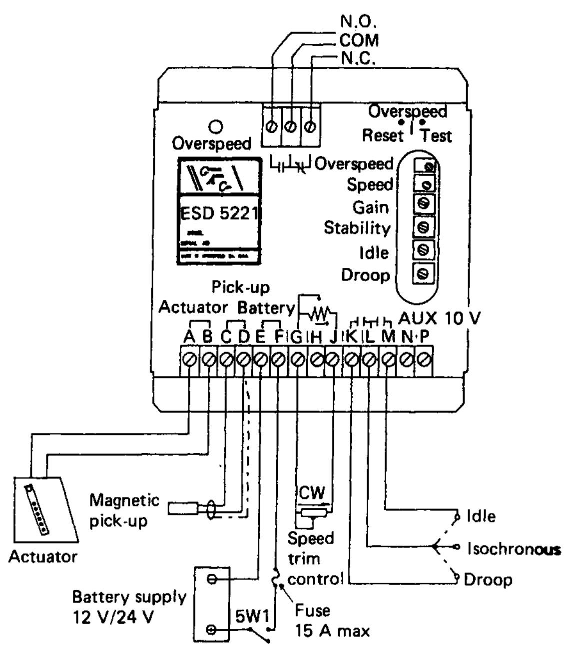



**Figure 6.30** Connection diagram of Type ESD 5221 speed control unit (Courtesy: Governors America Corp.)

droop control potentiometer. If more droop is required ajumper between terminals G and H doubles the droop available.

The control unit has several performance and protection features, such as:

1. a speed anticipation circuit which minimizes speed overshoot on engine start-up or when large load increments are applied to the engine;
2. the ability to accept accessory inputs for multi-engine control, for example, from load sharing modules, automatic synchronizers and ramp generators;
3. the inclusion of a single-element speed switch to give overspeed detection and activate an internal relay. A wide adjustment range is provided, as well as test, reset, and LED indication features.

## *Ancillary devices*

It is necessary for all, or all but one, of the engine governors to operate in droop if successful parallel operation of engine driven generators is to be guaranteed. The speed control units of electronic governors inherently give isochronous performance. If load is applied to two, or more, paralleled generators fitted with isochronous governors, one of the engines may tend to take all of the load within its capability. Some form of load sharing device is therefore required. The simplest method is to introduce speed droop. This is done by using the speed droop potentiometers provided on the controllers described in the preceding sub-section. A droop setting of 3 % is usually adequate for paralleled generators.

*Load sharing units:* Where constant frequency is a requirement on an isolated busbar fed by several paralleled generators, it is necessary to use some form of 'active' power measuring device. This should 'generate' an output voltage (proportional to the measured input power) to bias the reference point of each engine governor speed control unit. The voltage signal from each power measuring module must then be shared with those from the other engine-generators in the system using paralleling lines. The several voltage signals are thus 'averaged'. Each engine controller then compares this average voltage with its own reference point and biases its speed loop controller circuit to change the actuator fuel level setting and precisely maintain its own proportional share of system load. In this way system frequency is also maintained. (See Chapter *8: Parallel operation of a.c. generating sets;* and Figures 8.34 and 8.35 for a more detailed explanation.)

Load sharing modules are provided with droop adjustment for use when generators are operated in parallel with an infinite power source, such as a utility supply. In such cases, the utility regulates the system frequency and the droop adjustment sets the load assumed by each generator.

Versatility is enhanced in some proprietary equipments by the inclusion of additional features such as load anticipation signalling (to minimize speed transients) and forward and reverse power monitoring. (See Chapter 8 and Figure 8.35.)

The forward power signal is used in the automatic start-up and shutdown sequences of multiple generator installations. It is preset for a certain power level from the individual generator. Typically, the signal from the forward power monitor of the last generator to come 'on line' may cause another generator to be started when its (the last generator's) power level has reached a preset point.

A typical load-anticipation module is the Barber Colman 'single phase load pulse control unit'. As its description implies, it monitors the output of one phase of the generator. When a step load change occurs the control unit signals the governor to apply fuel before any actual speed change occurs. Thus, by anticipating impending speed change, offspeed transient performance is improved (by as much as 30 %). It may then be possible to meet the offspeed requirements for a particular installation by using a smaller generator.

*Import/export controllers:* These are used in conjunction with load sharing modules to control the power produced by generators paralleled to an infinite busbar system (such as a utility supply). A bus bar is considered to be 'infinite' if it has sufficient capacity to maintain frequency when the generators in the system are at their power limits. Although the load sharing and the speed controls are wired in the isochronous mode they do not provide true isochronous load sharing with the infinite system. Overall frequency is maintained should the infinite busbar be disconnected.

The Woodward Governor Model 8271-872 (Figure 6.31) senses power from, or to, an infinite busbar and compares it with a desired power level. The level and direction (i.e. the 'importing' or 'exporting') of the desired power may be set with an external potentiometer. Control output is applied to the paralleling line terminals of the load sharing governors (or load sharing controls) as shown in the block diagram of Figure 6.31(a). The infinite busbar receives, or provides. the desired power level because the import/export controller determines the generators' output.

Adjustable low and high limit 'clamps' prevent the generators from being 'motored' or from generating too much power.

*Automatic synchronizers:* These are fully described in Chapter 8. It is only necessary to mention, in this context, that they function to sense the frequency and phase of their associated generators and to adjust them to match those of a busbar or another generator. Control action is obtained by

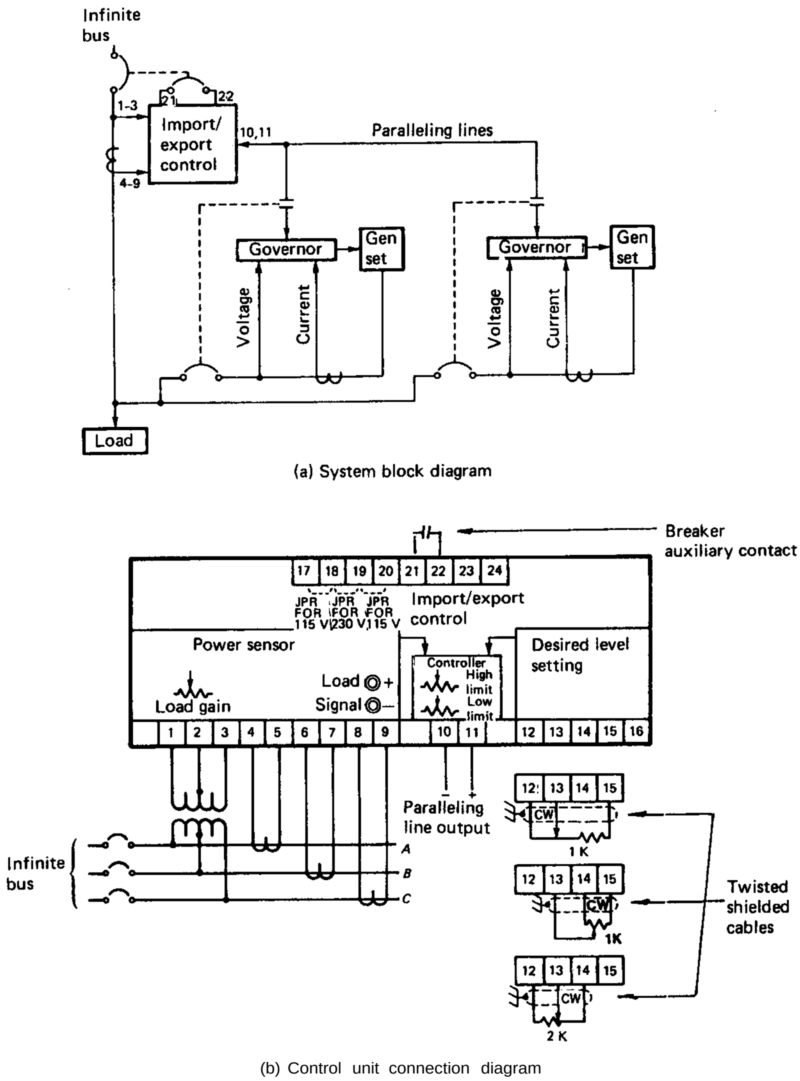



**Figure** 6.31 Application of import/export control to generators paralleled with infinite busbar systems (Courtesy: Woodward Governor Company)

feeding the synchronizer's speed bias signals into the engine's speed control input amplifier. Relay contacts within the synchronizer initiate closure of the output circuit breaker when the generator's frequency and phase match those of the busbar. Features such as:

- 'dead bus sensing' (which prevents attempted synchronization to a dead busbar),
- those which prevent synchronizing during severe offspeed conditions (e.g. on engine starting), and
- breaker closing angle selection,

are typical enhancements on proprietary units.

## 6.6 Recent trends in advanced control systems

Analogue electronic controls of the type described are rapidly being replaced by digital control systems (DeS) on those complex systems where economic and safety performance are primary considerations.. Some of the advantages of Des are listed below (M.J. Webb and J.A. Michigan 1989, personal communication).

1. They are programmable. This permits standard hardware to be manufactured while the software

is being defined. Retrospective changes to the control functions may then be made without expensive hardware modifications.
2. Highly complex mathematical computations can be performed and executed by the microprocessor, and at very high speed.
3. Serial and parallel communication links enable long distance communication along a single multicore cable bus for control, display, printing, data logging, monitoring and trend analysis.

DCS may be in simplex, duplex or triplex configurations. System reliability is enhanced in ascending order of format.

1. A simplex system uses one microprocessor, with each input normally having one transducer and each output one actuator/interface.
2. Duplex systems have two microprocessors, with one being the master control processor. An upper level supervisory board monitors the health of the master and switches to the back-up processor in the event of a fault.
3. A triplex system uses three microprocessors operating in a two-of-three 'voting' arrangement giving near 100% reliability. Two of the three processors must agree for system security. The failure of anyone is detected by the other two and results in its shutdown. The controlled machine continues to operate meanwhile. Each microprocessor has its own dedicated input/output in order to enhance system reliability.

## 6.7 References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7

# Automatic voltage regulation

**Contents**

## 7.1 Introduction

The term *automatically regulated* is applied to a machine which can regulate its own characteristics when associated with other apparatus in a suitable closed loop circuit (BS 4727: Part 2: Group 03). An *automatic votage regulator* (AVR) may then be defined as a device whose function it is to maintain operating voltage at the terminals of a generator within prescribed limits despite changes in external conditions such as speed, load, power factor, and temperature rise.

Electromechanical voltage regulators, now only found in the very oldest installations, were arranged to respond to signals from terminal voltage and line current. Regulators of this type, such as the vibrating contact Tirrill regulator and the multi-contact rolling sector and rolling ramp types, operated on the' overshoot-the-mark' principle [I]. In so doing they provided a greater level of excitation than was called for by a given increase in load. This was in order to overcome the slow build up of flux in the generator field due to the winding's inductance. Before the flux level could build up to a level corresponding to the enhanced excitation, the regulator acted to reduce the excitation. In due course, these regulators were replaced by those using magnetic amplifiers which gave increased stability and reliability - particularly in locations likely to be affected by vibration, e.g. machine-mounted, or in non-stationary work such as mobile equipment and shipboard use.

Modern solid-state AVRs of the type described in this chapter have eliminated the iron cores' masses and the volumetric bulk of the magnetic amplifier regulators by using semi-conductors in their control systems and power circuits. They give exceptional accuracy, response, stability and reliability, and, in conjunction with fully-laminated, medium-frequency exciters, are a marked improvement on the older electromechanical and magnetic amplifier AVRs [2].

## 7.2 Voltage regulation

The *regulation* of a generator is defined as 'the change in voltage resulting from a load change'; its *voltage regulation characteristic* is therefore the relationship between its primary voltage and load under specified conditions. See Sub-section 3.2.1 of Chapter 3 and Sub-section 4.2.5 of Chapter 4.

User requirements vary considerably. Generator performance under transient and steady-state conditions (voltage fluctuation, and recovery times when load is suddenly removed or applied) is of importance to the user.

Grades of voltage regulation are defined in National and International Standards (BS 4999: Part 140 and IEC34-1). The British Standard acknowledges that the *inherent voltage regulation* of a generator (see Section 3.2 of Chapter 3) is a condition not encountered in normal service because it assumes operation at a constant excitation. Accordingly, it applies the term *voltage regulation* to the behaviour of a machine running singly and not in parallel with others. The generator is assumed to operate (in conjunction with its own excitation control system and voltage regulating equipment) at constant rated speed and rated voltage, with its windings hot or cold. In practice, the governing of the prime mover will affect the value of a generator's voltage regulation. BS 5514: Part 4 defines the speed governing requirements for RIC engines. (See Chapter 6.)

Figure 7.1 (reproduced from BS4999: Part 140) shows a typical curve for overall voltage response on sudden application of load to a generator's terminals and gives the symbols to be used for defining voltage regulation characteristics.

The voltage regulation grades are sub-divided into four groups: Grades 0, 1, 2, and 3. The British Standard lists requirements for steady-state conditions in the last three grades; and for transient conditions in Grades 1 and 2.

1. steady-state voltage fluctuations should not be more than ±5 %, ±2.5 %, and ±I % for Grades 1,2, and 3, respectively.
2. In transient conditions, when driven at rated speed and giving rated voltage on no-load (under control of their normal excitation and voltage regulating systems) Grade 1 and 2 generators must give a voltage dip of not more than 15 p.u. when a load, which would absorb 0.35 p.u. of rated current at a power factor between 0.4 and zero lagging, is suddenly switched. The voltage must then recover to 0.94p.u. (Grade 1) and 0.97 (Grade 2) in less than 1.5 s.

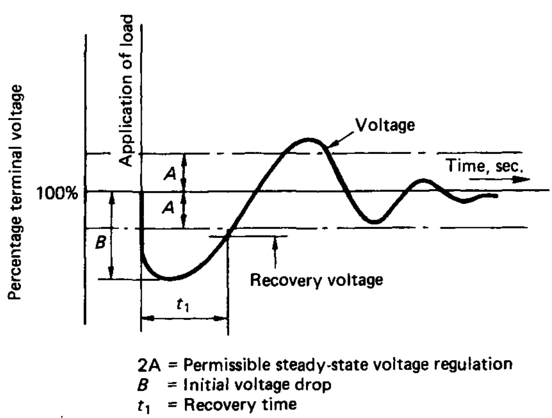


**Figure 7.1** Typical voltage response characteristics (Courtesy: The British Standards Institution)

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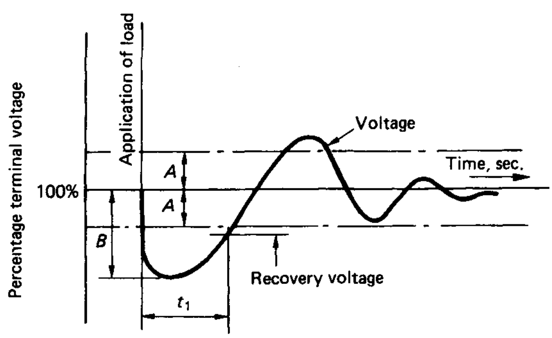



2A = Permissible steady-state voltage regulation
$B$ = Initial voltage drop
$t_1$ = Recovery time

**Figure 7.1** Typical voltage response characteristics (Courtesy: The British Standards Institution)

3. The transient performance for Grade 3 machines must be agreed between manufacturer and purchaser.
4. The permissible transient voltage rises occurring, when 0.35, 0.60 and 1.0p.u. rated loads at 0.8 p.f. are switched off Grade 2 machines, are specified in Table 1 of the Standard and vary from 0.15p.u. to 0.38p.u. The values of sub-transient reactance which could normally be expected to give the performances specified in the table vary from 0.25p.u. to 0.12p.u. at rated voltage.

BS 5000: Part 3 *(Generators to be driven by reciprocating internal combustion engines)* states that generators must comply with the requirements for any *steady-state* voltage regulation specified in BS 4999: Part 140. The supplier of the generating set should specify the *transient* voltage performance so that the generator manufacturer may make due allowance for the effects of engine speed variations.

BS 2949 and IEC 92-5 - the specifications for *rotating electrical machines for use in ships* - call for a steady-state regulation of ±2.5 % of rated voltage for all loads between zero and rated load at rated power factor, with the generator windings hot or cold. This may be increased to ±3.5 % for emergency generator sets. One of four transient condition requirements may be specified by the purchaser:

1. *When the starting kVA of the largest motor or group of motors liable to be started simultaneously from the generator does not exceed 60 % of the capacity of the generator:* the unloaded generator must be capable of accepting a suddenly switched load, absorbing 0.60p.u. of rated current at a power factor of between 0.4 and zero lagging, without its voltage falling below 0.85 p.u. The generator voltage must then be restored to 0.97 p. u. of rated voltage within 1.5 s, provided the speed of the prime mover has been restored to within the limits required by its appropriate governing class. These values may be increased to 0.96p.u. rated voltage and 5s for emergency sets.
2. *When the starting kVA of the largest motor or group of motors, liable to be started simultaneously from the generator exceeds 60 % of the capacity of the generator:* the unloaded generator must be capable of accepting or discarding a suddenly switched load, absorbing at least 1.0p.u. of rated current at a power factor of between 0.4 and Zero lagging without its voltage falling below 0.85 p.u. or rising above 1.2 p. u. Voltage restoration requirements are as for 1 above.
3. *When the generator* is *required to supply a.c. multi-speed cargo winches or loads having similar characteristics, or any load not included in conditions* 1, 2, *and* 4: the precise values of initial recovery and time should be agreed between purchaser and manufacturer.
4. *When the generator* is *required to supply a special load such as a cargo-pump motor:* the purchaser must specify the transient voltage response, based on service load requirements.

## 7.3 Basic excitation systems

Practical excitation systems were considered in Chapter 3 (Sub-section 3.2.2); and were classified by groups in the related block diagrams of Figure 3.5.

**In** the context of modern machines, and in the output range we are considering, it was established that systems employing separate excitation through shaft-driven d.c. exciters were no longer marketed. In practice, system choice now lies between those using *direct self-excitation* (Groups 1 and 2 of Figure 3.5), those using some form of a.c. or brushless excitation (the *indirect self-excitation* of Group 6), and those using *separate excitation* with a permanent magnet pilot exciter (Group 7 in Figure 3.5). These 3 basic systems are shown in Figure 7.2 and their particular features are summarized in the following sub-sections.

### 7.3.1 Direct self-excitation

This system affords very fast correction of excitation following load changes because it gives direct control of the generator's main field without having to work through an intermediate exciter field. Not only is the time delay in an exciter eliminated, but the machine's field current can also be forced down using the thyristors in the AVR to reverse the field voltage. The system is, therefore, particularly suited to:

1. generators required to respond to frequent and large load changes - such as those imposed by cargo winches in ships;
2. the need to maintain the transient stability of generators under short-circuit conditions on a power system; and
3. the need to quickly reduce the current resulting from a fault between the generator and its associated circuit breaker when field suppression is the only means available [3].

Among the disadvantages of the system is the requirement for slip-rings and brushgear to carry the relatively large excitation current to the rotor main field windings. Excitation power is of the order of 10 kW per MVA of machine rating.

The AVR must include some provision for building up the terminal voltage (from its residual level) when the generator is first run up to speed. Since the excitation supply voltage is lost when the machine's output is short-circuited, it is also necessary to use

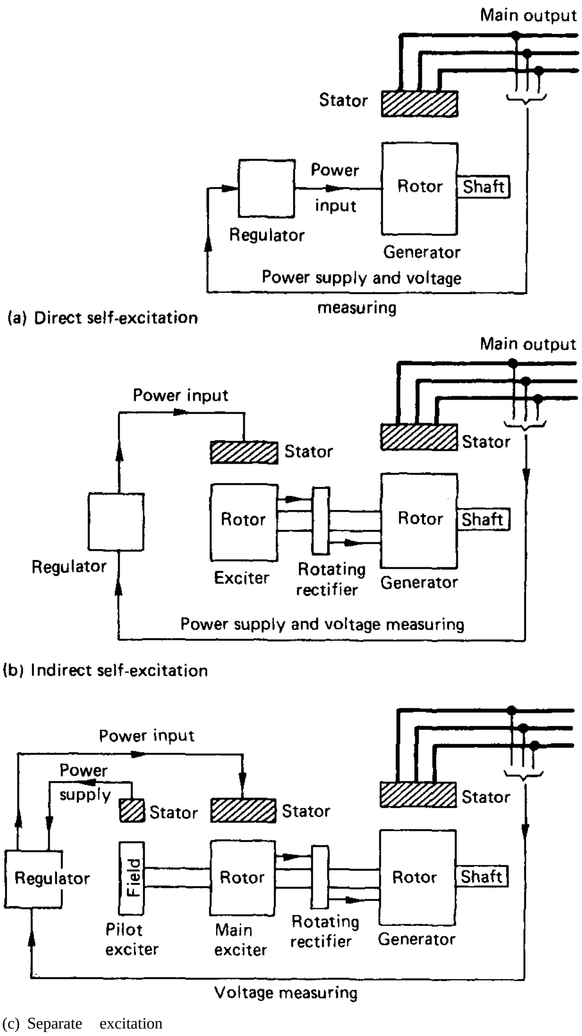



Figure 7.2 Basic excitation systems

series excitation current transformers in the generator output leads in order to sustain excitation (and therefore short-circuit current) so as to allow discriminatory protection by downstream circuit breakers in the power distribution network. (See also Sub-section 3.3.4 of Chapter 3.)

### 7.3.2 Indirect self-excitation

Because the AVR is now required to supply current to the exciter field and not directly to the generator main field windings, its output can be smaller than that for the system just described. Response using this form of excitation will not be as fast as with direct self-excitation. Nevertheless, it should be adequate for most duties - including large impacting loads such as motors started direct-on-line.

### 7.3.3 Separate excitation

As their description implies, these systems provide excitation power from a source independent of the generator output. The scheme shown in Figure 7.2(c) is the one most commonly employed and makes use of a small permanent magnet pilot exciter (p.m.p.e) or permanent magnet generator (p.m.g.) coupled to the common generator and main a.c. exciter shaft. Its advantages are:

1. The p.m.p.e. provides a power source not affected by load circuits external to the generator. Therefore, the series transformers - necessary for short-circuit maintenance on self-excitation schemes - are not required.
2. The p.m.p.e. provides near-constant excitation power under all operating conditions, including the build-up phase on first run-up.

For these reasons, performance under starting and fault conditions tends to be superior to either of the self-excited systems of Figure 7.2(a) and (b). As in the case of the system described in Sub-section 7.3.2, machine response is affected by the presence of exciter time constants. A high main-exciter ceiling voltage (of the order of 1.5 to 3 times the full-load field voltage) and a large output from the p.m. p.e. are needed if more rapid response is required [3].

It is not unusual to have permanent magnets built into the main exciter's field system, to initiate control.

## 7.4 The basic AVR circuit

An automatic voltage regulator is an *error-operated* device working on the *closed-loop control* principle. Systems employing this principle are used where a higher degree of control is required than is possible with *functional* or *open-loop* control systems (such as that used in the basic static-excitation scheme of the compounded machine described in Sub-section 3.3.4 of Chapter 3).

### 7.4.1 The closed-loop control system

The essential elements of any automatic closed-loop control system are:

1. a controlled condition;
2. a detecting element;
3. a measuring element;
4. a correcting unit (sometimes called a regulating unit or a final control element);
5. a controlling unit; and
6. the plant which is to be controlled.

When these elements are 'strung' together (as shown in Figure 7.3), it will be seen that the controlled plant forms part of the loop. It is therefore a most important element in the performance of the total control system [4].

The function of the measuring element is to receive and evaluate the signal from the detecting element(s). The correcting unit serves to effect changes in the controlled condition, and the controlling unit provides the means for operating the correcting unit. It responds to the difference between a signal representing the *desired vaLue* and that from element 3, representing the *measured vaLue.*

Control action is dependent upon the magnitude and sense of the difference between these two signals being fed, as an error signal, to the correcting unit - hence the term *error-operated.* It is important to realize that corrective action is made whether the error arises from external disturbances or from changes in input conditions. The control system must then function to minimize deviations and to return the controlled condition to its desired value as quickly as possible following a disturbance. The performance of any system is adversely effected by:

1. delayed information into it;
2. over-sensitivity; and
3. delayed response from it.

In the context of generator control, the *inherent voLtage reguLation* of the machine (a property which enables it to reach equilbrium after a disturbance - even in the absence of any other control) enhances the application of automatic control.

### 7.4.2 Basic error-operated AVR

A simplified block diagram of a typical AVR is shown in Figure 7.4. The generator terminal voltage ($V_g$), transformed to a suitable level and rectified within the measurement element (1), is compared (in 2) with a constant and stable voltage ($V_r$) on a zener diode reference circuit (3). Any difference between the two voltages (the *error signaL)* is fed to an operational amplifier (4). The amplifier output applies pulses of controlled phase, using a pulse generator circuit (5), to fire a thyristor circuit (6) and adjust the excitation level in either the generator or the exciter field. In this way, generator voltage is restored to its correct level and the 'error voltage' returns to near-zero. Small changes in the setting of the generator voltage are obtained by adjusting either the reference voltage or, as shown in Figure 7.4, that proportion of the measured voltage which is compared with the reference.

The purpose of the adjustable stabilizing stage (7) is to allow the AVR to be set for optimum stability and to give rapid and adequately damped voltage response to load changes. This is achieved by obtaining a transient negative feedback signal from the output current (or voltage) of the regulator and feeding this signal into the operational amplifier's input.

Not shown in the basic circuit of Figure 7.4 are those features, which are especially desirable for self-excitation schemes. These are:

1. *Wave-form smoothing:* an l.c.r. circuit designed to reduce any voltage spikes on the generator output wave-form.
2. *VoLtage transient suppression:* a C.r. network or an 'avalanche' device to suppress any high voltage transients that are generated across the machine's stator windings from external sources.

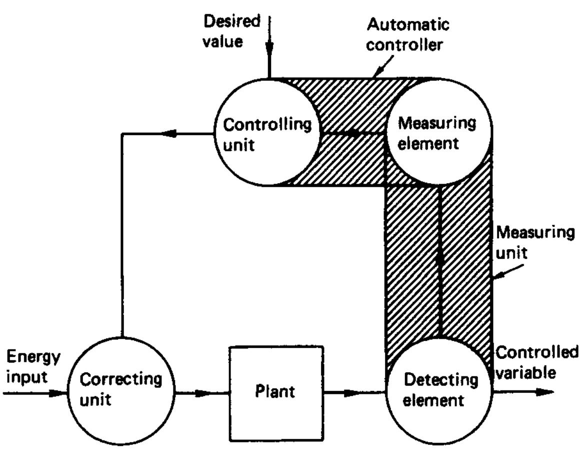



**Figure 7.3** Closed-loop process control system (Courtesy: The English Universities Press Ltd)

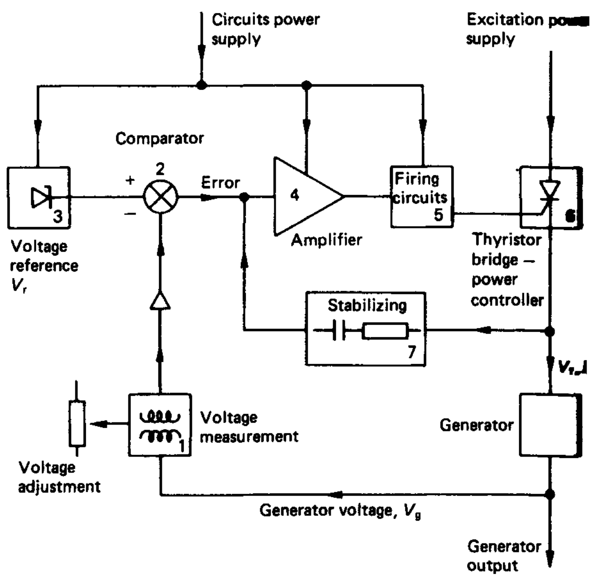



**Figure 7.4** Block diagram of basic AVR

3. *Voltage build-up stage:* a starting circuit to enable the generator to build up from a low residual voltage. The minimum residual required for reliable build up is usually 2.5 % of rated voltage - a level normally obtained with conventional brushless machines.

The easiest control systems to stabilize are those which contain one time delay which is much longer than any others in the 'loop'. For example, the delay in the field of a directly self-excited generator is much longer than that within the regulator itself. Indeed, response of the regulator is so fast that stabilizing is often unnecessary for machines using this form of excitation. However, the introduction of an exciter field into the control chain results in a second significant time delay in the machine's response. A closed-loop system which has two significant time delays is potentially unstable. Stability control is, therefore, always necessary when an exciter is used [5].

In discussing the performance of a.c. generators in Chapter 4 (Sub-section 4.2.5), we examined both open-circuit characteristics and load magnetization curves - the latter for machines delivering constant full-load current at various power factors. Figure 7.5 [6] reproduces the no-load and full-load (at 0.8 p.f.) characteristics of a generator, in curves 1 and 2 respectively. Intermediate characteristics would obtain for different load levels.

Superimposed on these two curves is the AVR characteristic (3), which shows the relationship between the AVR's input (the measured generator voltage) and its output (excitation current). This characteristic shows that, over the normal working range, large increases of excitation current are achieved for a very small fall in generator terminal voltage. At any particular load the generator voltage will be stabilized at the point where the generator and AVR characteristics cross. This represents the only point at which both relationships are satisfied. The relation between generator voltage and generator load current is, therefore, a voltage which drops only slightly with increasing load - as shown in Figure 7.6 [6].

## 7.5 The AVR in excitation systems

The AVR, which is often the only control component necessary for small machines, must include a number of ancillary control and protective features if it is to be employed on larger machines - particularly those running in parallel with other sets, or with a utility network. The extent of these features will also depend upon whether the plant is to be attended or unattended during operation. In the discussions that follow, the functions of various ancillary components are examined and the circumstances in which they are used are explained.

### 7.5.1 Voltage setting control

While a trimming potentiometer is provided in an AVR (to give generator steady-state voltage adjustment) it is often desirable to have this facility extended to a remote position, e.g. at a switchboard, which controls a number of parallel-running sets. The voltage of an individual generator may then be adjusted before it is synchronized to the busbars. Once the set is running in parallel, the remote potentiometer is used to adjust the generator's share of kVAr loading (see Chapter 8). The range of adjustment provided is of the order of ± 10 % of rated voltage. Where long distances apply between switchboard and AVR it is the usual practice to mount a motorized potentiometer close to the AVR and to control the motor from the switchboard.

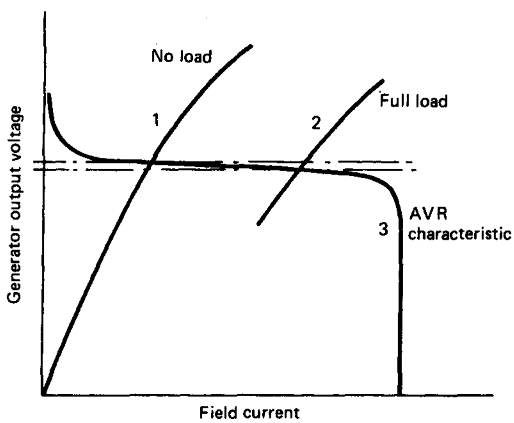



**Figure 7.5** AVR characteristics

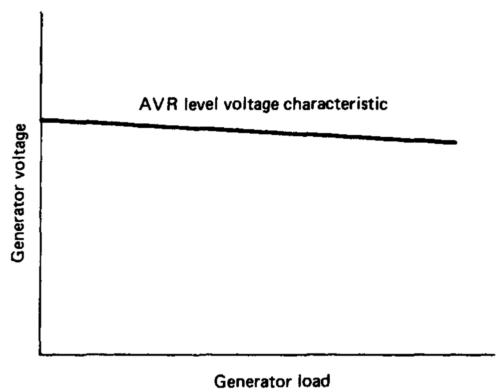



**Figure 7.6** AVR level voltage characteristic

### 7.5.2 Manual control

The primary purpose of this feature is to enable a generator to function in the event of a fault developing in its AYR. It provides a back-up control or power source. It can be particularly useful in those cases where the manually-controlled machine can 'trail' in parallel with others which have healthy AVRs. Its inclusion in the excitation schemes of marine generators is of particular importance since any loss of power constitutes an unacceptable hazard to ships operating in narrow waters.

Manual control is also useful during first commissioning of plant when checking out a machine's excitation system and setting the protective relays directly associated with the generator. It may also be used in maintenance and repair operations to give a controlled level of short-circuit current for drying out machine windings. Other applications are:

- the 'frequency' starting of large motors, where a generator electrically connected to the motor is run-up under manual control before being switched to AVR control;
- the dynamometer loading of the prime mover on factory tests, or after major overhauls in the field.

An example of a machine fitted with one form of emergency manual control is given in Sub-section 3.3.4 of Chapter 3. It is but one of several methods employed. In the simplest schemes the components of the manual control system are quite independent of the automatic and may comprise a transformer/rectifier with a variable transformer or rheostat to give the necessary excitation current. See Figure 3.34 of Chapter 3.

A more sophisticated approach is provided by the GEC Alsthom HC 15 manual control module, also designed to give a power source completely independent of the AYR. It consists of a low-gain, feedback loop affording stability against changes in the supply voltage and providing a single-phase thyristor/diode bridge for excitation power. A static counter is used to produce an analogue output control signal. The 'raise/lower voltage' control is by remotely-located pushbutton contacts. Alternatively, the static counter can be switched out and a standard linear potentiometer used instead. Preset limits are provided to set the minimum and maximum excitation levels. A useful feature is an LED (light emitting diode) bargraph, mounted on the front of the module, to display the excitation level.

Some systems operate on the principle of driving the manual control elements continuously to give the same excitation as that developed by the automatic control circuits. What must be avoided in such arrangements is the driving-down of the manual controls to excitation levels which, though stable with continuously acting control, are unstable with fixed excitation [3]. To prevent this happening a 'follow-down limiter' is usually fitted. This is designed to restrict the follow-up feature within the leading power factor zone of the generator's operation close to its stability limit. Other systems use the 'manual' circuits continuously for steady-state control. The 'auto' circuits then merely act to trim the manual controls, on minor changes in terminal voltage, load, etc. Any larger disturbances are countered by rapid automatic changes in excitation. If such disturbances persist for more than a few seconds, the follow-up circuits act to adjust the manual controls to the new steady-state level and the auto circuit output assumes its former trimming level. A simplified excitation control system allows the generator to be started in manual control and to be switched to automatic regulation only when the correct terminal voltage has been established [6].

### 7.5.3 Manual-automatic changeover

A null balance meter can be provided to facilitate smooth transfer. This enables the switchboard attendant to adjust the output of the 'incoming' control so that it matches that of the 'operating' mode before any transfer is made. This also gives reassurance that the 'incoming' control is functioning properly before the transfer is made. The manual and the voltage-setting potentiometers must be motorized to allow operation from a remote switchboard.

The more sophisticated equipments, such as the GEC Alsthom type HCI5, include null balance and follow-up circuits which ensure that the manual control continuously 'follows' the automatic. Any changeover from the AVR system to a manual (or a standby) system then takes place with the minimum disturbance to the generator output.

### 7.5.4 Parallel operation

Where generators are required to operate in parallel with others or with a utility, their AVRs are arranged to give terminal voltage droop with increasing kVAr load. Series current transformers measuring the generator output current give a signal to the AVR for what is called *quadrature droop compounding* (or *compensation).* This form of control is described in Sub-section 8.8.1 of Chapter 8.

### 7.5.5 Excitation contactor

The protective relaying associated with a generator is arranged to trip its circuit breaker when fault conditions are detected. Simultaneous interruption of its excitation would give the generator more protection. This is done by using a contactor either in the supply leads to the excitation equipment or in the connection to the exciter field. Where routine plant shutdown calls for excitation to be tripped the contactor must be fitted.

### 7.5.6 **Excitation limits**

Circuits may be introduced to inhibit regulator output current in response to various operating conditions.

#### *Over-excitation*

A two-stage current limit provides an output when the field current exceeds a set point. This permits short-time over-excitation to allow high field forcing currents to deal with transient overloads, but introduces a lower limit, after an adjustable time delay, to prevent machine overheating.

Circuits designed to provide under-speed or under-frequency protection come under the same category. Their purpose is to prevent overfluxing of generator transformers and overheating of machines on prolonged run-up or in slow speed operation. However, unlike the two-stage current limit just described, they employ negative feedback to reduce the AVR's reference voltage at a rate proportional to the decrease in frequency, for all generator frequencies below a preset 'cut-in' level.

Though the prime mover may be governed to give a predetermined speed droop or even isochronous operation it will, nevertheless, experience transient speed excursions during run-up and during full-load switching (see Chapter 6). If the under-speed protection circuit is activated by these excursions, the transient voltage performance of the generator will be adversely affected. In order to prevent this happening, operation of the protection circuit is momentarily inhibited by means of a non-adjustable time delay.

#### *Under-excitation*

Here the circuits act to prevent reduction of excitation current below a safe operating level under leading power factor conditions. This keeps the generator within its *stability limit* and prevents pole slipping or loss of synchronism. These so-called reactive power limiting circuits are used in schemes where the generator is run in parallel with a large power supply system. Any rise in system voltage would cause the AVR to decrease the excitation current with the risk of the generator falling out of step. The circuit is designed to respond to the amount of leading kVAr generated. Since the safe level of excitation depends upon the true load present on the generator, a bias proportional to kW is introduced. Independent adjustment of the kVAr limit point (and this kW bias) then enables the limiter to be set for particular machines and requirements.

The control circuit requires single-phase voltage and current signals from the generator's output. These are combined in such a way as to give two d.c. voltages, one proportional to $I\cos\phi$ and the other proportional to $I\sin\phi$. These voltages are mixed in a suitable proportion and compared with a fixed reference at the input of an operational amplifier. At the preset limit point the amplifier gives an output which overrides the sensing voltage within the AVR.

The generator operating chart of Figure 7.7 shows the typical characteristic provided by a leading-kVAr controller. The point along the leading kVAr base of the chart and the slope with the kW axis are both adjustable during plant commissioning. 'Generator operation charts' are discussed in Section 8.4 of Chapter 8.

#### *Power factor/kVAr control*

This enables a generator to be controlled at constant power factor (or constant kVAr) when it is operating in parallel with a large power supply system. It is a form of control particularly suited to those applications where parallel-running generators are not under constant supervision. Its basic feature, in contrast to that of conventional voltage control, is that the generator does not attempt to keep the local busbar voltage constant, and continues to operate at its preset p.f. or VAr, irrespective of changes in system voltage. It therefore obviates the need for any other excitation-limit controls. It should be appreciated, however, that this form of control is only stable when the generator runs in parallel with a power system capable of absorbing the resultant kVAr generated. It is therefore necessary to revert to voltage control:

- prior to synchronizing;
- if interconnection with the power supply system is lost during operation; and
- during start-up and shutdown operations.

For this reason, a relay is included in the control unit to give the necessary switching between voltage

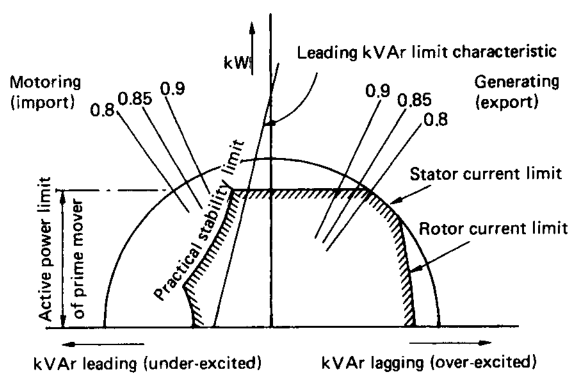



**Figure 7.7** Typical operating chart for a salient-pole generator

control and VAr/p.f. control. It may be activated by an external manually-operated switch interlocked with the generator breaker and other breakers in the power system.

## 7.6 **Protection against system component failures**

The modern trend towards the use of lower short-circuit ratio generators has resulted in greater dependence on excitation systems to maintain power system stability. More emphasis is, therefore, being placed on the reliability of all the elements within excitation schemes [7]. (See Sub-section 4.2.6 and Figure 4.19(b) in Chapter 4 for a definition of the term *short-circuit ratio).* Equipment manufacturers offer - in addition to those features just described - a range of 'modules' which may be incorporated into systems to enhance their reliability.

### 7.6.1 Excitation fault detection

The most reliable and comprehensive method for confirming the integrity of the AVR is to monitor the generator's output. Inconsistencies not in accordance with normal operating conditions must be detected and signals initiated to:

- switch excitation from automatic to manual control; or
- transfer to an alternative excitation control'circuit; or
- trip the generator circuit breaker and excitation contactor.

An ancillary unit, typical of those designed for this purpose, is the *GEC Alsthom* type FV 200-C module, which monitors the generator's output voltage and initiates a trip if the signal voltage is higher or lower than preset limits. The trip is inhibited for normal low voltage conditions such as on run-up, and for known 'no-excitation' conditions, such as shutdown. A feature of the unit is its use of a current signal (derived from a current compounding circuit) which is vectorially added to the voltage signal to give the tripping signal. This ensures that if the generator is running in parallel with others, an excitation fault will be detected even though the busbar voltage may remain unchanged. Under these conditions a high leading or lagging current will circulate in the faulty generator and the addition of the current signal significantly boosts or bucks (as appropriate) the voltage signal, so enabling the fault-sensing unit to detect the condition. This results in only faulty generators being tripped off the busbars. All the healthy units are unaffected. Signals to the trip relay are inhibited under the following circumstances:

1. When the field volts fall below a preset level, the high voltage trip is inhibited for a set time to prevent tripping during voltage transients caused by load rejection.
2. The low voltage trip is also inhibited for a fixed time during generator run-up and shutdown, and when the sensing volts are very low and the stator current is high. The latter provision enables a short circuit to be cleared.

A simplified block diagram of the FV 200-C excitation fault detector is given in Figure 7.8.

### 7.6.2 Voltage-transformer fuse failure protection

The failure of one phase of the voltage transformer supplying the 3-phase sensing circuit of the AVR will result in serious disturbance of the generator's excitation. In detecting this condition, a fuse failure relay compares the secondary voltage of the AVR's sensing transformer with that of a general metering! instrumentation transformer. Any appreciable difference between the two causes the system to trip to manual control. The metering voltage transformer is also monitored and an alarm is given if it fails.

### 7.6.3 Rotating diode failure protection

We have discussed (in Sub-section 3.3.2 of Chapter 3) the implications of failure of any of the shaft-mounted diodes in a brushless generator, and some proprietary forms of diode failure monitor were described. It is appropriate to summarize those discussions and reaffirm that failure of a diode to open-circuit is much less serious than a failure to short-circuit. Whilst the former condition does require an increase in exciter field current to maintain generator output voltage, the increase is only a small one which is well within the capability of a modern AYR. All that would probably happen is that response to load change would be impaired and short-circuit boosting would not operate correctly. Neither the generator nor the power system are at immediate risk. A diode failure detector need, therefore, only provide an alarm for supervisory staff, who would take the set out of service at the first opportune moment.

The failure of a diode to short-circuit is more serious, since a very large increase in exciter field current is required to maintain generator voltage. If the condition is allowed to persist, both AVR and exciter could be at risk. It is therefore necessary to arrange for the signal from the diode failure detector to trip the machine and shut down the prime mover.

Like those described in Chapter 3, the GEC Alsthom Type FV 223-C Exciter Diode Failure Detector unit (Figure 7.9) operates by monitoring the ripple current induced in the exciter field. The

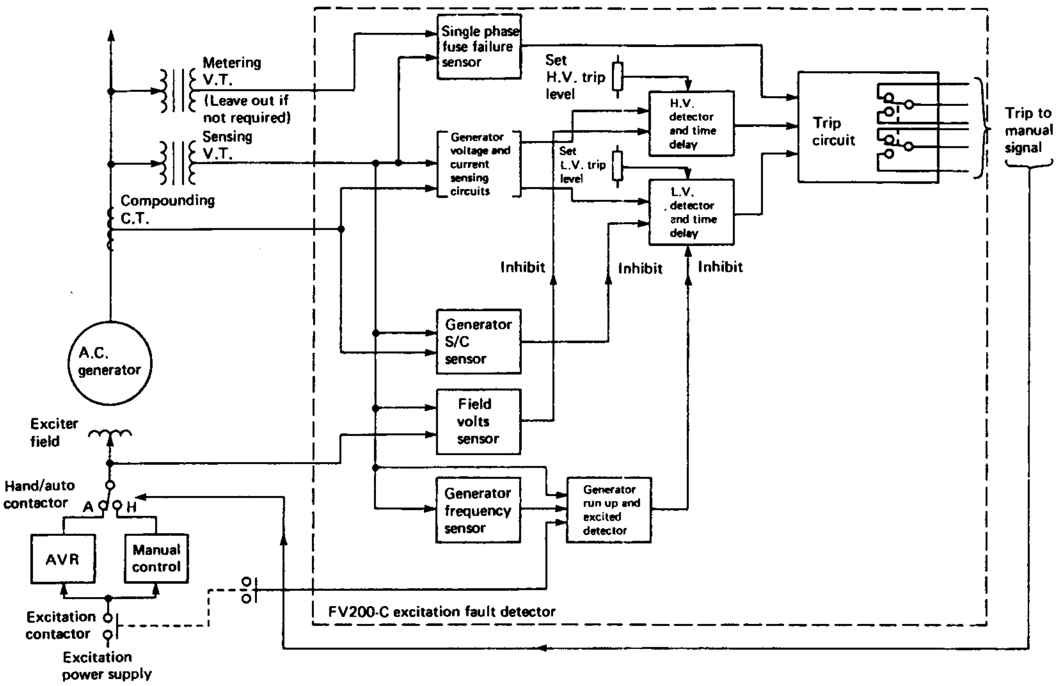



**Figure 7.8** Simplified block diagram of the FV 200–C excitation fault detector (Courtesy: GEC Alsthom Vacuum Equipment Ltd)

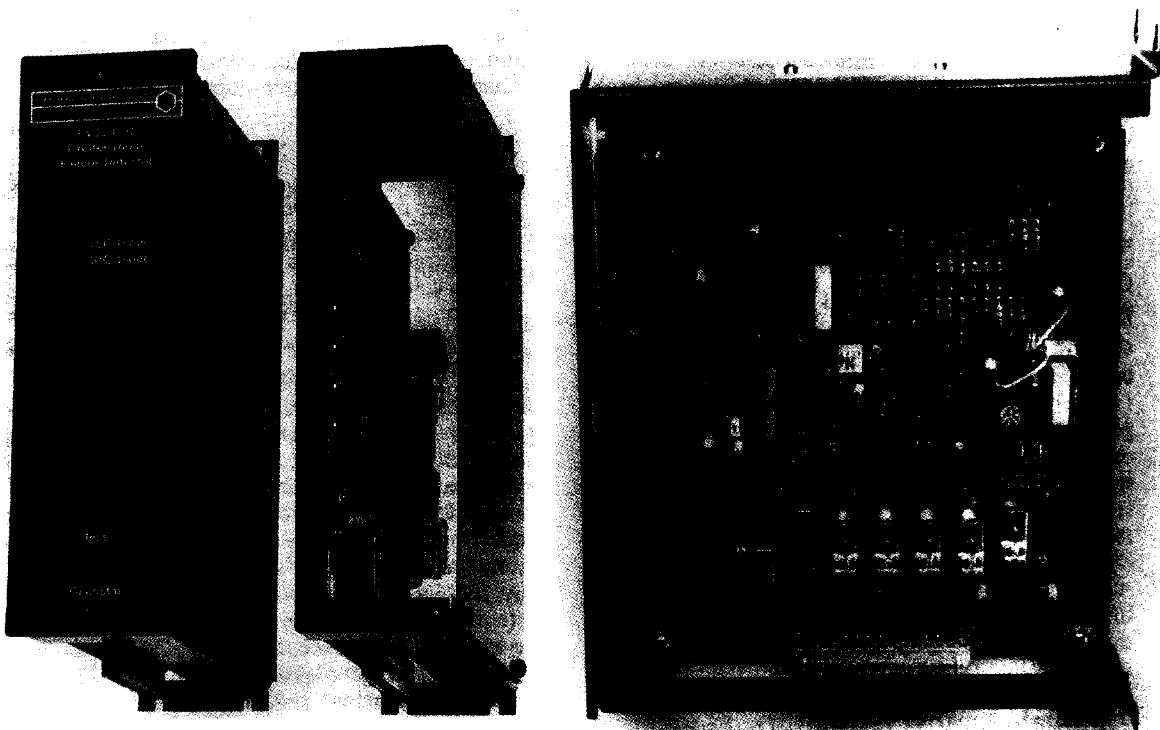


**Figure 7.9** Diode failure detector type FV 223–C (Courtesy: GEC Alsthom Vacuum Equipment Ltd)

frequency and magnitude of the 'ripple' changes quite distinctly if a rotating diode fails. The unit analyses this change to determine the nature of the failure, i.e. either to open-circuit or to short-circuit.

The exciter field current is monitored by looking at the voltage across an externally-mounted resistor in series with the exciter field. A special stabilizing circuit produces a signal which is a reproduction of the input, but is at a constant d.c. level. The ripple content of this signal is then applied to an amplifier with a band pass characteristic which amplifies the exciter fundamental frequency. The positive part of the amplifier output charges a capacitor to produce a d.c. voltage which is proportional to the peak a.c. input. The capacitor voltage is compared with two reference voltages: one for the open-circuit condition, and the other for the short-circuit condition. Separate relays are operated to differentiate between the two conditions.

The unit operates from a d.c. supply in preference to a.c. which cannot always be guaranteed to be available during the disturbance caused by a faulty diode. In most diesel-generator applications a d.c. supply is readily available. It may be derived from the secondary batteries used for engine starting or from those used for control and tripping circuits.

Although the unit is designed to be insensitive to the normal ripple currents (sometimes at exciter fundamental frequency) produced by modern thyristor AVRs, it may not function correctly if the peak-to-peak values of the ripple current exceeds 30 % of the mean d.c. value. There will also be applications where the induced ripple caused by a faulty diode is much less than normal (e.g. generators fitted with special damper windings on the exciter). To ensure correct operation of the diode failure detector, the manufacturer stipulates that the following *minimum* levels of peak-to-peak ripple must obtain under fault conditions:

| | |
|---|---|
| Open-circuit diode | 35 % of the mean d.c. |
| Short-circuit diode | 100 % of the mean d.c. |

On most conventional brushless machines the percentages are considerably greater.

Where machines employ several diode paths in parallel in each arm of the rotating rectifier bridge, correct indication is given if anyone diode fails to a short-circuit. If the complete bridge is open-circuited, only 'open-circuit' indication is given. Also, where in-series fuses blow, on diode short-circuit, an 'open-circuit' indication is given.

The unit incorporates a test facility which enables the functioning of the amplifiers and the two relays to be checked.

## 7.7 Dual-channel regulators

Although modern AVRs achieve demonstrable reliablity by using wide safety margins in semiconductor ratings and only well-proven control circuit designs, it is sometimes necessary to consider the use of dual- or double-channel regulators on vital generators, to enhance reliability in operation [3, 8]. In these regulators, components, circuits or channels may be duplicated so that, should anyone fail, control is automatically switched to the other. Duplication may extend to the automatic and manual control circuits and to the power controller feeding the exciter field. Each channel is capable of achieving the rated excitation duty and they may be arranged to operate in parallel at all times or in main and standby modes. Should, for example, one automatic control circuit fail, its duplicate would maintain unchanged excitation to the machine. Failure of the second circuit would then cause the system to trip to manual control. Appropriate alarms would be activated at each stage in the process.

## 7.8 Typical proprietary systems

The term automatic voltage regulator is only properly applied to a single generator-regulator system supplying a passive load. In such cases constant terminal voltage will be maintained within limits determined by the inherent regulation of the machine and the system's closed-loop gain. However, where a generator-regulator is connected to a large power system, it cannot maintain constant voltage at the machine terminals. It can only attempt to do so. The effectiveness of a generator's *excitation regulation* system depends upon:

- the size of the generator in relation to the power system to which it is connected;
- the system reactances, i.e. between the generator and other power sources and loads; and
- the contribution it makes to system stability, during transient fault conditions. Severe disturbances could result in loss of synchronism on the machine and on adjacent machines (the effect is cumulative since more load is thrown on to the remaining machines).

Clearly, the maintenance of constant terminal voltage is not the only, or even the prime, function of the regulator. In order to maintain system stability it is necessary to make the machine's regulator responsive to a number of control signals - such as those from the ancillary controls discussed under 'excitation limits' in Sub-section 7.5.6. The AVR is only the basic control element in the excitation system. It would, therefore, be more accurate to use the term *automatic excitation controller,* rather than 'automatic voltage regulator' when describing the function of a mllchine-regulator system.

The following examples of proprietary systems illustrate typical executions for direct and indirect self-excitation, and for separate excitation schemes. Applications will range from the single-machine installation to those where several machines operate in parallel in large co-generation power plants or with public supply networks. Schemes may differ as far as detailed treatment is concerned but the principles applied are common to all.

### 7.8.1 Direct self-excitation

Here the excitation system is supplied by power derived directly from the generator's stator output. Also, since the equipment combines the functions of self-excitation and automatic voltage regulation, it is commonly referred to as an *automatic static exciter* or just a *static exciter.*

*GEC Alsthom's GECOSTAT system*

The control elements (the AVRs) of many generators employing d.c. exciters, and built in the 1950s, 1960s and 1970s, require refurbishing and up-dating to modern practice in order to improve performance and reliability. When considering refurbishment, the decision is often made to replace the complete excitation equipment. The system shown in the schematic and block diagrams of Figure 7.10 illustrates a typical retrofit static excitation system, designed to replace older AVRs and rotating exciters. It is normally able to utilize the signals from existing voltage and current transformers. The old exciter may be left *in-situ,* with its brush gear removed. Cabling is relatively straightforward and there is little restriction on the positioning of the replacement exciter cubicle.

The static excitation system consists of a regulator controlling a thyristor convertor, which feeds the d.c. field of the generator through its slip-rings. The excitation power may be taken either from an isolating transformer directly connected to the generator output terminals (as shown in Figure 7.IO(a)) or from a separate 'safe' supply.

The sizes of the excitation transformer and convertor are dictated by the excitation power required. The ceiling voltage (from the secondary winding of the transformer) determines the response of the generator to load changes. For rapid response, a high forcing voltage must be applied to the field. This field-forcing action also compensates for low voltages at the generator terminals, caused by overcurrents.

The AVRs and convertors are usually housed within the one cubicle, which is located close to the machine.

Single-phase, naturally cooled, thyristor convertor bridges are employed on low excitation power installations. Three-phase bridges are used for higher currents. They may be naturally cooled or force cooled. The firing circuit is designed to operate down to 30% of rated voltage, with a frequency range greater than 25-100 Hz. The d.c. output of the convertor can be varied from fully-positive, in the rectification mode, through zero, to a negative ceiling voltage in the inversion mode. This inversion feature enhances the machine's transient response when load is removed from the generator.

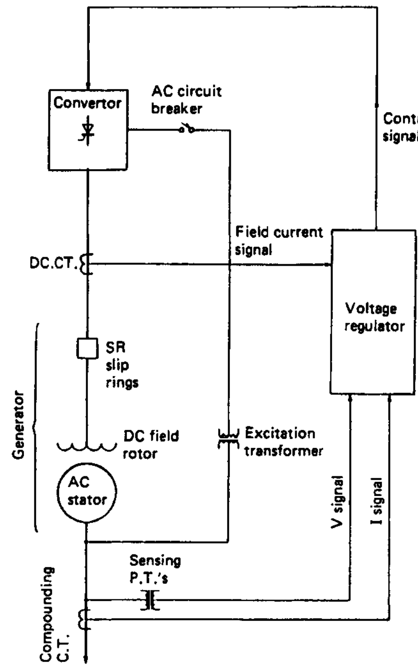
Because slip-rings are used, it would be possible to employ conventional field-suppression methods to limit the voltage rise on the machine. On retrofit applications existing suppression equipments are often retained. With thyristor systems, however, field suppression may be directly achieved by operating the convertor in the inversion mode. GECOSTAT convertors may be fitted with a *crowbar circuit.* This gives field suppression and prevents possible damage to the thyristors on loss of excitation supply or when the a.c. circuit breaker (Figure 7.10(a)) is tripped in fault conditions. The crowbar circuit consists of two thyristors inverse-parallel connected and in series with a discharge resistor which dissipates the stored energy in the generator rotor. In effect, the circuit operates in the same way as a d,c. field breaker.

Automatic excitation control is provided by the AVR - based on stator voltage, line current, and power factor. Limit circuits (as shown in Figure 7.1O(b)) are included to ensure that the generator keeps within its load and stability limits. The manufacturer's type C22/180 AVR is generally used. Its circuit features may be selected, as required, by means of switches mounted on the printed circuit boards. These ancillary features have been described in Section 7.5.6.

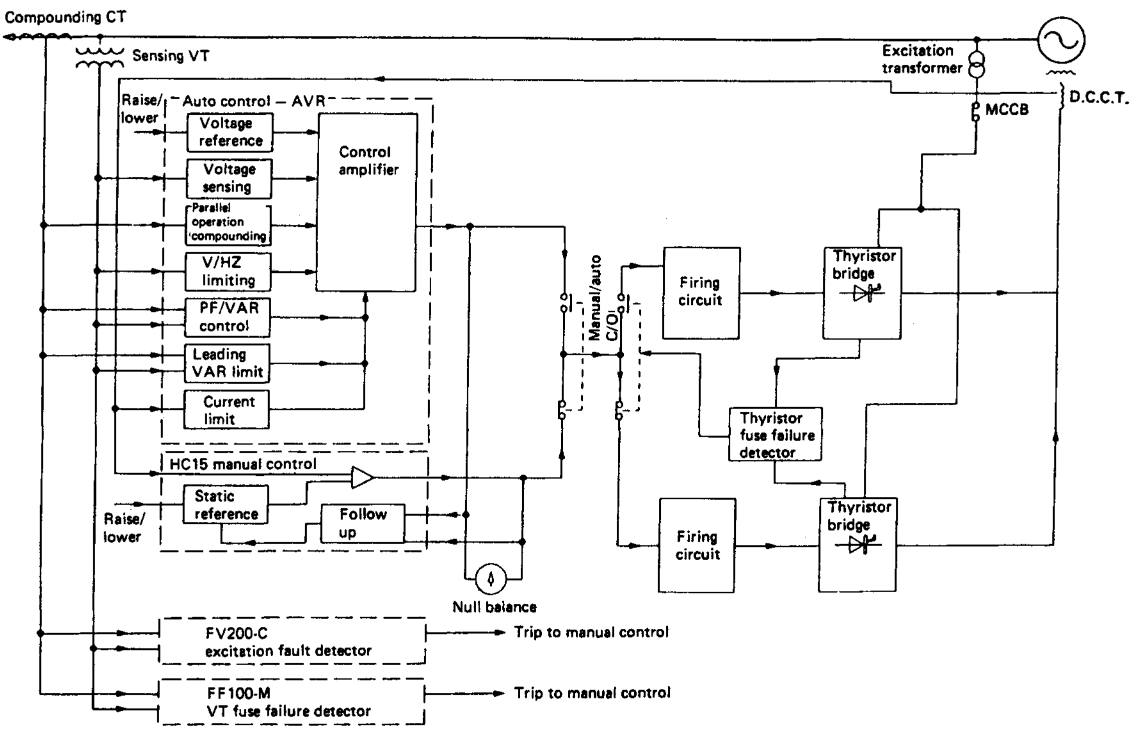
Manual control is provided through a low-gain, field current regulator. The manufacturer's type HC 15 module (see Section 7.5.2) controls the firing signal to the convertor bridge. A switch gives selection of either AUTO or MANUAL control. The module provides stable excitation control from zero upwards. For normal use, preset controls set the minimum and maximum levels. These are usually 80% of no-load excitation and 110% of full-load excitation, respectively. The excitation can be controlled down to zero current for commissioning and test purposes.

The actions of the 'excitation fault' and 'sensing voltage transformer fuse failure' detectors have already been described in Sub-sections 7.6.1 and 7.6.2.

The system includes provision for excitation build-up during generator run-up. This is achieved by producing a continuous pulse train for the convertor until generator voltage is raised from residual to a level where the firing circuit takes over. An external signal may be used during normal shutdown procedures to short-out the input control signal and retard the thyristor firing angle to the back stop. This enables the current in the power loop to be reduced as quickly as possible prior to the a.c. breaker tripping.




(a) Static exciter system




(b) Block diagram of static exciter

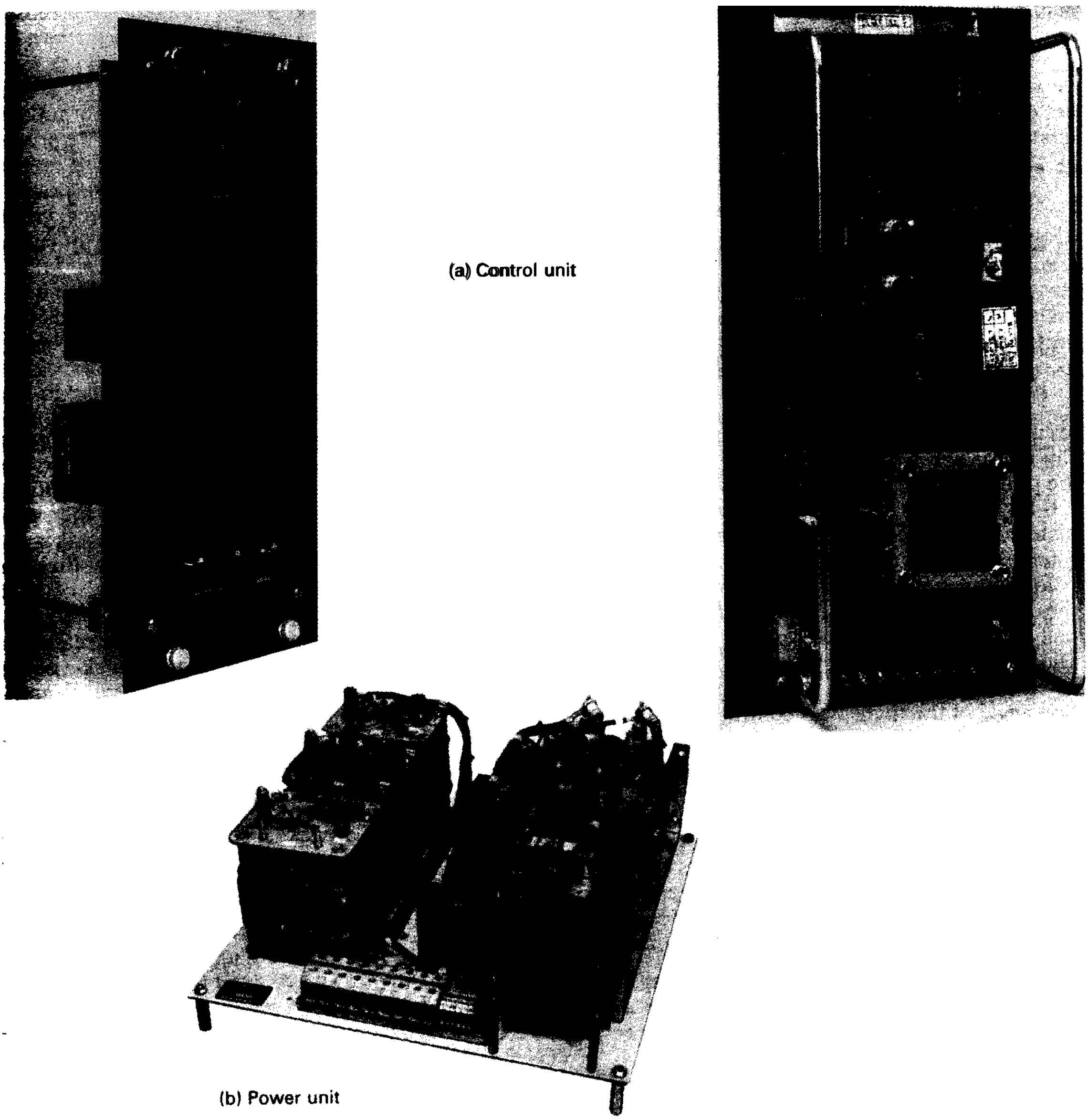
**Figure 7.10** Schematic and block diagrams for a static excitation system (Courtesy: GEC Alsthom Vacuum Equipment Ltd)

While it is the usual practice to protect the thyristor bridges with a.c. line fuses, the signal from externally mounted current transformers measuring the line current to the bridge may be monitored by an overcurrent circuit which initiates fast phase-back of the firing pulses and gives an appropriate alarm.

## *Brush Electrical Machines' TDE system*

This manufacturer's *thyristor direct excitation system* (TDES) comprises two main units in its standard arrangement: the power unit and the automatic control unit. The latter is designed for flush mounting on an instrument or switchgear panel, while the former may be mounted within the switchgear cubicles or in a separate cabinet adjacent to the generator (see the illustrations in Figure 7.11).

In the operational descriptions that follow, reference is made to the block schematic diagram of Figure 7.12. The power circuit, which comprises the thyristor (SCR), the power rectifier diodes (D1 and D2) and associated components, provides controlled



(a) Control unit

(b) Power unit

**Figure 7.11** The main units of the Brush Electrical Machines' TDES (Courtesy: Brush Electrical Machines Ltd)

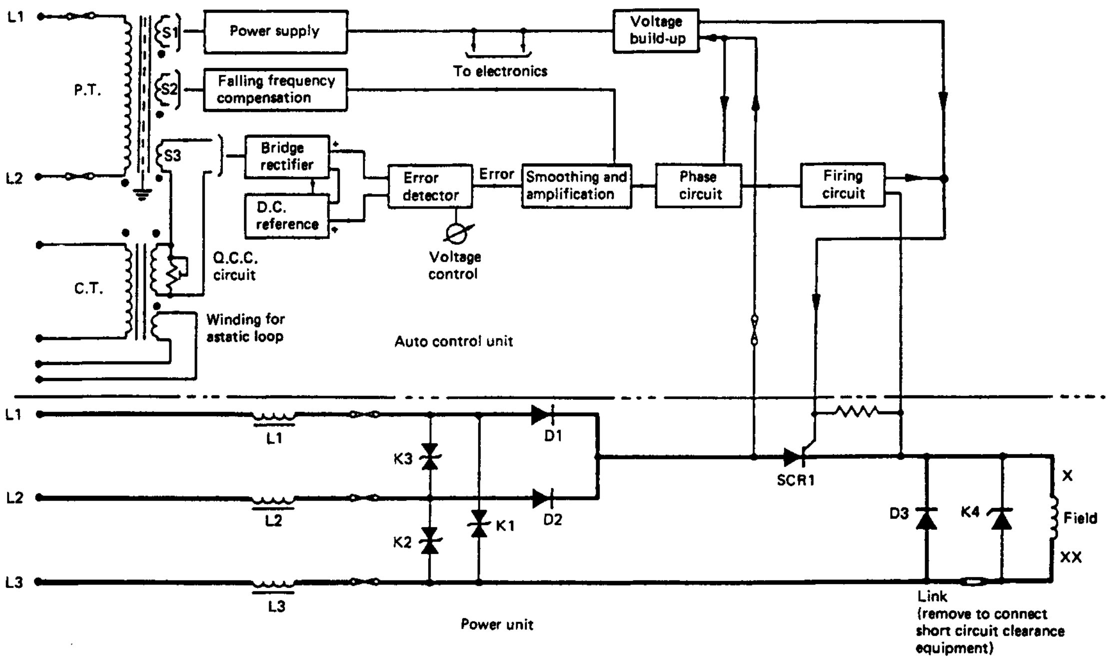



**Figure 7.12** Block schematic diagram of the TDES control and power units (Courtesy: Brush Electrical Machines Ltd)

excitation power to the generator field through slip-rings. The semi-conductor devices in the unit are protected from voltage surges by the suppressors K1-K4. The line reactors Ll-L3 are designed to match the parameters of the generator and serve to filter out the current disturbances caused by thyristor commutation which would otherwise distort the output wave-form. Diodes D1 and D2 are half-wave rectifiers in two phases of the supply. Diode D3 allows the field current to 'free-wheel' when the thyristor is not conducting. The conduction angle of the thyristor is controlled by the firing circuit located within the control unit.

The automatic control unit derives the supply for its electronic circuits from the secondary winding, S1, of the power transformer (PT). The supply is rectified, smoothed, and stabilized before it is fed to the circuits. The control circuit functions to generate triggering pulses to the thyristor at appropriate intervals during the positive-going portions of the supply voltage wave-form. It does this as follows:

1. The voltage across a secondary winding, S3, of transformer PT (the primary of which is connected across two lines of the generator output) is rectified to give two signals:
   (a) The first, used for sensing purposes, is directly proportional to the generator line voltage.
   (b) The second is a constant reference potential, derived from a zener stabilizing network.
2. The two signals are compared in the error detector and the difference (proportional to the line voltage error) is smoothed and amplified. The output from the amplifier is fed to a capacitor in the phase circuit. The time taken to charge this capacitor, and hence to fire the thyristor, is dependent upon the level of field current required to maintain the generator's nominal line voltage. The thyristor ceases to conduct when the positive-going excursion of the rectified line voltage wave-form returns to zero. The firing sequence is repeated when the capacitor commences to recharge at the instant that forward voltage reappears across the thyristor.

Voltage build-up during generator run-up is achieved by means 9f a current limiting resistor, a diode, and a normally-closed reed relay contact, connected in series across the thyristor's anode-gate junction. This effectively holds the thyristor in its ON condition until the reed relay is energized by the generator voltage building up to about 50 % of its nominal value.

The *falling frequency compensation* circuit acts to ensure that the voltage is reduced, should generator frequency fall below a preset minimum level. At this frequency the output of the amplifier (in the *smoothing and amplification* stage) is automatically short-circuited so that the thyristor ceases to conduct. The generator output voltage then falls rapidly and finally fluctuates about the operating voltage of the build-up circuit. If the supply frequency recovers sufficiently the short circuit is removed from the amplifier and the generator line voltage again builds up to its nominal value.

The purpose of the *quadrature current compensation* (QCC) circuit is to give the generator a drooping output voltage/kV Ar characteristic. The associated potentiometer provides the means of adjusting this droop to a maximum of 10% of the selected operating voltage, at full load kVAr. (See Sub-section 7.5.4.)

QCC gives accurate kVAr load sharing between paralleled generators, but it does so at the expense of a droop in the overall power system voltage. One way of eliminating this droop is to employ what is called *differential* or *astatic* compensation. (See Sub-section 8.8.2 of Chapter 8.) The inherent kVAR sharing capability provided by the QCC method is still maintained.

Basically a closed or series ('astatic') loop is formed of all the (paralleled) generators' quadrature current transformers. In the system shown in Figure 7.12, this loop is made by connecting an additional winding on each transformer in series with similar windings on the other generators. The voltage injected into each generator's error detection circuit then contains a signal which is proportional to the out-of-balance or circulating currents between the paralleled machines. Each additional winding should also be connected across a normally-closed auxiliary contact on the associated generator's circuit breaker. This is necessary in order to bypass that particular portion of the astatic loop while the generator is not running. The complexity introduced by the interconnections and switching arrangements seldom justifies the use of astatic compensation on small and medium size power systems.

Figure 7.13 shows the optional features that may be added to the manufacturer's standard excitation system. The hand control unit carries on its front panel a voltage adjustment potentiometer, an AUTO/HAND selector switch, and a self-return changeover switch which facilitates a smooth changeover from one control mode to the other. Manual control of the generator's output voltage is achieved by controlling the thyristor in the power unit. To enable a number of generators to be run in parallel under manual control each regulator is given a drooping voltage/kV Ar characteristic.

The purpose of the *short circuit clearance* equipment is to sustain excitation during short-circuit faults in the power system until such time as downstream protective devices operate to isolate the fault from the busbars. It consists of current transformers matching the generator's parameters and a bridge rectifier mounted on or near the power unit. Under normal-running conditions the equipment has no influence on the operation of the excitation system.

### 7.8.2 Indirect self-excitation

Here, the regulator in the system also derives its supply from the generator. Unlike the direct excitation systems described in Sub-section 7.8.1, its output now supplies the excitation to the stationary field coils of an a.c. exciter whose rotating armature is directly coupled to the generator's rotor shaft. In the brushless machine configuration the output of the exciter armature is fed, in turn, to the (rotating) generator main field windings through a shaft-mounted bridge rectifier. See Figure 7.2(b).

#### *ABB type* 2214 *regulator*

This is the basic unit in the firm's UNITROL range of thyristor voltage regulators. It may be adapted for use in a wide range of synchronous machine applications including the control of synchronous motors and the speed control of d.c. motor-generator convertor sets. It is capable of controlling generators up

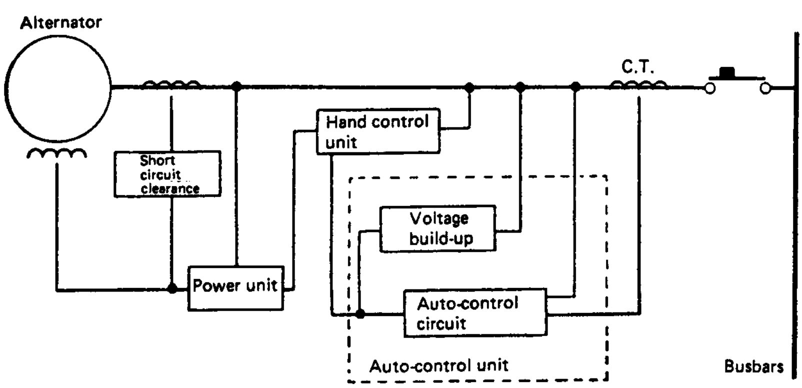



**Figure 7.13** Block diagram of the TDES with optional circuits fitted (Courtesy: Brush Electrical Machines Ltd)

to about 200 kYA in direct excitation schemes, and four- and six-pole machines up to 25 MYA in indirect excitation arrangements.

The schematic diagram of Figure 7.14 shows its application to a high voltage brush less generator. Rectifier 1 converts the 3-phase measuring voltage to a d.c. voltage. The current signal from the line transformer (f2) is 'added' to the a.c. voltage signal to give quadrature current compounding and stable sharing of reactive power when the generator is running in parallel with others (see Sub-section 7.5.4). The voltage reference value is set by means of an internal (6a) or an external (6b) potentiometer. The difference between reference and measured values of voltage is magnified by the operational amplifier (2). The purpose of the PID (proportional, integral and derivative; see Section 6.2, Chapter 6) feedback circuits (3) forming a closed loop across the amplifier is to provide fast and stable response to voltage changes by varying the gain as required. Due account is taken of the time constants of both generator (m1) and exciter (m2). The gate control (4) converts the amplifier's output voltage into pulses of the correct phase to trigger the firing of the thyristors in the convertor (7) at the appropriate point in the positive half-cycle of the exciter supply wave-form. The power pack (5) provides the regulator with the necessary supply for its electronic circuits. Its input is obtained from the secondary of transformer m9, whose primary is connected to a power station service transformer m6.

The exciter field is fed via circuit breaker a3_ which also serves to discharge the field through resistor r3. The excitation build-up circuit is supplied, in this case, from an auxiliary mains which is disconnected by relay k1 when 60 % of rated voltage is reached.

### *Brush Electrical Machines' thyristor divert AVR*

This is a panel-mounting unit (see Figure 7.15) which differs from the more conventional forms of series thyristor controllers described in the previous examples. A single thyristor is used to *divert* the excess current from the exciter field by shoTt-circuiting the excitation supply rectifier. The pri~ ciple of operation is illustrated in the diagrams of Figure 7.16.

The field current to the exciter is supplied from a high impedance compounding circuit through a single-phase bridge rectifier. This circuit provides more output than is required by the exciter under aD conditions. Current in excess of requirement is diverted from the field windings through the thyristor whose gate is controlled by the action of a sensing circuit which monitors the line voltage and current. The compounding circuit consists of a choke (which has a high impedance relative to the

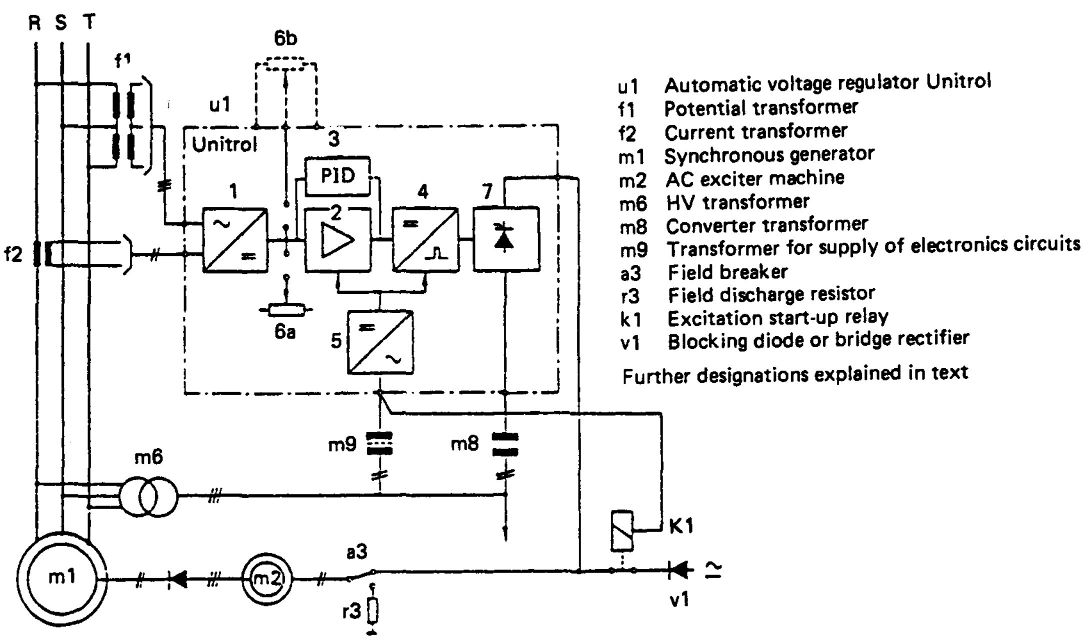
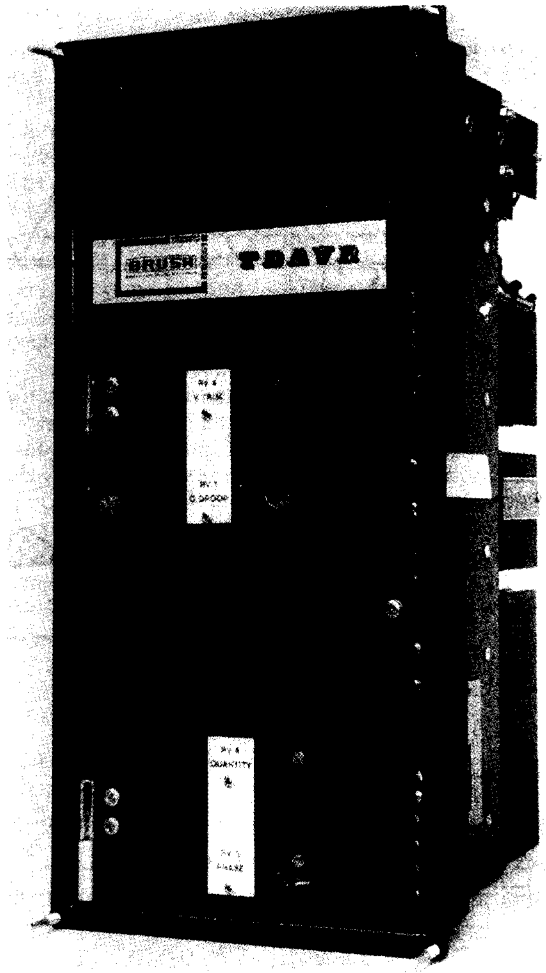
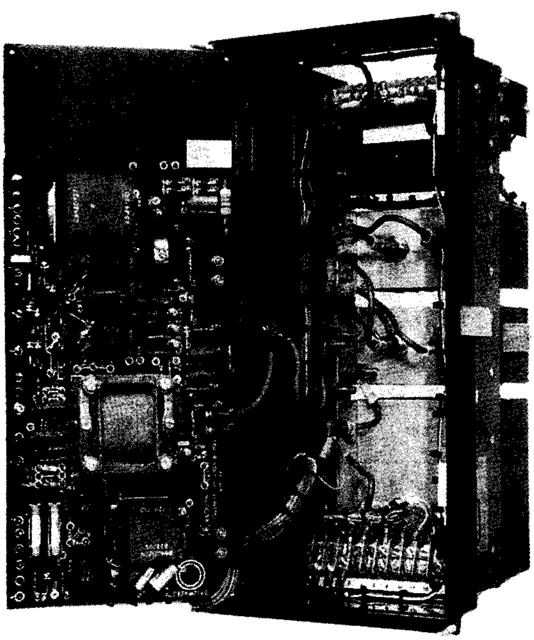



**Figure 7.14** Block schematic of the UNITROL 2214 regulator applied to a high-voltage brushless generator (Courtesy: ABB – Asea Brown Boveri Ltd)

(a)

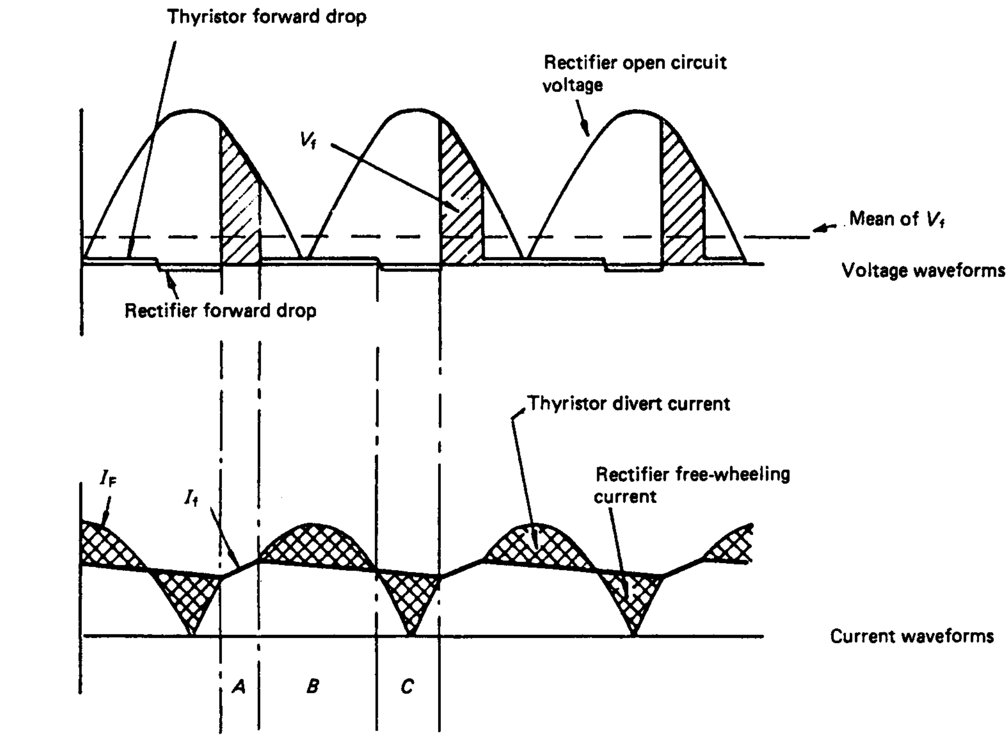



(b)

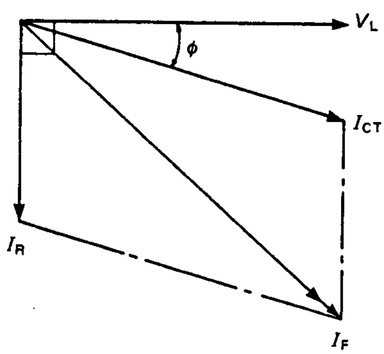


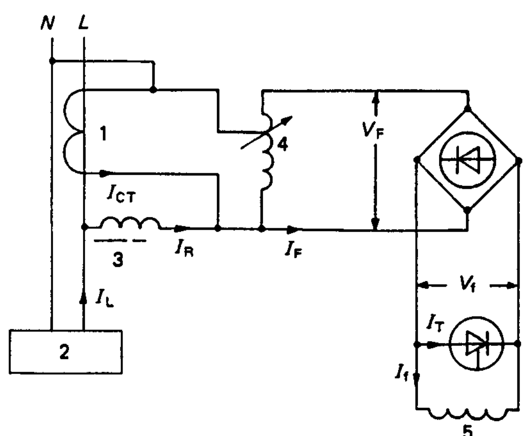
(c)

**Figure 7.15** The thyristor divert AVR (a) Showing access to the nominal voltage control potentiometer, with front cover fitted (b) Hinged electronics chassis behind the front cover. The potentiometers marked 'quality' and 'phase' are stabilization controls. (c) The chassis-mounted p.c.b. hinged out for access. The two power diodes, the thyristor and the outgoing terminals are housed within the case.
(Courtesy: Brush Electrical Machines Ltd)




(a) Operational wave-forms




h = Une current
$V_L$ = Line voltage
ICT = Current transformer secondary current
$I_R$ = Choke current
IF = Field rectifier input current
VF = Field rectifier input voltage
I, = Field current
IT = Thyristor current
V, = Voltage acrossfield and thyristor

1 Current transformer
2 Generator
3 Choke
4 Hand controller
5 Field

(b) Approximate vector diagram

(c) Circuit diagram

**Figure** 7.16 Diagrams illustrating the principle of the thyristor divert AVR operation (Courtesy: Brush Electrical Machines Lld) exciter field resistance) and current transformers. The latter enable the excitation to be sustained when the generator is subjected to a short circuit. The circuit also provides a suitable source of supply for hand control and affords a measure of automatic compensation for load changes (see Figure 7.17).

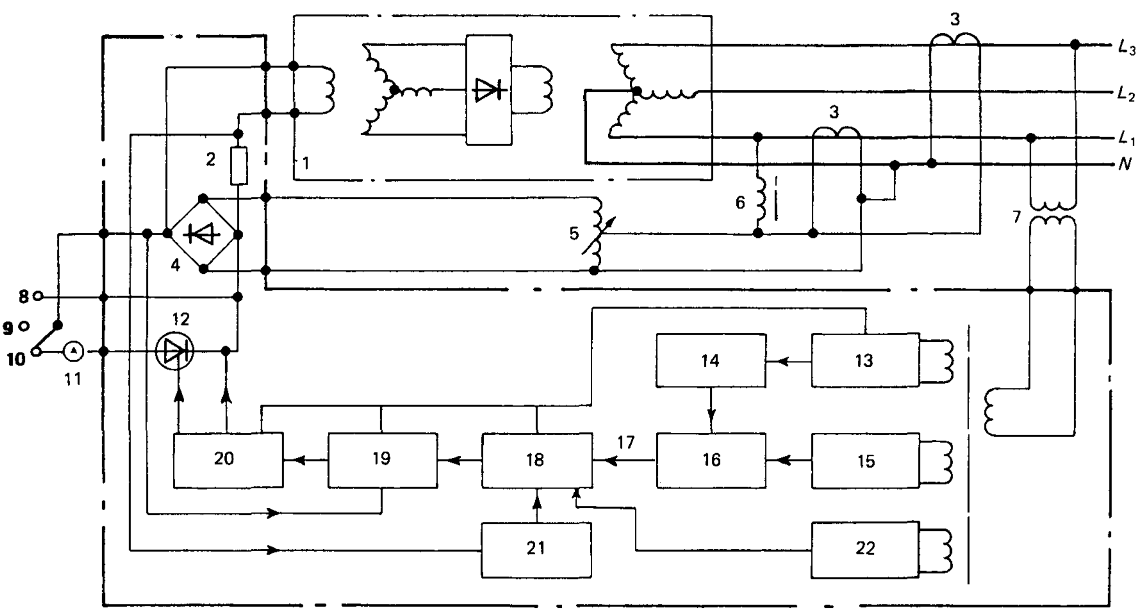
The operational wave-forms of Figure 7.16(a) show that a typical half-cycle is divided into three 'phases' as follows:

1. In the first phase (A), the rectifier conducts normally so that the rectifier input and output currents are both equal to each other and to the exciter field current, which is approximately constant due to the inductance of the field. Current in the choke 3 (Figure 7.16(c» is substantially constant and the rectifier input voltage $V_F$ is therefore equal to the supply voltage.
2. In the second phase (B), the thyristor conducts and hence diverts current from the exciter field by short-circuiting the rectifier.
3. In the final phase (C), the rectifier input current drops below the exciter field current value. This results in the thyristor switching off and the rectifier 'free-wheeling'.

Reference is also made to Figure 7.17, in the following description of the regulator's operation and the interrelationship of its sub-circuits.

We shall first consider the compounding circuit. Choke 3 draws a current $I_R$ which lags the generator voltage by approximately 90° (see Figure 7.16(b)). The excitation C.Ts. (one only is shown in Figure 7.16(c)) supply a secondary surrent $I_{CT}$. This current is in phase with, and proportional to, the line current $I_L$. The field rectifier input current $I_F$ is the vectorial sum of $I_R$ and $I_{CT}$. The actual field current, $I_f$, is proportional to $I_F$ when the thyristor (connected across the rectifier) does not conduct.

$I_f$ could be controlled to maintain the line voltage within 5 % of nominal by the compounding circuit alone, i.e. if this circuit were used in accordance with the usual principles applied to self-regulating generators (see the discussions in Sub-section 3.3.4 of Chapter 3). Here, however, the compounding circuit's primary purpose is to supply a current in excess of field requirements under all operating conditions – the surplus current being diverted by the thyristor. In this way a closer control (to within 1 %) of generator line voltage is achieved.




1 Brushlessgenerator
2 Stabilizing resistor
3 Excitation current transformer
4 Field rectifier
5 'Hand control regulator'
6 Choke
7 Potential transformer
8 Off
9 Hand
10 Auto
11 Divert ammeter
12 Divert thyristor
13 Power supply to electronics
14 DC reference
15 Voltage detector
16 Comparator
17 Error
18 Smoothing and amplification
19 Phasecircuit
20 Firing circuit
21 Stabilizing network
22 Frequency cut-off

figuI'e 7.17 Schematic of the thyristor divert automatic 1IOltage regulator (Courtesy: Brush Electrical Machines Ltd)

The thyristor is switched off in every half-cycle by the high inductance of the exciter field. Whilst the voltage $V_f$ reaching the exciter field consists of a series of pulses at twice the supply frequency, the field current $I_f$ remains substantially constant during the period of a pulse. Because of the high source impedance of the supply the current $I_F$ to the rectifier is approximately sinusoidal. The exciter field current $I_f$, therefore 'free-wheels' through the field rectifier during that period of each half-cycle in which the instantaneous value of $I_F$ is less than It. During these 'free-wheel' periods the exciter field voltage becomes slightly reversed due to the forward drop in the rectifier, and the thyristor turns off.

The thyristor is triggered at an appropriate instant during the normal conducting period of the rectifier thereby short-circuiting the field winding for the remainder of the conducting period. Advancing or retarding the instant of firing has the effect of varying the width of the voltage pulse and, hence, the mean value of the voltage applied to the exciter field (see the wave-form diagrams in Figure 7.16(a». The field current $I_f$ is proportional to the mean applied voltage $V_f$.

The rectified terminal voltage of the machine is compared with a stabilized d.c. reference and the error signal is smoothed and amplified (see Figure 7.17). The amplified output voltage from the comparator stage is fed to a capacitor. The time taken (from the instant at which voltage first appears on the thyristor) to charge this capacitor to a voltage sufficient to turn on a transistor in the firing circuit and hence fire the thyristor, is proportional to this amplified output voltage from the comparator. The time interval is, in effect, the width of the voltage pulses applied to the exciter field (see Figure 7.16(a».

The stabilizing signal is a voltage developed across a resistor connected in series with the exciter field. This voltage is fed back through a series resistor and capacitor to the input of the transistor amplifier. Separate magnitude and phase controls are provided to optimize the level of stabilization. Response depends very much upon the characteristics of the generator, the exciter, and the compounding circuit. Nominal voltage should, typically, be restored within one second, when full load at low power factor is applied to a 500 kVA generator.

The regulator includes a *frequency cut-off* circuit, to prevent damage to the controlled machine or its load during short-duration low-speed operation in run-up or shutdown conditions. The circuit operates to reduce the terminal voltage of the machine when the generator frequency falls below a preset level - about 10% below nominal. At this frequency the input of the amplifier is short-circuited. This advances the firing angle of the thyristor, thereby diverting the entire field current and causing the terminal voltage to fall rapidly. Once the frequency has recovered above the preset level the short circuit is removed from the amplifier and the line voltage again builds up to its nominal value. Use of this circuit must be inhibited when the regulator is fitted with an optional *frequency fall-off* feature. The latter is designed to reduce terminal voltage to one-half of its rated value at 50-75 % nominal frequency, and is employed in those applications (such as load shedding to prevent prime mover stalling) where it is necessary to achieve a more accurate rate of line voltage reduction with falling freq uency .

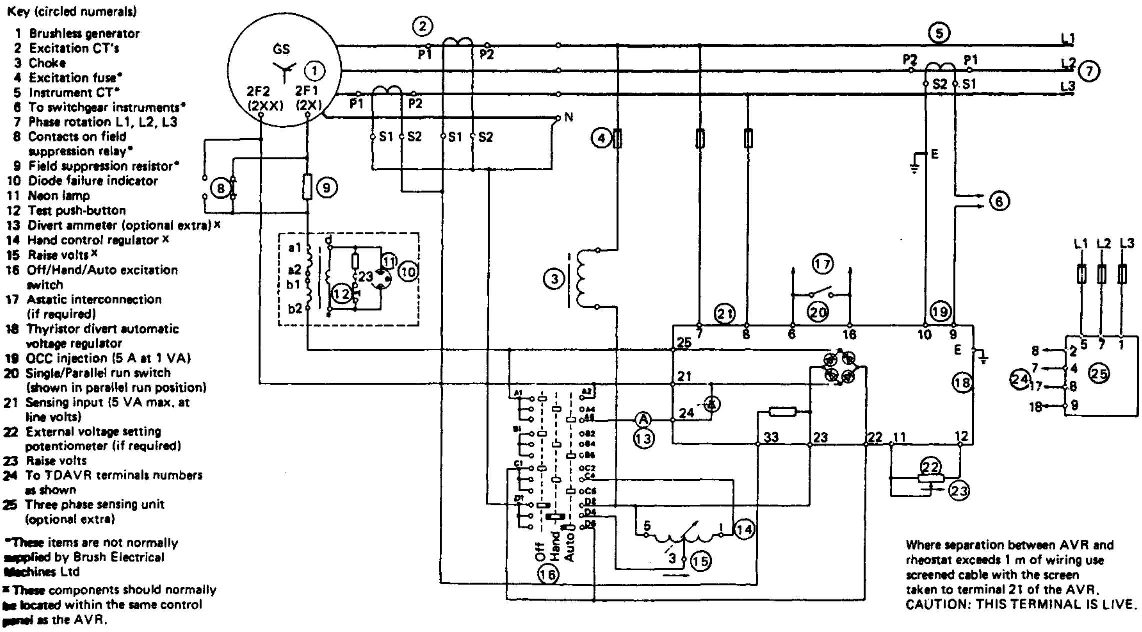
The complete excitation system, as applied to a medium voltage generator, is shown in Figure 7.18 in which the circuit details of the AVR itself have been omitted.

When automatic control is selected the thyristor is connected across the field rectifier. To switch-off excitation the exciter field is simply short-circuited through a discharge resistor (items 8 and 9 in the schematic diagram).

Use may be made of a switchgear instrument transformer (5) to supply the 'quadrature droop' circuit when the generator is required to operate in parallel with others in a power system. A potentiometer within the AVR enables the voltage droop to be preset - to a maximum of 10% of rated voltage - for full-load reactive kVA. Alternatively, all the AVRs in the system may be interconnected within an 'astatic loop' to eliminate the voltage droop (17 and 20). See Sub-section 7.8.1.

The diode failure indicator circuit (10, 11 and 12) provides detection of failure to open-circuit in any arm of the rotating rectifier bridge network of a brush less machine. Failure may be caused by a series fuse blowing or by a diode open-circuiting. The circuit comprises the primary winding of a c.T. connected in series with the exciter field, and a neon lamp which responds to the change in ripple content of the exciter field following an open-circuit in a rectifier bridge path. The lamp is shunted by a resistor to reduce the sensitivity of the indicator so that it does not respond to the ripple present in normal operation. A test push button is included to give a means of checking the circuit. (See also Sub-section 3.3.2 of Chapter 3, which describes this and other proprietary forms of diode failure monitoring.) Among the optional facilities available for this AVR are:

1. power factor/kV Ar control, through an excitation bias circuit (see the discussion in Section 7.5.6);
2. three-phase detection (25), giving a signal to the AVR proportional to the mean of all three terminal line voltages; and
3. smooth changeover from AUTO to HAND control, and vice versa. In addition to the ammeter (13), this involves the use of a special four-position changeover switch.




**Agure** 7.18 Complete excitation system, as applied to a medium-voltage generator, using the thyristor divert AVR (Courtesy: Brush Electrical Machines Ltd)

## 7.8.3 Separate excitation

In these schemes excitation power is derived from a source independent of the generator's output. The most usual arrangement is one which uses a small auxiliary exciter (the pilot exciter) giving 'constant' a.c.or d.c. voltage, coupled to the common Fnerator/main a.c. exciter shaft. (See Figure 7.2(c).) As discussed in Sub-section 7:3.3, the pilot exciter may be self-excited or it may have a permanent magnet field. If the latter is adopted, the abbreviations p.m.p.e. (permanent magnet pilot exciter) and p.m.g. (permanent magnet generator) are Y3riously applied.

The regulator in this form of excitation is supplied **from** two separate sources:

I. the main generator's stator, which provides the reference voltage; and
2. the pilot exciter which presents a constant source impedance to the regulator's electronic circuits.

1be advantages of the permanent magnet machine are:

I. It provides the necessary voltage during generator run-up to give self-excitation to the system.
2. Since its output is constant, excitation forcing is not affected by the voltage 'sags' which occur when heavy loads are imposed on the generator. Performance during motor starting and in short-circuit maintenance is therefore enhanced.
3. Because a highly-stable magnetic material is used, loss of residual magnetism is virtually impossible, and stator and rotor may be separated without loss of magnetic output [9].

### *GEC A/sthom GECOSTAT* C *22/180 A VR*

Reference has already been made to this regulator in Sub-section 7.8.1. It is designed for front mounting in a 19"(483 mm) rack, or for rear mounting on any suitable surface inside a control cubicle (see Figure 7.19). It is particularly intended for use where the AVR power supply is obtained from a shaft-driven permanent magnet pilot exciter, and is then capable of giving voltage control accuracy better than ±0.5 %. The block diagram of Figure 7.20 shows its various circuit features. The basic regulator consists of:

1. a three-phase voltage sensing circuit which measures the average of the three line-to-line voltages;
2. a zener diode reference;
3. an error-operated amplifier;
4. firing circuits which enable a full wave, fully controlled, single-phase thyristor bridge to be

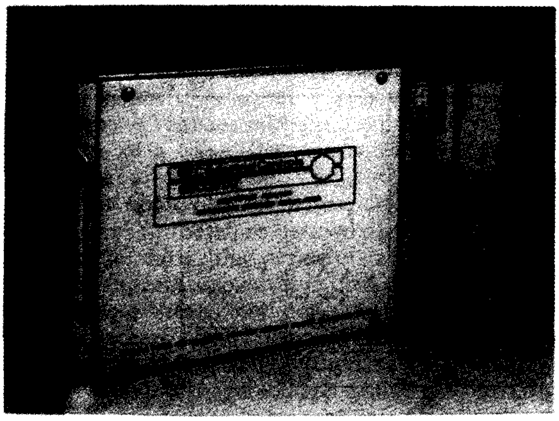


**Figure** 7.19 Rack-mounting GECOSTAT C22/180 AVR (Courtesy: GEC Alsthom Vacuum Equipment Ltd)

operated in the inversion mode to give negative field forcing on non-brushless generator applications - as described in Sub-section 7.8.1; and
5. a stabilizing circuit with scaled and lockable potentiometers to facilitate setting-up for optimum stability and rapid voltage response to load changes.

The following additional circuits are included on printed circuit boards, selectable, as required, by means of p.c.b. switches. The Sub-section numbers, in parentheses, indicate where these features have been described in preceding text.

1. quadrature droop compounding (7.5.4);
2. over-excitation - or exciter field current limit (7.5.6);
3. under-excitation - or leading kVAr limit (7.5.6);
4. V/Hz limit (7.5.6). Two characteristics are provided. The one preferred is selected by a p.c.b. mounted switch:
   - constant V/Hz, irrespective of what the generator voltage is at nominal speed, and
   - a constant-frequency 'knee point' on the V/Hz characteristic - again, irrespective of what the generator voltage is at nominal speed;
5. power factor/kV Ar control (7.5.6);
6. VAr shedding (7.8.1) - using an external signal to automatically reduce the reactive load on the gen~rator to near-zero prior to taking it out of service.

An independent 'manual control' unit - the HC15 described in Sub-section 7.5.2 - may be incorporated within the system (as shown in Figure 7.20).

It is worth reiterating, at this point, why it is necessary to inhibit excitation during slow speed operation - especially where maintenance personnel are in the habit of running engines at idling speeds. As we have seen, excitation systems are designed to give about 2.5 times field forcing in order to overcome machine time constants and to give good transient performance. Since this power is always available it follows that, unless it is inhibited, there is the danger that the machine's rotor (main field windings) will overheat during prolonged slow speed operation - when machine ventilation and cooling systems will not be at their most efficient.

Frequency sensing also helps the engine to recover its speed when it is subjected to high impacting kW loads. The use of turbo-charged engines of relatively low inertia with fast-response generators often results in 'stalling' under such conditions. If under-frequency sensing is fitted, the generator is able to recover its voltage to the level determined by the engine's speed. Then, because power is proportional to the square of the voltage, the load impact on the engine is reduced and it can recover its speed [10].

Figure 7.21 [10] gives typical speed/excitation characteristics for voltage sensing only (a), and for both voltage and frequency sensing (b). That at (a) shows the operating area (between 40 % and 70 % speed) in which prolonged running could lead to rotor failure.

## 7.9 Recent trends and future developments

The requirements for any excitation control system must be influenced by those operational characteristics that are most suitable for the generator's particular application. The degree of sophistication required will vary both with the mode of operation and with the generator's role within the power supply system. For example, the minimum set **of** requirements might suffice in those applications where the generator forms part of a multi-set plant supplying an isolated load and where shutdown **of** one generator will have only minor consequences. In contrast, on those installations where only two generators may be operating in parallel (and where availability is highly valued) somewhat more than just a basic excitation system is necessary. Single generators in isolated operation, such as emergency units on board ship or standby units supplying critical technical loads, may require more sophisticated controls employing dual-channel (or back-up) and protective features in order to guarantee maximum reliability.

### 7.9.1 The modular approach

Aware of the need to offer control packages that can be readily engineered to match the needs of such a wide range of excitation system requirements, manufacturers are now marketing 'modularized' equipment which is structured to give a **high**

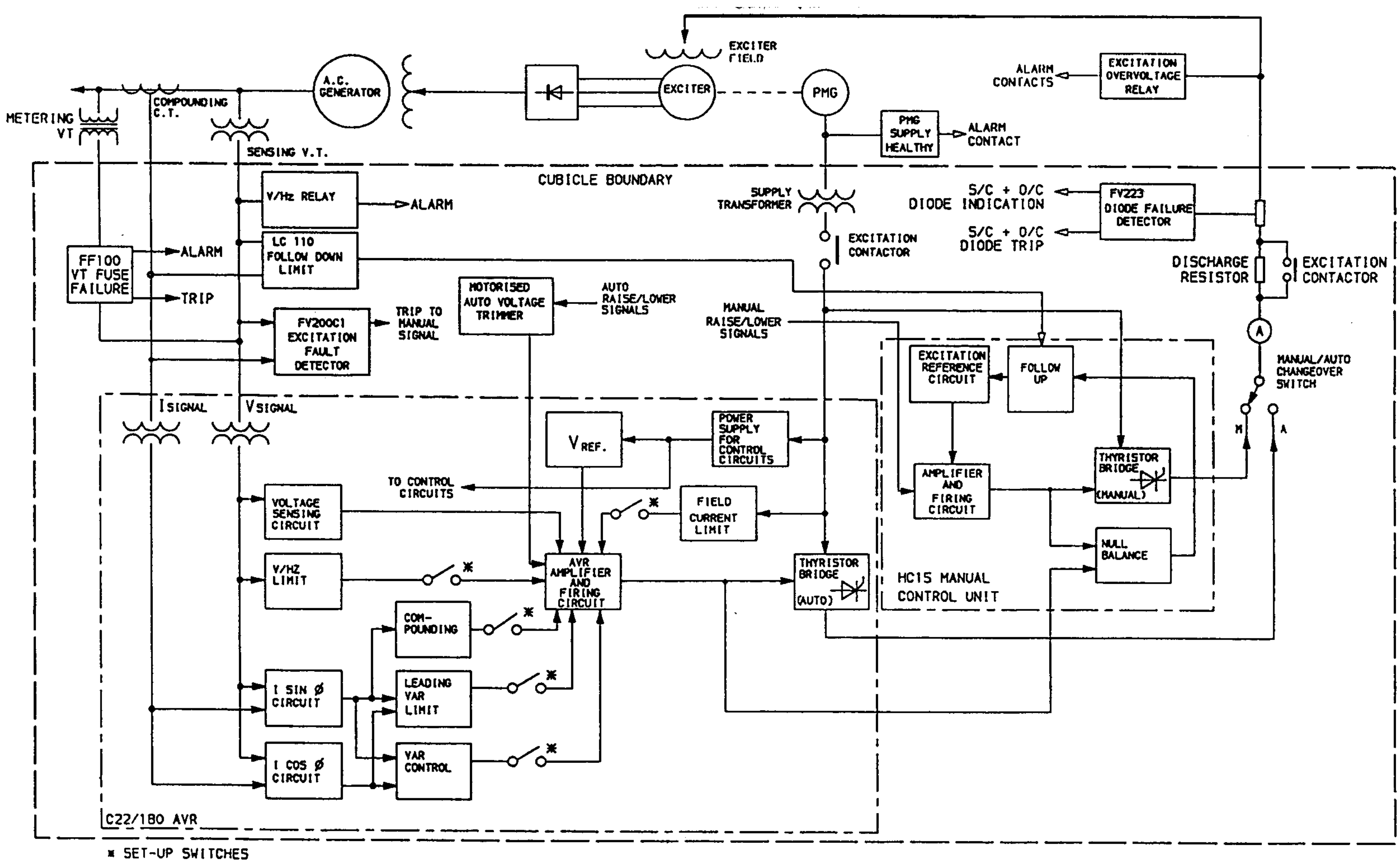
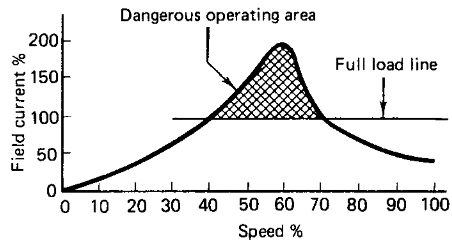
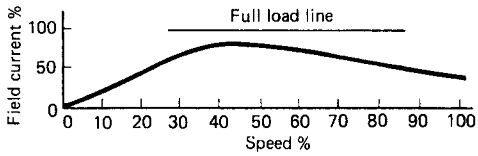



**Figure 7.20** Block diagram for a C22/180 AVR applied to a separately-excited, brush less generator (Courtesy: GEC Aisthom Vacuum Equipment Ltd)




(a) Using voltage sensing only




(b) With voltage and frequency sensing

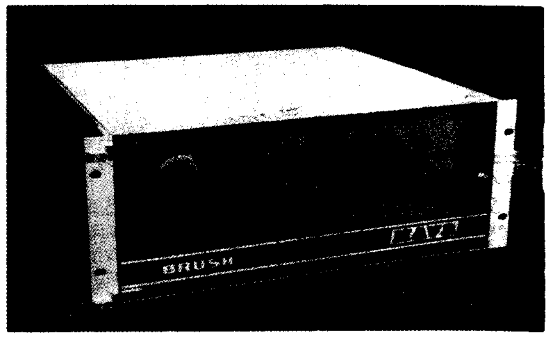
**Figure** 7.21 The effect of frequency sensing on the speed/excitation characteristic (Courtesy: *International Power Generation)*

degree of flexibility in application and economic benefit in production programmes.

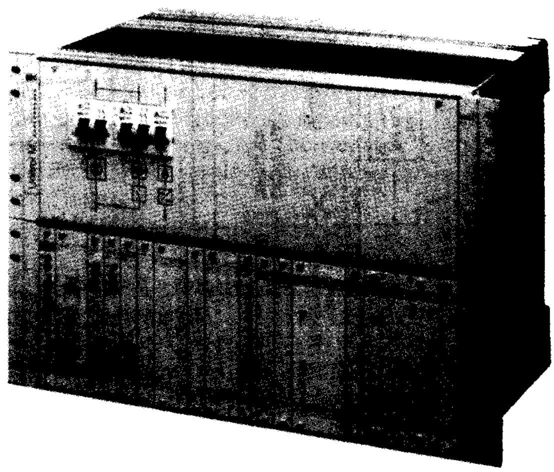
The manufacturer may use a series of standardized basic and ancillary units (or modules) as 'building blocks' to provide systems to meet specific requirements. Methods of implementation vary from one manufacturer to the next. Generally, modularization takes the form of units housed in standard 19"(483mm) rack assemblies, or trays, suitable for mounting into cabinets or into switchboard cubicles. Some manufacturers base their modularization programme on the use of discrete, separately housed units which offer compatibility with rack mounting arrangements but give the user a degree of flexibility in engineering his own schemes and in modifying existing systems where necessary.

Brush Electrical Machines' *Modular Automatic Voltage Regulator* (MA VR) employs 19" rack assemblies to house the electronic and electrical circuits for a comprehensive excitation control system (see Figure 7.22). Typically, the main MA VR assembly rack would incorporate the following plug-in modules:

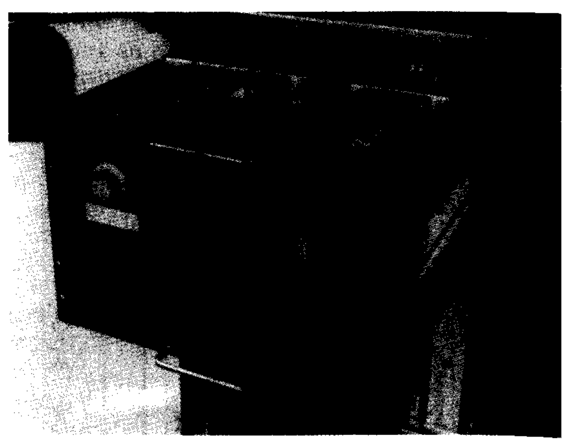
- the auto control rectifier;
- the voltage control card, which includes an overflux limiter, a diode failure detector and a fast-acting current limiter;
- an excitation limiter card;
- a front-mounted, motorized, voltage setting rheostat suitable for manual and remote operation; and
- any optional circuits such as kVAr/p.f. control, Var shedding, and voltage and excitation monitors to initiate transfer to manual control or to a standby AVR in the event of a fault.




(a)



(b)



(c)

**Figure** 7.22 Examples of proprietary, modular system configurations (Courtesy: The equipment manufacturers) (al Brush Electrical Machines Ltd (b) ABB-Asea Brown Boveri Ltd (c) GEC Alsthom *Vacuum* Equipment Ltd

An auxiliary equipment rack would then incorporate the other items necessary to complete the excitation system, such as:

- the exciter field suppression contactor and the field discharge resistor;
- an electronic, manual control regulator;
- an automatic follower unit; and
- null balance indication.

A sufficiently extensive range of additional features enables the manufacturer to offer very comprehensive schemes for brushless and for statically excited generators. However, experience suggests that the great majority of excitation requirements can be met by one of these three standard system packages:

Type A A single MAVR with manual control, auto follower and null balance indication, and where manual control is selected by the plant attendant.
Type B As Type A, but with voltage and excitation monitors fitted to the MAVR to initiate automatic transfer to manual control in the event of a fault monitor operating.
Type C A dual MAVR system with manual control, auto follower, and null balance indication. The 'duty' AVR incorporates excitation and voltage monitors which automatically transfer control to the 'standby' AVR in the event of a fault. Manual control is selected by the plant attendant.

The basic design of the Asea Brown Boveri UN1-TROL M modular type regulator system is illustrated in Figure 7.22. It is capable of controlling diesel engine driven brushless generators up to approximately 50 MVA rating.

The lower tier of the rack assembly includes all the function modules, such as the voltage regulator, excitation limiters, gate control pulse generators, diode failure relays, etc. The upper tier houses the power section components, the miniature circuit breakers for the incoming supply, the thyristor module (whose heat sinks are mounted on the outside rear of the casing), and the instrument voltage and current transformers. Where necessary, dual-channel variants are obtained by duplicating the basic modules and, therefore, the number of tiers. A simple form of manual control is provided with even the most elementary systems offered.

GEC Alsthom's GECOSTAT modular range of AVRs and accessories are also accommodated in 19" rack mounting trays, fitted with slides to give maximum accessibility to components when the trays are incorporated within switchboards or rack cabinets. The AVR and auxiliary elements of the control systems are usually housed in separate trays (see the illustration of Figure 7.22) and come complete with an interconnecting cable. Typically, the division of control and power units between trays would be as follows.

1. in the AVR tray: the AVR itself, the excitation limit module, and a latched, excitation contactor;
2. in the auxiliaries tray: the manual control unit, the excitation fault detector, the fuse failure detector, the diode failure detector, the manual/auto contactor, the commutating diode, and the field discharge resistor.

Figure 7.23 shows the block diagram for a typical, comprehensive scheme based on the use of the manufacturer's type CI01120-M AYR.

### 7.9.2 Future developments

Excitation control regulators of the types just described incorporate analogue control amplifiers using continuous signals derived from a comparison of reference and measured values. They will soon be replaced by *digital regulators* using fast microprocessors. Such processors are available at commercially attractive prices and are being increasingly applied in power system control and protection equipment. A few digital regulators are now in service and are state of the art on new plants with very large generators [11]. It may be some time before the experience gained in type tests on very large, statically-excited, hydroelectric plants is translated into competitively priced hardware for all but the largest diesel generator installations.

The next generation of regulators will, therefore, include a microprocessor which will manipulate the input binary data obtained from analog/digital converters (ADC) (which 'translate' the analog values of generator voltage and current, and field current, into binary signals) and compare them with reference values and limits pre-programmed in digital form. This will be done on a very rapid basis, using a crystal oscillating at several MHz. Comparisons of preset reference and measured values will be made at discrete millisecond intervals, in a sequence defined by the program stored in the data processor's memory. The memory device is likely to be an EPROM (an Erasable Programmable Read-only Memory), which can hold its data permanently. Temporary memory facilities would be provided by read-write devices such as RAMs (Random Access Memory). The calculated error signals in digital form would then be used to create the firing pulses for the excitation power thyristors, through an auxiliary microprocessor. Interfaces with peripheral power system controls and indicating instrument drives, etc., will be made through digitaVanalog converters.

One of the significant advantages of this type of regulator is that 'on-line' communication is possible with a central processing unit. Reports on stored parameters and measured values may be called-up

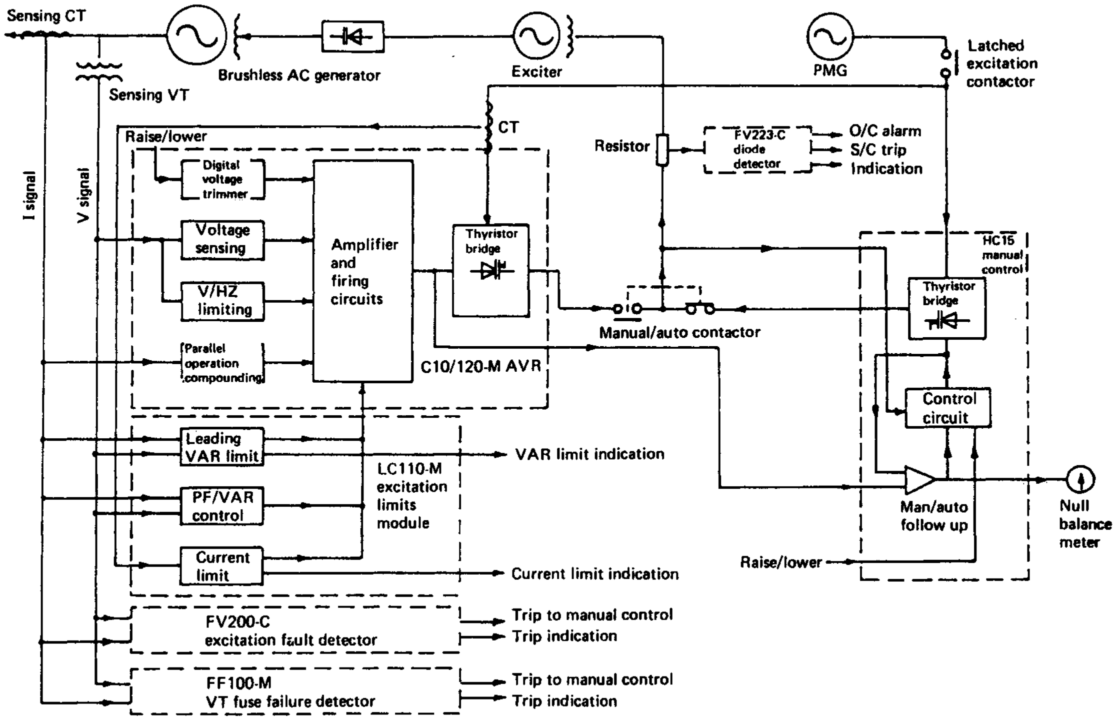



**Figure** 7.23 Block diagram for a typical excitation system, using a modular configuration (Courtesy: GECAlsthom Vacuum Equipment Ltd)

and limit and characteristic values changed as required. Besides indicating failure of programme-detected conditions, the microprocessor will also have the ability to self-check for program malfunctions.

## 7.10 Referenced Standards

Reference has been made in this chapter to the following British Standards. Corresponding International- ISO or IEC - standards are given in brackets. They are not necessarily identical to the British Standards, but have varying degrees of agreement with them.

BS 4727 - *Glossary of electrotechnical, power, telecommunication, electronics, lighting and colour terms*
Part 2: Group 03 [IEC 50(411)] - *Rotating machinery terminology*

BS 4999 - *General requirements for rotating electrical machines*
Part 140 (IEC 34-1) - *Specification for voltage regulation and parallel operation of a.c. synchronous generators*

BS 5000 - *Specification for rotating electrical machines of particular types or for particular applications*
Part 3 - *Generators driven by reciprocating internal combustion engines*

BS 2949 (IEC 92-5) - *Specification for roatating electrical machines for use in ships*

BS 5514 - *Reciprocating internal combustion engines: performance*
Part 4 (ISO 3046/4) - *Speed governing*

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# 8

# Parallel operation of generating sets

**Contents**

## 8.1 Introduction

The paralleling of synchronous generators is a more complex problem than that associated with d.c. generators. The a.c. machines must operate in *synchronism,* i.e. they must run at their synchronous speeds - as determined by system frequency. **In** this respect they differ from d.c. generators which may run at differing speeds.

D.C. generators only supply real (or active) power, while a.c. generators supply both active and reactive power. Load division between direct current machines may be effected by controlling the speeds of the prime movers or the fields of the generators. This chapter describes the principles involved for a.c. generators, where division of active power is controlled only by prime mover speed, and where reactive power sharing is controlled only by generator field excitation.

Descriptions are given for typical load-demand and load-sharing controls for automated plants. Busbar arrangements and the interconnection of generator neutrals are then discussed. Finally, consideration is given to some of the transient problems likely to arise from electromechanical disturbing forces acting on any system of paralleled generators.

## 8.2 The synchronizing of generators

A machine requires to be *synchronized* onto (energized) busbars to which other machines are already connected. Before this is done, the following conditions have to be satisfied:

1. the instantaneous voltages of the incoming machine and the busbar must be equal;
2. the frequency of the incoming machine must be the same as the busbar frequency;
3. there must be synchronism of phases, i.e. the phase of the incoming machine must be coincident with the phase of the busbar voltage; and
4. the incoming machine and the busbar must have the same phase rotation. This is a check that is usually made when any sets to be paralleled are first installed and commissioned, and it is good practice to check phase rotation on either side of the paralleling switch. Once checked, it is unnecessary to do so again unless the direction of mechanical rotation of any of the generators in the system is changed.

When all of these requirements are met, any two or more generators may be synchronized.

Requirements 1, 2 and 3 must be met each time generators are paralleled: 1 is indicated by a voltmeter and conditions 2 and 3 by synchronizing gear.

The operations necessary for paralleling a generator with others already on load are:

1. The voltage of the incoming machine must be adjusted to equal that of the busbar - with modern automatic voltage regulated (AVR) systems, accurate voltage matching presents little difficulty.
2. The speed of the incoming machine must be adjusted until its frequency approximates closely to that of those machines already connected to the busbar.
3. The paralleling breaker is closed as nearly as possible when the above two conditions are met, i.e. when the instantaneous voltages are equal in magnitude and in phase.

Synchronizing gear is provided on the switchboard to facilitate these operations. **In** its simplest form it consists of lamps detecting the angular phase displacement between incoming machine and busbar terminals. Three different connections are possible, as shown in Figure 8.1.

Lamps may be connected so that they are either *dim* (Figure 8.1(a» or *bright* (Figure 8.1(b» at the moment of synchronization. For paralleling with 'lights dim' the lamps must be connected across like phases. For 'lights bright' they should be connected across unlike phases.

If the three-lamp *sequence method* of Figure 8.1(c) is used, the order in which they light up indicates whether the incoming machine is fast or slow. At synchronism, lamp 1 (or the 'key' lamp) is dim and lamps 2 and 3 are equally bright. If mounted in a triangular fashion, as shown in the diagram, the lamps will appear to rotate and the rotational sequence in which they brighten and darken (clockwise or anti-clockwise) indicates whether the incoming machine is fast or slow.

Note that the lamps should be rated for at least twice the machine voltage. Since lamps suitable for voltages above 250 are not generally available, it may be necessary to use 2 or 3 in series, or to use step-down voltage transformers for each lamp. The more practical solution of a lamp and series resistor combination is illustrated in the diagrams.

Synchronizing lamps are generally augmented by some form of rotary *synchroscope.* The instrument has two windings, one of which is connected to the busbars and the other to the incoming machine - on the generator side of the paralleling switch or circuit breaker (Figure 8.2). Only one phase is used from each supply source. The synchroscope is, in effect, a two-phase motor, the rotor of which rotates at the difference frequency (or *slip)* between the voltages applied to its two windings. Where there are several generators in a system, the synchroscope's incoming-machine winding is connected to a number of sockets - one for each machine in the power system, and a transferable plug is used to make the synchroscope connection to each machine as required. Alternatively. use may be made of a

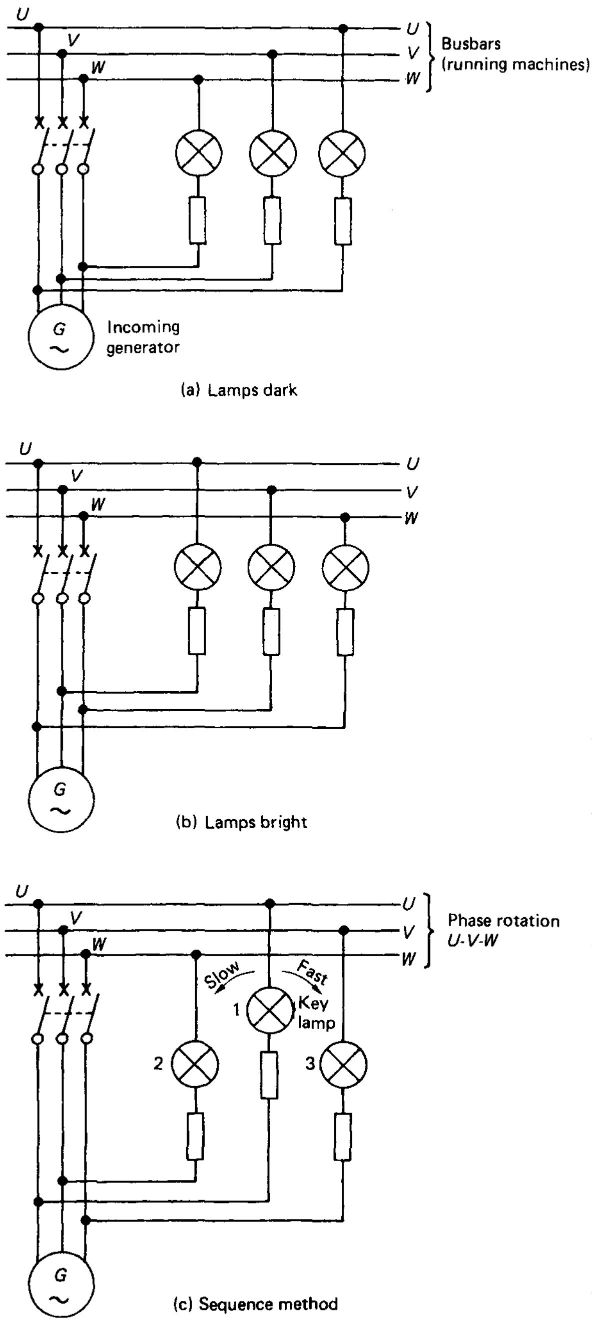



**Figure 8.1** Connections of synchronizing lamps

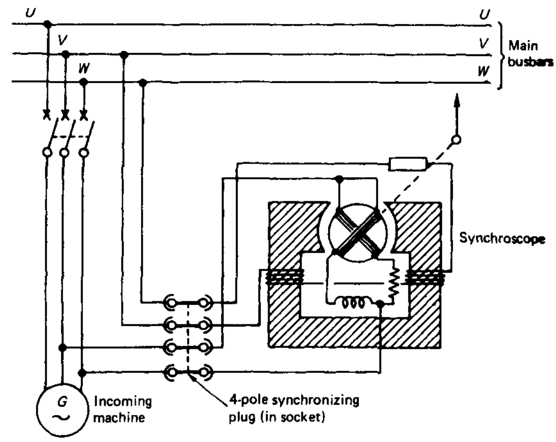



**Figure** 8.2 Circuit diagram for synchroscope, showing 4-pole socket connections to busbar and incoming machine

multi-position, two-pole switch to, effectively, provide the same facility. The synchroscope should not be left in circuit when not in use as it is only a short-time rated instrument. The selector switch must therefore have an 'off position, and if sockets are used, there must be a *dummy* or parking receptacle for the transferable plug.

The movement of the instrument consists of a soft-iron rotating vane, the shaft of which carries a single-ended pointer. This rotor is magnetized by an alternating field produced by a fixed coil energized from the incoming machine. The field in which the vane rotates is produced by split-phase stator windings energized from the busbars (see Figure 8.2). A progressive phase shift of one complete cycle (360°), between the two circuits corresponds with one revolution of the pointer. When the frequencies are equal the pointer position indicates the angular phase difference between the two supplies. When the supplies are in synchronism the pointer should be at its 12 o'clock position.

When commissioning the synchroscope it is necessary to check, by means of synchronizing lamps, at which point on the dial face synchronism does occur. If it corresponds with the vertically downwards (6 o'clock) position, the connections to the busbars should be reversed.

The direction of rotation of the spindle is determined by whether the incoming machine is running too fast or too slow. The dial of the instrument is labelled accordingly - with corresponding directional arrows (see Figure 8.3).

In summary, the synchroscope informs the switchboard operator of the phase and the frequency difference between the two voltage supplies to be paralleled.

Typically, synchronizing panel instruments on a switchboard would consist of:

- a synchroscope;
- two voltmeters (one for busbar voltage, the other for the incoming machine voltage);
- two frequency indicators (one each for busbars and for incoming machine); and

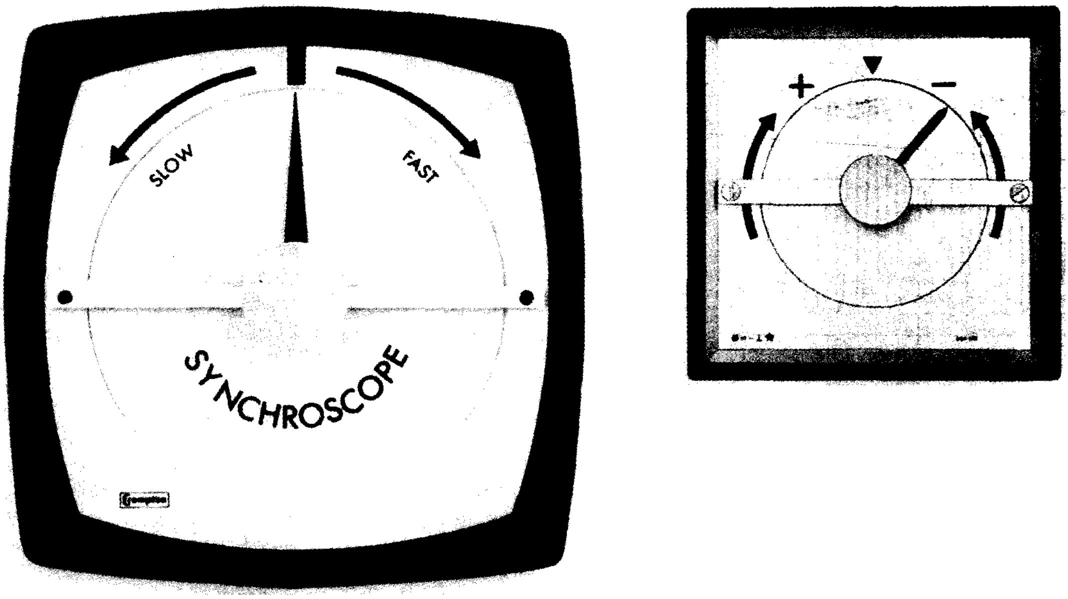



**Figure** 8.3 Synchroscopes with alternative dial formats (Courtesy: Crompton Instruments)

- the necessary instrument selector switches and/or sockets and plug.

It is good practice to also include sequence-indicating synchronizing lamps to cater for occasions when the synchroscope is out of commission for any reason.

Synchronizing devices must be fully visible when the generating sets are being paralleled. Mounting arrangements using swivelling brackets projected from the plane of the main switchboard and a hinged synchronizing panel give the ideal perpendicular relationship between instrument dials and the switchboard operator's direction of vision.

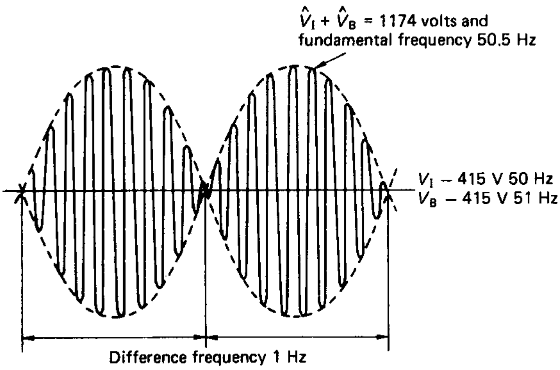
To summarize, we have established that if two generators or supplies are to be connected in parallel they must be synchronized. The frequency, phase angle, and magnitude of the phase voltages must be matched. When these conditions are satisfied the synchronizing breaker of the incoming machine may be closed. In practice, a difference in voltage between the two generators (or supplies) of between 5 and 10% would be quite acceptable. The high internal reactance of the generator reduces the amount of wattless current flowing when the synchronizing switch is closed. Any transient surge soon settles down because the out-of-phase voltages give rise to a synchronizing power circulating between the machines, acting to bring the voltages into phase. (See Section 8.5.)

Normally, the voltage and frequency of the incoming set are adjusted slightly above that of the busbar supply so that the incomer immediately accepts load. If the on-coming machine were to be switched when running slow, it would receive motoring power from the busbars, with the possibility of the reverse power protection operating.

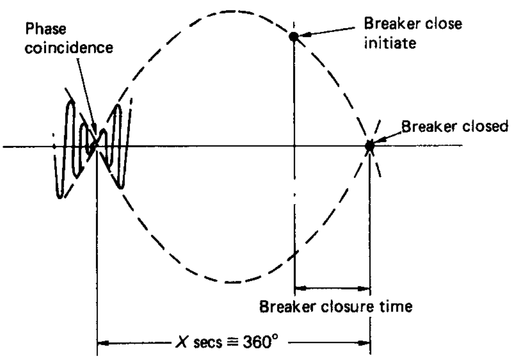
It is almost impossible to adjust the incoming generator's speed so that the synchroscope pointer is stationary at 12 o'clock. The pointer speed should be about 1 revolution in 5 seconds before the synchronizing breaker is closed at the pointer's 11 o'clock position. The delay in the breaker's closing operation will mean that paralleling is affected at about 12 o'clock. A breaker requires a finite closing time (typically 350 milliseconds). Closing should therefore be initiated at least this amount of time before the instant of phase coincidence of the two supplies.

The effect of frequency difference between the incoming generator and the busbar supply is illustrated in Figure 8.4, which shows the modulated voltage that develops across the incoming synchronizing switch. The voltage across the circuit breaker undergoes changes similar in character to the beats produced when two sources of sound of dissimilar frequencies are blended. It will be seen that the maximum voltage of the modulated waveform is the sum of the individual peak voltages $V_I$ and $V_B$; and that the fundamental frequency of this waveform is the mean of the incoming and busbar frequencies. The number of zeros (or points where phase coincidence occurs) per second in the envelope equals the difference between the two supplies, $f_I - f_B$.

Thus, when an incoming generator at 415 V 51 Hz is to be connected to a busbar whose voltage is 415 V




(a) Modulated voltage across circuit breaker




(b) Breaker closure time on difference voltage waveform

**Figure** 8.4 Modulated voltage wave-form seen across the synchronizing circuit breaker

at 50 Hz, the voltage across the circuit breaker has a peak value of 1174 V and a fundamental frequency of 50.5 Hz (i.e. (51 + 50)/2), before closure. (In fact, the waveform of Figure 8.4(a) is a suppressed carrier arrangement with two sidebands at 50.5 Hz ± 0.5 Hz.) Furthermore, phase coincidence occurs once per second (i.e. 51 - 50). At these zero points on the waveform envelope the incoming machine and busbar supplies are identical both in voltage and phase. The problem is to ensure that the incoming generator's circuit breaker is closed at one of these zero points on the envelope.

Figure 8.5 shows, diagrammatically, the pointer position on a synchroscope in time-relationship to the voltage modulated waveform. The pointer's rotational speed, in revolutions per second, corresponds to the number of zeros per second in the waveform envelope; its angular position, at any moment, indicates the relative phase of the two supplies to be paralleled.

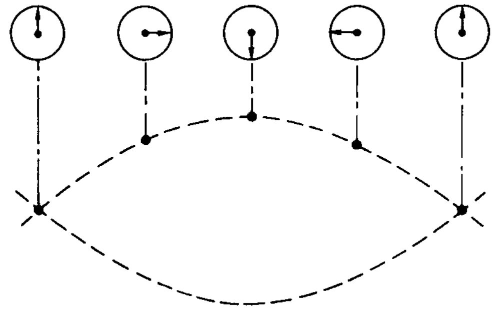


**Figure** 8.5 Angular position of synchroscope related to difference voltage wave-form

For a circuit breaker closing time of 350 ms and with a frequency difference of 0.5 Hz, breaker closure should be initiated at a phase angle 63° before zero. With a difference of 0.05 Hz the closure should be initiated 6.3° ahead of the zero. Figure 8.6 illustrates this. The breaker closing time represents a phase angle on the difference-voltage envelope which varies with the difference in frequency.

A synchroscope is only accurate within 30° of phase coincidence, and its speed of rotation provides an approximate indication of slip or difference frequency. Thus, an operator must obtain a very close frequency match before synchronizing.

It will be appreciated, therefore, that the manual synchronizing of generators calls for some skill on the part of operators. Failure to meet the required criteria for synchronization could result in mechanical damage to couplings and also give rise to transient field voltages, with resultant damage to

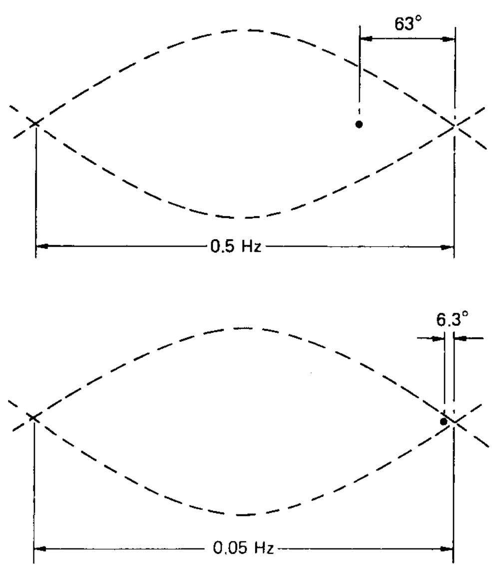



**Figure 8.6** Breaker closure time, as a phase angle on the difference voltage wave-form

rotating rectifiers in the case of brushless generators. For example, if synchronization is affected 120° out of phase, the coupling torque can be as high as 12 times full load torque, depending on the ratio of engine and generator inertias.

It is advisable therefore for larger generators, or where operators are not skilled, to fit some form of check synchronizing unit (or paralleling phase switch, as it is sometimes called) to ensure that the incoming generator's circuit breaker can only be closed when that generator is in synchronism with the existing busbar supply.

A typical check synchronizer made by the Woodward Governor Company is shown in Figure 8.7. The unit illustrated is 152mm long, 140mm wide and 70 mm high. The block schematic diagram is given in Figure 8.8. Synchronization of the generator and busbar supplies is checked by the breaker close circuit. The circuit output permits the closing of the breaker (see Figure 8.9 for the system schematic diagram) if conditions are acceptable. The 'breaker close enable' signal is not issued unless the relative phase angle between the busbar and generator supplies is less than the selected value (i.e. within the 'window'), and has been within the window for at least the window dwell time. The units' phase window $(\theta_W)$, and the window dwell time $(T_{WD})$ may be chosen by jumper options on the circuit board.

The 'breaker close enable' signal consists of normally open contacts on the breaker close relay. This relay changes state only when the breaker close circuit says that the generator is synchronized. If the breaker does not close and the generator drifts out of synchronism the 'breaker close enable' signal ceases. Conversely, when the breaker closes, synchronization continues and the 'breaker close enable' continues. Note that the unit will not issue a 'close breaker' command when attempting to parallel a generator to a dead busbar.

A range of phase windows and match-up times is available. Typical window values are 10°, 15° and 20°; with 1/16, 1/4, 1/3 and 1/2 second match-up times. It is advisable to select a match-up time that is three to four times longer than breaker closure time.

A calculation on the following lines will ensure that the check synchronizer selected will provide adequate synchronization before the breaker contacts engage. Figure 8.10 illustrates the terms used. It assumes the busbar voltage is fixed, and is vectorially in the 12 o'clock position - as is the pointer on a synchroscope - when it is in the synchronism position.

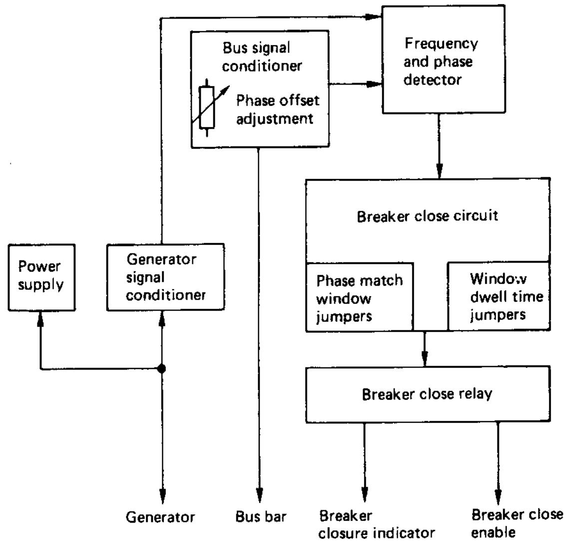
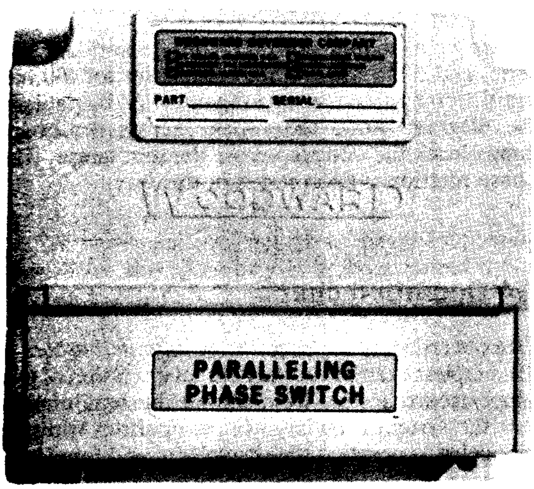



Figure 8.8 Block schematic diagram of check synchronizer



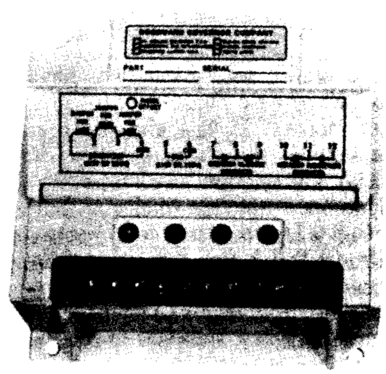



**Figure 8.7** A proprietary check synchronizer (Courtesy: Woodward Governor Company)

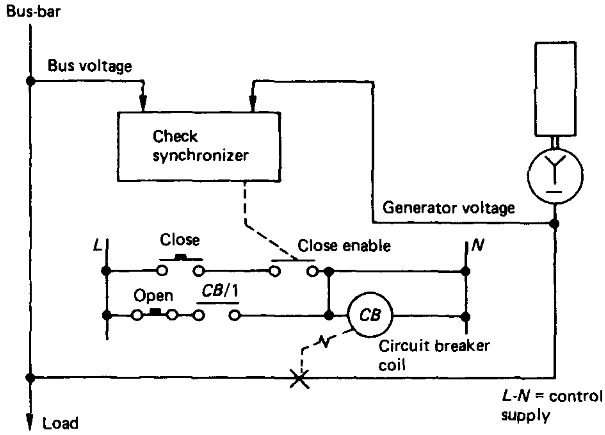



**Figure 8.9** System schematic diagram for check synchronizer

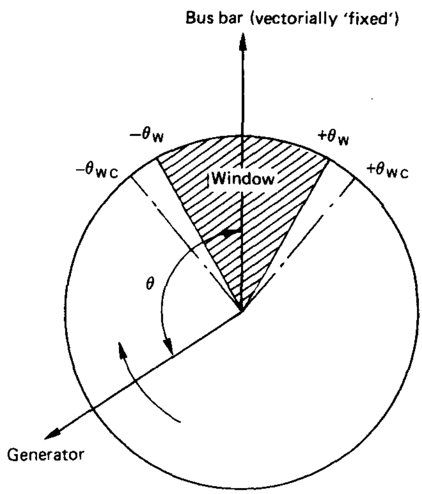



**Figure 8.10** Phase angle, allowable phase shift, and the 'window' for check synchronizer operation

Every generator set system will have its own permissible worst-case phase shift ($\theta_{WC}$) at the time of breaker closure. If $\theta_{WC}$ and the breaker time delay are known, the check synchronizer's phase window ($\theta_W$), and window dwell time ($T_{WD}$) may be chosen by jumper selection to ensure that angle $\theta$ is less than $\theta_{WC}$ when the breaker contacts close. The synchronizer will not give the 'close breaker' command unless $\theta$ is within the window (i.e. $\theta$ has to be equal to, or less than, $\theta_W$) and has been there for at least $T_{WD}$ seconds.

If we assume that $\theta$ continues to rotate at a constant rate, the worst-case value that the *synchronizer will allow* for the relative phase angle ($\theta_S$) at the instant the breaker contacts engage, may be predicted as follows:

$\theta_S$ is equal to $\theta$, at the time the synchronizer issues the 'close breaker' command ($\theta$ is $\theta_W$ in the worst case) PLUS an increment accounted for by the breaker delay ($T_B$, in the worst case)

$$\theta_S = \theta_W + (2\theta_W . T_B / T_{WD})$$

A typical example might include a synchronizer window of ±10°, a window dwell time of 1/2 second, and a breaker that has a closing time never slower than 10 cycles. In this case:

$$\theta_W = 10°$$
$$T_{WD} = 0.5\,s$$
$$T_B = 10/50 = 0.200\,s \text{ (i.e. 10 cycles/50 Hz)}$$

Then

$$\theta_S = 10 + (2 \times 10 \times 0.200/0.5)$$
$$= 18°, \text{ the worst case}$$

## 8.3 Phase sequence testing

An indicating instrument is available for this purpose. It is, effectively, a miniature 3-phase motor. Its marked loose leads are connected to the supply terminals which need to be checked for phase rotation. When the indicator disc of the instrument rotates in the arrowed direction, the phase sequence of the terminals under check is indicated by the marked leads of the instrument connected to them (e.g. R, Y, B; A, B, C; or U, V, W).

Alternative, do-it-yourself circuits, suggested in [1] and [2], are given in Figure 8.11. Circuit (a) requires a high impedance voltmeter. The widest difference between its readings will obtain when resistance and capacitive reactance values are equal. The voltmeter reading will exceed the line voltage for a sequence U-V-W, and it will be less than the line voltage for U-W-V.

Circuit (b) requires two 230 volt, 25 watt lamps in series and a 2 to 3 microfarad condensor for 400 volt supply terminals under investigation. As the table in the diagram shows the voltage across the bright lamps leads the voltage across the dim lamps. The phase rotation is determined in this way.

## 8.4 Operation charts

The operation of a generator on *infinite busbars* is the simplest example of the parallel operation of two supply sources. The term infinite busbars implies that the system is so large (in comparison with the paralleled generator) that its voltage and frequency is unaffected by the behaviour of the generator. By this definition, a National Grid supply is a most obvious infinite busbar system.

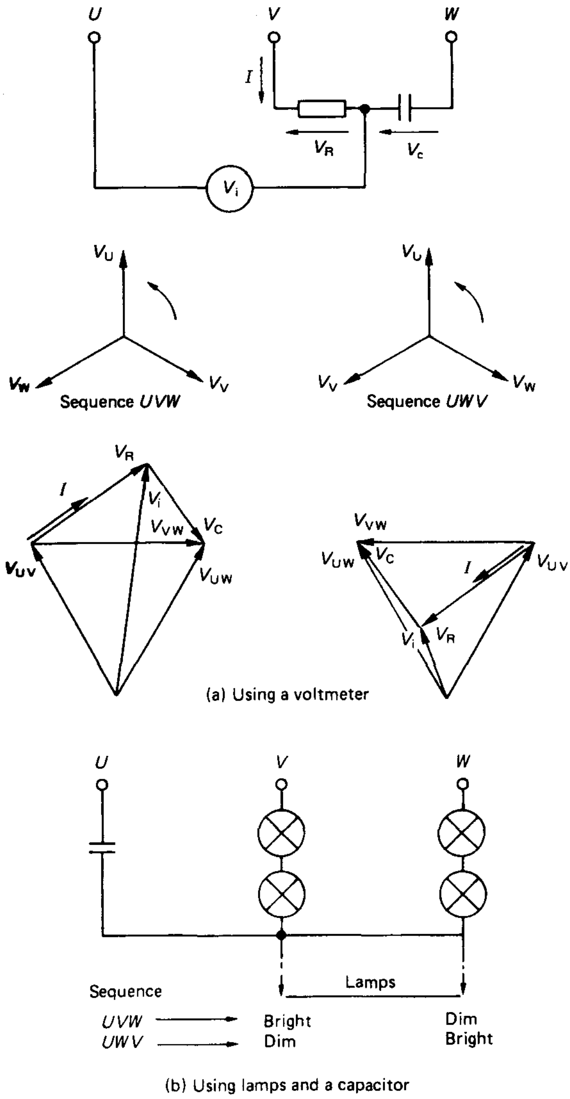



Figure 8.11 Methods for determining phase rotation of a 3-phase system

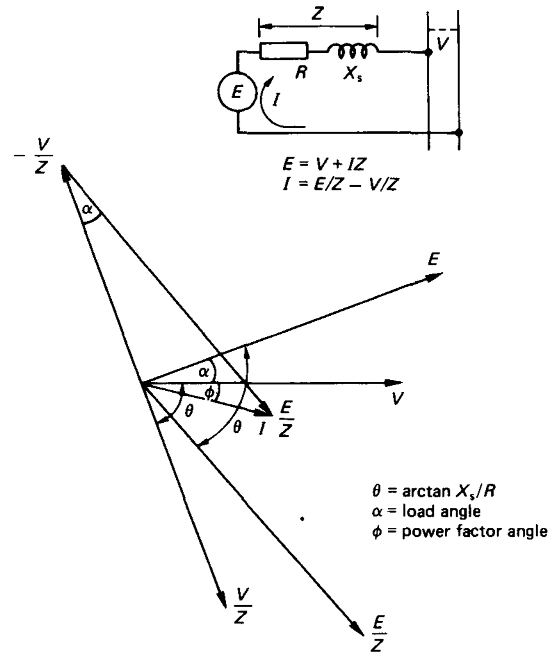



Figure 8.12 Vectorial interpretation of a generator connected to an infinite busbar

We have seen, in Chapter 4, that the equivalent circuit for this situation can be represented by that shown in Figure 8.12, where:

$$E = V + IZ$$
or $$I = (E/Z) - (V/Z)$$

1be diagram of Figure 8.12 interprets this, vectorially.

Developing this further, we may go on to construct what is called an *operation* (or *capability)* **chart,** which defines the operating limits imposed by the prime mover, excitation and stability.

The conditions of Figure 8.13 may be taken to represent a diesel generator whose excitation has been adjusted so that the generated e.m.f. of the machine equals the busbar voltage, *V*. This condition is known as 1.0 per unit excitation. As the fuel supply to the generator is increased, the load angle o: increases. Loci for differing values of p.u. excitation are drawn as circles of differing radii from centre O. The corresponding load angle and excitation may then be found for any given current.

The in-phase and quadrature components of ***I*** represent the kilowatts and reactive kilovolt-amperes (kVAr) supplied by the generat·)f. The inset of Figure 8.13 shows how the chart may be revised to give direct values of these powers.

The essential points of difference between single- and parallel-running generators may be highlighted by the following observations:

1. The power factor of a generator running singly and feeding a load is determined by the power factor of the load it supplies. The application of a load taking either lagging or leading current calls for an excitation adjustment to neutralize the demagnetizing or magnetizing effect of the load current and to maintain a constant voltage. In a parallel-running machine (with a fixed voltage) cause and effect are reversed; a change of excitation is automatically countered by a current of correct phase and magnitude to neutralize this excitation change. It will be seen from Figure

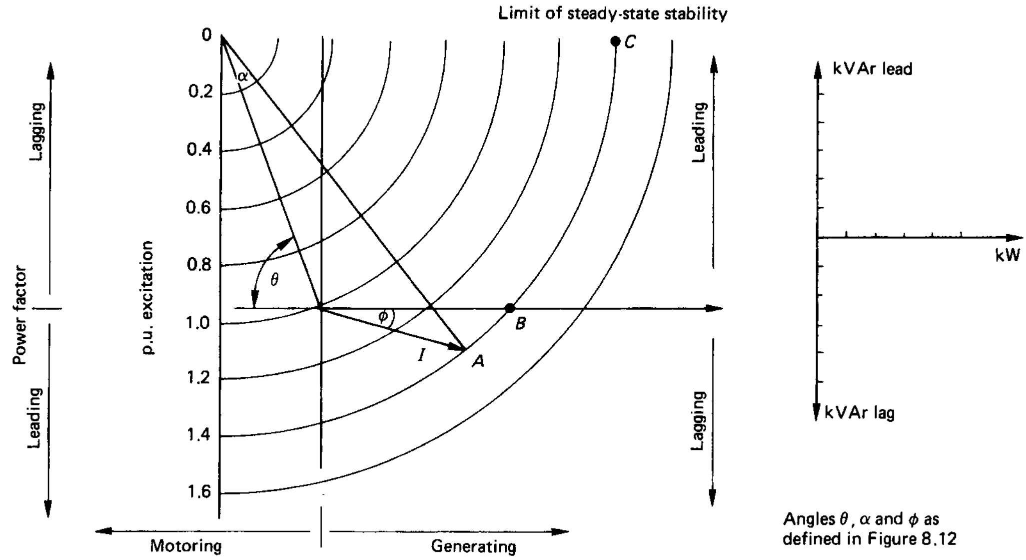



**Figure 8.13** Development of the generator operation chart

8.13, that, for a constant load current condition, an increased excitation is associated with lagging power factor. In other words, adjusting the excitation changes the power factor of the load current, *f.*

2. The kW loading of a single-running set is solely determined by load requirements. If more fuel is admitted than the load demands, the speed of the diesel generator will rise, and vice versa. System frequency, however, fixes the speed of a parallel-running generator; the amount of load it takes is determined by the governor fuel setting. In the diagram of Figure 8.13, the machine operating at point A is generating current *f* at power factor cos<j>,with a corresponding excitation of 1.4p.u. If the fuel to the diesel engine is increased (excitation remaining constant), load angle *a* will increase and the operating point will move on the circular locus of 1.4 p.u. excitation to a point B where the power factor is unity. The kilowatt loading of the machine will have increased but the kVAr will have decreased. If the prime mover's driving torque increases still further, the level of kw load will also increase until a point C is reached. This corresponds with the maximum kW output. It is the point at which any further increase of load angle results in a reduced retarding torque from the load. The machine will break out of synchronism. The horizontal line OC therefore represents the 'theoretical limit of steady state stability'.

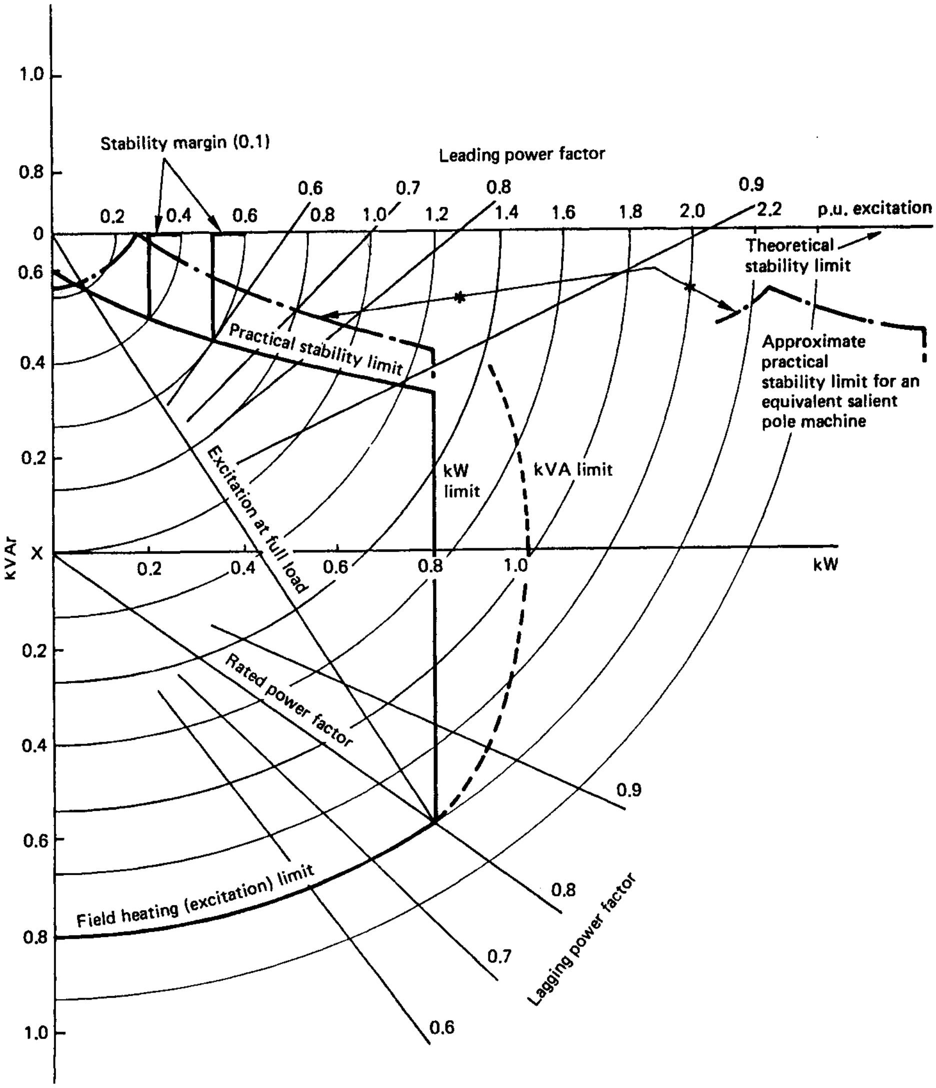
To summarize this discussion, we have established that:

- control of the fuel throttle alone alters kW load;
- control of excitation alters kVAr load and, in conjunction with the fuel throttle, the power factor.

Before going on to consider the load-sharing aspects of paralleled machines, we shall develop an operation chart for a round rotor machine. Figure 8.14 **has** been drawn for a machine with a synchronous reactance of 1.5 p.u. and zero resistance. The **full**-load rated power factor is 0.8 lagging. The vertical axis is calibrated in kVAr and the horizontal axis in kW. The length of OX is 1/1.5 (=0.67 units).

Practical operation of the machine as a generator on infinite busbars is restricted to the portion of the figure contained within heavy lines. The boundaries of this *working* area of the chart, reading anticlockwise, are:

1. the zero-power (Y) axis;
2. the field heating limit - the excitation circle corresponding to full-load excitation (in this case 2.2p.u.);
3. the kW limit - if imposed by the maximum power available from the diesel engine;
4. the kVA limit - a circle of unit radius about X;
5. the practical stability limit - which is obtained from the theoretical limit, by subtracting an agreed margin from each point on it. This **en-**




**Agure** 8.14 Operation chart for a typical round-rotor machine. showing practical limits of capability

sures that the generator has a margin of power in hand (usually 0.1 p.u.) before the actual stability limit is reached.

An operating chart may also be derived for a salient pole machine, starting from a vector diagram similar to that of Figure 8.12 drawn for the round rotor machine. In this case, however, the direct and quadrature reactances have to be considered, and not merely the single synchronous reactance of the round rotor machine. The development, however, is outside the scope of this handbook. The interested reader should refer to specialized text-books, such as publications [4] and [6], listed in the Bibliography - Section 8.13.

Figure 8.14 shows the approximate practical stability limit for an equivalent salient pole machine.

## 8.5 Synchronizing current, power and torque

A generator on no-load and running in parallel with an infinite bus bar system is represented by the phasors shown in Figure 8.15(a), where the generated

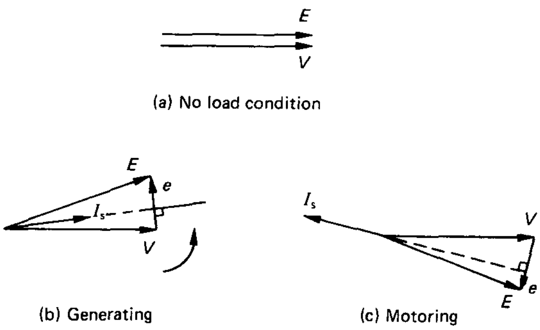
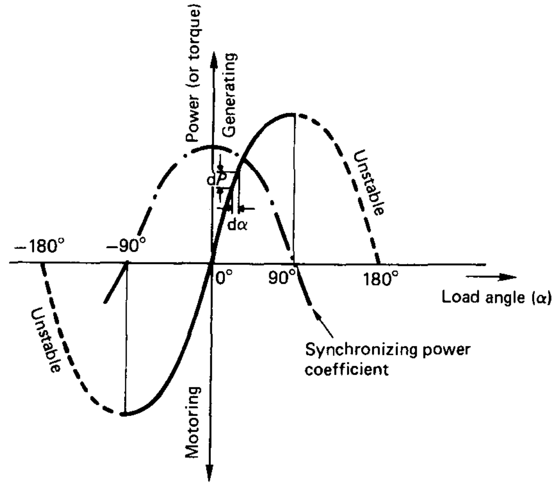
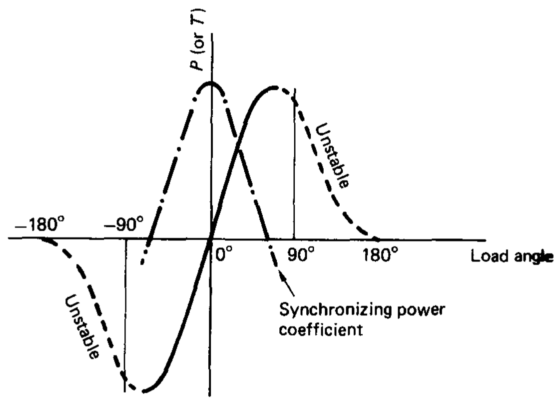



**Figure 8.15** Illustrating flow of synchronizing current




(a) Power/angle characteristic for round rotor machine (neglecting armature resistance and assuming constant excitation)




(b) Power/angle characteristic for machine with saliency (neglecting armature resistance and assuming constant excitation)

**Figure 8.16** Power/load-angle diagrams illustrating differences between round-rotor and salient machine characteristics

e.m.f. $E$ and the busbar (or terminal) votage $V$ are in phase – since no armature current is present. Should more fuel be admitted by the engine governor the generator will speed up and phasor $E$ will be advanced. Meanwhile, the terminal voltage $V$ is fixed (both in magnitude and in position) because it is 'tied' to the infinite system. The resultant voltage $e$ ($EV$) will cause a current $I_S$ to flow between the generator and the system. This current will have a value $I_S = e/X_S$. Neglecting armature resistance, $I_S$ will lag $EV$ by 90° (see Figure 8.15(b)). This *synchronizing current* $I_S$, being almost in phase with both $V$ and $E$, produces a kilowatt loading on the generator. This, in turn, has the effect of slowing down the rotor and pulling phasors $E$ and $V$ back into synchronism. This restoring power is known as the *synchronizing power* $P_S$, and the torque associated with it, the *synchronizing torque* $T_S$.

Conversely, if the governor reduces the power input from the diesel engine, the generator slows down and phasor $E$ will lag behind $V$. The resultant voltage, $e$, is now reversed and the current $I_S$ produces a motoring action which tends to accelerate the rotor and bring $E$ and $V$ back into phase (see Figure 8.15(c)). The current $I_S$, and its associated synchronizing power, are, for small deviations, proportional to the load angle α.

The slope $dP/d\alpha$ of the load power/power angle curve in the diagram of Figure 8.16(a) is called the *synchronizing power coefficient*. It is expressed in watts per electrical radian. Multiplying the coefficient by $(\pi/180)(p/2)$ converts watts/electrical radian to watts/mechanical degree of rotor displacement, where $p$ is the number of poles in the machine.

Also shown, as a chain dotted line in Figure 8.16(a), is the curve of the relationship between synchronizing coefficient and power angle. In the case of the round rotor machine, the coefficient is greatest at no load ($\alpha = 0$); and is zero when $\alpha = 90°$.

Figure 8.16(b) shows the same curves developed for the salient pole machine. They emphasize the variation of load power with increasing values of excitation. Note that the synchronizing power coefficient is now zero when the load angle is approximately 65°. The salient pole machine curves also have a steeper rise for the smaller values of α. This gives correspondingly greater values for the synchronizing power coefficient than those obtaining for the equivalent round rotor machine. To summarize: the restoring action of the synchronizing torque is greatest when α is zero and it is least when α is 90°, in the case of the round rotor machine. For equal values of voltage and (direct-axis) synchronous reactance, a salient-pole machine develops a given torque at a smaller value of load angle a.

Also, the maximum torque which it can develop is somewhat greater [3].

A generator, therefore, has the inherent ability to remain in synchronism - within the limits of maximum power. Any tendency to pull it out of step immediately produces a synchronizing current and an associated torque which tends to restore synchronism. It is as if the engine were connected to its load through a torsion spring which is wound up one way or the other, depending upon whether power is being fed to the busbar or taken from it. The wind-up of the spring is analogous to the displacement of the generator's rotor field from the stator's synchronous field. The latter is constrained to follow the busbar frequency.

It should also be noted that production of synchronizing torque depends entirely on the generator's armature reactance. If there were no reactance and only resistance, the synchronizing current in Figure 8.15 would be in phase with the voltage phasor *EV*, and almost at right angles to phasors *E* and *V*, thereby producing a wattless current and, therefore, no synchronizing power.

## 8.6 Load sharing

In an earlier discussion in this chapter we established that, for diesel generators operating in parallel with each other, or with an infinite system such as a public utility supply, active power (kW) load sharing was a function of the engine governor, and reactive power (kVAr) sharing that of generator excitation. It is convenient, therefore, to study this topic under two headings: kW load sharing and kVAr load sharing.

### 8.6.1 Active power sharing

We have examined governor characteristics in Chapter 6, and differentiated between governors with droop and those giving isochronous speed regulation. Both characteristics play an important part in the parallel operation of generator sets.

For convenience of treatment we shall first discuss the operation of a diesel generator in parallel with infinite busbars, and follow that with the common case of two generators running in parallel with each other. In both instances we use the frequency-load characteristics of the generator sets to determine the kW load sharing.

#### *Operation on an infinite system*

The relationship between speed and load on the diesel prime mover, operating independently under control of its governor, may be represented by curve A of Figure 8.17 (for a governor with a 4% *speed-droop* characteristic over its no-load to full-load travel). Horizontal line F represents the normal system frequency. When the generating set is paralleled with the system supply the generator will operate at a load OP determined by the point of intersection of curve A and line F (since the generator is forced to run at the same frequency as the infinite system). To alter the generator loading, its governor speed setting must be adjusted by raising, or lowering, the governor characteristic (curve A). Raising it to curve B increases the generator load to $OP_2$, and lowering it to curve C reduces the load to $OP_1$. Effectively, therefore, because the generator's shaft speed cannot *droop* when tied to the infinite busbar's frequency, the speed governor becomes a load governor. In other words, it becomes a fuel flow governor.

Similarly, should the system frequency change, the governor loading will also change - since the point of intersection between the constant frequency line and the governor characteristic is moved. This is shown in Figure 8.17, where a fall in supply frequency (line $F_1$) results in the generator set (operating on governor speed curve A) accepting a larger share of the load ($OP_4$). Conversely, if the system frequency rises to line $F_2$, the set's load decreases to $OP_3$. Finally, had system frequency fallen by 2% (line $F_3$) the generator, operating on speed curve A, would have been on its full-load rating. Had it been operating on curve B, this decrease in system frequency would have resulted in some 24% overload being imposed on the machine.

The operating principles described above will particularly apply to privately-owned, peak-lopping generating plant. Such plant is installed for the purpose of generating, on-site, a part or the whole of the consumer's maximum electrical demand during national peak demand periods. It serves to reduce the maximum demand tariffs levied by Supply Authorities for purchased electricity. An excessively high maximum demand, for only half an hour, greatly increases the cost of imported power. In an attended peak-lopping plant, load monitors may be employed to warn the plant operators that imported demand has reached a predetermined level. The engine governor(s) may then be adjusted to allow the generator(s) to accept more load, or unessential electrical loads on site. Once a governor is set, the public supply system will accept all variations in the user's electrical power demand. Systems are available which operate to automatically maintain a constant level of electrical power imported from, or exported to, the public supply system. These are mentioned later in the chapter.

When generators operate in parallel with each other and independent of a public supply system, they run at synchronous speed and behave just as if they were mechanically coupled. When the load increases the frequency of the system falls until the total output of all the units matches the new load.

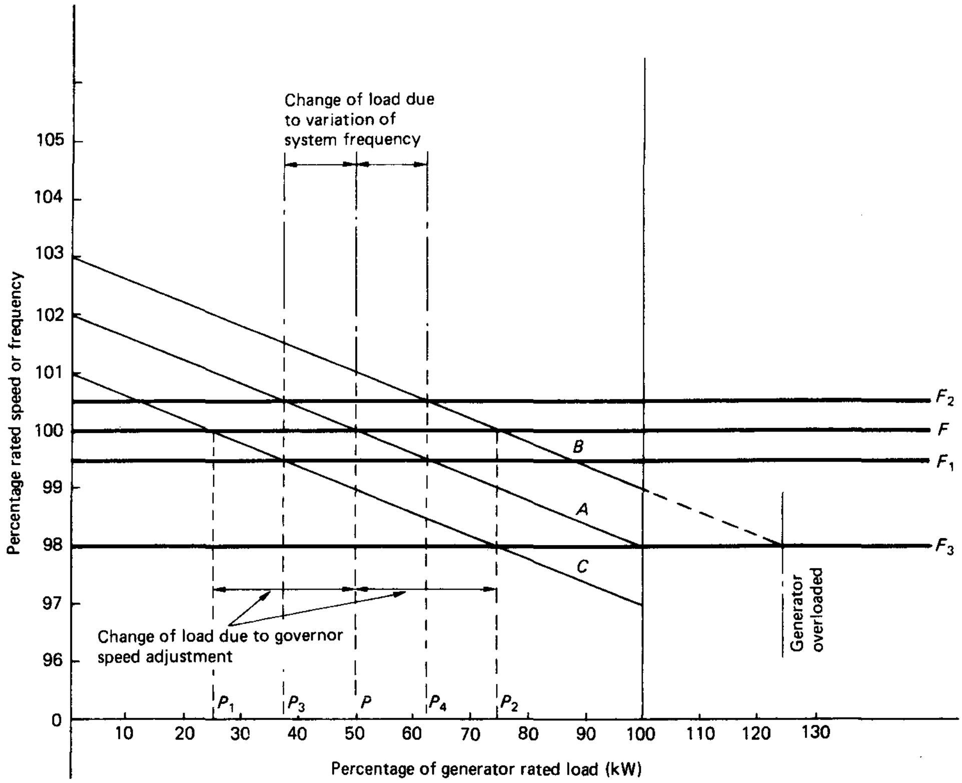



**Figure** 8.17 Load sharing of a diesel generator operating on an infinite system

Active power (kW) load is shared between the generators in accordance with the speed droops of their engine governors.

Let us now consider two identical generating units with equal speed droops (4 %) operating in parallel with each other. We may first assume that both are set to run on curve A of Figure 8.18 and that the total load is equal to the rating of one unit, i.e. 100 % of its site output capability. Each engine then carries 50 % of its full-load rating, and the frequency of the common busbar is 102 % of nominal (this is case 1).

Should one unit then be set at curve B (the other remaining on curve A), the frequency at which both must now operate, whilst still carrying the same total load, is 103 % of nominal. Note that the increase in system frequency is not as great as the increase in speed setting of the unit on curve B. The unit on A assumes 25 % of the load while that on B takes 75 % of its rating (case 2).

Should the total load now be increased to 150 % of one unit's rating, assuming that the generators are still at settings A and B, the additional (50 %) load is shared equally between them. The unit on A now

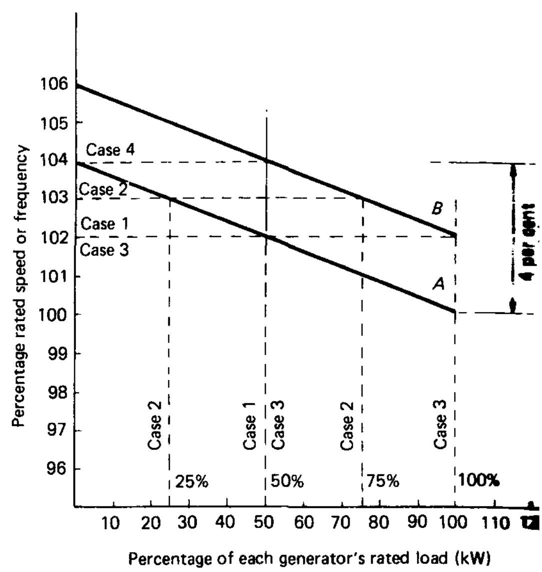



**Figure 8.18** Load sharing by two diesel generators with identical speed droops operating in an independent system

takes 50 % of the load while that on B carries 100 % . System frequency reverts to the 102 % level (case ').

Any further increase in load results in the unit on B being overloaded. Effectively, therefore, the capacity of the system is only 150 % - against the theoretical 200 %, had the speed settings been identical. When the total load falls to 50 % of one unit's rating, it is carried by the unit on B. The unit on A is unloaded and system frequency rises to 104 % of nominal (case 4).

Now let us consider two paralleled units of equal rating but with different governor speed droops - as represented by curves A and B of Figure 8.19. The regulation of unit B is twice that of unit A.

When the system frequency is 102 % of nominal each set carries 50 % of its rated load (case 1). If the load increases until the frequency drops to 101 %, unit A will carry 100 % load; and unit B 75 % (case 2). On the other hand, if the load decreases such that system frequency rises to 102.5 %, unit A will absorb 28% load and unit B 38% (case 3).

Reverting to case 2, if the speed setting of unit B were readjusted to curve BI>the total load of 175 % would have been equally shared at 87.5 % each and there would be an increase of system frequency. Clearly, any desired value of frequency may be obtained for this total load level if the speed settings of both A and B were so readjusted as to ensure that the point of intersection of their speed curves was maintained at 87.5 % load on each.

One unit may be made to accept all the load change if so required - up to its full rated capacity. Consider case 1 again, where each set carries 50 % load and the system frequency is at 102 %. If the load were to increase by 50 % of unit capacity, and if the speed setting of A (which has the smaller speed droop) were moved up to chain-dotted line AI>unit A would acccept all of the load change. System frequency would remain at 102 %.

Let us now consider the situation where one of the generator units has an isochronous governor while the other has a speed droop governor (curves A and B, respectively, of Figure 8.20). In this arrangement it will be the isochronously-governed unit that will absorb all load changes. For example, if the load were increased to a total of 150 %, unit B, which is in the droop mode, would continue to carry 50 % load; and isochronous unit A would be fully loaded. The system frequency would remain constant at 100%.

This technique of varying load at constant frequency is obviously limited to load changes within the rating of the unit operating in the isochronous mode. Were the load to be increased beyond 150 %, unit A would be overloaded and the system frequency would drop, allowing the droop-mode unit (B) to pick up a portion of the load. However, if system frequency is to be maintained at 100 %, adjustment must be made to B's speed setting so that its share of the load is changed. For instance, an adjustment to curve $B_1$ would result in unit B carrying 75 % of the total load.

This means that hydro-mechanical governors can be employed to give a constant frequency system. All that is necessary is that one of the governors be set to operate in an isochronous mode while the

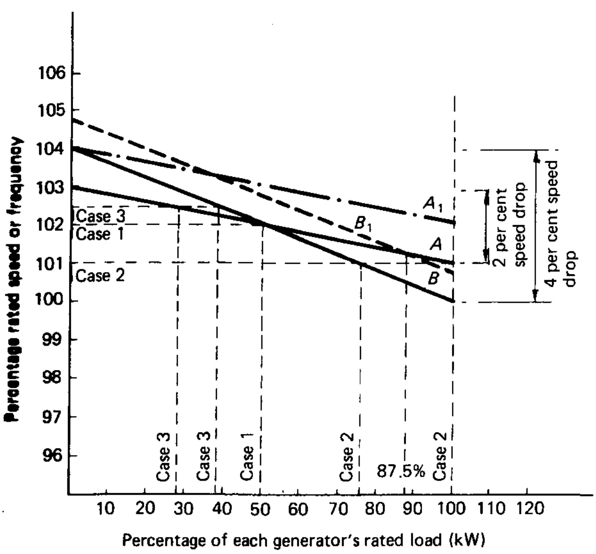



**Figure 8.19** Variable load sharing between two diesel generators with differing governor speed droops

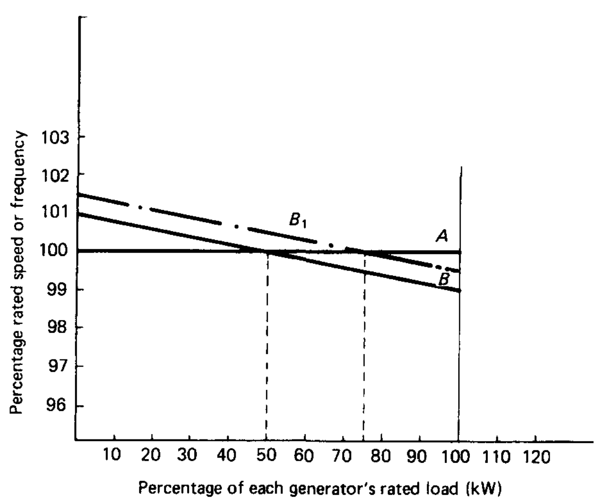



**Figure 8.20** Variable load sharing between two diesel generators, one having an isochronous speed governor

others are in a droop mode. In such a scheme the unit with the isochronous governor will be the one that absorbs all the load changes. But load may be transferred to the other unit(s) by increasing the speed settings of their droop governors so as to shed load from the isochronous unit.

We have dealt so far with parallel~running machines sharing variable loads. Now let us consider the sharing of a constant kW load. Figure 8.21, in which the two diesel generator frequency-load characteristics are plotted back-to-back on a base representing the total (and constant) load, illustrates this. The point of intersection ofthe characteristics determines both the sharing of the load and the common system frequency. Transfer of load from one unit to the other is affected by raising or lowering one, or both, governor settings. For example, raising curve A to AI gives a different division of load, with a small rise in system frequency. To raise the frequency but maintain the load-sharing ratio, both frequencylload characteristics must be raised by equal amounts. This is shown at the intersection of lines AI and BI. An interesting situation arises at point X, where line B is intersected by an excessive raising of speed setting A to Az. Here, not only does unit 1 supply the total load, but also sufficient power to *motor* unit 2.

Several important conclusions may be drawn from these discussions on kW load sharing:

1. In order to ensure that load is adequately shared between two or more engines it is necessary to accurately adjust the speed droop on all engines.
2. The mismatching of speed settings seriously affects load sharing, even if the speed droop curves are correctly set; so also does the presence of hysteresis in the governor frequency/load curves (see Sub-section 8.6.4).
3. The flatter the speed droop characteristic (i.e. the nearer the droop is to isochronous) the greater the sensitivity to slight disturbances when load sharing.
4. Machines fitted with mechanical-hydraulic governors, paralleled together and operating isochronously, will not share load equally. It is impossible to set both machines at exactly the same speed before paralleling. After they are 'tied' together the machine which is running slightly faster will absorb all the load; conversely, the machine running just slightly slower will shed all its load. The operating mode that is required is *isochronous load sharing* [4]. This is achieved with electronic governor systems having load control circuitry and giving much faster response and greatly reduced time constants. Typical systems are described in Section 8.9.

## 8.6.2 Reactive power sharing

Diagrams similar to Figures 8.19 and 8.21 may be used to determine the sharing of total reactive (kVAr) load by plotting voltage against kVAr loading (see Figures 8.22 and 8.23).

Referring first to Figure 8.22, it will be seen that the generator with the flatter kVAr characteristic (in this case unit A) will tend to take the greater share of reactive load. Relatively speaking, it has a lower synchronous reactance than unit B. The situation is analagous to that (shown in Figure 8.19) for engines with differing governor speed droops sharing kW load.

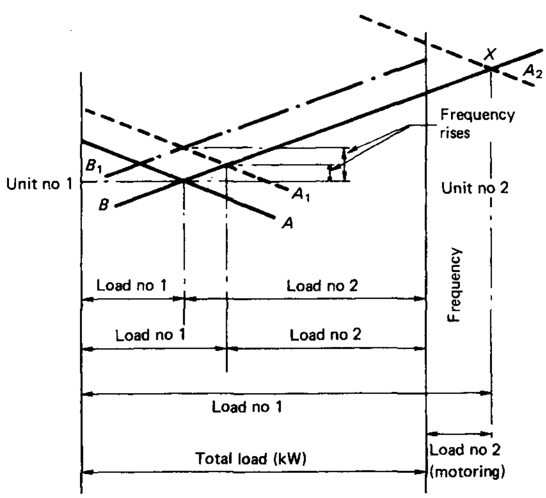



**Figure 8.21** Variable sharing of a constant kW load by two generators

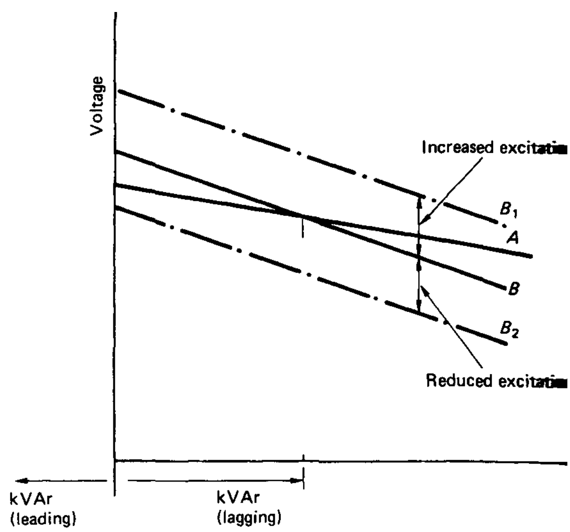



**Figure 8.22** Variable load sharing between two generators with differing kVAr/voltage characteristics

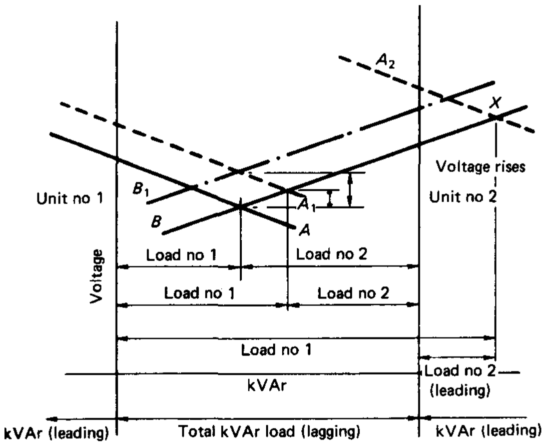



**Figure 8.23** Variable sharing of a constant kVAr load by two generators

Adjustment of generator excitation has the effect of moving the machine's kVAr characteristic-raising it for increased excitation (curve $B_1$), and lowering it for reduced excitation (curve $B_2$). In practice, the sharing of kVAr load is a function of the machines' automatic voltage regulators. This aspect of system operation is discussed in Section 8.8. As with kW load sharing, stable operation is only possible if both kVAr characteristics are drooping or if one is level and the other drooping. The latter condition equates to a generator running in parallel with an infinite busbar system.

Figure 8.23 illustrates the sharing of constant kVAr load. The interesting point to note is that if one machine is considerably under-excited (as represented by point X for generator B), it operates at a 'leading' load despite the fact that the total kVAr load is 'lagging'.

The effect of increasing the excitation on unit 1 from A to $A_1$ is to cause that generator to take a larger share of the kVAr load and raise the system voltage. However, raising the characteristics of each machine by similar amounts (i.e. A to $A_2$ and B to $B_2$), while also altering the voltage, maintains the relative load sharing.

### 8.6.3 A load sharing mechanical analogy

As a young student the author was helped to an understanding of the implicit principles involved in load sharing by the mechanical analogy of the tandem bicycle. Figure 8.24(a) represents a tandem bicycle with fixed-pedal driven sprocket wheels (i.e. they do not have free-wheel mechanisms). Figure 8.24(b) is the equivalent electrical diagram for generators and their load.

It will be appreciated that the tandem's driven wheel, powered by its own sprocket wheel, can

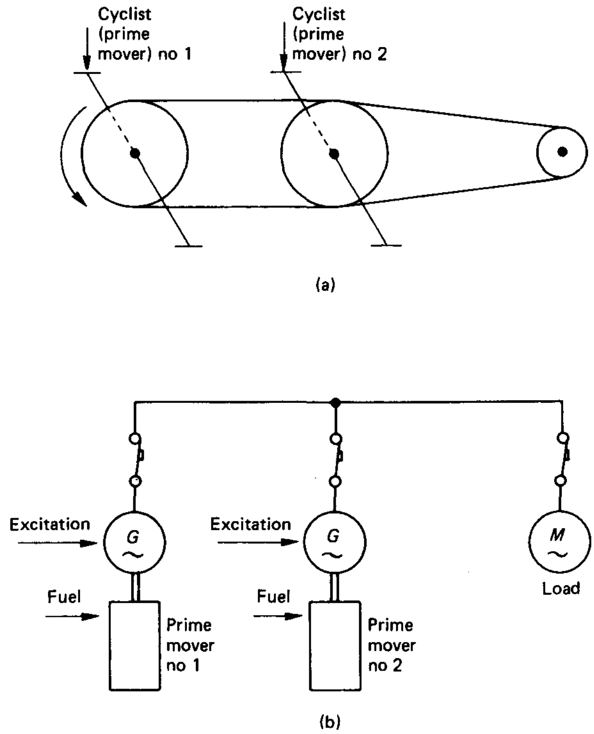



**Figure** 8.24 Load sharing - a mechanical analogy

impose varying tractive load demands on the cyclists, depending on the terrain traversed, etc. Both cyclists can contribute equally, or disproportionately, to the varying load. In the extreme, one rider may not only be providing all the tractive effort for forward propulsion but may also be 'carrying' the other rider, who is, effectively, being 'motored'. This situation equates to the electrical system shown in diagram (b), where diesel generators may contribute wholly, partially, or not at all, to load demands.

Just as both riders' sprocket wheels always have the same rotational speed, the generators have a common system frequency (or speed) and voltage.

The analogy may be an oversimplification, and has its discrepancies, but its use will have been justified if it helps the reader to understand the fundamental principles involved.

### 8.6.4 Accuracy of load sharing

It should now be clear that even if speed and voltage droop curves have been correctly set to be equal, a mismatch in speed (or voltage) setting will have a marked effect on actual load sharing. Figure 8.25 illustrates this point. The two units operating in parallel have 4% droops but a 1% error in matching. The resultant imbalance in load sharing will be 1/4 (or 25%)

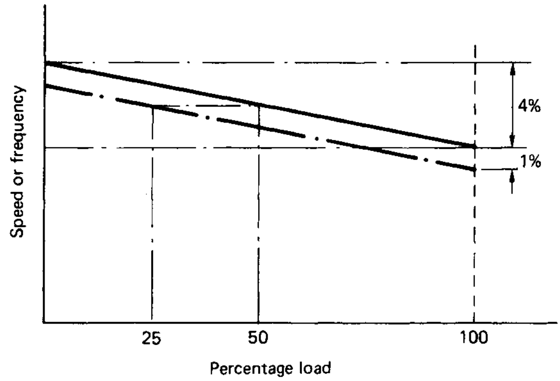



Figure 8.25 The effect of mis-matching speed settings

Predicting the variation from true load sharing is possible by means of graphical treatments using the appropriate droop curves constructed in the manner of the preceding diagrams in this chapter. Coleman [3] presents simple algebraic expressions for Ca!, '-lating the divergence from true kW and kVAr load sharing of two equal-output paralleled units. Where droop characteristics are straight lines, the difference between the actual load supplied by a unit and the proportionate load that should have been supplied, expressed as a percentage of full load, is given by:

where $F$ is the percentage of total load and $d_1$ and $d_2$ are the droops of generator units 1 and 2, respectively - being speed droops when $F$ is in kW, and voltage droops when F is in kVAr.

For example, given two units of equal rating with speed droops of 3.5 % and 4 %, the value for D at 75 % total load would be

$$D = (100 - 75)(4 - 3.5)/(4 + 3.5)$$
$$= 1.67\ \%$$

The diagram of Figure 8.26 defines the terms used in the expression.

In practical applications, the droop characteristics are seldom mathematical lines but, rather, bands of finite width. The width is a measure of the sluggishness of the governor in response to speed change owing to friction and lost motion in moving parts, or sensitivity of the AVR in response to voltage change because of the machine's excitation time constants.

If the speed or voltage bands are not zero the expression for D is modified to:

$$D = [(100 - F) \times (d_1 - d_2)/(d_1 + d_2)] + 25b\,(1/d_1 + 1/d_2)$$

where $b$ is the percentage total width of the speed (or voltage) band. It is assumed that $b$ is the same for both generator units. Figure 8.27 illustrates the terms used in the expression.

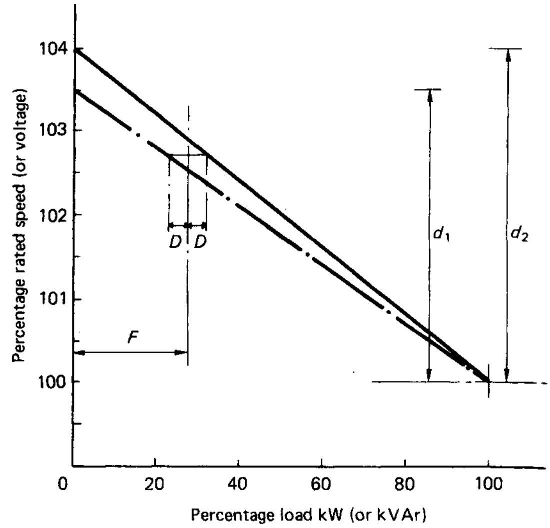



**Figure 8.26** Predicted load sharing for two units of equal output but with unequal straight line droops

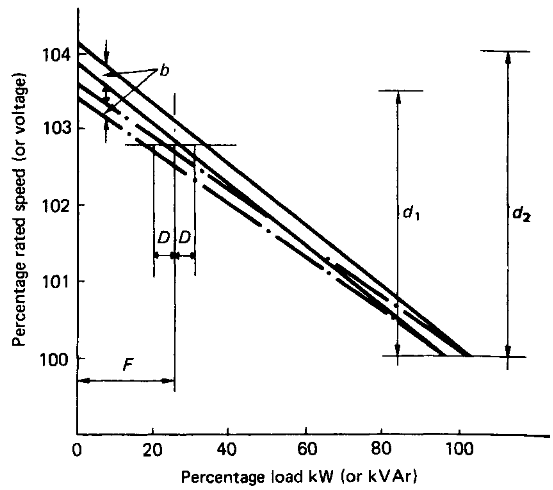



Figure 8.27 Predicted load sharing for two units of equal output but with unequal bandwidth droops

Using the same example as that above, but assUllting, in this case, a 1/4 % droop band, the possible load divergence at 75 % of full load would be:

$$D = 1.67 + (25/4)(1/3.5 + 1/4)$$
$$= 5.02\ \%$$

The cited reference [3] then goes on to develop a simple expression for parallel-running multi-generators, each with equal outputs, matched droops and similar speed or voltage bands. The possible divergence of anyone machine from iIs proportionate active or reactive load share becomes:

$$D = [100b/d][(n-1)/n]\ \%$$

where $b$ = bandwidth, %
$d$ = the droop, %
$n$ = the number of machines

Thus, if five machines are paralleled, each with 4% droops and 1/4% bandwidths, it is possible for one generator to diverge by 5% from its proportionate share of the load.

Finally, consideration is given to two machines of differing output but with matched droops and bandwidths. The possible difference between the actual loads supplied and the proportionate load may then be expressed as follows:

for machine No. 1: $D_1 = 100bL_2/dL_T\,\%$
for machine No. 2: $D_2 = 100bL_1/dL_T\,\%$

where $L_1$ and $L_2$ are the outputs of machines 1 and 2, respectively, and $L_T$ is the total output. (When $L$ is in kilowatts, $b$ and $d$ refer to speed; when $L$ is in kilovars, $b$ and $d$ refer to voltage.)

If two machines, one rated at 500 kW and the other at 1000 kW, are paralleled, and both have speed droops of 4% and equal speedbands of 1/4%, the divergence of the larger set from its proportionate share of load is 2.08%, and that for the smaller set is 4.17%.

## 8.7 Circulating currents

Consider the case of two generators running in parallel with identical operating conditions (each machine takes 50% of both the active and reactive content of the toal load). Under these conditions the operating power factors of the machines are equal to each other and to that of the load. The vectorial relationships of the currents is shown in Figure 8.28(a). The current drawn from machine 1 is shown as $I_1$ and that from machine 2 as $I_2$. In the condition of equal excitation on both machines these currents are equal, and may be represented by $I$. The load current is therefore $2I$ and is in-phase with both $I_1$ and $I_2$. Increasing the excitation on machine 1 makes generated e.m.f. $E_1$ greater than $E_2$. The difference voltage, $E_1 - E_2$, sets up a *circulating* (or *cross*) *current*, which is equal to this voltage difference divided by the total impedance of the two machines, i.e.

$$I_C = (E_1 - E_2)/2Z$$

The circulating current lags $E$, by an angle $\theta = \arctan Xs/R$, and is superimposed on the original current distribution – as shown in diagram (b) of Figure 8.28. It is vectorially added to the load current of machine 1 and subtracted from that of machine 2. The resulting currents, $I'_1$ and $I'_2$, are shown in diagram (c).

The power factor ($\cos\phi_1$) of machine 1 is now decreased and that of machine 2 ($\cos\phi_2$) is increased. The main effect of the circulating current is, therefore, to increase the kVAr output of machine 1 and to reduce that of machine 2. There is also a slight lowering of the busbar voltage. Adjustment of the machines' excitation will correct this.

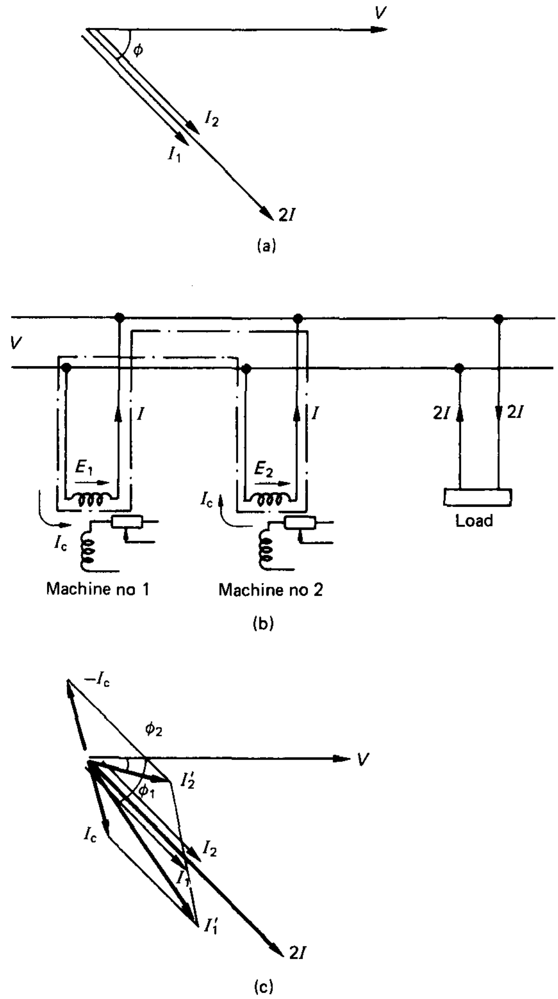



**Figure 8.28** Circulating current paths and phasor diagrams for two generators in parallel

## 8.8 Reactive power equalization in paralleled generators

We have discussed the expediency of having all parallel-running generators carry their proportionate share of total reactive load. To do this they must each have the same generated e.m.f. - which is a function of field excitation. If the e.m.f.s are not the same, circulating currents are set up between the generators. The additional loading, and the subsequent heating effects, limit the active power output of those generators which have the higher excitation.

The pictorial diagrams of Figure 8.29 (adapted from [6] show the effect of differences in generated e.m.f. on identical machines operating in parallel. Where the excitation of both machines is the same, they supply equal reactive currents (or power) to the load reactance. If, as in Figure 8.29(a), the excitation of machine 1 is increased and that of machine 2 reduced, so as to hold their common terminal voltage constant, machine 1 will supply increased reactive power to the load and machine 2 will supply less. There is a boundary condition, at which machine 1 will supply all the reactive load and machine 2 will only supply active power. Beyond this boundary condition, as the excitation of machine 1 is increased still further and that of machine 2 correspondingly reduced (to keep line-voltage constant), machine 1 will supply not only all the reactive load demands, but will also feed circulating reactive current (or *cross current)* to machine 2. Where the load is purely resistive, any reactive current flowing must be cross current between the two machines.

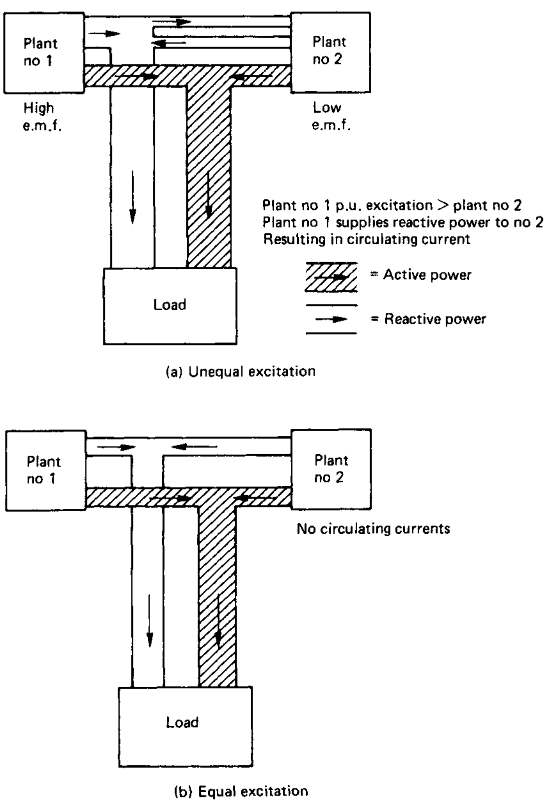



Figure 8.29 The effects of differences in excitation on paralleled generators

One of the major objectives when paralleling generators is not only to prevent circulating currents, but also to equalize reactive currents. The phrase *reactive power equalization* needs to be clearly understood. The aim must be for *equalization* on a per-unit basis. For example, if 100 kW and 50 kw generators of the same power factor rating are paralleled, the 100 kw machine should supply twice the active power and twice the reactive power of the 50 kw unit at any load level.

Automatic voltage regulated generators tend to behave like infinite busbars by trying to hold constant-output voltage regardless of the reactive load or of the power factor of the generators. AVRs are broadly divided into two groups:

- The *astatic* type which regulate to within very close limits, over the full load range. This equates to a flat kVAr/voltage characteristic which tends to give unstable parallel operation.
- The *static* type, where the voltage obtained is not constant but falls as the excitation increases from no-load to full-load (usually, by 3 to 5 %). The methods used to achieve reactive power equalization endeavour to bias the voltage-sensitive elements of the AVR in direct proportion to the machine's reactive current output, so that the output voltage decreases (or droops) as reactive current increases.

Two methods are fundamentally employed:

1. individual compensation - an open-loop method;
2. differential compensation - a feed-back arrangement.

A third method (called *static compensation)* is infrequently used and only briefly described in the discussions which follow.

### 8.8.1 Quadrature current compensation

In open-loop methods the compensating droop adds to the voltage droop inherent in most regulated generators. One system commonly applied is known, variously, as: *quadrature droop compensation* (QDC), *cross current compensation* (CCC) or, more accurately, as *quadrature current compensation* (QCC). As Figure 8.30(a) shows, it merely requires the addition of a current transformer in line W, and an adjustable resistance across which a smaD voltage - proportional to the line current - is induced. This voltage is, in turn, put in series with the generator terminal voltage at the point where it is 'sensed' by the automatic voltage regulator.

Note that the current transformer is connected ill the phase not used for voltage sensing and, because it is the reactive component of the line current whi~ is required to influence the droop, the curre•• injected into the series resistor is advanced 90" ill phase. On single-phase generators the injection res-

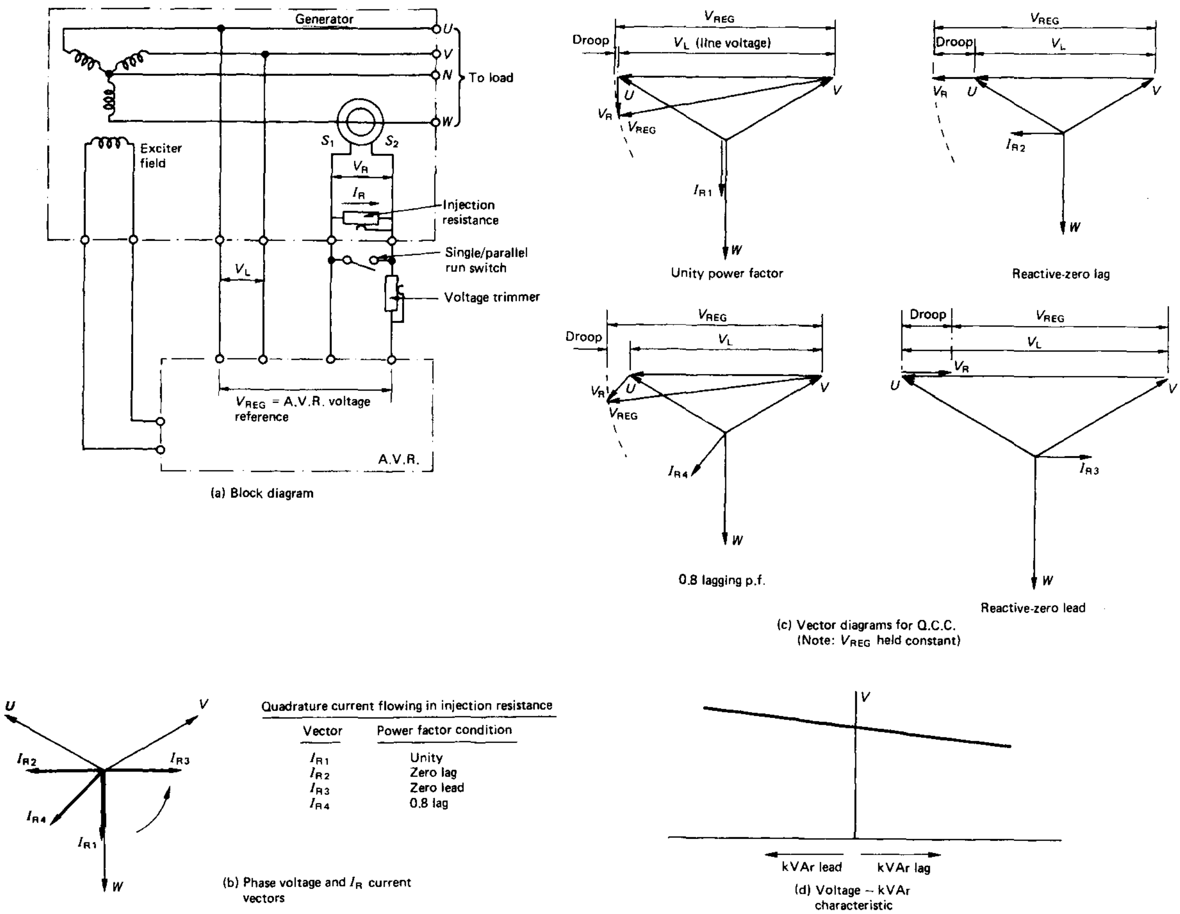



**Figure 8.30** Quadrature current compensation for parallel-running generators

istance is replaced by a choke to give a voltage in phase with the line voltage. In the jargon of the generator manufacturers, the QCC transformer and injection resistance are referred to as the 'quad droop kit'.

Phasor diagram Figure 8.30(b) shows the relationship of the phase voltages of the generator and the current *(IR)* flowing in the injection resistance at various power factors. The series of phasor diagrams in Figure 8.30(c) follow naturally from (b). The first relates to a unity power factor (purely resistive) load where the injected voltage is at right angles to the generator terminal voltage *UV*. The magnitude of the voltage sensed by the AVR is very marginally affected.

The second phasor diagram shows the condition for a purely reactive current (e.g. the no-load, magnetizing currents of transformers). The injected voltage is now in phase with voltage *UV*. The voltage $V_{REG}$ (sensed by the AVR), which is required to be kept constant, is now greater than the generator's line voltage. *UV* therefore drops in magnitude to compensate. In other words: there is a voltage droop equal to the voltage injected by the quadrature current transformer. The 'injected voltage' is proportionate to the line current.

The third diagram in Figure 8.30(c) shows the vector relationship for a 0.8 power factor lagging load - the type of load to be found in most marine and industrial generator applications. It will be seen (from a comparison of its magnitude in the first three phasor diagrams) that the value of the line voltage *(UV)* reduces as the reactive load increases towards zero pJ. lagging. Conversely, taking the opposite extreme of load condition (i.e. zero p.L leading, shown in the fourth diagram), we see that the magnitude of *UV* has increased. The QCC system's voltage/kV Ar characteristic thus takes the form shown in Figure 8.30(d) - the voltage drooping with increasing kVAr lagging loads and rising with leading reactive loads.

A generator fitted with QCC equipment and independently connected to a load would exhibit the same voltage droop/rise response to lagging/leading currents. Conversely, if the generator were connected to a fixed voltage system the kVAr supplied by it would increase with voltage drop and decrease with voltage rise. In either case the kVAr supplied by the generator can be independently adjusted using the voltage trimmer on its AVR.

Typically, the voltage droop caused by QCC at 0.8 power factor lagging full load would be of the order of 3% greater than that with an uncompensated AYR. If a generating set is to operate singly for lengthy periods, and this order of droop is not acceptable, it can be eliminated by connecting a switch across the quadrature current transformer - as shown in Figure 8.30(a). The switch is closed for single running and opened for parallel running. To avoid the risk of an operator leaving the transformer shorted when the machine is running in parallel with others the switching action may be made automatic by using normally-closed auxiliary contacts on all generator circuit breakers in the system. The current transformer of any machine in the system may then be arranged to be shorted by a series circuit containing the auxiliary switches on all the other generator breakers. This would ensure that the current transformer of a single-running set is shorted only when the remaining sets are disconnected from the common busbar.

The QCC droop (expressed as a percentage of nominal voltage for a reactive load equal to the full load kVA rating of the generator) is usually of the order of a maximum of 5 to 10%. If the regulation of the fitted AVR is ±1.5%, a droop setting of around 5% is recommended for parallel operation with other similarly-controlled generators. At a rated full-load power factor of 0.8 lagging the kVAr would be 0.6 x kVA. The quadrature droop would therefore be:

$$0.6 \times 5 = 2.5\,\%$$

Where a generating set is run in parallel with a large utility supply, for *peak-load lopping* purposes, it is possible to have the generator unit and the utility operate in one of several kW and kVAr load sharing modes, and to use the local generator to improve the power factor of the installation. The reader's attention is directed to Section 11.3.4 of Chapter 11, in which parallel operation with grid supplies is discussed in some detail.

Care needs to be taken when commissioning and operating plant using quadrature current compensated AVRs. Primarily, the action of the compensating current transformer must be proven. Its 'polarity' is most important. Incorrect connection will result in a rising voltage characteristic giving unstabilized parallel operation. The connections shown in the switchboard diagram must be checked to ensure correct phase rotation. The current transformers (and voltage transformers, where applicable) must be in the correct phases and a check made that all transformer polarity markings have been correctly observed.

The critical aspect of the setting-up procedure concerns adjustment of the voltage droop level. It has already been suggested that the best parallel performance using an AVR with ±1.5% regulation is obtained with a droop setting of about 5% - this, at a zero power factor current equal to the full-load rating of the machine. Unloaded transformers, motors, or welding sets are required, if one is to obtain anything like a zero power factor lagging current. These types of load are not always readily available. More commonly, resistive load banks or w,!ltertanks with immersed electrodes are the norm in manufacturer's works tests, or during site commissioning tests. These, being unity power factor loads, are of little use in checking the voltage droop (see Figure 8.30(c». It is just feasible to use them, but the results are unreliable. Fortunately, a practical simulation of zero power factor load can be made when using a unity power factor resistive load. This is simply achieved by replacing the QCC injection resistance with an electrolytic capacitor in the case of 3-phase machines, and the choke with a resistor on single-phase machines.

The capacitor should only be in circuit for a few seconds at a time. A switch connected across **it** enables it to be taken out of circuit rapidly. If the machine's terminal voltage droops when the capacitor is in circuit the quadrature current transformer has the correct polarity connections. Conversely, if there is a voltage rise on load, the leads to the secondary terminals Sl and *Sz* (see Figure 8.30(a» should be reversed, either at the transformer itself or at the capacitor - whichever is more convenient. This test not only checks the QCC kit's polarity, **but** it also gives a good indication of the amount of resistance required in the injection resistor. Should the voltage droop the desired 5%, using, say, a 50 microfarad capacitor, then a 60 ohm resistance i5 required in circuit. A greater droop requires **less** resistance and a lower droop, more resistance.

The above checks must be made on all machines in the system when they are single running and switched from no-load to full-load. All vol~ droops must be set as nearly equal as possible.

The next step in the operation is to parallel two of the machines, following the correct synchronizinc procedures. Then, increase the load until each gea-erator is on full load. At each load increment, kilowatt and current readings should be takea. (Ideally, kVAr and power factor readings shouW also be recorded when these instruments am fitted - which, unfortunately, is not always the C3IC on smaller plants.) As the load builds up, adjustments may be necessary to the engine governor settings to ensure balanced kW load sharing. When the kW readings match, the corresponding current readings should be within about 5 % of each other. *H* they are outside this limit the machine with the higher current reading is over-excited, which means it is taking a greater share of the kVAr load increase and is operating at a lower power factor. Its droop should be widened by increasing the value of the injection resistance.

When full-load current has been attained on each generator the load should be reduced in decrements. Again, kW and current readings should be noted at each load level. Variations greater than 5 % require the same corrective actions as those outlined above. Unequal ammeter readings at the top end of the load range indicate incorrect droop levels, while differences in readings when approaching the no-load condition imply incorrect voltage settings.

Once these adjustments have been made there are basically two methods of operating paralleled machines. The first is to leave all the AVR trimmers z set. The no-load to full-load voltage/kV Ar droops are then adjusted up the voltage axis so that all ttimmers are preset to give nominal system voltage at the machine's half-load point. A kVAr imbalance will occur on initial synchronizing. This is caused by the difference between the incoming machine's voltage and the system voltage. The difference is small enough to be acceptable, and it disappears when active loads are shared. Using this method of operation it is advisable to mount the preset trimmers so that they are out of direct access to unauthorized personnel.

The alternative method requires the switchboard attendant to trim the AVRs occasionally in order to maintain nominal system voltage - especially on installations where a great deal of single running obtains. Attention must then be focused not only on the voltage but also on the kVAr load sharing at each trimmer adjustment.

The following table shows some of the more common symptoms of mal-operation in parallel running plant, as first detected on switchboard instruments. Probable causes and remedies are listed against each.

## 8.8.2 Differential compensation

It should be appreciated that, while QCC gives fairly accurate kVAr load sharing, it does so at the expense of a droop in the (overall) system voltage. If voltage regulation is of importance in parallel operation, droop may be eliminated by interconnecting all the parallel-running current transformers in series to form a closed loop. The system using this arrangement is known as *differential* or *astatic* compensation, and the loop so formed as the *astatic loop.* The inherent kVAr-sharing capability of QCC is maintained. The difference between QCC and *differential compensation* lies in the fact that, with the former, the voltage injected into the sensing circuit of anyone generator's AVR is proportional to that generator's total load, whereas with the latter, the injected voltage depends only upon the out-of-balance (or circulating) current between the paralleled machines.

| *Symptom* | *Cause* | *Remedy* |
|---|---|---|
| I. Kilowatt meter, ammeter and voltmeter pointers oscillating or fluctuating irregularly | Engine governor is hunting or sticking<br>Injector failure | Check governor and its damping; rectify/reset or replace with proved unit<br>Check injectors and fuel supplies |
| 2. Unbalanced ammeter readings, but kWs stable and balanced | Circulating current rising from incorrect voltage setting | Adjust voltage setting<br>Check QCC connections and correct if necessary<br>Adjust QCC droop, if necessary |
| 3. Rapid rise of current as generator breaker is closed OR unbalanced ammeter readings at no-load | QCC connections reversed or incorrect voltage settings | Check QCC connections and correct if necessary<br>Adjust voltage setting |
| 4.. Kilowatt and current readings unbalanced as load increases or decreases | Unmatched governor speed droops/settings | Adjust speed regulations and/or governor settings |
| S.. Ammeter readings unbalanced as load increases, but kWs balanced | QCC droop settings not equal<br>OR<br>one set of QCC connections reversed | Adjust QCC droops to be identical on each generating set<br>Check QCC connections; and correct, if necessary |

Figure 8.31(a) shows, in simplified form, the connections for a two-generator system. Note that the current transformer secondaries are now connected in series and that the injection resistances are also connected in series, but across the transformer secondaries. It is normal practice to interconnect the separate QCC circuits through isolating transformers in order to avoid multiple earthing problems. The windings of these transformers operate at a very low level of current. This minimizes the voltage drops in the interconnecting cables that are necessary with the system.

Diagram (b) in Figure 8.31 illustrates the conditions that arise in the injection resistance circuit, with both balanced, and unbalanced, transformer secondary currents. When the two generators' line currents are unbalanced the current transformers' *difference* current flows through the resistances in *inverse* senses, causing their respective AVRs to adjust excitation in opposite directions and thus counteract the current imbalance. The system is therefore sensitive to *wattless* current and maintains the current balance (as in QCC), but without the voltage drop that the QCC method produces.

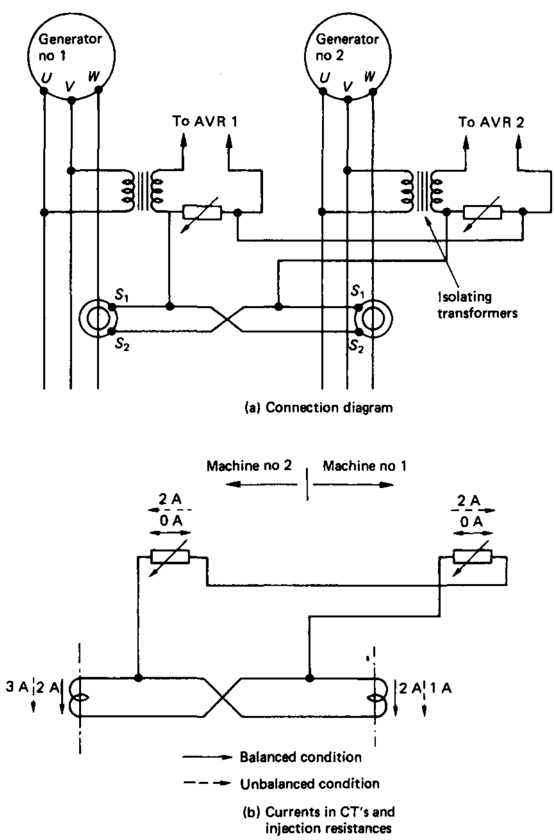



**Figure 8.31** Differential compensation for parallel-running generators

A practical schematic for two generators paralleled to a grid (utility) supply is shown in Figure 8.32. The drooping voltage/kVAr characteristics required in such circumstances are restored by breaking the astatic loop by means of the normally-closed auxiliary contacts on the grid supply breaker.

Although differential compensation gives a more constant busbar voltage than the straight QCC system, the complexity it introduces by way of interconnections and switching arrangements is seldom considered worthwhile - especially on small and medium output plants. Also, it is not possible to operate generators controlled by differing makes, or types, of AVR, in an astatic compensation mode. In such circumstances the smaller machines in the system may be allowed to 'trail' on QCC.

### 8.8.3 Static compensation

Some reference must be made to the third method of reactive equalization - that known as *static compensation.* The method can only be applied to certain types of AVR. Individual manufacturers offer differing schemes but they all operate to offset the voltage droop due to reactive load by 'inducing' a voltage rise from the active-load element. The system voltage can be made to be reasonably constant for variations of load at a given power factor.

A generator controlled in this way and connected to a grid supply will operate at a fixed power factor. independent of the load - the kVAr adjusting itself to be automatically proportional to the kWs.

## 8.9 Automatic multi-generator plant

The demand for medium-output, fully automatic and semi-automated diesel generating plant first arose in the marine industry in the mid-1960s. "The major reason at that time was the shortage of qualified sea-going engineers. Coupled with this was the desire of ship owners to create equal, or better, working conditions afloat than those pertainin& ashore, whilst aiming for a normal working day and a five-day week. Ships introduced into service at that time increasingly made use of centralized c0ntrol rooms (CCRs), where monitoring and control facilities were provided not only for the main p~pulsion units but also for the major auxiliaries sudt as generating plant.

It was found that these automated systems ga'IC more than marginal improvements in running eCO&omy and installation efficiency. Resulting reductio•• in control and monitoring tasks were reflected • fewer manning personnel, but this was offset by the need for more highly trained engineering staff f(ll" the maintenance of the more sophisticated insu. mentation and control devices installed.

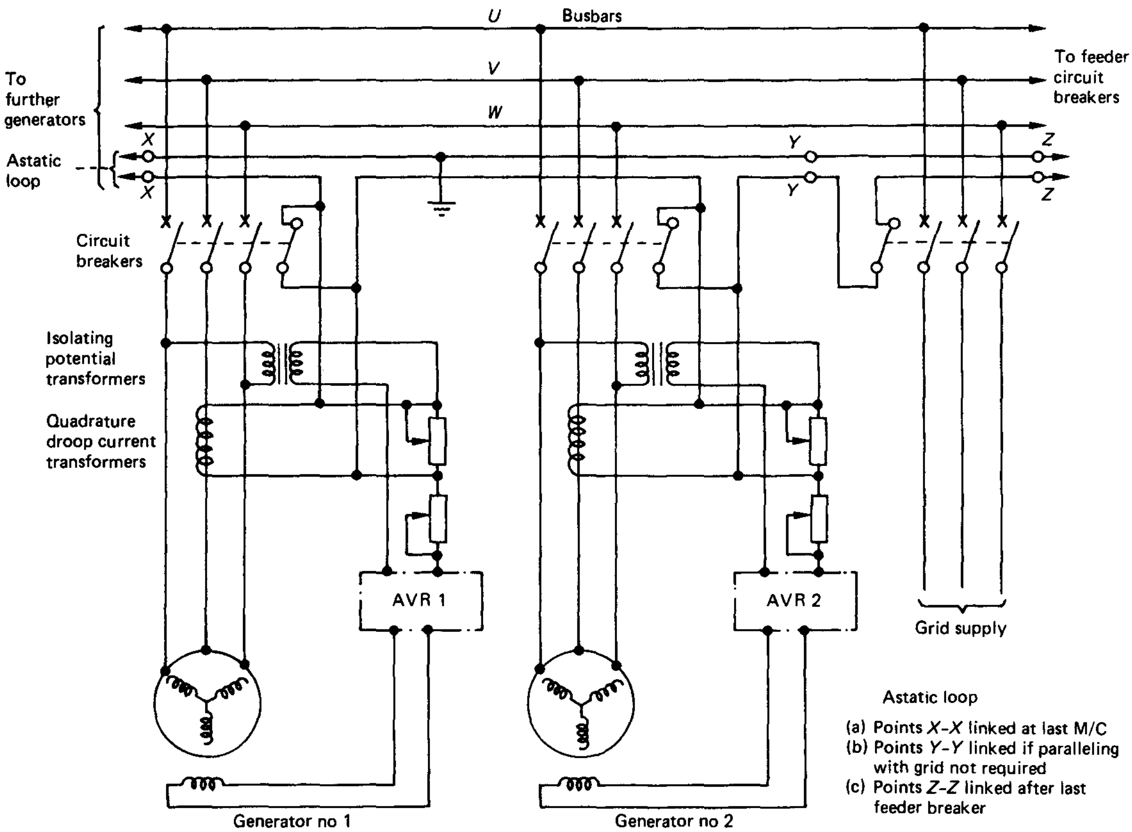



**Figure** 8.32 Astatic loop arrangement for two generators paralleled to a grid supply

We shall now consider the basic operating principles of both partly-automated and fully-automated plant and the more important functional features of the control devices used. The degree of automation can be designed to suit the particular requirements of an installation. The table in Figure 8.33 [7] shows typical progressive stages in automation.

In stage 1 only the circuit of an incoming machine breaker is automatically closed, once the machine has been synchronized. In stage 2 this function is preceded by automatic adjustment of the incoming generator's frequency so that its speed matches that of the system. In stage 3 synchronism and paralleling is followed by automatic load sharing by all units in the parallel mode. In stage 4 the diesel engines are started from local or remote push-button station(s) with subsequent automatic operation. Stage 5 goes back one step further, to introduce automatic call-up and shutdown of additional generator capacity as load demands change.

| Required features | Stages of automation | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Automatic demand control | | | | | X |
| Automatic diesel start | | | | X | X |
| Automatic frequency adjustment | | X | X | X | X |
| Automatic synchronizing and paralleling | X | X | X | X | X |
| Automatic power adjustment | | | X | X | X |

**Figure 8.33** Stages in the automation of multi-generator plant

As a minimum, the following main functions should be automated in a partially unmanned multi-generator system which is operating on independent (or isolated) busbars.

1. Call-up and shutdown of sets in response to load demand.
2. Synchronizing and circuit breaker closure.
3. Load sharing of active and reactive load between generators.
4. Protection against prime mover and electrical system faults.
5. Selection of duty, standby, and emergency reserve plant, so that the total running hours of

individual units may be matched to planned maintenance programmes.

There are other functions that add sophistication only, but are not essential to the requirements of the fundamental system. These might include for example:

- *preferential tripping* (or *load-shedding)* of non-essential loads on system overload and, conversely, their controlled reconnection after overload conditions have been removed;
- automatic data logging or analogue recording, with trend indication, to improve system maintenance efficiency.

We shall deal with the minimal functions listed above and illustrate them with a typical system.

### 8.9.1 Load demand controls and load sharing

The starting of the first set in an isolated busbar system is usually by a master start switch. Thereafter, it is desirable to run every set at efficient loadings - commensurate with the requirement for there to be sufficient connected capacity at all times to cater for known and sudden peak demands.

The load must be monitored continuously and signals initiated to call-up and shutdown sets as load demand changes. The controls associated with load monitoring, automatic synchronizing and load equalization call for a large number of comparison and switching functions. We have seen in Chapter 6 (Engine Governing) that the advent of solid-state, semi-conductor devices has added impetus to the development of electronic type governors, giving flexibility of application in complex automatic operating systems. Most governor manufacturers now market all-electric governor systems in modularized form, giving add-on capability to provide very sophisticated controls. Fairly simple diagnostic routines encourage the on-site replacement of modules rather than the tracing of internal faults and replacement of discrete components within them.

We established earlier in this chapter that it is practically impossible to run two or more engines in parallel when they are fitted with mechanical-hydraulic speed governors which operate in an isochronous mode. Either all the governors, or all but one, must operate in droop. Even so, there are two major characteristics that may be undesirable [4]:

1. busbar frequency changes with load changes; and
2. each time a generator is added to the busbar, the governor speed settings must be reset in order to establish a new load balance and re-establish system frequency.

A droop governing system of this type could be automated through governor speed setting motors but the hardware is cumbersome and complex.

A more desirable solution is to use electric isochronous load sharing governors [4]. Here, a load sensing module is added to the speed control loop (see Figure 8.34). This measures the active electrical power developed from its own generator through potential and current transformers, and compares it with other generators operating in the system. Any difference in the power measured sets up a circulating current in the load-sensing bridge circuit. The output from the bridge directly biases the controlling amplifier (within the speed control unit) without disturbing the speed loop. The actuator mounted on the engine then assumes a new fuel setting to keep the engine running at unchanged speed and allow it to take its proportionate share of the total load on the busbar.

A typical governor system for load monitoring and load sharing is illustrated in block diagrammatic form in Figure 8.35.

The nub of the system is the *load sharing unit* (LSU). All load sharing units in the system are connected to paralleling lines which are the communication link between two or more load sharing speed controls. Connections are made through normally-open auxiliary contacts on the generator circuit breakers (CB). Internal output of the load sharing unit is a d.c. voltage proportional to active load. If this voltage differs between paralleled units, a small d.c. current flows in the paralleling lines. This current causes the respective governor control references to be set to a slightly different speed - some raised, some lowered. But, because they are paralleled, the generators are constrained to run together at the same speed. Also, because tbe increases in reference speeds are balanced by tbe decreases, the system speed remains unchanged. Only the load contributions change - in a direction to reduce the current in the paralleling lines to a minimum. The sensitivity control feature on each load sharing unit may be used to match its genera-

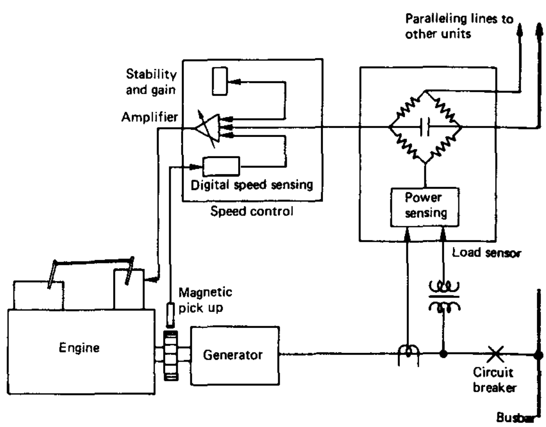
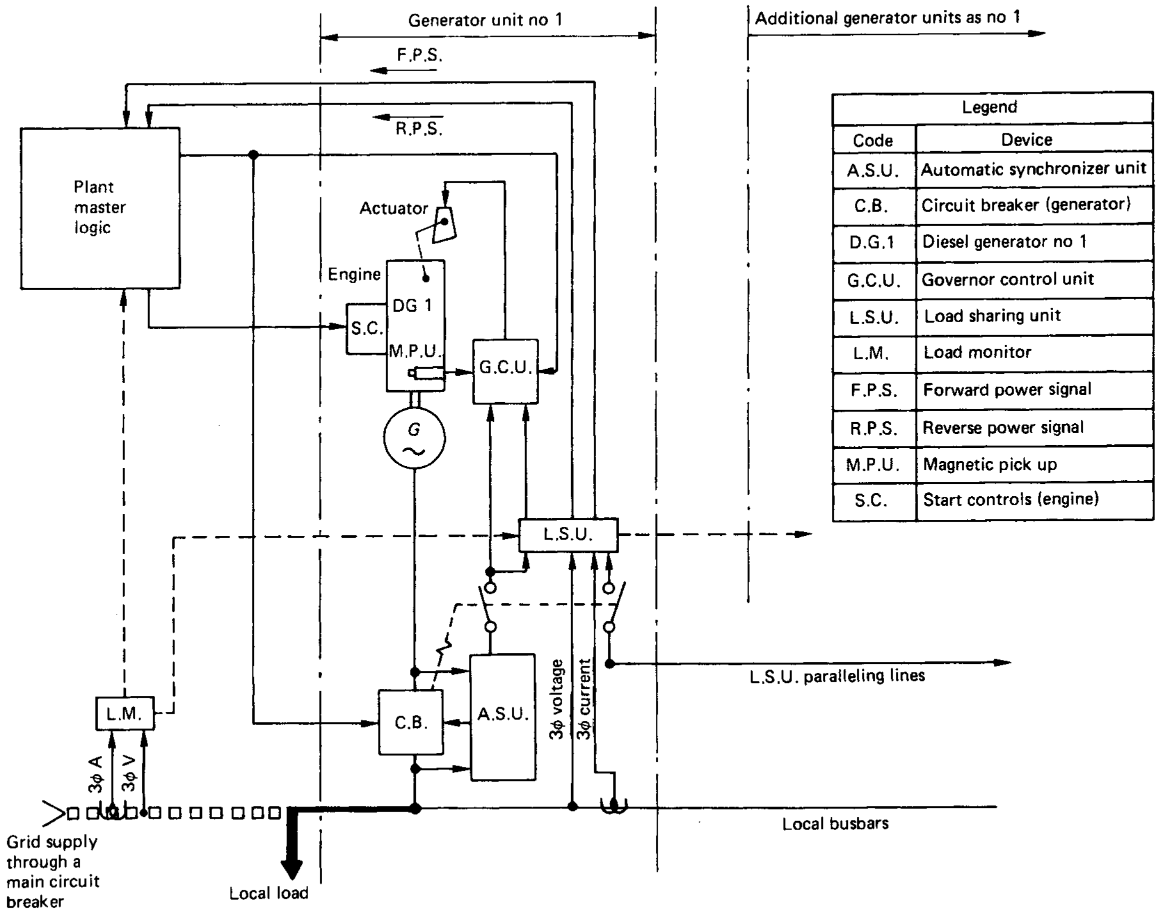



**Figure 8.34** Block schematic illustrating speed control loop and load sensing related to parallel operating generators




| Legend | |
|---|---|
| Code | Device |
| A.S.U. | Automatic synchronizer unit |
| C.B. | Circuit breaker (generator) |
| D.G.1 | Diesel generator no 1 |
| G.C.U. | Governor control unit |
| L.S.U. | Load sharing unit |
| L.M. | Load monitor |
| F.P.S. | Forward power signal |
| R.P.S. | Reverse power signal |
| M.P.U. | Magnetic pick up |
| S.C. | Start controls (engine) |

**Figure 8.35** Block diagram for automated multi-generator installation with conversion to a peak-lopping scheme

tor's power output to that of the others in the system.

Some load sharing modules may have additional features, such as forward and reverse power monitoring, which operate to close contacts at preset power levels. These contacts are used (see Figure 8.35) for automatic start-up or shutdown of additional generators. The reverse power contacts indicate loss of power for any reason and remove an engine from service. The forward power relay trip is time delayed, and is usually adjustable to close from between 20 to 100% load, and to open from 80% to zero load. The reverse power relay, also time delayed, may be adjusted from 0.5 to 20%. Another feature offered on some load sharing units is a *load anticipation* function which minimizes the speed transients resulting from large load steps.

The plant master logic is programmed for a predetermined starting sequence of the generating units. The first in sequence is manually commissioned to the busbars. Subsequently, if load demand rises to the first generator's forward power monitor set-point, a pair of contacts in its load sharing unit will close. This signals the master logic that another generator must be started and brought on line. The logic decides which engine is to be started and in what order the others (when needed) shall follow. Once a generator set is started, the automatic synchronizer unit (ASU) will parallel the generator to the busbar, and the set will take up its proportionate share of the load demanded. (The ASU is described in Sub-section 8.9.2, which follows.)

As load on the last set on line rises, its forward power monitor signals when its power level reaches the preset point. This signal (to the master logic) causes another set to start and come up to speed. Automatically synchronized with the busbar, the incoming set then takes up its share of the load.

Conversely, when load on the running generators is reduced below the desired minimum level, the 'OFF' control contacts on the load sharing units will open to signal the master logic to remove one diesel generator from the busbars. This is normally the unit which was last brought on line. The system thus ensures that any engines needed will run at power levels which provide good fuel economy and optimum engine performance. A refinement worth adding is a *generator loading* (or *transfer) control,* which reduces the power from a generating set and unloads it before it is disconnected from the busbars. This helps prolong the life of the circuit breaker contacts.

If the system contains any loads which are automatically switched, and whose known ratings are such that the reserve capacity of running generators is likely to be exceeded, interrogation of the master logic can be designed-in so that, before such loads are switched, an additional generator is automatically brought on to line. (See also Section 9.16 of Chapter 9). Any well-designed system will also include manual override control facilities so that, for example, on marine installations, precautionary power reserves may be connected to the busbars when a vessel is operating in close waters or is entering harbour.

The additions, shown in dotted lines on Figure 8.35, convert the system to a multi-engined *peak-lopping* or *power shaving* installation. This is achieved by using a load sharing module as an incoming load monitor (LM) on the grid busbar. Should the local demand rise to the forward power preset point on this monitor, the first generator in the selected sequence is started as before, and is synchronized to the busbars. This set then accepts all load above the power level set on a *power control bias* adjustment. This is usually an external potentiometer circuit used in conjunction with each generator's load sharing unit. The load monitor (LM) signals the engine governors to deliver all power in excess of that which is to be taken from the grid. As local demand increases or decreases, so additional generators are cut-in and cut-out following the method previously described for plant operating, independent of grid support, on local busbars.

Provided the right steps have been taken to introduce similar droop characteristics into the AVR circuits of all the machines (using one of the methods described earlier in this chapter), the paralleled generators will also share the reactive power demands of the system.

### 8.9.2 Automatic synchronizing

Earlier in this chapter we considered the use of a check synchronizer as an aid to accurate manual synchronization of generators. The unit described allowed the 'paralleling' circuit breaker to be closed only when in-coming frequency and phase were matched (within pre-selectable limits) to the busbar. It did not trim speed to achieve this, nor did it compare busbar and generator voltages - as must any unit that has to perform automatic synchronizmg.

The requirements of an automatic synchronizer are:

1. to synchronize rapidly;
2. to effect incoming breaker closure at a phase coincidence point and so minimize system shock;
3. to have the highest degree of reliability; and
4. to be adjustable enough to provide the capability of matching the synchronizing system to the diesel generator set and to the circuit breaker being controlled.

Preferably, it should also be compatible with any associated governor controls - to the extent that it directly interfaces with them.

Automatic synchronizers meeting these requirements are marketed by all electronic governor manufacturers. A typical unit (the SPM Synchronizer), manufactured by the Woodward Governor Company, will serve to illustrate the operational features which give compatibility with the manufacturer's electric governor controls. Its important circuits are shown in the schematic block diagram of Figure 8.36 [8], and are:

- the *speed bias* circuit;
- the *breaker close* circuit;
- the *enable* circuit; and
- the *voltage comparator* circuit (on those models in which it is included).

The synchronizer checks the frequency and phase angle of the busbars and the incoming generator. These voltage inputs are fed to separate *signal conditioners* which are filter circuits designed to change the shape of the input signals to allow more accurate measurement of them. The conditioners also amplify the busbar and generator signals before applying them to the *frequency and phase detector.* This detector compares the two signals, and any frequency difference between them is corrected by the *'speed bias'* circuit, working through the load sharing and governor speed control units, to restore the voltage phase relationship between busbars and generator. The speed bias can affect a $\pm 1.5$ Hz frequency change at the generator. Output of the synchronizer is matched to the requirements of the various load sharing and speed control modules marketed by Woodward. This compatibility is obtained by jumper selection prior to the output terminals.

The *breaker close* circuit also takes its input from the frequency and phase detector. It checks the phase angle between the conditioned inputs. When this angle falls within the jumper selected *window,* the circuit starts measuring the amount of dwell time for which the inputs are in phase and ensures that these signals remain in-phase during the breaker closure. When selected phase angle and dwell time conditions are met, the circuit signals the *relay driver/inhibitor.* (See Section 8.2 for an explanation of the window and dwell time.) Meanwhile, the *enable circuit,* which affords an additional coarse check of relative phase angle and voltages, turns on

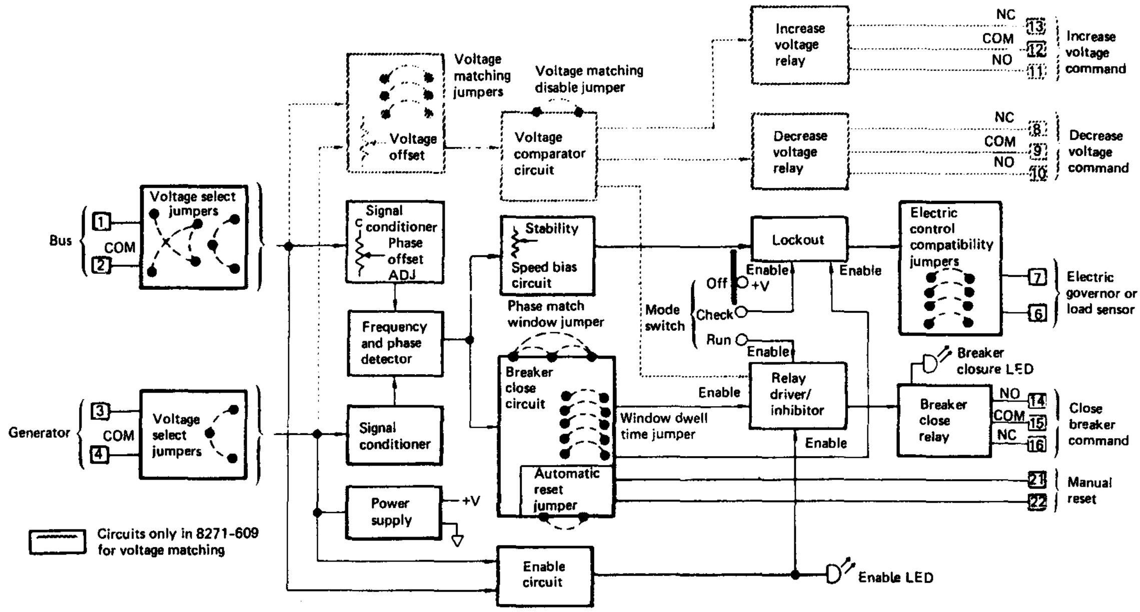



**Figure** 8.36 Schematic diagram of automatic synchronizer (Courtesy: Woodward Governor Company)

a light-emitting diode (LED) and gives a confirmatory signal to the driver/inhibitor. This, in turn, sends a signal to the *breaker close relay.* The relay changes state for about one second and the close breaker LED illuminates.

A three-position switch on the synchronizer chassis controls the relay driver and the *lockout* circuit to give:

1. a normal RUN mode;
2. a CHECK mode, where the normal functions occur but the close breaker signal is not given; and
3. an OFF mode, where the synchronizer is inoperative.

The purpose of the lockout circuit is to 'disable' the synchronizer once the breaker close signal is given. It resets automatically when the generator is disconnected from the busbars.

On certain models in the manufacturer's range synchronizers are fitted with a *voltage comparator* circuit. Any difference in busbar and generator voltage signals causes either the *increase* or *decrease* relays to operate. These commands, in the form of normally-open or normally-closed contacts, may be used to energize an external motor-operated voltage trimmer in the automatic voltage regulator circuits. The voltage comparator also gives an additional input to the relay driver/inhibitor to ensure that generator and busbar voltages are within the selected matching range before the 'close breaker' command is given.

The synchronizer offers phase window options of 5, 10, 15 and 20 degrees and dwell times of 1/8, 1/4, 1/2 and 1 second, and (when applicable) voltage matching tolerances between the busbar and generator voltages of 1, 5 and 10%. In addition to controlling the generator's voltage within these preset tolerances, the synchronizer wiH not issue the 'close breaker' command if the generator voltage is outside these limits.

Figure 8.37 suggests that one synchronizer is used to control a single generator set and is therefore dedicated to that set. However, by suitable jumper selection on the 'electric control compatibility' stage, the SPM may be used for sequentially paralleling generators to a busbar. Figure 8.38 shows how this may be done.

Generator selection is set for the next generator to be paralleled to the bus-bars. Contacts SEL 1A ... NC are associated with relays in the master logic and close when their related generator is started, on a demand signal. There is no practical limit to the number of generators that may be sequentially controlled by the synchronizer in this way. One obvious weakness of such a scheme is the total reliance placed on the one master synchronizer for the entire generator system - as opposed to a dedicated synchronizer for each generator.

Remote speed adjustment on mechanical-hydraulic and mechanical governors is provided by geared, split-field, series wound, reversible a.c.ld.c. type motors (see Figure 8.39), or by permanent magnet d.c. motors. Obviously, when these governors are fitted in parallel running multi-generator installations, this type of synchronizer (designed for use with electronic governor controllers) cannot be employed.

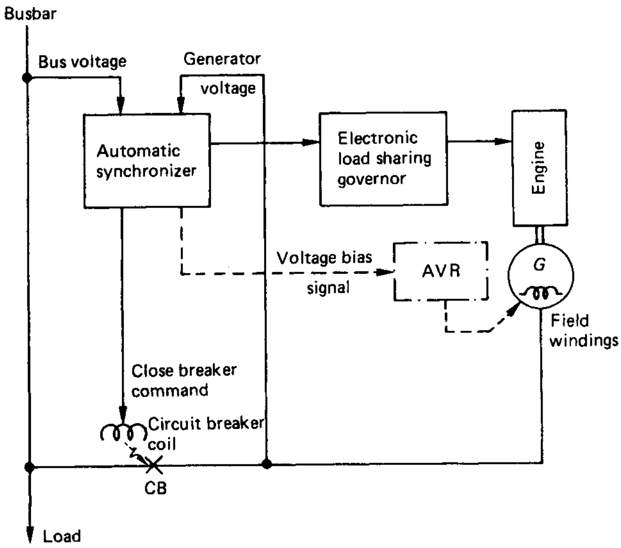



**Figure** 8.37 Block schematic diagram for application of an automatic synchronizer, and compatible load-sharing and governor speed controls

What is required is a synchronizer that can pulse the incoming generator's governor speed setting motor through 'clean' relay output contacts. Figure 8.40 [9, 10] shows a simplified schematic for one such automatic synchronizer. The *voltage comparator* compares busbar and generator voltage and adjusts the incoming voltage as necessary. The *frequency comparator* compares the difference (or beat) frequency and adjusts the speed of the incoming machine by one pulse per cycle of beat frequency. The *pulse width* potentiometer adjusts this pulse width to suit the characteristics of the particular governor used. Finally, the *phase comparator* measures the rate of decrease of the beat frequency envelope from 15° to 7° and initiates breaker closure.

Again, it is possible to use one synchronizer of this type for all the generators in a multi-set system using signal routeing relays and switching. But the low cost of modern synchronizers based on microprocessor technology (such as the type MAS 100 from Brush Electrical Machines) makes it viable to use one synchronizer for each generator in the system. This concept also gives greater standardization of circuitry, easier system expansion, and increased overall reliability.

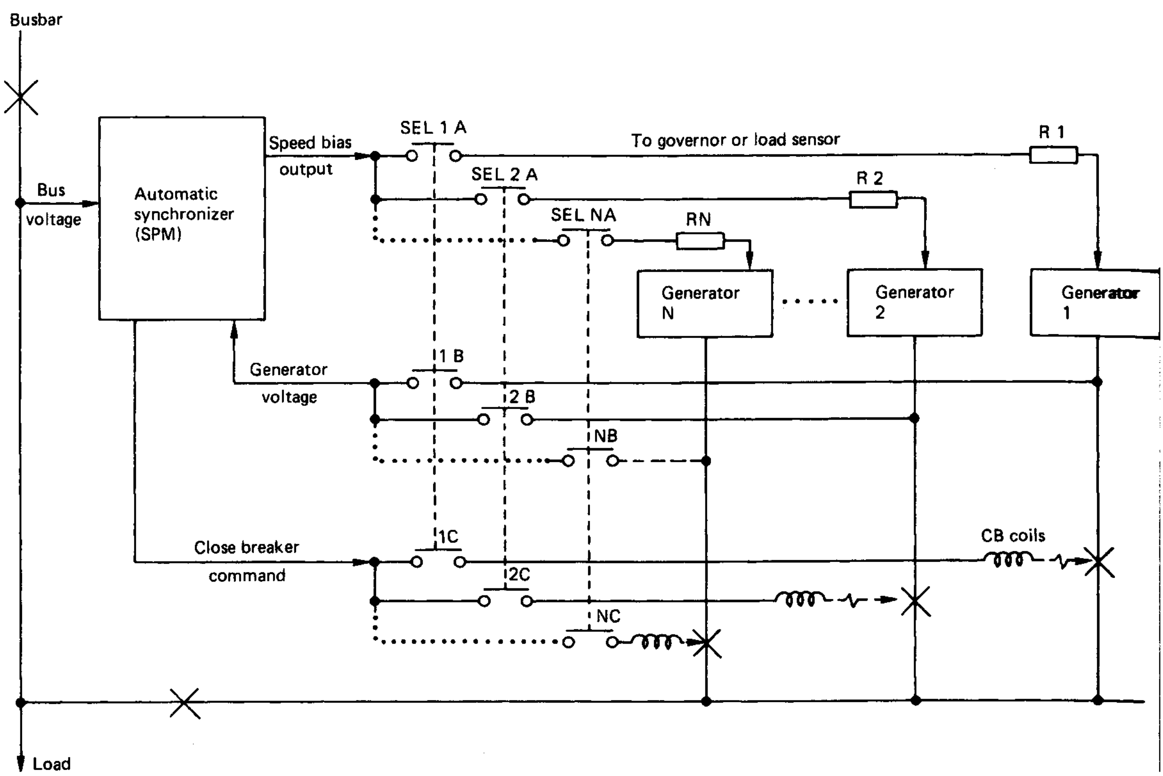



**Figure** 8.38 Block schematic for sequentially synchronizing generators

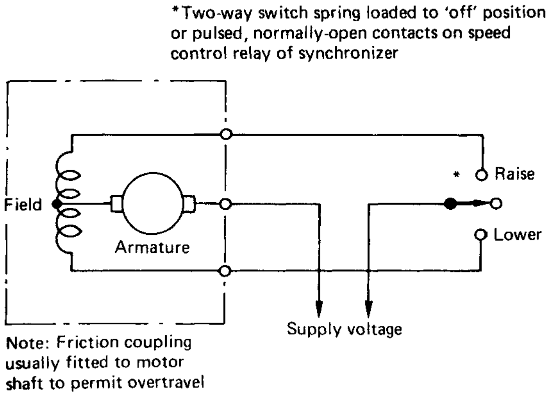



**figure** 8.39 Split-field. series wound. reversible motor connections for governor remote speed control adjustment

## 8.10 System busbar arrangements

Although busbar systems will be discussed in some detail in Chapter 9, it is appropriate to briefly refer to the subject in the context of automatic power generating plant. Busbar and switching system configurations must be designed to take full advantage of the features offered by such plant. On shipboard installations in particular, required criteria are:

- maximum reliability and continuity of service;
- simple operation and maintenance; and
- adaptability for future load additions.

Most stationary and marine installations have tended to employ the single busbar arrangement, with all connected generators operating in parallel. This system has the merit of flexibility with the minimum of attendant staff. Its major disadvantages are that it does not give maximum continuity of supply (a fault on the busbar means total loss of power), and choice of maintenance periods is seriously restricted.

Where continuous supply is important, a sectionalized (or split) single busbar system offers a simple and economic answer without recourse to more complex arrangements, such as duplicated busbars. True, a higher degree of discipline is required from operational staff, but the advantages (security of supply and ease of maintenance) more than counter this.

Figure 8.41 shows a typical system arrangement for a four-generator automatic plant. Under normal circumstances the busbar sections are connected together so that all generators may operate in parallel. Sectionalization is affected only when short-circuit occurs. It will be appreciated that the generator bus-sections must be synchronized before the relevant couplers are closed, and that the sectionalizing switches should be fully-rated circuit breakers and not off-load air break isolators. Care should also

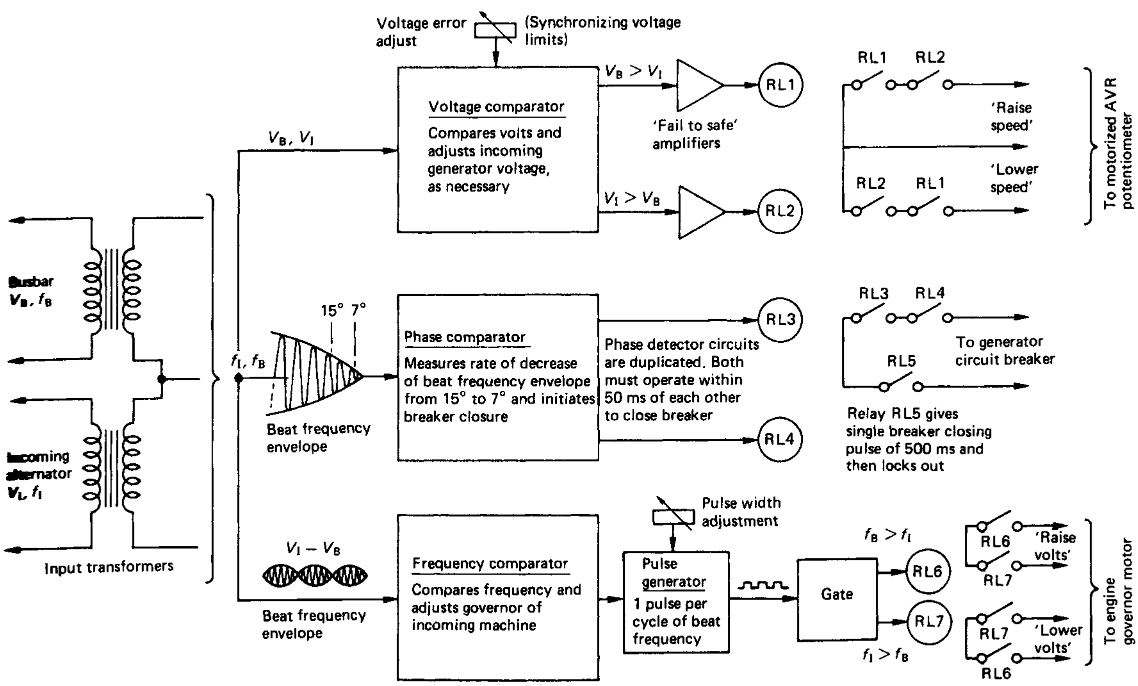



**Figure 8.40** Simplified block schematic for automatic synchronizer (Courtesy: Brush Electrical Machines Ltd)

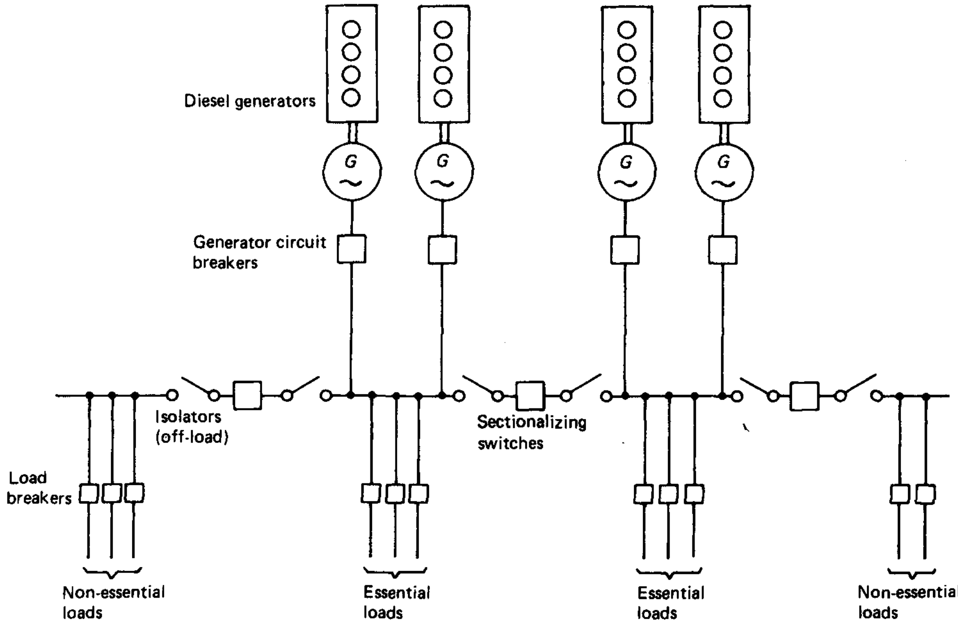



**Figure 8.41** Split busbar system configuration showing position of sectionalizing switches

be taken to ensure that feeder loads taken off different sections of the busbar are not paralleled elsewhere, e.g. at remote points in the distribution system.

## 8.11 Interconnection of generator neutrals

The output of generators is normally four-wire, i.e. the neutral point of the windings is brought out. (Three-wire systems are used if the load is entirely three-phase - which it seldom is, since most loads normally have elements of single-phase content.) An out-of-balance current results where there is practical difficulty in balancing the single-phase loads across all three phases. This out-of-balance current flows in the neutral conductor. Current will also flow in the neutral during an earth fault, if, as is common practice, the star point of a machine is connected to a neutral bar which, in turn, is earthed. The possibility also exists of large harmonie currents circulating in the interconnected neutrals when machines are paralleled. Careful consideration should therefore be given to the paralleling of neutrals in any system.

The flux distribution of salient pole generators, being approximately rectangular; can produce harmonies in output wave-forms. Even where care is taken to ensure a sinusoidal output, certain non-linear loads (such as rectifiers and iron-cored windings) give rise to harmonics in the current waveform. It is unusual for even harmonics to be present, but the *trip/en* harmonics (i.e. the third harmonic, and multiples of it) can cause problems, since these are in time-phase with the fundamental frequency. The total power supplied by complex voltage and current waveforms is the *sum* of the powers supplied by each harmonic component.

If the generator's windings are star connected, the line-line voltages (being the difference between successive phase voltages) will not contain third harmonics since these are the same in each phase. But, in a four-wire system fed by a single generator, the line-to-neutral voltages may contain a third harmonic component. If so, this gives rise to a harmonic current in the load and, if this load is balanced, the result is that the neutral conductor-carries three times the third harmonic line current. For a balanced load there will be no neutral currents at the fundamental frequency or at any harmonics other than the triplen. But, whether the load is balanced or not, there will be some third harmonic current in the neutral.

We established earlier in our discussions, that when two generators are paralleled, the e.m.f.s they generate (related to the local path around their connecting bus bars) are in phase opposition. If the wave-forms are purely sinusoidal and equal in magnitude, no circulating current will flow between the machines. If the wave-forms are not identical and one contains a third harmonic frequency, then. whilst the fundamentals may be in opposition, the third harmonic e.m.f. has no generated voltage of the same frequency to oppose it. The result of this inequality in third harmonic e.m.f. is a wattless circulating current in the local path (which consists of both stators and the busbar). This third harmonic current is limited only by the leakage reactance of the machines and can, therefore, be fairly large - possibly of the order of 60 % of one generator's full-load current. It is easy to see how stator overheating may result if currents of this magnitude, albeit divided between the three phases of the stator winding, are superimposed upon existing load currents.

The neutrals of generators of dissimilar construction and differing output and power factor ratings should, therefore, never be interconnected. Switchgear should be designed to cater for this and, in attended installations, particular care should be exercised by staff to ensure that only one machine's star point is connected to the neutral bar at any given time. If, as is normal practice, the neutral bar is earthed, it is equally important for the staff to ensure that system earthing is not interrupted when machines are taken out of service. On fully automatic or semi-automated installations the master logic for the neutral contactors should be designed to maintain system earth continuity while observing the requirement for only one running machine to be connected to the neutral busbar at any time. It is usual to select the largest running machine in the system for this duty. If the system contains an unbalanced load, the unbalanced fundamental frequency current will be carried by the generato,r with the earthed neutral. Due account should be taken of this fact when rating machines for the system.

With generators of identical type, operating at similar loads and power factors, there should be no unbalanced third harmonic e.m.f.s and no circulating harmonic currents. The neutrals of such machines may be connected in parallel, but it is always prudent to consult the manufacturer before so doing. The author knows of at least one installation where eight machines of identical type and rating have been operating satisfactorily with all their neutrals linked to a common bus. Bear in mind, however, that when an incoming machine is paralleled to like machines on the busbars, it will initially be on no load - while the others are loaded. Until load has been equalized between all the machines, harmonic currents could flow. The condition will only last for a few minutes but steps should be taken to ensure that protection devices do not operate on these harmonic currents.

Figure 8.42 shows the arrangement for neutral switching of parallel-running generators.

## 8.12 Electromechanical transients

As reciprocating machines, diesel engines have a non-uniform, or cyclic, driving torque. For simplicity of treatment, this may be considered as a sine wave superimposed on a constant mean torque. In its turn, this pulsating torque produces a cyclic variation of speed, and varying rotor angles - in other words, an *oscillation.* This can be minimized by increasing the speed and number of cylinders for a given output, and by using heavier flywheels to increase the combined inertia of engine and generator.

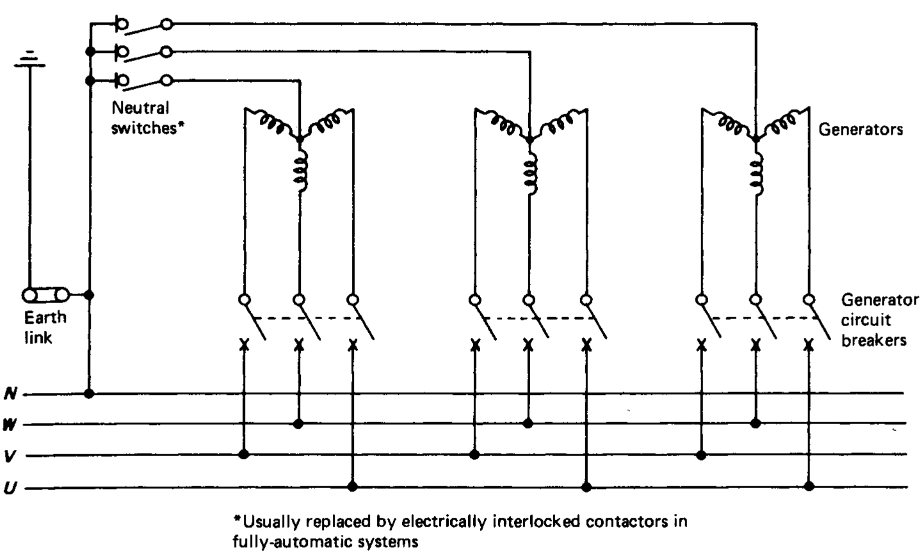



**figure** 8.42 Neutral switching for parallel-operating generators

### 8.12.1 Cyclic irregularity and angular deviation

The variation of speed about the mean speed over one engine cycle is expressed as a ratio called *cyclic irregularity* (C1).

cyclic irregularity = (maximum speed - minimum speed)/mean speed

It is usually written as a fraction, e.g. 1/150, 1/250, etc.

The maximum angle by which the rotor deviates from its mean position in either direction during one engine cycle is known as the *angular deviation.* It is expressed, in electrical degrees, as:

±28.6 [(cyclic irregularity) x (electrical frequency)] -:- (engine impulses per second)

It is the divergence for a single-running machine working on a dead load. The engine impulses per second are equivalent to the frequency of cyclic irregularity and depend upon the type of engine (i.e. whether it has a 2- or 4-stroke cycle), the number of cylinders, and the engine speed. They are calculated from the expression:

[2 (speed)(number of cylinders)] -:- [60 (strokes per engine impulse)]

so that, for a 12 cylinder, 4-stroke engine, running at 1000 rpm, the impulses per second would be:

[2 (1000)(12)] -:- [60 x 4] = 100

and, for an 8 cylinder, 2-stroke engine, at 900 rpm, they would be:

[2 (900)(8)] -:- [60 x 2] = 120

In engine-driven generators the fluctuating speed results in a corresponding voltage variation, which becomes noticeable when it is of sufficient amplitude to cause filament lamps to flicker. The permissible cyclic irregularity, as a function of the number of power impulses per second, is shown in the lamp flicker characteristics plotted in Figure 8.43 [11, 12] for individual generator operation. Unless the cyclic irregularity for a given engine's moment of inertia is within the flicker-free region, the inertia must be increased. Inertias required for flicker-free parallel operation will be greater than those reqired for flicker-free individual operation.

The maximum permissible values of cyclic irregularity were tabled in British Standard BSS 649:1958 (now replaced by British, European and International Standards - BSS5514:1977, DIN 627:1979, and ISO 3046) for all diesel engines driving d.c. generators or a.c. synchronous generators. It is the responsibility of the engine manufacturer to provide sufficient prime mover inertia to limit the cyclic irregularity to the values given in these standards.

A machine running in parallel with a large system is tied to the frequency of that system. Its stator

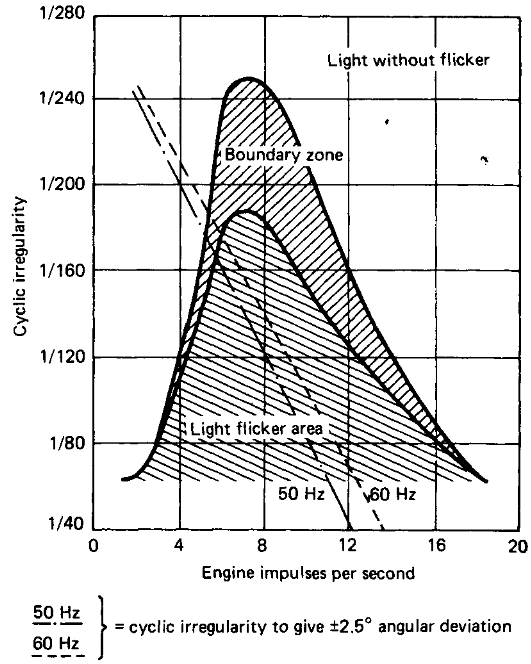



**Figure** 8.43 Cyclic irregularity as a function of frequency of power impulses, Showing light flicker and flicker-free areas

voltage phasor therefore rotates at a uniform angular velocity determined by that frequency. The rotor, on the other hand, has a non-uniform angular velocity (because of its cyclic irregularity) which means that the machine's *load angle* varies cyclically. The result is a cyclic variation of generator load about a mean level - variations being in phase with, and proportionate to, the angular displacement of the rotor. The maximum angular displacement (by definition, the *angular deviation)* will, therefore, have a corresponding value of power pulsation.

If one is to limit this power variation, it follows that the angular deviation must also be limited. The National and International Standards, cited above, place this limit at ±2.5 electrical degrees. This equates to a maximum power pulsation of approximately ± 15% full-load level on generators (typically) working at 20 degrees load angle at fun load.

The formula for angular deviation may be re-written to give the permissible cyclic irregularity (CI) for ±2.5 electrical degrees:

CI = [0.0875 (engines impulses per second)] -:- (electrical frequency)

We have seen that the cyclic irregularity for single running machines need only satisfy the requirements for flicker-free lighting. For parallel-running sets. however, there is the additional limitation imposed by the restraint on angular deviation.

Referring again to Figure 8.43, the straight-line characteristics indicate the cyclic irregularities corresponding to the ±2.5 degrees angular deviation limit for 50 and 60 Hz operation. It will be seen that for frequencies above 5 impulses per second, permissible cyclic irregularity is governed by the light flicker limitation and not by considerations of angular deviation. Most engines have a cyclic irregularity frequency well above 5 impulses per second, with corresponding angular deviations considerably below ±2.5 electrical degrees. Power pulsations are therefore so small that the effects of angular deviation are rarely, if ever, seen in the switchboard ammeters and wattmeters.

When a generator is being paralleled with one of *identical* design, its voltage will be in phase with that of the running set in as many angular positions of its rotor as there are numbers of pole pairs in the rotor. If, by pure chance, the angular displacements of both machines are exactly in phase at the moment of synchronism, their rotors will move backwards and forwards in angular unison about their mean position and there will be no power pulsation between the machines. They effectively function as one machine. Conversely, at the other extreme, if the machines synchronize at the instant when their angular displacements are completely out of phase, one will be at the maximum forward position of its oscillation, while the other is at its maximum backward position. The resulting power pulsation between the two machines will have the same magnitude as would one machine, when it is operating singly on an infinite system. Depending, then, upon conditions at synchronism, the power pulsation between the two machines could have any value between zero and maximum. At worst, the power pulsation of any generator can never be greater than that obtaining when it is connected to infinite busbars.

Irrespective of rotor relationships at the point of synchronism, two machines with unequal cyclic irregularity (e.g. different speeds and unequal numbers of cylinders) will have their angular displacements continuously moving in and out of phase, relative to each other. The maximum power pulsation between them will be that corresponding to the angular deviation of the smaller machine. The conclusion to be drawn from this discussion is that, regardless of the possible operational combinations, one needs only consider the power pulsations due to individual machines, when these machines are operating in parallel.

## 1.12.2 Cyclic disturbing torque

The phase relationships of the engine driving torque, acceleration, speed, and rotor angular displacement are shown in Figure 8.44, in which the vertical scales are much magnified. We have established (in Section 8.5) that when a generator is running in parallel with other machines, any angular displacement of its rotor gives rise to a proportional synchronizing torque. The phase relationship of this torque, referred to the 'displacement' characteristic (above it), is shown in the last curve of Figure 8.44. It is also in phase with the engine's driving torque, so that the sum of both torques acts on the engine-generator rotating masses. This increases the angular displacement, which further increases the synchronizing torque, which, in turn, increases the displacement - and so on.

The effect of the synchronizing torque is then analagous to the engine being connected to its load through a torsion spring. The combination of this spring action and the rotating masses results in a

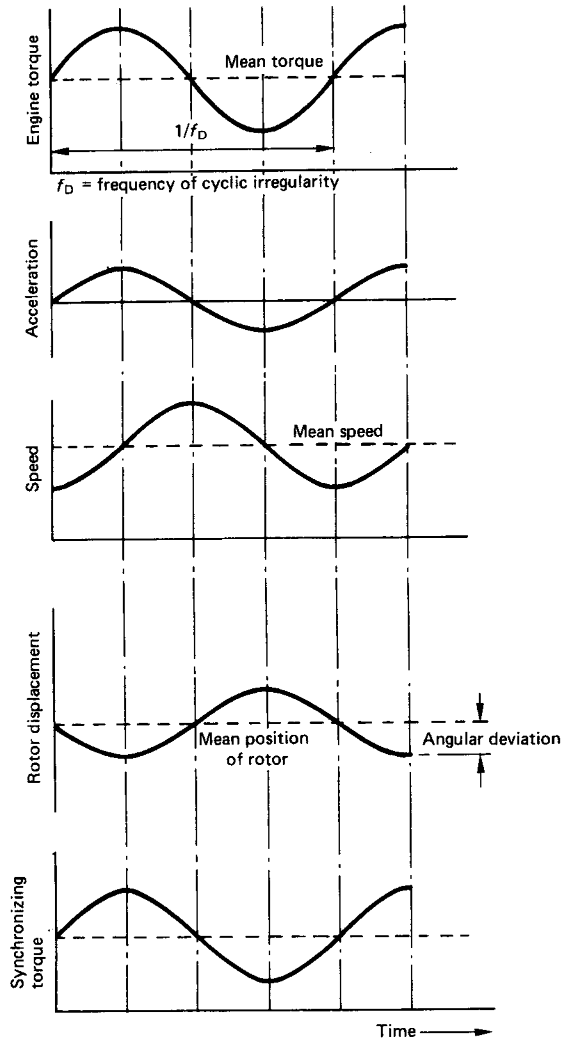



Figure 8.44 Generator displacement curves for cyclic driving torque

system capable of oscillation at some *natural frequency*.

The oscillation could continue for some time after a forcing disturbance, before being attenuated. The continuous oscillation is known as *hunting* (or *phase swinging*). An engine-generator system may be said to be *underdamped* if it merely relies on the torsion spring action of the synchronizing torque and the inertia of the rotating masses. Some additional form of damping is therefore essential in the design of diesel engine driven generators - particularly when the machines run in parallel with others.

The natural frequency of oscillation of an engine-generator running on an infinite busbar may be expressed, in electrical terms, as:

$$\text{Natural frequency, } f_o = (1/2\pi) \times [\sqrt{(T_s/J)}]$$

Where $Ts$ = the synchronizing torque coefficient (in Nm/mech. radian)

J = the moment of inertia of the rotating masses (in kg/m$^2$)

An alternative expression for the natural frequency is:

$$f_o = 3220\sqrt{\ }[(P_s\, p)/(nWR^2] \text{ in cycles per minute}$$

Where $Ps$ = the synchronizing power per radian (kw/elec radian)

$p$ = the number of generator poles

$n$ = synchronous speed (rpm)

$WR^2$ = the moment of inertia of the rotating masses (lb/ft$^2$)

Note: if $GD^2$ (kg/m$^2$) is used, the appropriate conversion is:

$WR^2$ (lb/ft$^2$) = 5.925 $GD^2$

Figure 8.45 shows the effect of *underdamping, overdamping,* and *critical damping,* when a steady-state load torque is suddenly increased. Critical damping occurs when the damping produces a *dead beat,* or *optimum damping.* A measure of the amount of damping (the *damping ratio,* D) is represented as a percentage of critical damping, i.e. as the ratio of the actual damping present to that required for critical damping (Co),

If the damping of the rotating system is small and the frequency of a disturbing force (td) approaches the natural frequency of oscillation *(to),* the rotor displacement may increase sufficiently to pull the generator out of step. The ratio of the maximum amplitudes of rotor displacement, in the parallel to the single running modes, is given by:

$$\frac{\text{amplitude after paralleling}}{\text{amplitude before paralleling}} = 1/[(f_d/f_o)^2 - 1]$$

$$= 1/(K^2 - 1)$$

where $K$ = forcing frequency/natural frequency.

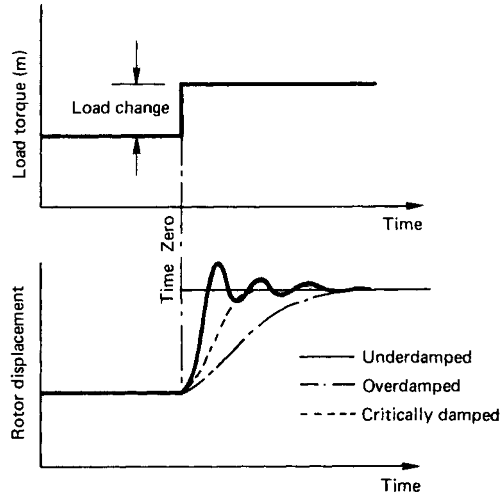



Figure 8.45 Response diagram illustrating rotor damping after a load step change

Clearly, the ratio will have an infinite value when $K$ is unity. This condition (at coincidence of forciD& and natural frequencies) is the *resonant point* of the rotating system and is shown, in Figure 8.46, as the 'theoretical curve with no damping'. The family of curves plotted in Figure 8.46, shows the influence of damping on the amplitude ratio.

When two dissimilar generators are paralleled, it may be shown that the expression for the natural frequency of load exchange between them, is:

$$f_{o_{1-2}} = 3220\sqrt{\left[\frac{P_{s_1}\, p_1}{n_1 . WR_1^2} \times \frac{1 + \left(\dfrac{WR_1^2}{WR_2^2}\right)}{1 + \left[\dfrac{P_{s1}}{P_{s2}} \times \left(\dfrac{p_1}{p_2}\right)^2\right]}\right]}$$

and $t0$ is in cycles per minute.

If a number of machines are to be paralleled, it i possible, using the above expression, to determia the natural frequencies of all combinations of pail in the system. For example, machine 1 with macm. 2, machine 2 with machine 3, and machine 1 will machine 3, in a 3-machine installation. But sud complication is not really necessary when it is ral ized that, in a multi-generator system, the nat\ml frequency of any possible combination of pairs wi always lie between the highest and lowest calculata values of the natural frequency of individual units ~ the system. Each machine may be considered as i single unit operating on an infinite busbar •• values of $fo$ may be computed using the expressd given earlier.

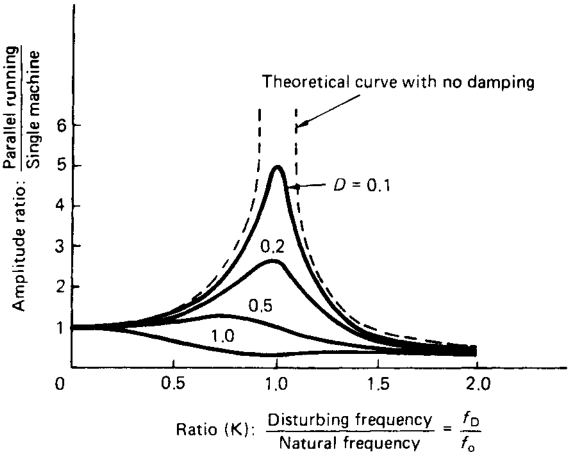



**Figure** 8.46 Resonance curve showing the influence of the damping ratio *(0)*

The conclusion to be drawn from this discussion is that, since the disturbing or forcing frequencies cannot, generally, be controlled, it is important to ensure, by judicious choice of inertia, that the natural frequencies are kept well below the lowest forcing frequency likely to occur. The natural frequencies of all the sets in a paralleled system are usually limited to a maximum of 80 % of the lowest forced engine frequencies present in the installation. It is important to ensure that these natural frequencies do not approach the natural frequencies of the engine governing systems. The effect that dynamic governing characteristics may have on parallel operation is summarized by Brodin [13], as follows:

> Good parallel operation can be obtained if the diesel engine governor has a high undamped resonant frequency (2.5-5 times the resonant frequency for the set when running in parallel with an infinitely rigid network), and a small damping ratio. If the governor has a low resonant frequency, a satisfactory parallel operation can only be obtained if the alternator is equipped with an effective damping winding; and if the governor damping ratio is large.

Disturbing forces may come from:

- sudden changes of load;
- recurring variations in driving torque (e.g. a misfiring cylinder);
- an unstable auxiliary control, such as an automatic voltage regulator;
- governor hunting or fuel supply problems;
- cyclic irregularity of other parallel running machines; and
- faults, or even switching operations, in the system supplied by the generators.

It is worth noting here that the time lag in an AVR has the effect of negative resistance in the damping mechanism and an unfortunate combination of AVR time constant and resonant frequency can cause trouble (C.J. Yarrow, 1983, personal communication).

Finally, it should be realized that disturbing forces may have a number of harmonics and anyone of them could coincide with the natural frequency to give resonance. The lower order harmonics demand particular attention in this respect.

### 8.12.3 Damper windings

Modern engine-driven generators usually incorporate some form of *damping windings* (or *amortisseur windings)* in their design to obviate the need for heavy and costly engine flywheels to give increased inertia. These windings usually take the form of copper or aluminium conductor bars embedded in slots or holes in laminated rotor pole-shoes. The bars are then brazed or welded to rings at their ends, as in the cage windings of an induction motor. This form of construction is known as a *closed damper winding.* Machines without these end rings have *open damper windings* - a far less effective form of damping.

When the rotor is running without oscillation the bars are rotating in synchronism with the stator field. During oscillation the relative motion of bars and magnetic field induces a voltage in the bars. This produces a current, resulting in a force opposing the oscillation and damping it. This current, because of the resistance of the bars, dissipates the energy absorbed from the oscillation in the form of heat.

Cylindrical or round rotor machines usually rely on the eddy current induced in a solid rotor to provide a considerable damping effect - although, additional cage windings are occasionally provided. In solid-pole salient machines total reliance is often placed upon the damping effect of the eddy currents near the pole surfaces.

Brodin [13] lists the relative merits of various forms of electrical damping and compares damping coefficients in per unit (p. u.) terms. The higher the constant, the more effective the damping.

| *Machine* | *D per unit* |
|---|---|
| with laminated poles and without damper winding | Less than 1 |
| with solid poles | 5-10 |
| with open damper winding | 5-20 |
| with closed damper winding | 20--70 |

Thus it will be seen that the damping constant for a generator with solid poles can be increased four to sevenfold if the same machine were fitted with laminated poles and a closed damper winding. Increasing the cross-section of the conductor bars in the cage winding improves the damping coefficient.

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# 9

# Switchgear and controlgear

**Contents**

## 9.1 Introduction

*Switchgear* may be defined as 'apparatus for controlling the distribution of electric energy or for controlling or protecting apparatus connected to a supply 01 electricity' [1]; and a *switchboard* as an assembly 01 such switchgear. It may include devices such as circuit breakers, switches, protective relays, instrumentation, metering, and the equipment for the control of these devices and of any electrical machines and prime movers in the installation.

The purpose of this chapter is to outline the principles affecting the choice, design, and application of switchgear and controlgear associated with diesel-generator installations. Examples of proprietary types are used to illustrate the design and operational features of the more important devices.

The concluding sections list and briefly outline the scope of those National and International Standards which govern the characteristics and performance of switchgear and controlgear apparatus and assemblies.

## 9.2 Planning

Among the factors affecting the choice and design of switchgear will be:

1. the size and characteristics of initial and future loads;
2. in-service conditions;
3. economics;
4. the requirements for reliability and security of supply; and
5. the requirements for maintenance and safety.

We shall now briefly discuss each of these criteria.

### 9.2.1 Load considerations

The plant designer should establish initial system capacity and the provisions to be made for future growth. The extent of the installation will be determined by the number of circuits for incoming and outgoing power. Generating plant will already have been sized against the known dynamic characteristics of the connected loads. The elements that should be considered in these computations have been discussed in Chapter 5 of this handbook.

The prudence of planning for future expansion was also emphasized in those discussions. The size of future loads is all too often underestimated. Liberal provision of surplus capacity in the first instance has much merit. Equipment cost is not directly proportional to capacity. Replacement of equipment with that of larger capacity at some future date can be expensive. Also, it is difficult to dispose of or sell the removed equipment. Often, the operation of partially loaded equipment provides better reliability and gives extended service life [2].

### 9.2.2 In-service conditions

These relate to those environmental aspects of the installation that affect not only choice of components but also enclosure design. They would include unusual space limitations and ambient conditions, such as temperature, humidity, altitude, the presence of any contaminants, excessive vibration and shock, restricted ventilation, etc.

Compliance may be required with local regulations and codes. For example, the provisions of the National Electrical Code (ANSUNFPA 70-1987) relating to the minimum access and working clearances to be provided around electrical equipment would be mandatory for those installations required to conform with American practice.

### 9.2.3 Economics

Effort should be made to use standard factory-built assemblies of switchgear and controlgear, and avoid 'specials'. Foreknowledge of the equipment available in the market is essential if competitive bids are to be sought. Custom-built equipment is not justified when standard and competitive units may be readily adapted. Besides reducing initial cost, standardization will minimize the cost of future system expansion programmes and improve one's chances of selling those units that are replaced at a future date.

### 9.2.4 Reliability and security of supply

The degree of reliability and security required influences the choice of busbar system (see Section 9.3). Plans may include for the provision of spare equipment or for automatic transfer to emergency power sources (using arrangements such as those discussed in Chapter 11 of this handbook). Circuit redundancy may have to be considered in high-security installations to allow for equipment maintenance.

### 9.2.5 Maintenance and safety

Overall design will be influenced by the requirement for a well-planned preventive maintenance programme. Selection of equipment must be made with the need for safe and easy access for inspection and repair very much in mind. Although the reliability of modern proprietary equipment is high, this reliability is only achieved by implementing routine maintenance programmes. The system that cannot be maintained because of a need for supply continuity is badly designed.

Far more can be accomplished by the proper selection of circuit arrangements than by economizing on equipment details. The use of inferior apparatus in making cost reductions is never justified if it is at the expense of safety and performance [3]. The safety of operating and maintenance personnel should be the most important consideration in the design of the system. Established national safety codes must be followed in the selection of equipment and components. Where removable circuit breakers are to be used, mechanical interlocks are essential to ensure a proper and safe operating sequence. For fixed breakers, particularly where any possibility of feedback exists, it may be necessary to include double isolation switching, key-interlocking, or mechanicaVelectrical interlocking. It must also be possible to isolate generators, transformers, and sections of busbar, for inspection and maintenance purposes. Earthing arrangements will also be necessary for H.V. equipment during maintenance operations.

The legal requirements of the Electricity at Work Regulations 1989 must be met in the United Kingdom. Switchgear designers and users should be aware of the precautions to be taken against the risk of death or personal injury from electricity in apparatus and systems. The *Memorandum of Guidance* on the 1989 Regulations is available from HMSO Bookshops and Publication Centres, accredited agents, and through good booksellers.

## 9.3 Busbar Systems

The criteria influencing the choice of busbar system are:

1. the degree of supply security required;
2. the degree of operational flexibility required;
3. the importance of the installation; and
4. capital cost.

A major generating plant may justify the use of an elaborate busbar system. A shutdown may result in unacceptable outages to key consumers, and a system that enables reconnection in the shortest possible time is essential. On the other hand, on those installations where the nature of loads permits short interruptions the simple single-busbar system may be used. One example would be a factory where no night shift or weekend working applies. Maintenance may then be undertaken during shutdown periods. First cost is often a primary consideration in such cases, where the elaborations justifiable on a major plant are not warranted [4].

No hard and fast rules apply. The merits and disadvantages of the following basic alternatives must be considered for individual installations. Combinations are possible and may be necessary in certain circumstances, for example, where loads sensitive to voltage and frequency variations must be separated from those parts of the network likely to cause such disturbances (see Chapter 11).

### 9.3.1 The single-busbar system

This is the simplest of busbar arrangements and uses a single set of bars which run the length of the switchboard. All parallel-running generators and feeder circuits are connected to it. It is a system that is usually applied to small power stations, and is one that is preferred on shipboard installations since it offers maximum stability with the minimum of operating staff [5]. As shown in Figure 9.1, feeders and generators are normally connected alternately to the bars in order to reduce the busbar cross-sectional area [6].

The disadvantages of the system are:

1. it does not give maximum security of supply - a fault at the busbars results in a total loss of supply;
2. busbar cleaning and maintenance can only be undertaken when the plant is shut down;
3. under fault conditions, all the elements of the power system feed into the fault - these elements include not only the generators but also all running motors in the plant;
4. when plant installed capacity is increased, circuit breakers of higher interrupting capacity will be required.

Factors 3 and 4 place practical limitations on the size of installation that can use continuous busbars. Gray [5] suggests that where motor loads are 50 % of the installed generator capacity and where breakers of 100 kA interrupting capacity are used, 6 MW is the maximum practical rating for single busbar 440 V a.c. shipboard systems. He also assumes that the generators will contribute less than 10 times f.l.c. to a fault condition. Above 6MW, therefore, it is necessary to either employ sectionalized (or split busbar) systems, or to raise the voltage level **of**

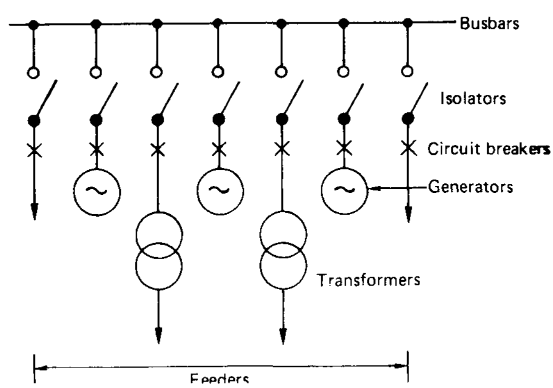



**Figure 9.1** Single-busbar system

generation. Where non-drawout pattern breakers are used, it is good practice to include isolators in series with the breakers. Double isolation is particularly necessary on those circuits feeding transformers that may be parallelled, however indirectly, on their L.V. side (e.g. within the L.V. distribution network [4]).

By definition, *isolation* implies the cutting-off of an item of equipment (in this case the series circuit breaker) from every source of electrical energy. In their simplest and most economical form, *isolators* are merely disconnecting devices having no interrupting rating, and are designed for operation under no-current or negligible current conditions. Switches of this type therefore need to be interlocked with their in-series breakers in order to prevent operation when they are carrying current. *Isolating switches* or *load interrupters,* on the other hand, are capable of breaking current up to and including their rated current at rated voltage. They usually have stored-energy mechanisms of the quick-make, quick-break type, which are independent of the speed of handle operation. They may also have a close and latch rating to provide maximum safety should they be closed onto a faulted circuit. The purpose of the latching is to prevent the switch opening under the magnetic forces which result from heavy fault currents [3].

In American practice, particularly, use is made of *bolted pressure contact* safety switches. They consist of movable blades and stationary contacts (fitted with arcing contacts or flicker blades) and a simple toggle mechanism for applying pressure to both binge and jaw contacts - in a similar manner to a bolted busbar connection. Quick-make and quick-break action is provided by a spring which is compressed by the operating handle and released at the end of the operating stroke. Opening and closing speed is, therefore, independent of the operator. Electrically operated versions (using a motor-driven linear actuator to charge the spring) are also available.

### 9.3.2 The sectionalized single-busbar system

The split or secti'onalized busbar system of Figure 9.2 offers the following advantages over the single solid bus scheme described above:

1. greater security of supply, since a fault at one of the bus sections does not result in total loss of power;
2. one section (or more, in the case of multi-section configurations) may be shut down under fault conditions, or for maintenance and repair, without interrupting the services supplied from the other section(s);
3. in shipboard applications, maximum security of supply may be obtained by locating the separate

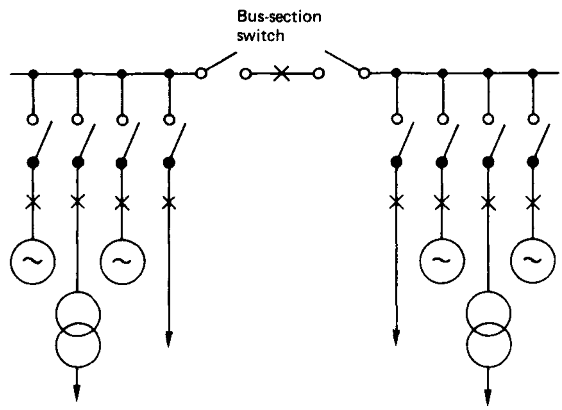



**Figure 9.2** Sectionalized single-busbar system

sections in different compartments so as to protect the ship's electrical system from collision damage or fire in one compartment [5];
4. when the sections are electrically segregated in normal operation, breakers of lower interrupting capacity may be employed, because of the reduction in fault level.

The split system has certain disadvantages. These include:

1. the need to ensure that feeders to duplicate or standby equipment is connected to different sections. Care must be taken that such feeders are not paralleled at a remote point in the system. Sectionalizing may, therefore, also be necessary at the remote point. [4, 5];
2. the requirement. for more operational discipline from switchboard attendants. For example:
   - when sections are *coupled* they must be synchronized;
   - if the sectionalizing switch is an isolator it must only be switched when it is carrying no load and, therefore, all incoming and outgoing feeders on *one of the sections* must be switched off. (The isolator should be suitably interlocked, so that it may only be operated under no-load conditions.) The more appropriate device is a circuit breaker which will allow the sections to be coupled and uncoupled at will without interruption of supply. Note, the breaker's current rating should be as high as or higher than any other switch on the board. It should be provided with double isolation (as shown in Figure 9.2) so that it may be completely isolated from adjacent sections [4].

### 9.3.3 Sectionalized ring-busbar system

This is a logical adaptation of the split bus scheme, in that the 'open' ends of a multi-section busbar are joined together to form a ring (see Figure 9.3).

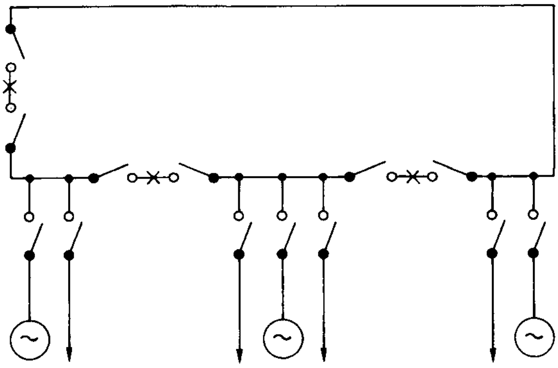


**Figure 9.3** Sectionalized ring-busbar system

Although the total busbar length is increased, it allows the generator on a section to supply the feeders on any adjacent section [4]. The overall length of the switchboard may be reduced by arranging the switch compartments in a double tier configuration. It should be appreciated that in all sectionalized schemes the incoming and outgoing circuits must be so distributed between the sections that the power input to each equals the demand from it, i.e. generation and demand should be balanced on each section.

## 9.3.4 Duplicate busbar system

The provision of reserve feeds to permit temporary shutdown of plant for routine inspection and maintenance becomes more difficult the greater the power handled. Where continuous supply is essential it is, therefore, necessary to introduce a second busbar. Its additional cost is usually far outweighed by the advantages given in operation and maintenance. As shown in Figure 9.4, one set of bars is designated as the *main* and the other as the *reserve* busbar. This arrangement allows work to be carried out on one set of bars while supply is maintained. It also enables supplies to be quickly restored in case of trouble. Another advantage is that it allows tests to be made on new or serviced plant without interrupting services from the main bars.

In the scheme shown in Figure 9.4(a) the feeder circuit is connected to either busbar by means of off-load selectors which may take the form of conventional isolating switches in cubicle type gear. On metal-clad switchgear the selection may be made by means of breaker position transfer. The bus coupler switch is used to parallel the two busbars before the selector switches are operated or breaker transfer is made.

For metal clad gear and plug-in breakers a duplicate breaker system would have a cable box on each unit, but paired units would have cable boxes linked for the one outgoing or incoming cable connection.

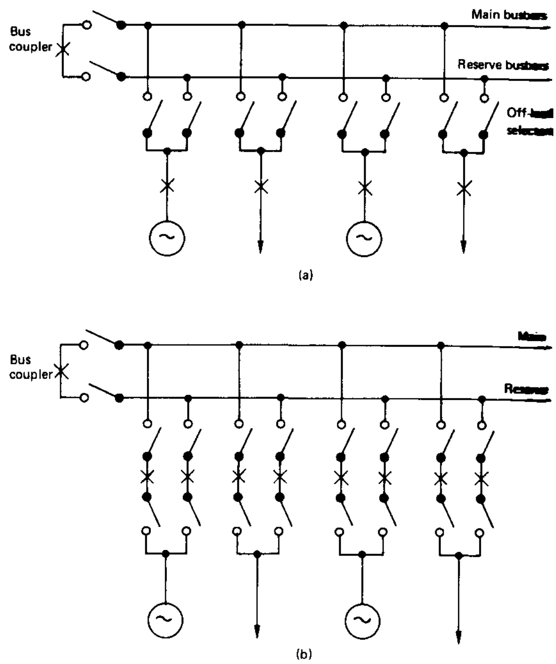



Figure 9.4 Duplicate busbar system

Duplicate breakers (and series isolators) for eadi circuit are used in a variant of this scheme (Figun: 9.4(b» to give the best facility for circuit breaka maintenance and to provide uninterrupted suppIJ during changeover from main to reserve busbars- and vice versa. Its cost restricts application to oolJ the very largest installations.

## 9.3.5 Sectionalized duplicate busbar system

As with all 'solid bus' systems, care should be takCli in the scheme just described to ensure that tile: switchgear is rated for the increased short-circuil capacity resulting from all incoming power circuill being switched to one busbar. This may be avoidell by splitting the busbar into sections, in each of whida the power input and demand is balanced (see Figune 9.5). The prospective short-circuit power in eadI section must be less than the interrupting capacity 01 any breaker which may be connected to that bar- except a coupling breaker, which could only see iIs own contribution or the contribution from othlCl' in-feeds to the bars.

It is not essential to sectionalize the resene busbar, and busbar couplers may be fitted to eadI section. Both options are shown in dotted lines • Figure 9.5.

Many other configurations are possible, inclu~ multiple schemes using three or more busbars. Tbcy mainly relate to very large power systems •••• descriptions are outside our scope. It must be ~

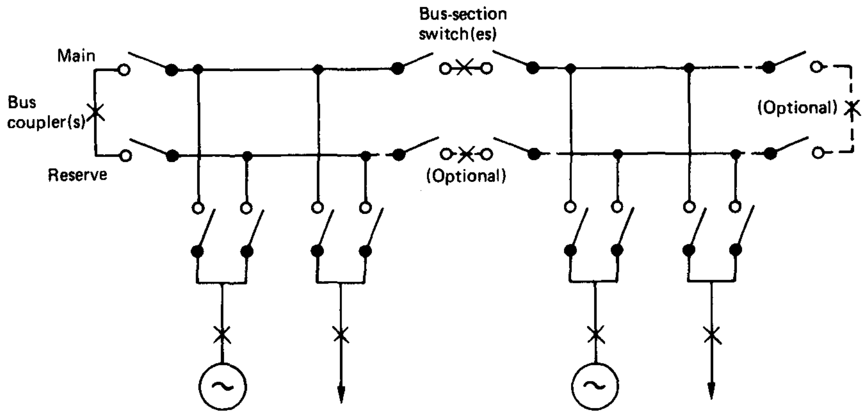



**Figure 9.5** A sectionalized duplicate busbar system

tioned that on some stations, of the size we are considering there will be a need to provide a high security supply for station auxiliaries. Some of the methods employed to provide a supply to the auxiliary busbars include:

- small house-generators;
- alternative sources of supply from different bus sections using flexible changeover switching arrangements; and
- the direct connection of station transformers to the terminals of different generators.

Where transformers are not used, it may be necessary to include series reactors, fuse-type devices such as *Is* limiters, or short-circuit limiting couplings (SLCs - resonant link devices) to limit the prospective fault current at the auxiliary switchgear [7].

## 9.4 Busbars

The two major materials used for bus bars are copper and aluminium. Because of its greater strength, high-conductivity hard-drawn copper is universally preferred to the cold rolled types. The choice in aluminium lies between electrical conductor grade (so-called pure grade) material and an alloy containing approximately 0.5 % each of silicon and magnesium. Annealed or hard-drawn forms may be used.

For the same current rating, aluminium is lighter than copper and less costly. However, because of its lower conductivity (62 % of that of copper), an aluminium conductor requires a larger cross-section to carry the same amount of current. This increased size makes the aluminium busbar less attractive to the manufacturer of metal-enclosed and metal-clad switchgear, more so because the controlling factor in determining the size of busbars is often that of mechanical strength - more material being required than would be necessary for current rating alone. In effect, copper gives higher conductivity than aluminium for a given switchgear enclosure area.

In terms of current-transfer requirements, the most satisfactory joint for aluminium bars is the welded joint. When exposed to atmosphere a hard oxide film quickly forms on aluminium. This film acts as an insulant, and it is necessary to electroplate the contact surfaces (with tin or silver) before an effective mechanical joint can be made. Clamped joints using non-magnetic materials are successfully employed but they contribute to the 'space problem'.

Effective aluminium-to-copper joints are required in switchboard installations because most circuit-breaker terminals which must be connected to the busbars are made of copper [8]. Copper-clad aluminium bars (where the copper is molecularly bonded to the aluminium) are used to overcome the jointing and copper-interfacing problems. Although cheaper than copper for the same current rating, they have lower conductivity and, therefore, require more area in a busbar arrangement.

### 9.4.1 Factors affecting busbar design

*Rating*

The current carrying capacity of busbars is determined by the material's conductivity and the operating temperature. In the air insulated busbar arrangements with which we are concerned, heat is dissipated from the bars in varying degrees by:

- convection;
- radiation; and
- conduction.

Because bars are supported on insulating materials the amount of heat conducted away is small indeed. It is even smaller where bars are 'sleeved' in thick insulation.

Convection and radiation account for dissipation of most of the heat generated. Efficiency of heat transfer to the surrounding air depends very much upon the shape and size of conductors and the temperature difference between them and the surrounding air. Optimum convection cooling of a rectangular bar is achieved when. it is mounted edgewise (i.e. with its major cross-sectional axis vertical). As much as 18% more heat can be dissipated by a bar mounted in this way than when it is mounted horizontally. This equates to a 9% increase in current-carrying capacity.

Painting the bars (with dull or flat paints) or wrapping/sleeving them with *moderate* thicknesses of insulation can improve their heat-dissipation qualities through surface radiation [9]. Current-carrying capacity has been known to increase by as much as 25%, without an increase in temperature rIse.

Where busbars are laminated (i.e. a number of rectangular bars are used in parallel) their current carrying capacity is reduced. This is partly due to the reduced loss of heat by convection, and partly due to the screening of the inner conductors - which decreases dissipation of heat by radiation. The maximum capacity of a laminated bar is obtained when the laminations are mounted on edge with as wide a space as possible between them [9]. It is the usual practice to make the spacing equal to the thickness of the laminations. This simplifies interleaved joints and connections (see Figure 9.6).

In a.c. application, phenomena known as *skin* and *proximity effects* cause the current carried by laminated formations to be concentrated in the outer bars. The two 'effects' combine in edge-mounted bar assem.blies to s.ubject the outer conductors to greater temperature rises than the inner bars. This, despite the lower dissipation of heat from the surfaces of the inner bars. As the number of laminated bars is increased the proportion of current carried by those in the centre of the formation rapidly reduces until a point is reached where any additional bars give no appreciable increase in current-carrying capacity. The cut-off number is eight laminations. In practice, not more than five can be justified [8]. Single-bar a.c. ratings need to be multiplied by one of the factors given in Table 9.1 to obtain the current rating of multiple copper and pure aluminium bar arrangements [4].

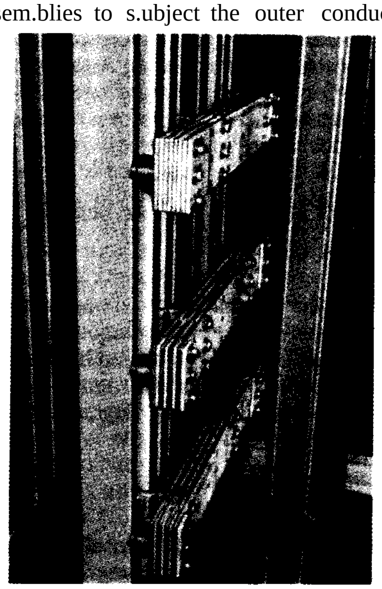


**Figure 9.6** Laminated bars in an edge-to-edge arrangement (Courtesy: Westinghouse Electric Corporation)

**Table** 9.1 Multiplying factors for a.c. copper and aluminium bars

| *Total area of cross-section* ($mm^2$) | *Multiplying factors* | | | | | |
|---|---|---|---|---|---|---|
| | *2 bars* | | *3 bars* | | *4 bars* | |
| | *Cu* | *Al* | *Cu* | *Al* | *Cu* | *Al* |
| 500 | 1.78 | 1.72 | 2.45 | 2.37 | 3.13 | 2.88 |
| 1000 | 1.72 | 1.69 | 2.36 | 2.21 | 3.00 | 2.52 |
| 1500 | 1.65 | – | 2.24 | – | 2.84 | – |
| 1600 | – | 1.71 | – | 2.24 | – | 2.54 |
| 2000 | 1.60 | 1.70 | 2.16 | 2.20 | 2.70 | – |
| 2500 | 1.55 | 1.70 | 2.10 | – | 2.60 | – |
| 2560 | – | 1.70 | – | 2.20 | – | – |
| 3000 | 1.52 | – | 2.02 | – | 2.52 | – |
| 3200 | – | 1.70 | – | – | – | – |
| 3500 | 1.48 | – | 1.98 | – | 2.48 | – |
| 4000 | 1.44 | 1.59 | 1.96 | – | 2.45 | – |

The influence of the skin and proximity effects on a.c. ratings may be illustrated by the fact that the a.c. capacity of a copper four-bar lamination of 2500 $mm^2$ total cross-sectional area is about 70% of its d.c. rating. Because of the skin effect the current-carrying capacity of laminated bars is severely limited.

## *Short-circuit effects*

The busbars must have the ability to withstand the thermal and mechanical stresses imposed on them by prospective fault currents in the power system (see Section 9.5). Their momentary and short-time current ratings should correspond to the equivalent ratings of the switching devices connected to them.

In Section 4.3 of Chapter 4 we examined the transient conditions that apply when a generator is subjected to a sudden short-circuit. Of the several types of fault considered (balanced 3-phase, and unbalanced line-to-line and line-to-earth), we concluded that the 3-phase *bolted fault* condition generally gives the maximum short-circuit current values, and is therefore the one on which power system fault calculations should be based. *(Note:* a bolted fault implies zero impedance between the phase conductors and is equivalent to the conductors bting bolted together; hence the term.)

Power system faults often involve arcing. The values of arcing-fault current may approach those due to a bolted fault at the same location. Usually, because of the limiting effect of the impedance of the arc itself, medium-voltage fault currents are appreciably less than those for bolted fault conditions. For example, the per unit value of a 440V 3-phase arcing fault (referred to the bolted fault level) would be about 0.85. Therefore, calculations based on bolted fault currents cover worst-case conditions and will provide an adequate safety margm.

Reverting to the stress-inducing effects that momentary and short-duration fault currents have on busbars, we shall now consider each in turn.

*Thermal stress.* This is directly related to the square of the r.m.s. value of the fault current and to its duration. In practical case studies it is usual to ignore asymmetry in fault currents. The period for which the current flows is determined by the break time of the circuit protective device (breaker or fuse). It is so brief that one must neglect all possibility of heat dissipation by convection or radiation. The heat generated is, therefore, entirely absorbed by the conductors, and their temperature rise is governed only by their specific heat and weight.

The following formula [4] enables the temperature rise per second to be determined. An intelligent estimate may have to be made of the conductor's temperature at the instant of fault.

$$T = k(I/A)^2\,[1 + \alpha\theta] \times 10^{-2}$$

where $T$ = temperature rise per second (0C)
$I$ = current, r.m.s. symmetrical (amperes)
$A$ = cross-sectional area of conductor ($mm^2$)
ex = temperature coefficient of resistivity at 20°C/oC
= 0.00393 for copper
= 0.00386 for aluminium
= 0.0036 for aluminium alloy
e = temperature of the conductor at the instant at which the temperature rise is being obtained CC)
$k$ = a constant: 0.52 for copper, and 1.166 for aluminium

Final-temperature limits (initial temperature + temperature rise over the duration of the fault current) are a matter of judgement, but the general consensus is 200°C for bare copper and 180°C for bare aluminium.

Conductors will expand or contract with variations in temperature. For example, the expansion of a 6 m length of copper conductor on a temperature rise of 100°C under fault conditions, is about 8 mm.

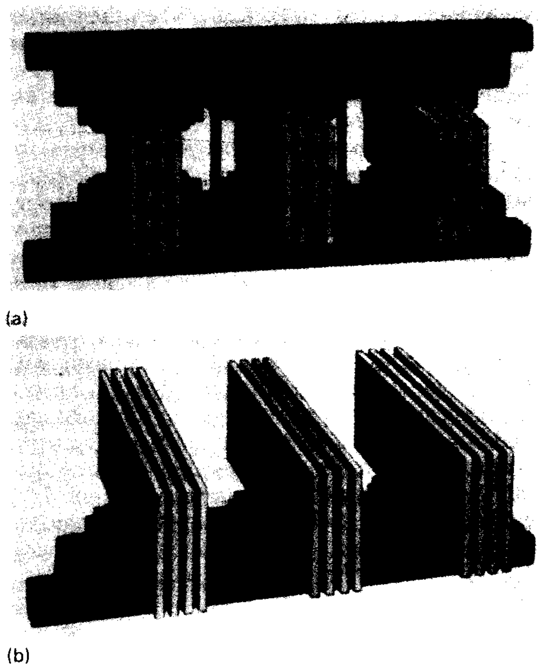



Figure 9.7 An example of an adjustable insulated busbar support (a) With top and bottom slide rails and slideable clips (b) Without top rail (Courtesy: Brush Switchgear Lld)

Clamps of the type shown in Figure 9.7, which allow movement of the bars in a longitudinal direction, are ideal for heavy current bars.

Laminated expansion joints made up of numbers of thin strips of conductor material of the same width as the busbars and bent in a U- or S-form are used on those switchboards which incorporate long straight runs of bar. An alternatiye type is one which uses a braided conductor(s). Expansion joints are particularly recommended for connecting the 'rigid' terminals of switchgear apparatus to heavy busbars. The joints must, of course, have the same current-carrying capacity as the bus bars or terminals to which they are connected.

*Electromagnetic stresses.* Current -carrying conductors in a magnetic field are subjected to forces which tend to deform the circuit in such a way as to increase the number of magnetic lines of force enclosed. When the currents flowing in two adjacent conductors are in the same direction the force between them is one of attraction (the *pinch* effect), but when the currents are in opposition it is repulsive (the *loop* effect).

This mechanical force depends upon the magnitude of the current and the geometrical configuration of the conductors, i.e. their shape and their relative spacing. In the case of parallel busbars, it is uniformly distributed along their length At the extreme ends of the bars, the force actually tails off due to the so-called 'end effect'. When the ratio of the length of the bars to their spacing is larger than about 20, this end effect may be ignored. The maximum forces near the middle of the bars are used in design calculations.

It can be shown that, in three-phase busbars, the maximum force is that produced by a two-phase short circuit (line-to-line); and busbar designs should, therefore, be based on the stresses set up in this condition. In practice, two-phase shorts are more likely to occur than those involving all three phases.

The maximum force on the bars, and their associated structures and insulators, will coincide with the instantaneous maximum peak value of the short-circuit current. It is prudent to cater for worst-case conditions, and assume that the short-circuit current wave-form will be completely asymmetrical; so that, with the 'doubling effect' (explained in Section 4.3.1 of Chapter 4) the peak current could be as much as twice the r.m.s. symmetrical value. Due allowance is made for this in the numerical terms of the force equation [4] given below.

$$F_m = \frac{16 \times I^2 \times K \times 10^{-4}}{S} \ N/m$$

where $F_m$ = maximum force under conditions of asymmetry
$I$ = r.m.s. current (amperes)
$K$ = a shape factor for rectangular bars (see Figure 9.8) ($K$ = 1 for circular conductors)
S = spacing between conductor centres (mm)

Because the period of application of this *peak* force is very short (within the first half-cycle after the fault), the slight flexibility always inherent in bars and support structures will cushion some portion of it. It should be appreciated that, although it is unidirectional, the force pulsates betweed zero and its peak value. It 'alternates' initially at supply frequency but, when the current wave-form becomes symmetrical, its frequency is doubled. This fact should be taken into account when designing busbar structures, to avoid the possibility of partial resonance occurring in the system. It is unlikely that any serious vibrational stresses will coincide with the initial peak value of the short-circuit current. In practice, it is found that if bars and structures are strong enough to withstand the peak force due to the maximum value of asymmetrical current, they will cope with any stresses due to vibration [9].

Where resonance is a possibility, the natural frequency of the busbar may be modified by varying one or more of the following [9]:

1. the flexibility of the supports;
2. the span length between supports;
3. the flexibility of the conductors.

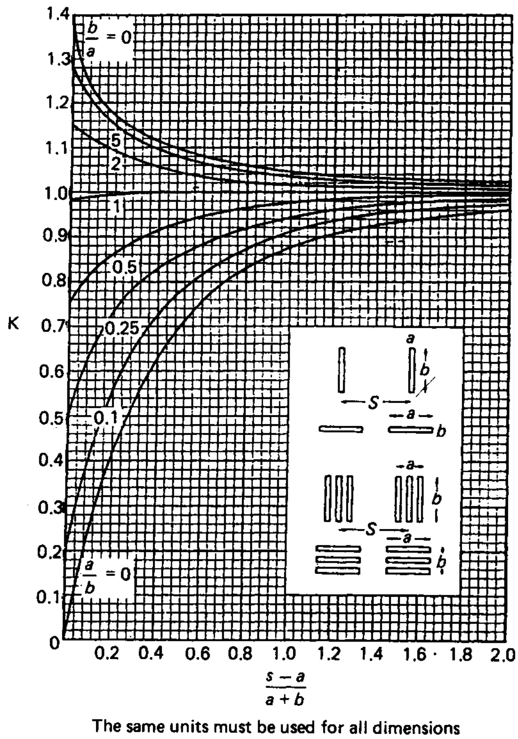



**Figure** 9.8 Shape factor (K) for rectangular conductors (Courtesy: The Copper Development Association)

The adjustable insulated busbar support shown in Figure 9.7 illustrates one manufacturer's approach to the design of versatile supports. An alternative arrangement is illustrated in Figure 9.6 where use is made of insulated bushing supports. The positioning of the phase bars one above the other in a vertical plane offers the following advantages:

1. it minimizes the destructive effect of the short-circuit forces on the bars;
2. it prevents the accidental bridging of phases by falling metallic objects, e.g. during maintenance; and
3. it permits better natural ventilation of the bars.

## *Creepage and clearance*

Busbar assemblies must be designed to give adequate clearances between phases and to earth. In British practice compliance with BS 159 *(Busbars and busbar connections)* is obligatory. This standard also offers guidelines on minimum creepage distances over insulation for indoor type switchgear. It is difficult to be too precise on creepage distances since much depends on the environment in which the apparatus is used and on the degree of protection afforded by the switchgear enclosure.

## 9.5 Power supply fault current determination

The values of currents that are likely to flow through the various branches of any power system when faults occur at points within it must be assessed before switchgear ratings can be specified. Calculations of prospective fault currents on large systems, especially those containing several voltage levels, can be very complex and usually require the use of computers or network analysers. We are concerned with relatively small, privately-operated generating plants, and with first-stage power distribution to industrial and commercial installations. Here, simplified longhand calculations generally suffice. They give a sufficient degree of accuracy to enable selection of apparatus for the performance required.

### 9.5.1 Fault conditions

Faults may be classified in one of two groups:

1. *Three-phase short circuits:* where all three phases are short-circuited to each other or to earth. This normally gives the highest level of fault current likely to occur within a circuit. It is therefore the value which is used for determining the interrupting-rating of circuit breakers. The assumption is always made that the fault is a *bolted* one having zero impedance and giving the worst-case condition. Hence the *prospective fault current* for switchgear apparatus being defined as 'the r.m.s. symmetrical current that would flow in a circuit due to the nominal applied voltage when a short circuiting link of negligible impedance replaces the assembly to be tested.'
2. *Unsymmetrical faults:* where only one or two of the three phases are involved. Fault current levels are usually less than the bolted 3-phase value. For example, bolted line-to-line currents are about 87 % of the 3-phase value, and bolted line-to-earth currents may vary from 25 to 100 % of the 3-phase value, in industrial and commercial systems [10].

Before we go on to examples of calculations, we shall examine the sources from which fault power can originate and discuss the behaviour of the short-circuit currents generated by them.

### 9.5.2 Fault current sources

The basic sources of short-circuit capacity are:

1. the public utility service;
2. synchronous machines, both generators and motors; and
3. induction motors.

In theory, the utility service would be an infinite source of fault current. In fact, at the point at which electrical energy is delivered to the consumer's installation (the so-called 'origin of an installation'), the prospective fault level is considerably attenuated by the impedance of transmission and distribution lines, and by supply step-down transformers. Before any short-circuit calculations are made it is necessary to know the present and projected values of short-circuit current at the point of origin. In the United Kingdom the Supply Authorities are under no statutory obligation to guarantee a particular value. They realize they may have to reinforce a local network to cater for future load demands but, usually, cannot forecast with any certainty what measures they will take to achieve expansion.

Where the impedance of the Supply Authority's network is not known, the MVA rating of the HV switchgear associated with the step-down transformer feeding the consumer's insallation should be used. See the worked example which follows.

As far as in-house generators are concerned, we have already established that they react to short-circuits in a characteristic way (see Chapter 4). Fault current decreases exponentially from a high initial value (occurring during the first half-cycle after the instance of fault and determined by the subtransient reactance ($X''d$) of the machine), through a lower value determined by the transient reactance ($X'd$), before settling (after 0.5 to 2s) to a steady-state value determined by the synchronous reactance ($X_d$). Most protective devices will have operated before the steady-state condition is reached, therefore, the synchronous reactance is not used in calculating the fault currents for protective devices such as circuit breakers, fuses, etc. Steady-state currents do, however, have some significance in protection co-ordination studies.

*Synchronous motors* act in much the same way as generators and supply an exponentially decreasing current to a fault. The time-related magnitude of this current is also determined by the same three reactances, $X'_d$, $X'_d$ and $X_d$, albeit of different numerical value to those applying to generators. A fault in the power system results in a drop in supply voltage to the motor. It then acts as a generator - deriving its power from its own inertia and that of its load. The machine's excitation is maintained by induced currents in its magnetic field structure and in its exciter windings. The fault current diminishes as this excitation decays, and as the energy released by the rotating masses is dissipated.

*Induction motors* also generate fault power by release of kinetic energy. The field flux is produced by induction from the machine's stator. This flux decays rapidly as the system voltage falls and disappears completely after two or three cycles once voltage is lost. The motor's contribution to total fault current is therefore of very short duration. The level of current generated is determined by a reactance similar to that of the synchronous machine's subtransient reactance *(X"d).* This reactance is approximately equal to the locked-rotor reactance of the motor. Fault current contribution will, therefore, be about four times the motor's full-load current (i.e. equal to the direct-on-line starting current). Squirrel-cage motors, those wound-rotor machines which normally operate with shorted slip-rings, and induction generators will all behave in like manner. It is possible that large wound-rotor machines operating with external resistance in their rotor circuits will have sufficiently low short-circuit time constants to allow their fault contribution to be ignored. Manufacturers should be consulted before any decision is made to neglect the contribution from a wound-rotor motor [3, 10].

The wave-form of the total short-circuit current, made up of components from the various sources of fault current, would look like that shown at the bottom of Figure 9.9 [10].

The wave-form is said to be symmetrical because it has the same axis as the current which flowed before the fault occurred. Asymmetry exists when the short-circuit current is offset from the normal current axis because of the presence of a unidirectional current – the so-called *d.c. component* (see the discussion in Section 4.3.1 of Chapter 4). Maximum asymmetry occurs if the short circuit starts at voltage zero at a time angle equal to 90° + θ (measured in degrees from the zero point of the voltage wave) where tan θ equals the *X*/*R* ratio of the circuit from the fault power source to the fault [10].

Typical per-unit values of subtransient and transient reactance (on a machine-rating basis) are given in the following table.

| | $X''_d$ | $X'_d$ |
|---|---|---|
| Salient-pole generators (with damper windings): | | |
| up to 12-pole | 0.16 | 0.33 |
| Synchronous motors: | | |
| 4 and 6 poles | 0.15 | 0.25 |
| LV induction motors: | 0.25 | |

## 9.6 Short-circuit current calculations

The routine procedure for calculating power system short-circuit currents involves five stages:

1. Preparing a system single-line diagram showing generators, motors, circuit breakers, switchgear, fuses, cables, etc., and collating all impedance data for the various elements in the system.
2. Changing these impedances to per-unit values using a chosen base (the method is described in the worked example) and then entering the p.u. values into the diagram. *(Note:* for generators, transformers and motors, *reactance* and *impe-*

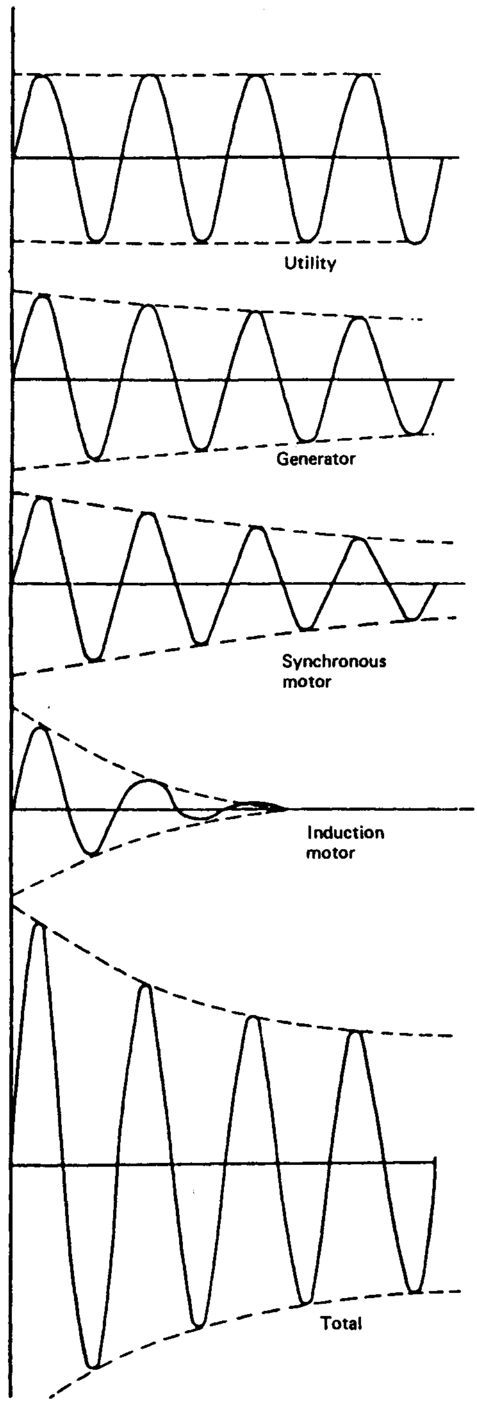



**Figure** 9.9 The make up of total short-circuit current from the several sources in a circuit (This figure has been reproduced from *IEEE Std* 242-1975, *IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems.* © 1983 by the Institute of Electrical and Electronics Engineers. Inc., with the permission of the IEEE Standards Department) *dance* are considered to be equal. This is because their resistance is negligible in comparison with their reactance. On LV systems, however, cable resistance should not be ignored.)

3. Converting the single-line diagram (of stage 2) into an impedance diagram. System elements are represented by inductance and/or resistance symbols. Per-unit values are shown. Also, the fault points to be considered in the study are located.
4. Rearranging the diagram (of stage 3) to solve for the first fault by combining p.u. impedance values (to the point of fault) into a single equivalent impedance. Figure 9.10 shows how impedances are combined.
5. Finally, the short-circuit current for the fault point is calculated. One then proceeds as from stage (4) for all other selected fault points. Short-circuit currents are calculated using first-cycle maximum symmetrical values. For protection co-ordination, minimum current values are also required - especially where time-delay relays and fuses are used.

The following example will show how the procedure is applied.

### 9.6.1 An example of short-circuit calculations

The installation under study derives its primary power from the local supply authority through a 1500kVA sub-station transformer. The HV switchgear associated with this transformer has a fault rating of 250 MVA. The consumer intends operating two 600kVA generators in parallel with the utility for load peak-lopping purposes. The generators will also provide a standby supply for the essential loads on the consumer's premises. Changeover from utility to generator(s) supply is made through a transfer switch (or through mechanically and electrically interlocked contactors).

Our objective is to determine the prospective fault currents that will result from bolted 3-phase short-circuits at selected points in the consumer's power system. Of particular concern are the first-cycle maximum symmetrical values and those to be expected during the 0.5 to 2s period after the instant of fault. The latter are needed to estimate the performance of protective relays and downstream fuse gear.

We also need to assess the minimum prospective fault current levels at the essential load distribution board when only one generator is operating in the emergency mode.

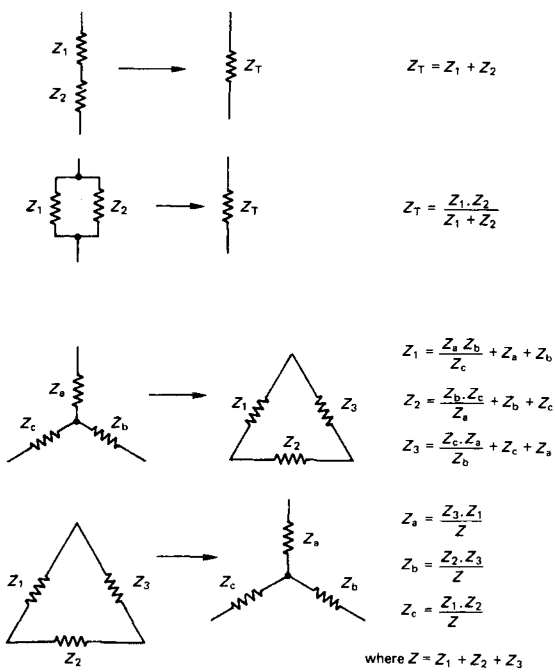



**Figure 9.10** Combining impedances

*Stage 1*

The power system under consideration is that shown in the single-line diagram of Figure 9.11. Impedances are given in ohmic values for cables or in per-unit reactances for power fault sources (referred to the individual element's kVA rating - kVAa).

*Stage 2*

The next step is to convert all the impedance data in Figure 9.11 into per-unit values, referred to a kVA base (kVAb).

The kVA base chosen need not be related to the kVA rating of any element in the system. We shall select 1000kVA as our base.

1. The utility's per-unit impedance on the kVA base, is given by:

   Z p.u. = (kVAbase )/(power source kVA fault capacity)
   = 1000/250,000
   = 0.004 p.u.

2. Convert all motor ratings to kVA. **In** the absence of detailed information on efficiency, power factor, etc., a motor's h.p. rating may be approximately converted as follows:

| | |
|---|---|
| induction motors | kVA = 1.0 x h.p. |
| synchronous motors (at unity pJ.) | kVA = 0.8 x h.p. |
| synchronous motors (at 0.8 p.f.) | kVA = 1.0 x h.p. |

**In** our example, motor kVa and h.p. ratings are taken as being equal to each other.

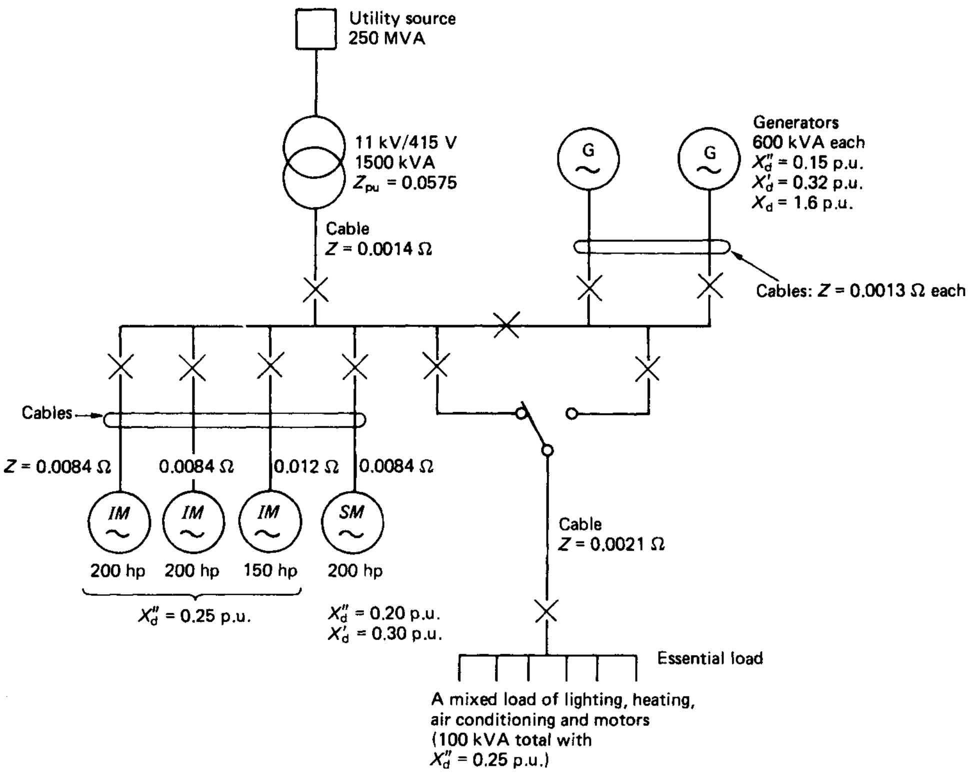



**Figure 9.11** Stage 1 – power system single-line diagram

3. Change the per-unit impedances from actual kVA references to base kVA values using the expression:

$$Z_{pu_{base}} = \frac{kVA_b}{kVA_a} \times Z_{pu_a}$$

(a) Transformer:

$$Z_b = \frac{1000}{1500} \times 0.575 = 0.038\,\text{p.u.}$$

(b) Generators:

$$Z_b = \frac{1000}{600} \times 0.15 = 0.25\,\text{p.u.}$$

(c) Induction motors:

$$200\,\text{h.p.} \quad Z_b = \frac{1000}{200} \times 0.25 = 1.25\,\text{p.u.}$$

$$150\,\text{h.p.} \quad Z_b = \frac{1000}{150} \times 0.25 = 1.67\ \text{p u}$$

100 kVA of motors in essential load $\quad Z_b = \frac{1000}{100} \times 0.25 = 2.5\,\text{p.u.}$

synchronous motor 200 h.p. $\quad Z_b = \frac{1000}{200} \times 0.20 = 1.0\,\text{p.u.}$

4. Convert cable impedances from ohmic values to per-unit impedances referred to the base kVA using the expression:

$$Z_{pu_b} = \frac{(\text{ohms impedance})\ (kVA_b)}{(kV)^2\ (1000)}$$

(a) Transformer feeder $\quad Z_b = \frac{(0.0014)(1000)}{(0.415)^2\ (1000)}$

$$= 0.0081\,\text{p.u.}$$

(b) Motor feeders:

$$200\,\text{h.p.} \quad Z_b = \frac{(0.0084)(1000)}{(0.415)^2\ (1000)}$$

$$= 0.049\,\text{p.u.}$$

150 h.p. $Z_b = \dfrac{(0.012)(1000)}{(0.415)^2\ (1000)}$

$= 0.070$ p.u.

(c) Generator feeders $Z_b = \dfrac{(0.0013)(1000)}{(0.415)^2\ (1000)}$

$= 0.0075$ p.u.

(d) Essential load feeder $Z_b = \dfrac{(0.0021)(1000)}{(0.415)^2\ (1000)}$

$= 0.0122$ p.u.

Figure 9.12 repeats the single-line diagram but with the per-unit impedances referred to kVAb'

*Stage 3*
The single-line diagram of Figure 9.12 is now converted into an impedance diagram as shown in Figure 9.13. Two hypothetical fault points are located on the diagram.

*Stage* 4 *(Fault 1)*
Next, we rearn~nge the single-line impedance diagram of Figure 9.13 to calculate the fault current for the first of the two faults. By combining the series and paralleled impedances in the manner

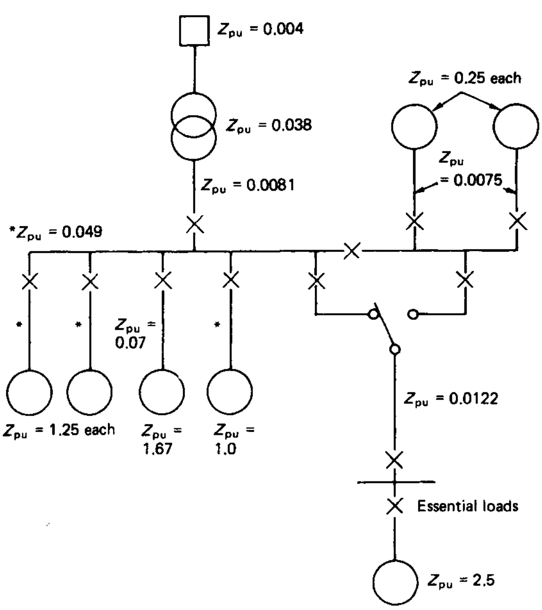



**Figure 9.12** Stage 2 – system single-line diagram with per unit impedances referred to kVA base

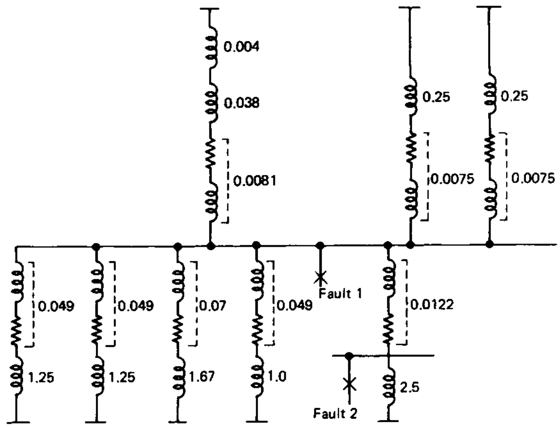



**Figure 9.13** Stage 3 - impedance diagram constructed from single-line diagram Figure 9.12

shown in Figure 9.14, we arrive at a total impedance to the fault of 0.032 p.u.

*Stage* 5 *(Fault 1)*
We can now calculate the symmetrical short-circuit current at the fault using the expression:

Symmetrical short-circuit current at fault

$$= \frac{\text{3-phase kVA base}}{(Z_{pu_b})(\sqrt{3})(\text{kV})}$$

In our example the symmetrical short-circuit current at Fault 1 would be:

$$= \frac{1000}{(0.032)(\sqrt{3})(0.415)}$$

$= 43{,}476$ A r.m.s.

Reverting to the single-line impedance diagram of Figure 9.13, we rearrange this to calculate the fault current for the second of the two faults, that at a feeder from the essential-loads distribution board. We are, effectively back to stage 4 of our procedure.

The essential loads may derive their power supply from two sources; (i) the utility and the generators running in parallel, or (ii) the generators. The first source will give the maximum prospective fault current. The minimum fault current will obtain when only one generator is feeding the essential loads through the transfer switch. We shall calculate for both conditions.

*Stage* 4 *(Fault 2)*

1. Figure 9.15 is the impedance diagram for the maximum fault current conditions at fault 2. By combining impedances we get a total impedance of 0.043p.u. at the fault.

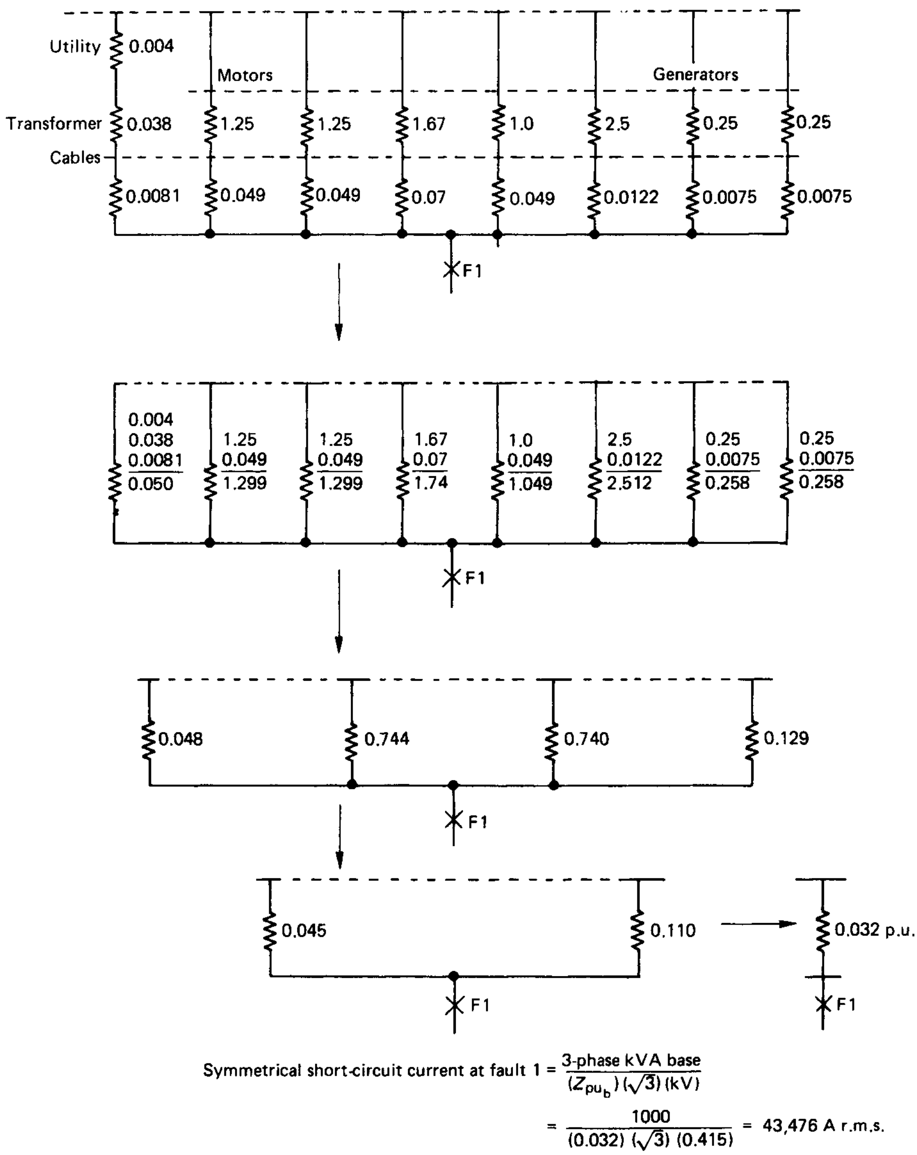



**Figure 9.14** Stage 4 - calculations for maximum half-cycle short-circuit current at fault F1, combining impedances and sources

2. Figure 9.16 represents the minimum fault current condition i.e. with one generator running. Combining impedances we arrive at a total impedance of O.244p.u. at the fault.

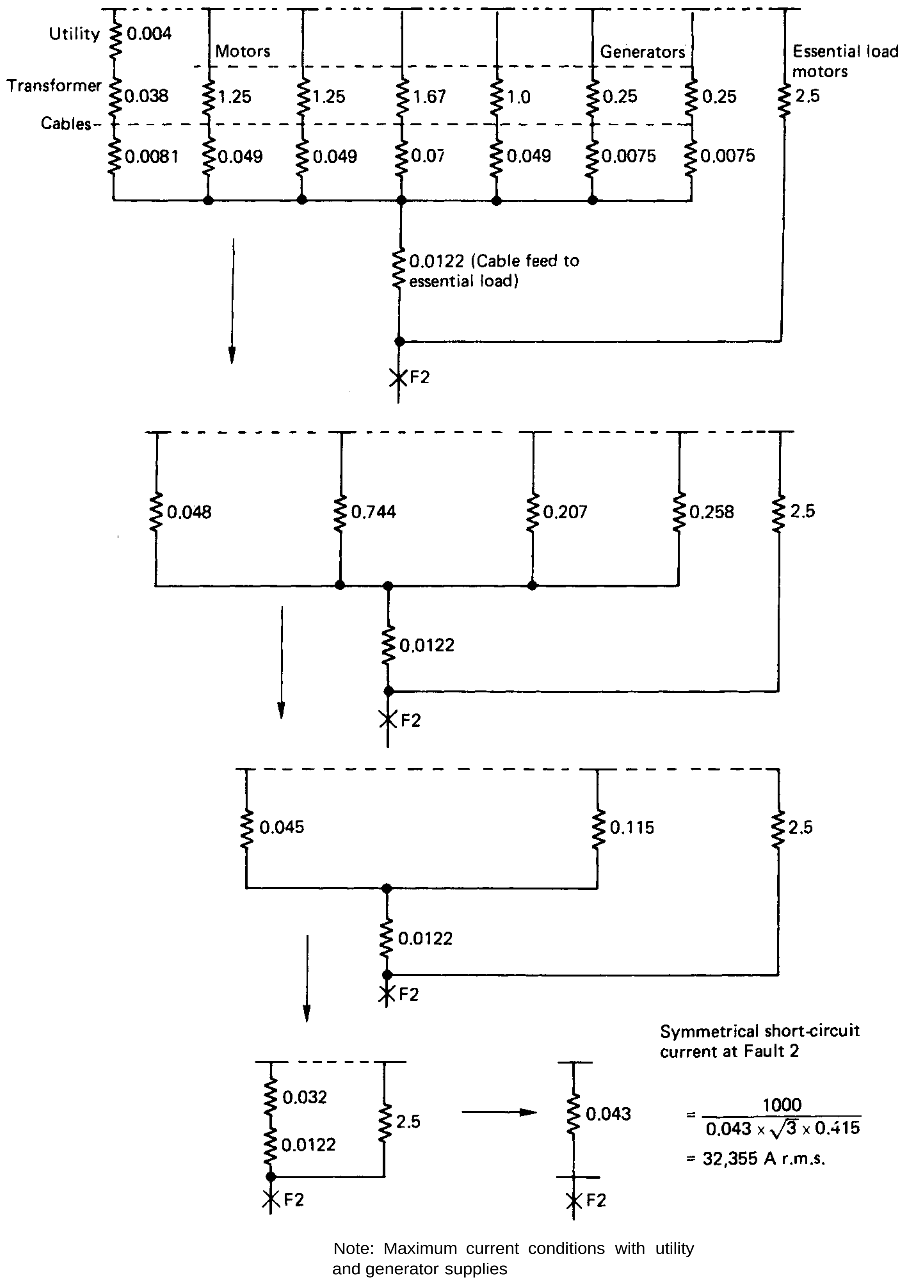
*Stage* 5 *(Fault 2)*

1. The maximum symmetrical short-circuit current at the fault is then given by:

$$\frac{1000}{(0.043)(\sqrt{3})(0.415)}$$

$$= 32{,}355 \text{ A r.m.s.}$$

2. The minimum symmetrical short-circuit current at the fault is given by:

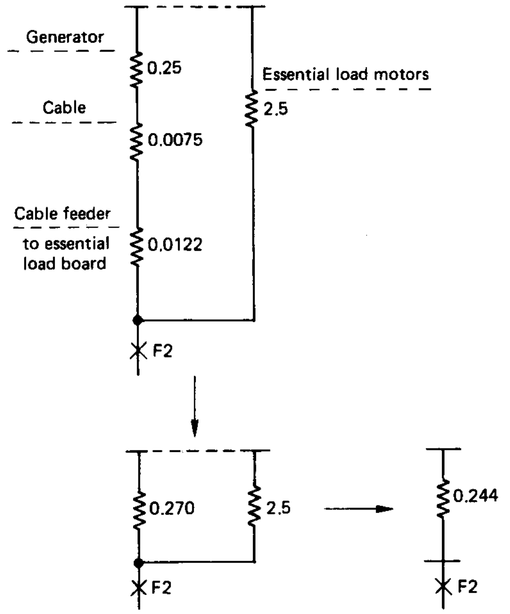



**Rgure 9.15** Stage 4 - calculations for maximum half-cycle short-circuit current at fault F2, combining impedances and sources

$$\frac{1000}{(0.244)(\sqrt{3})(0.415)}$$

$= 5{,}702$ A r.m.s.

Summarizing the results of our calculations for the first-cycle symmetrical currents at fault points 1 and 2 we have:




Symmetrical short-circuit current at Fault 2 = $\dfrac{1000}{0.244 \times \sqrt{3} \times 0.415}$

= 5,702 A r.m.s.

**Figure** 9.16 Stage 4– Calculations for minimum half-cycle short-circuit current. Conditions with one standby generator supplying the essential load

| | *at £1* | *atF2* |
|---|---|---|
| Maximum 3-phase short-circuit current | 43.5 kA | 32.4 kA |
| Minimum 3-phase short-circuit current | | 5.7kA |

The next phase of our calculations will be to determine the fault currents to be expected at both fault points some 0.5 to 2 s after 3-phase bolted faults 'have occurred.

The synchronous machine reactance to be used in the calculation is the transient reactance *($X'_d$).* We can assume that there will be no fault current contribution from the induction motors in the system (see Section 9.5.2: Fault current sources).

The first step is to convert the per-unit impedances for the generators and the synchronous motor to their equivalent kVA base values, using the expression

$$Z_{pu_{base}} = \frac{kVA_b}{kVA_a} \times Z_{pu_a}$$

Generators: $Z_b = \dfrac{1000}{600} \times 0.32 = 0.53\,\text{p.u.}$

Sync motor: $Z_b = \dfrac{1000}{200} \times 0.30 = 1.50\,\text{p.u.}$

We then construct an impedance diagram in the form of that shown in Figure 9.13 but excluding the induction motor branches (see Figure 9.17). We combine these impedances to arrive at total impedances for both faults *(Fl* and F2).

*Fault 1*

The diagrams of Figure 9.18 show the steps in the calculation of total impedance (0.041 p.u.) to Fault 1.

The symmetrical fault current at Fl is given by:

$$\frac{1000}{(0.041)(\sqrt{3})(0.415)}$$

$$= 33{,}393\ \text{A r.m.s.}$$

*Fault 2*

The diagrams of Figure 9.19 show the steps in the calculation of total impedance (0.053 p.u.) to Fault 2.

The symmetrical fault current at F2 is given by:

$$\frac{1000}{(0.053)(\sqrt{3})(0.415)}$$

$$= 26{,}250\ \text{A r.m.s.}$$

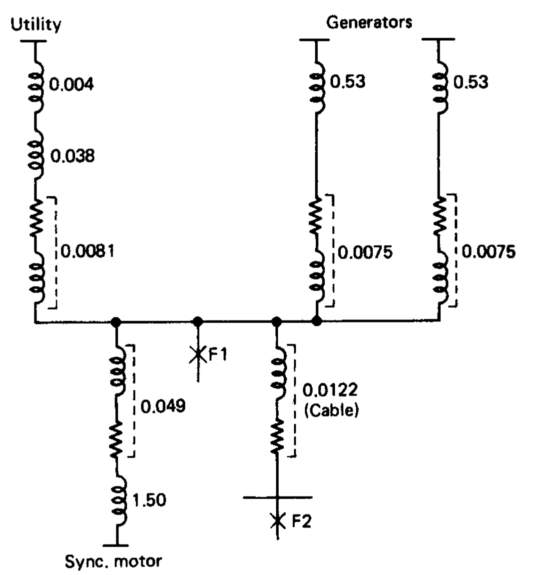



**Figure 9.17** Impedance diagram for calculating short-circuit currents 0.5 to 2 s after fault

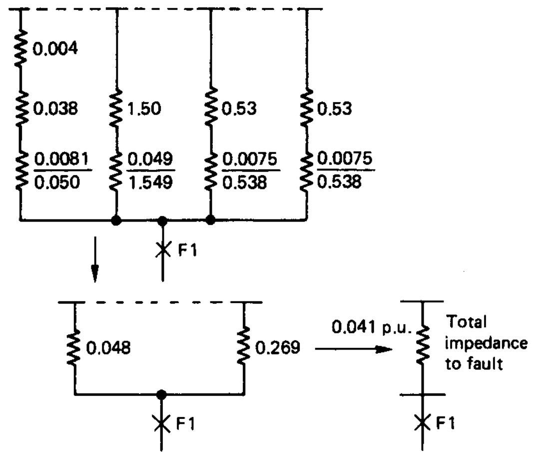



**Figure 9.18** Calculation of total impedance to fault F1 for short-circuit currents at 0.5 to 2 s

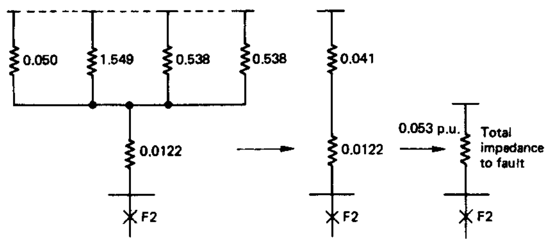



Figure 9.19 Calculation of total impedance to fault F2 for short-circuit current at 0.5 to 2 s

The total impedance to fault F2 with only one standby generator as a power fault source is 0.550p.u. (0.538 + 0.0122). This means that the minimum prospective 3-phase short-circuit current at F2, up to 2 s from fault, will be:

$$\frac{1000}{(0.550)(\sqrt{3})(0.415)}$$

$$= 2{,}530\ \text{A r.m.s.}$$

Summarizing the results of these calculations for the prospective short-circuit currents up to 2 s after fault, at points Fl and F2, we have:

| | *at Fl* | *at F2* |
|---|---|---|
| **Maximum 3-phase short-circuit current** | 33.4 kA | 26.3 kA |
| **Minimum 3-phase short-circuit current** | – | 2.5 kA |

*Conclusions*

This simplified approach to the calculation of prospective fault currents is justified on the grounds that it gives levels higher than those which might be expected in practice. This is because no account is taken of the resistance present in the switching devices and in the busbars and connections to them. Nor is any allowance made for diversity in motor operation.

The prime objective is to ensure that the ratings of selected switchgear are adequate for the purpose. The nearest (higher) standard rating equipment should be chosen.

We have only considered symmetrical fault currents since circuit breakers are rated for them. Where asymmetrically rated fuses are used, for example, it may be necessary to determine the maximum asymmetrical fault current levels. Calculations are very complex. In American practice, simple multipliers are applied to the symmetrical r.m.s. values to give good approximations of the probable maximum asymmetric values to be expected at various locations in power networks. In general, 1.6 is used on all systems above 5kV, and 1.25 on all industrial and commercial systems below 600V [3, 10].

## 9.7 Power switching apparatus

A switching device may be defined as one which may be used for opening, closing, or changing a circuit's connections. Depending upon its design it may be capable of making, carrying, and breaking current under normal and specified overload conditions, and of carrying and making (but not necessarily breaking) current under abnormal conditions such as short-circuit. Such devices would, therefore, include isolators, fuse-switches, contactors, transfer switches, and circuit breakers. The limitations of a single chapter allow only a brief discussion of their general features and the requirements for their application in the context of generator switchgear.

### 9.7.1 Isolators and isolating switches

Mention has been made earlier (Section 9.3) of low-cost switches of both the no-load-break and load-break type, as used in the isolation of busbar sections and individual fixed-type circuit breakers.

### 9.7.2 Fuse-switches and switchfuses

Fuse-switches and switchfuses are hand-operated low voltage switches housed in individual surface- or cubicle-mounting enclosures. Fuses are high rupturing (or breaking) capacity type (h.r.c./h.b.c to

BS 88: Part 2 (IEC 269: Part 2», type-tested and certified at 80 kA symmetrical at 415 V to provide protection against overload and/or short-circuit. Mechanisms are of the quick-make quick-break type and the operating handles are interlocked with the front access doors of the enclosure. The fuse-switch is a unit in which the fuselink (or fuse carrier with fuselink) is an integral part of the switch, in that it forms its moving contact. The switchfuse incorporates a separate switch whose blades are in series with the fuses.

Before the advent of the moulded case circuit breaker (m.c.c.b), the fuse-switch was frequently used as the main output switch on small mobile generators. Now it is more likely to be found in the distribution circuits of modular construction composite generator-distribution switchboards of the type illustrated in Figures 9.20 and 9.52. The switches are then rated in accordance with the various duty categories of BS5419 (IEC408), the two most applicable being:

- AC22 - switching of mixed resistive and inductive loads - including moderate overloads; and
- AC23 - switching of motor or other high inductive loads.

When the fuse links are replaced by copper links the switches may be used as on-load or off-load isolators. Ratings are then as for BS 5419 AC 21 and AC20 duty categories, respectively.

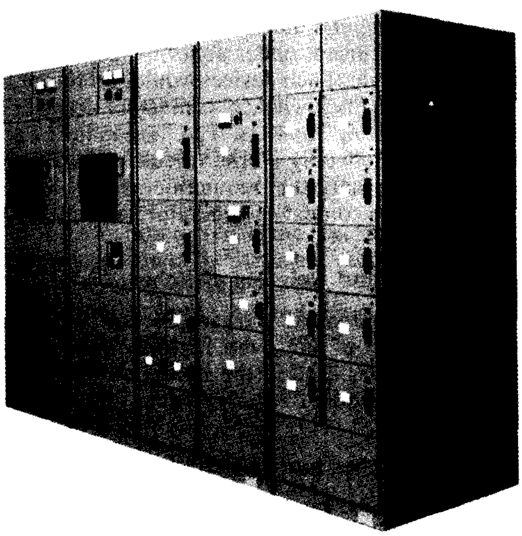


**Figure** 9.20 Example of a cubicle switchboard incorporating distribution fuse-switches (Courtesy: Delta Electrical Systems Ltd)

### 9.7.3 Contactors

Contactors, in the generator switchgear context, are used in small- and medium-power low-voltage standby and emergency generator switching schemes (see Chapter 11). They may be one of two types:

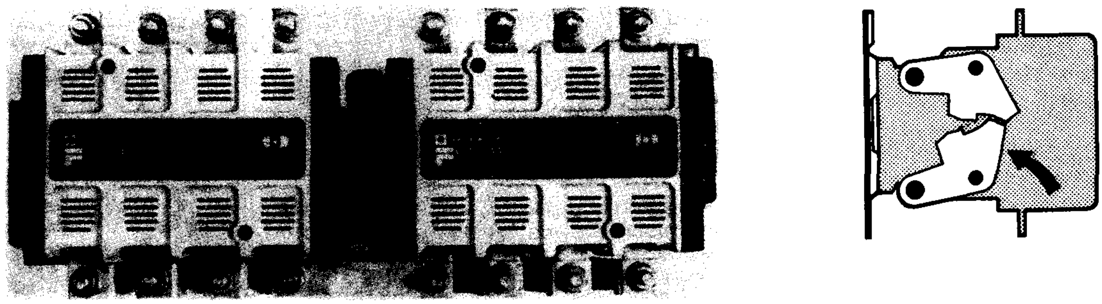
1. *moulded block* (abbreviated to *block)* in ratings up to 1600 A; and
2. *bar-and-shaft* (or *clapper)* in ratings up to 2000 A.

Ratings are based on BS 5424: Part 1 (IEC 158-1) and duty category AC 1 is used for generator applications. Although this applies to loads where the power factor is not less than 0.95, it is recognized that duty requirements in standby plant are not onerous - perhaps two or three operations per day.

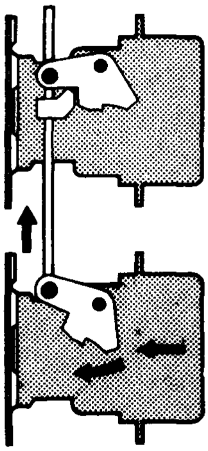
British power plant designers have tended to restrict the use of interlocked changeover contactors to current levels below about 1200A, preferring to use changeover circuit breakers above this rating. The inherent protection given by the circuit breaker and its faster switching time are cited as the main reasons. For comparable front access, withdrawable circuit breakers are usually preferred, and mechanical interlocking then becomes far more complicated than it is for contactors.

Figure 9.21(a) shows a pair of horizontally-interlocked block contactors which use double-break contacts to reduce wear due to arcing. It illustrates the compact configuration that is possible. Where panel layout requires, vertical interlocking may be fitted (see Figure 9.21(b». In either arrangement movement of one contactor is prevented as soon as its partner has covered about one-fifth of its travel.

The bar-and-shaft contactor is larger and costlier than its block counterpart. In its favour however is the fact that it usually provides more generous space for copperwork connections and its component parts are easily inspected and removed. For example, arc chutes are usually detached with a simple pull-off action to expose the contacts for inspection. The magnetic blow-out coil, which carries the main current, assists in the expulsion of the arc from the contact region when the contacts separate. The purpose of the arc chute is to contain the arc and prevent flashover between phases or to earth. Heavy duty contactors (and air circuit breakers) use chutes fitted with either metal or insulated splitter plates, which serve to extend the length of the arc and to cool it. The low-velocity products of the arc are then diffused above the chute through baffles or dividers. Arcing horns (contacts or runners) provide a path for the roots of the expanding arc as it is forced upwards into the chute by the electromagnetic forces of the blow-out coil, and by the action of thermal convection currents.



(a)



(b)

**Figure** 9.21 Mechanically-interlocked block type contactors (a) A horizontally-interlocked pair of 4-pole contactors. The interlocking system (fitted between the two contactors) is shown in the accompanying line drawing (b) Diagrammatic illustration of the alternative vertical mechanical interlocking system (Courtesy: Telemecanique Ltd)

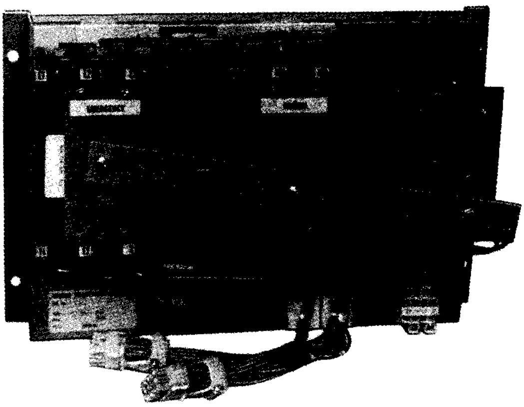
Contactors rated above 100 A must, in accordance with BS 5424: Part 1, be capable of making 10 times and breaking 8 times their AC 1 operating current levels. Typically, such contactors will carry 10 times their maximum operating current *(Ie)* for 5 s, and 18 times *Ie* for 1 s. Above this level there is some risk of contact welding occurring. This 'short-term' capability should be related to the fact that generators would only be capable of sustaining about 3 times their full-load current (f.l.e.) rating on short circuit (see Chapter 4).

'H.r.c. fuse-contactor-overload relay' combinations provide a cost-effective means of protecting and switching standby generators. Machine protection is handled by the overload relay, and the fuses protect both contactor and relay. In the event of a short circuit, the fuse cut-off characteristic (i.e. its pre-arcing + arcing time) must be below the *weld-in* characteristic of the contactor. The fuses must also protect the cables feeding the emergency loads. Cut-off time must be short enough to prevent the conductors exceeding their permitted maximum temperature under short-circuit conditions. The prospective fault current from a public utility supply will be very much higher than that expected from an in-house standby generator.

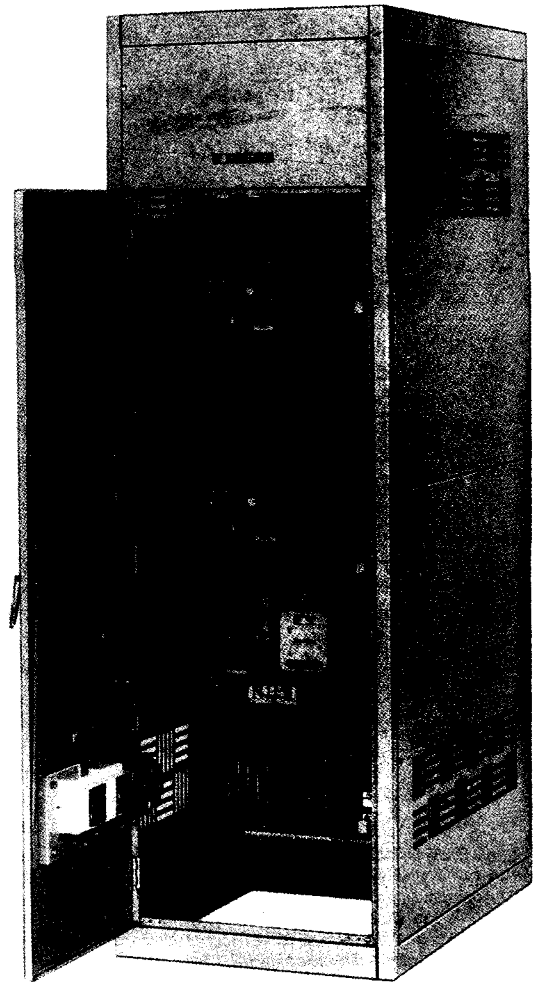
Choice of the number of poles to be provided on the changeover contactors will depend upon the consumer's supply and on the system's design requirements for a switched neutral (see Chapter 11).

### 9.7.4 Automatic transfer switches

Where American influence prevails, so-called *automatic transfer switches* of the type illustrated in Figure 9.22 are used as load transfer devices. They are listed in Underwriters Laboratory Standard UL 1008, and are available in ratings from 30 A to 4000 A up to 600Y. They may incorporate operating coil contactors, moulded case switches or instantaneous trip, moulded case circuit breakers, electrically and mechanically interlocked. Since they



(a)



(b)

Figure 9.22 Example of an automatic transfer switch (a) A 100 A power switching panel, with instantaneous trip only circuit breakers. Interlocking by means of a walking beam interlock. The mechanism is motor driven. (b) An automatic transfer switch incorporating intelligence and supervisory circuits. Housed in a NEMI 1 ventilated enclosure (Courtesy: Westinghouse Electric Corporation)

include not only these power switching devices but also the intelligence/supervisory circuits to constantly monitor the condition of the power sources and provide the intelligence for the switch to correctly perform its transfer function, they are comparable to the *automatic mains failure panels* of European practice.

The transfer switches must be protected by properly selected current limiting fuses or moulded case circuit breakers if they are to be capable of withstanding the effects of high fault currents. Manufacturers' rating tables typically list:

- interrupting current capacity,
- withstand current ratings,
- maximum instantaneous peak let-through current, and
- inrush current,

for both types of back-up.

### 9.7.5 **Circuit breakers**

Circuit breakers may be grouped in accordance with their construction and the method of arc interruption employed. In the voltage and current range under consideration, the three types in common use are:

1. air;
2. vacuum; and
3. sulphur hexafluoride ($SF_6$) breakers.

Air-break circuit breakers (a.c.b.s) are mostly used in low-voltage systems (up to 600V). They may be either of the metal-frame type or of the moulded-case type. The former also predominates in indoor switchgear up to 15kV but meets with increasing competition from vacuum break (v.c.b.) and $SF_6$ types.

Until a few years ago oil filled (or bulk oil) plain-break circuit breakers (o.c. b.s) were popular in low-voltage industrial systems but have now been largely superseded by the metal-frame air break types. Among the reasons for this are:

- the oil's flammability and, therefore, its potential hazard in certain installations (e.g. marine and off-shore) ;
- the maintenance requirements; the carbonized oil needed to be changed or purified at intervals dictated by duty cycle; and
- the advances made in heavy duty air-break devices, especially in terms of physical compactness, resulting in highly competitive, space saving, multi-tier switchboard assemblies.

Low oil content (or small oil volume) circuit breakers continue to find application, particularly in continental Europe, in metal-clad switchboards for voltages up to 36 kV. In this type of breaker, oil content is reduced to that which is sufficient for the arc control device in the circuit-breaking compartment. It is still necessary to routinely maintain the oil in good condition.

Before we go on to look at proprietary examples of the various types of circuit breaker, we shall briefly examine the mechanisms of circuit-breaking and arc extinction and explain some of the terms used in the current-breaking process.

## 9.8 The current-breaking process

As the moving contact of any current-carrying switch parts from its fixed contact an arc is drawn across the gap. The arc exists because of the *ionization* of the air gap - caused by the difference in electrical potential between the contacts. Ionized air is conductive. The arc will, therefore, be sustained unless the airgap can be de-ionized, or the potential difference is reduced. This, in a nutshell, is the problem in switching.

In plain-break air circuit breakers the objective is to control the arc in such a way as to cause its resistance to increase rapidly. This would have the effect of reducing the current until it falls to a level that is too low to sustain the ionization process. Lengthening, cooling, and splitting the arc will raise its resistance. Space constraints limit the amount of contact separation that is possible. Air circuit breakers, therefore, employ magnetic blow-out coils (or plates) to assist and hasten the arc lengthening process. When the arc is cooled, the ionization decreases and the arc voltage rises - as is shown in the arc current/voltage characteristic of Figure 9.23, which is based on an empirical expression for arc voltage derived by Ayrton [11].

Circuit breakers make use of *arcing chambers* to help increase the arc voltage. They accomplish this by dividing the arc into a number of sub-arcs. The chamber is fitted with a number of steel plates placed at certain intervals. (See the sectional arrangement drawing in Figure 9.24). These arcing (or cooling) plates may have V-shaped cut-outs, in which the arc initially burns. Since the arc is a current-carrying conductor it is surrounded by a magnetic field. The plates offer this field a circuit of considerably lower *reluctance* than that of air so that the chamber exerts an attractive force on the arc and draws it in. The chamber not only splits-up but also cools the arc because the plates give it a substantial thermal capacity [11].

The quenching of arcs in a.c. circuits is made easier than those in d.c. circuits by the fact that the current wave-form passes through a zero in a fixed relationship to its frequency. In a 50 Hz system there are 100 'zeros' per second, i.e. one every lOms. The arc would thus be extinguished every 10 ms, even without the influence of the switch. The problem is to prevent the arc being re-ignited or re-struck. Taking an extremely simplistic approach, it might be

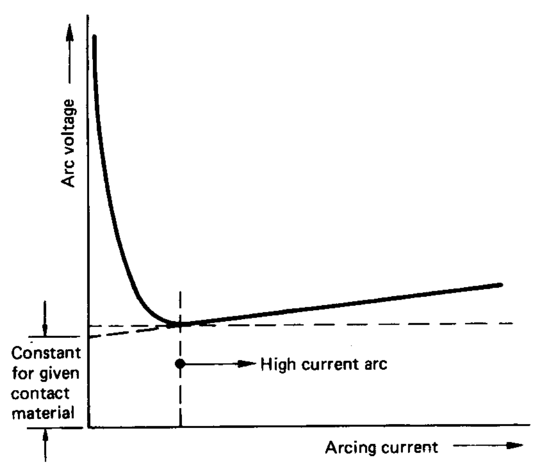



**Figure 9.23** Arc voltage/current characteristic (Courtesy: Klöckner-Moeller Ltd)

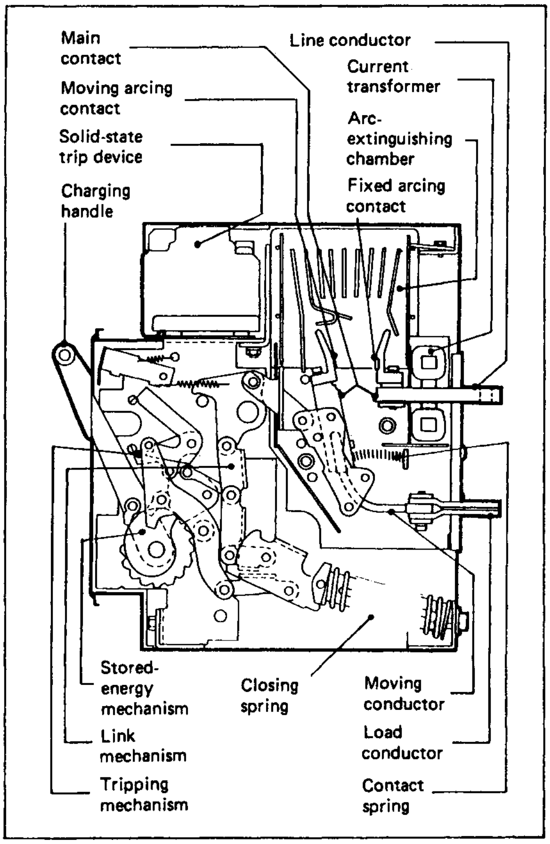



**Figure 9.24** Section through the contact system of a proprietary air circuit breaker (Courtesy: Mitsubishi Electric Corporation)

said that after each zero point a race begins between:

1. those processes which influence the recovery of the insulation strength between the contacts (e.g. speed of contact separation, arc cooling, and de-ionization of the airgap), on the one hand; and
2. the rate of rise of the voltage between the contacts, on the other hand.

The arc will not restrike if the processes in 1 build-up more rapidly than the rate at which the voltage rises in 2.

The voltage between the contacts has two components:

1. the *recovery voltage;* and
2. the *restriking voltage.*

The *recovery voltage* is the power frequency voltage occurring across the circuit breaker contacts after the current is interrupted and following the decay of the restriking process (after final arc extinction). In the case of a 3-pole circuit, where the voltage in each phase is $V_L/\sqrt{3}$, the r.m.s. recovery voltage across the first path to be extinguished is equal to [9]:

$$1.5 \times V_L/\sqrt{3}$$

Also, where a generator's current is interrupted, the recovery voltage will be less than the nominal system voltage $V_L$ due to the machine's armature reaction, leakage reactance, and resistance, and will remain so until the armature reaction effect ceases [6].

The *restriking voltage* is defined as the voltage which occurs across the contact path directly following the interruption of current. It has an extremely rapid rise. Its peak value and its rate ofrise (r.r.r.v.) are both circuit-dependent; that is, they relate to the power factor of the circuit up to the point of fault. When interrupting normal load current at normal working power factors the peak restrike voltage would be very low. Under short-circuit conditions, when power factors are low, the peak value of the restriking voltage will approach that of the peak recovery voltage. See the wave-form in Figure 9.25.

The capacitance between the breaker contacts, which is an important part of the circuit capacitance, falls as the contacts move apart. Each time the arc extinguishes (i.e. when the fault current passes through its zero points) the energy stored in the inductive elements of the circuit is transferred to the capacitance (112$CV^2$). Therefore, at each successive arc extinction, because C reduces, $V$ increases. Also, the voltage required to restrike the arc after each arc extinction increases and the 'voltage drops' across successive arcs increase slightly [6]. (See Figure 9.25.)

After current zeros, the capacitance is discharged in a high frequency aperiodically damped manner. The frequency of the discharge is no longer related to the power frequency but is in a considerably higher range. Depending upon the circuit characteristics it may be anywhere between 2 kHz and 200 kHz [9]. When arc interruption is finally successful (the fourth current zero of Figure 9.25), the oscillating, high-frequency, restriking voltage rapidly decays down to the recovery voltage level [4].

The pre-arcing time (or opening delay) of Figure 9.25 represents the time delay between the start of the short-circuit and the instant of breaker contact separation. The total opening or clearance time is the time interval between the start of the short-circuit and the instant when the arc is finally extinguished. It is the duration of the short-circuit.

The first task of the circuit breaker is to effect the quickest possible opening of the contact path. The opening delay is made up of a *tripping time* and a *response delay* (see Figure 9.26). The former includes a *command time-delay,* which is determined by the type of protection provided for the circuit breaker. For example, if an instantaneous magnetic overload release is fitted, this time-delay would

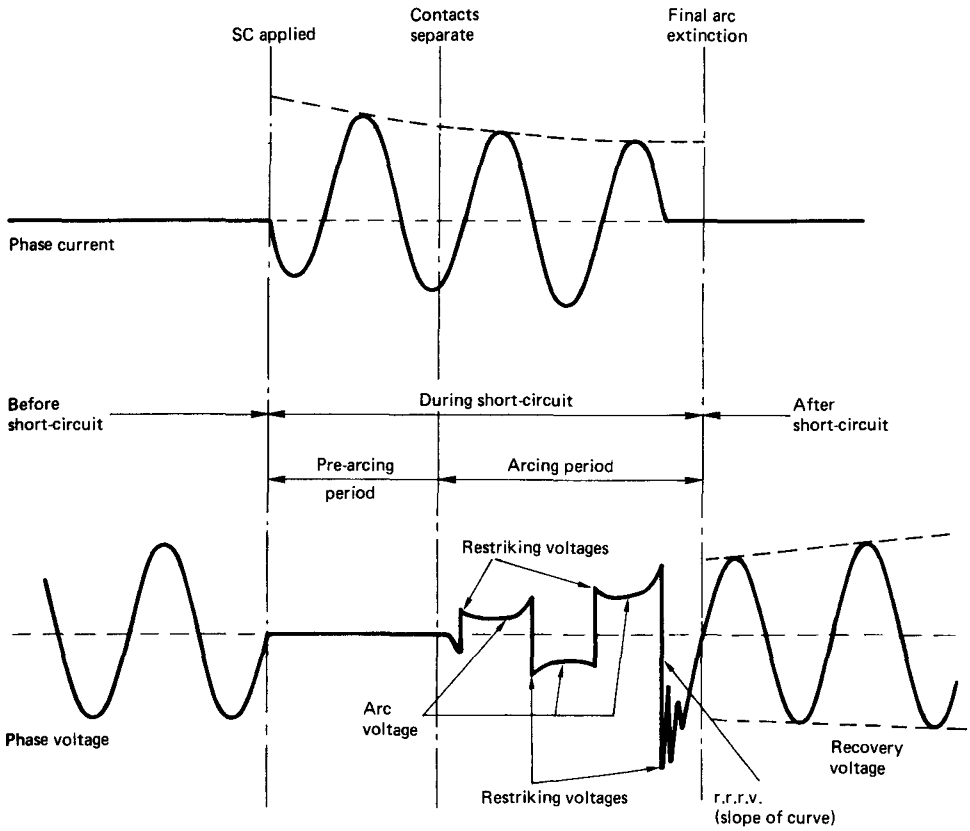



**Figure** 9.25 Oscillogram of phase voltage and current before. during and after a 3-phase short circuit

include the time taken for the release mechanism to unlatch the circuit breaker's trip-free mechanism. Where protective relays are used the command time-delay would include:

1. the time-lapse between fault inception and the energizing of the circuit breaker's trip coil; and
2. the time taken for the current in the trip coil to rise to a level at which it operates to initiate the breaker's trip operating mechanism.

Element 1 will include the operating time of the protective relay(s) themselves. Those of the electro-mechanical type would be slower than those of the solid-state or static type (see Chapter 10).

The response delay is directly related to the operating speed of the breaker itself. It is the time which elapses between the breaker's trip latch being triggered and the arc being initiated. Breaker opening is *assisted*, usually, by the release of stored energy from a charged spring. The movement toward contact opening would include acceleration of the mass of the switch mechanism and any contact over-travel.

Overall tripping times will then depend upon the type of protection fitted, the breaker's tripping mechanisms, and its arc-extinction capability. Typically, where the total opening time of an air circuit breaker interrupting 100 kA r.m.s. symmetrical might be 45 ms, the arcing time could be of the order of 15 ms. The command time would be about 20 ms if a built-in, solid-state, overcurrent relay is used. This means that the delay between activation of the trip latch and the breaker contacts opening would be 10 ms.

The objective in this discussion has been to give the reader some understanding of the problems associated with switching. The *mechanisms* of arc extinction and re-ignition, for example, are very much more complex than these over-simplified explanations might infer. This treatment should therefore only be considered as an introduction to the subject of the current-breaking processes. It is largely drawn from the excellent material of [4, 6, 11, and 12]. Those readers who wish to study the topic further would do well to make those references their starting point.

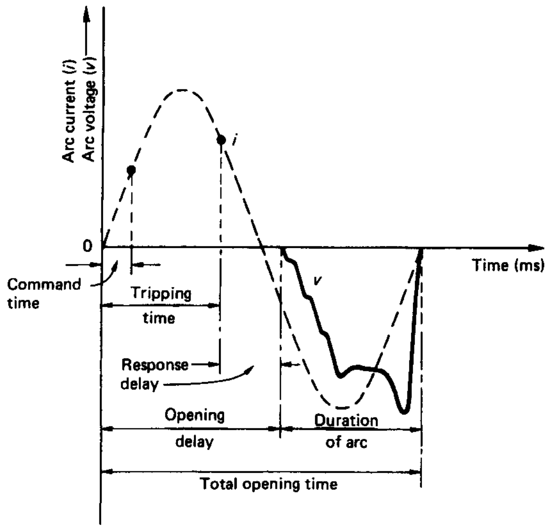



Figure 9.26 Explanation of terminology in relation to switching operation

## 9.9 **Air-break circuit breakers**

In this section we shall be looking at air-break devices which use atmospheric air as the insulating medium - as opposed to those types which use compressed air. The latter are employed on EHV systems and therefore fall outside our scope.

Air circuit breakers (a.c.b.s) employing arc chambers of the type described in Section 9.8, may be subdivided into two classifications:

1. metal-frame units; and
2. moulded-case units.

### 9.9.1 Metal-frame a.c.b.s

Figures 9.27 through to 9.30 illustrate proprietary examples. In every case they are designed to be incorporated into dead front cubicles. They may then be of horizontal draw-out or of fixed type construction.

The first form consists of the breaker and a cradle. The switchboard builder designs the cubicle structure to accommodate the cradle which comes complete with sliding and telescopic extension rails, safety interlocks, and main and control circuit safety shutters, etc. - as shown in the illustration of Figure 9.27 for a Terasaki AT series breaker. The builder is also responsible for designing and providing the bus risers to which the fixed isolating contacts on the rear of the cradle are connected and, of course, the main busbars within the cubicle structure.

The movement of the breaker into its 'isolated' position is small enough as to be easily contained within the cubicle depth (see Figure 9.28). The hinged breaker compartment door should be provided with a rectangular cut-out to accommodate the operating facia on the front panel of the breaker.

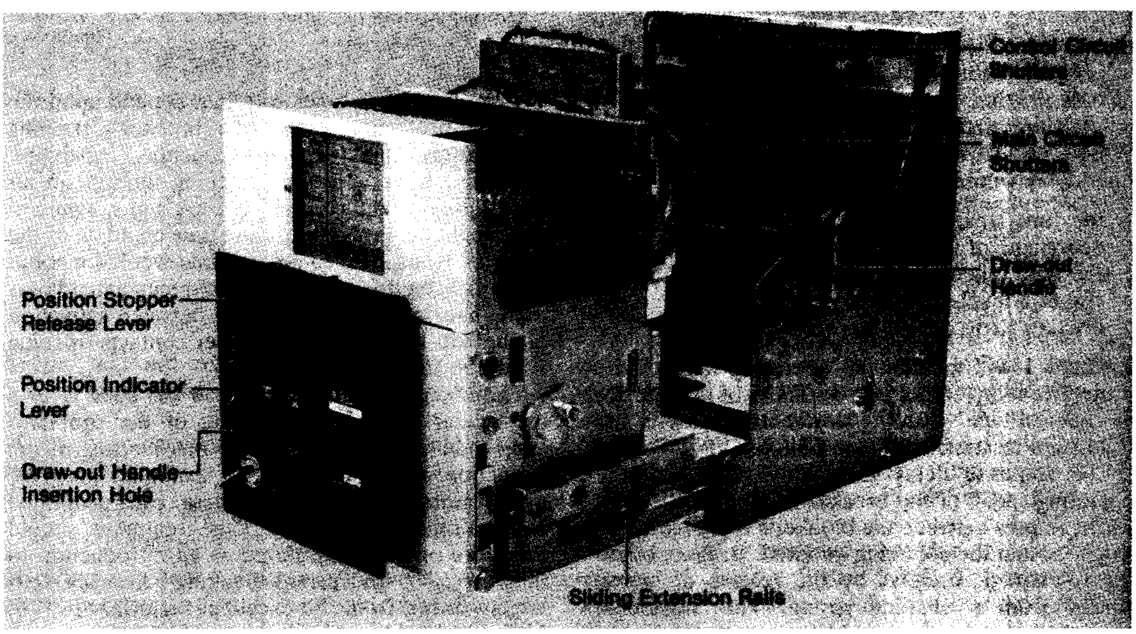



Figure 9.27 A draw-out type circuit breaker (Courtesy: Terasaki Europe Ltd)

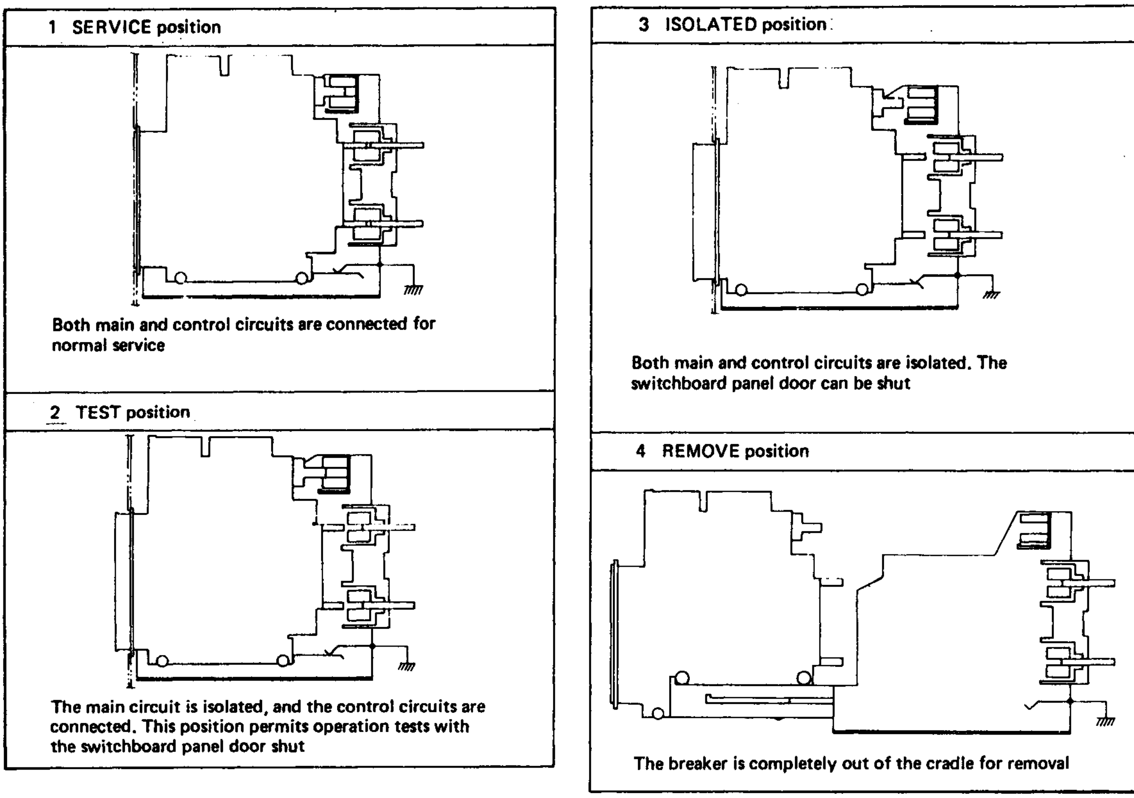
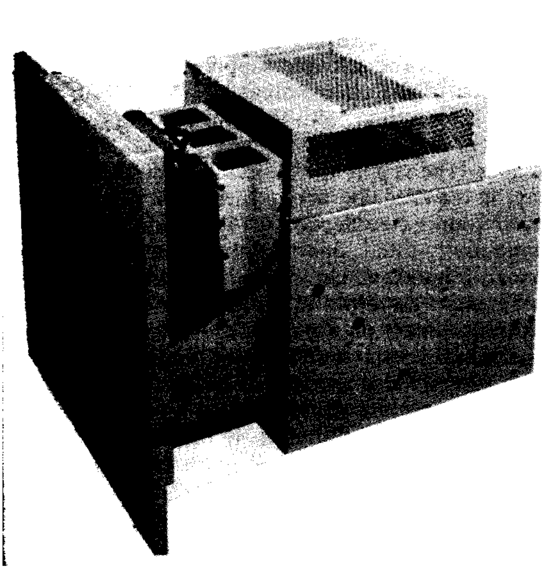



**Figure** 9.28. Breaker positions for the draw-out a.c.b. illustrated in Figure 9.27. The breaker may be fully isolated or tested with its switchboard panel door closed. (Courtesy: Terasaki Europe Ltd)



•••••• 9.29 Draw-out type a.c.b. with integrally mounted ~ plate. The cassette enclosure gives IP 20 internal protection (Courtesy: George Ellison Ltd)

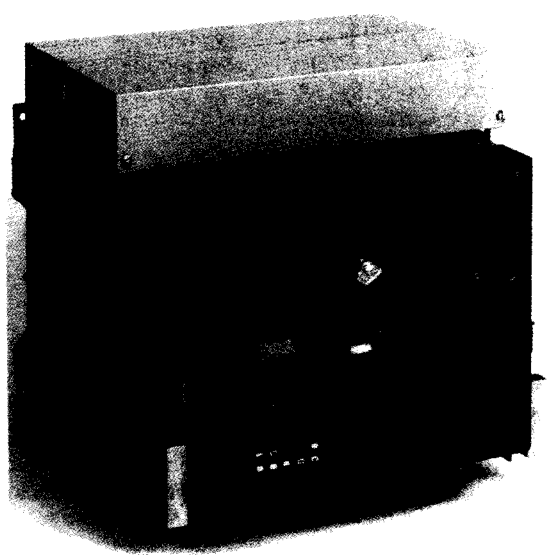


Figure 9.30 One of a range of withdrawable a.c.bs. sharing one single overall size with common cutout and fixing dimensions (Courtesy: Merlin Gerin Ltd)

The door should also be interlocked to prevent its being opened when the breaker is CLOSED; and to allow it to be opened only when the breaker is OPEN.

An alternative form of construction offers an integrally mounted front plate as shown in Figure 9.29, which illustrates a breaker from the Ellison GEA range.

The units in Figures 9.27 and 9.29 cover a range of ratings from 630 A up to 3200 A (Terasaki AT series), and up to 5000A (Ellison GEA series). Overall dimensions and weights vary with current rating and the number of poles provided, but the breakers are compact enough to permit double or triple-tier stacking arrangements in standard 2200 mm high cubicles. The fixed cradle offers the switchboard builder a low cost alternative to the need to purpose-design internal cubicle shrouding and metal barriers, or to provide safety clearances for a variety of cubicle arrangements.

The withdrawable circuit breaker shown in Figure 9.30 is a Merlin Gerin *Masterpact* unit - one of a range in ratings from 800 A to 3200 A, sharing one single overall size with common panel door cut-out and fixing dimensions. This allows the switchboard builder to rationalize on cubicle metalwork and to provide for future plant growth by including spare, standard-dimension, breaker compartments.

In all the breakers illustrated, full access is available to components for inspection and routine maintenance once a breaker has been retracted into its removal position (see Figure 9.28). However, since it may be necessary to completely remove units from a switchboard either for replacement or for bench repairs, it is wise to provide 'transporter' facilities that are specifically designed for the task. This is especially desirable where heavy units are stacked in high positions (a 2500 A breaker module may weigh as much as 90 kg) A typical transporter is the so-called *lifter* available from Terasaki and illustrated in Figure 9.31.

The standard and optional features available on breakers will, perforce, vary from one manufacturer to the next. The one feature that the three units illustrated have in common is the inclusion of solid-state, adjustable, overcurrent protection. The extent of the protection provided varies from the single' inverse characteristic of the Ellison GEA, through the multi-characteristic capability (including earth-fault protection) provided on the Terasaki AT, to the universal control unit of the Merlin Gerin *Masterpact.* The latter, which is microprocessor based, offers alarm self-monitoring, contact wear indication, over-temperature alarm, and watchdog alarm for the electronics. It also gives remote transmission of data (to a programmable controller) on all settings, fault currents, alarm self-monitors and maintenance indicators.

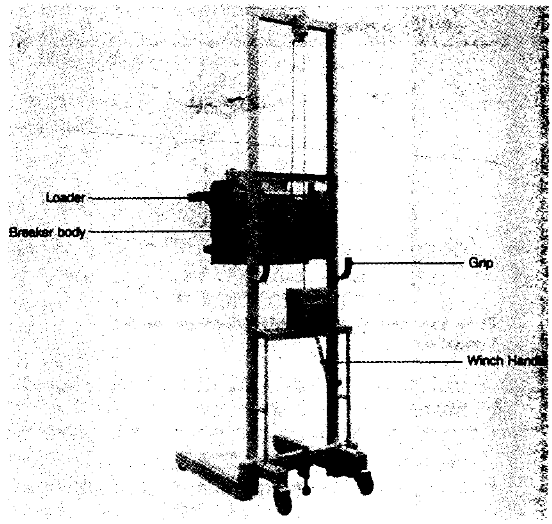



**Figure** 9.31 Example of a transporter for removing and replacing circuit breakers fitted to switchboards (Courtesy: Terasaki Europe Ltd)

Closing mechanisms are of the stored energy type, using a spring which is either manually charged by pumping a lever, or automatically charged by means of an electric motor. When the PUSH TO CLOSE button is pressed, the spring is released to close the breaker. With the breaker closed, the motor automatically starts to charge the spring ready for the next closing operation. Slow-close devices, operative only when the breaker is in the fully-withdrawn position, are provided for breaker inspection and maintenance purposes.

Where a remote control facility is required, breakers may be fitted with solenoid operated mechanisms. The solenoid supply is taken from the 'live' side of the circuit breaker. The closing contactor, the rectifier, and the anti-hunting (or anti-pumping) relay are then integrally mounted on the breaker. The supply for the closing contactor's coil may, if required, be derived from an independent power source (see Section 9.14). In contrast to the continuously-rated operating coils used in contactors, a breaker's closing coil is short-term rated. Its circuit is therefore interrupted by means of an auxiliary contact on the breaker - after the closing operation is completed. The anti-hunting relay prevents protracted operation of the closing solenoid when attempts are made to close against a short-circuit. In this way, continuous CLOSE-TRIP sequences (or breaker 'pumping') are avoided - even if the initial CLOSE command is maintained.

Breakers are fitted with two voltage-operated auxiliary trips which operate to release the latch on the opening mechanism. The first of these is the *shunt trip* coil which must be energized to open the breaker. It is usually wound for a fixed voltage (between 0.5 and 1.1 p.u.). An adjustable return spring is sometimes fitted to allow precise setting of the trip's response value. Because the coil is only short-term rated it must be isolated through an auxiliary switch once the breaker has opened. The shunt release is used for remote control of the breaker either through a pushbutton or through the contacts of a protective relay(s).

The second device is an *under-voltage trip.* It acts to automatically open the breaker when its control power voltage drops below a predetermined value - typically, 30 to 65 % of nominal. This is called the *drop-out voltage.* The breaker must, however, be capable of reliably reclosing at 80 % of rated voltage. Under-voltage trips include a *drop-out delay* feature. An adjustable delay mechanism retards the action of the trip's magnetic armature when voltage falls below the preset drop-out level. Should the voltage then recover to a value above the adjustable *pick-up* or *reset* level (say, 90 % of nominal) before the time lag expires, breaker tripping is inhibited. The under-voltage trip coil is continuously rated.

The *draw-out type* breaker is best suited to those installations where routine switchgear maintenance has to be undertaken with the main busbars live. This is of particular significance in shipboard installations where it is rare for the bars to be made dead after the ship enters service - electrical supply of some sort is always needed. Even in dry-dock a shore supply will be taken [13]. On marine installations space limitations usually preclude the adoption of duplicate bus bars and single sectionalized systems are employed (see Section 9.3.2). Using withdrawable breakers also means that it is possible to carry spare unit(s) for replacement of faulty or suspect equipment.

An interesting variation on the straight horizontal draw-out arrangement is that provided for the Westinghouse insulation-encased SPB system's Pow-R circuit breakers, where a rotating facility is incorporated in the draw-out rail design to give easier inspection of the moving primary and secondary contacts. (see Figure 9.32.)

In industrial applications, where space is not usually a critical problem, the *fixed type* a.c.b. offers a very compact and cost-benefical alternative to its corresponding draw-out version. Figure 9.33 shows the Ellison GEA breaker (of Figure 9.29) in its fixed form. The unit is fitted with a small front plate with provision for interlocking with the switchboard's hinged front door. The applicable standard and optional features of its draw-out counterpart are available. Separate means of breaker isolation must be provided as discussed in Section 9.3.

Our examples have been concerned with low-voltage (up to 600 V) circuit breakers. High-voltage

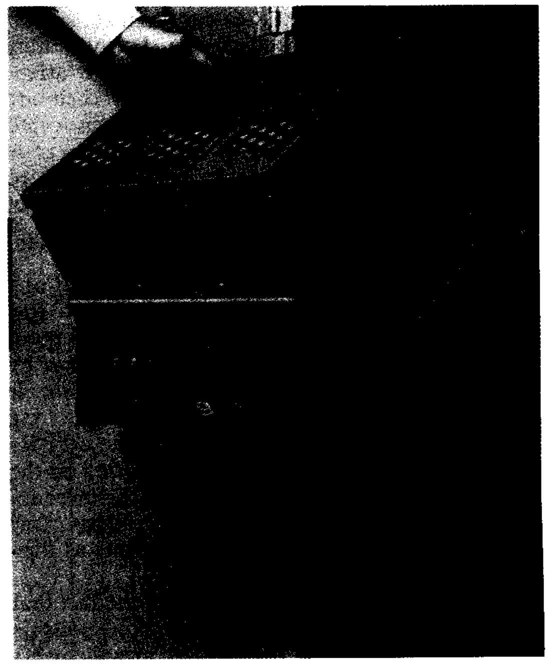


Figure 9.32 An insulation-encased breaker rotatable on its draw-out rail for moving contacts inspection (Courtesy: Westinghouse Electric Corporation)

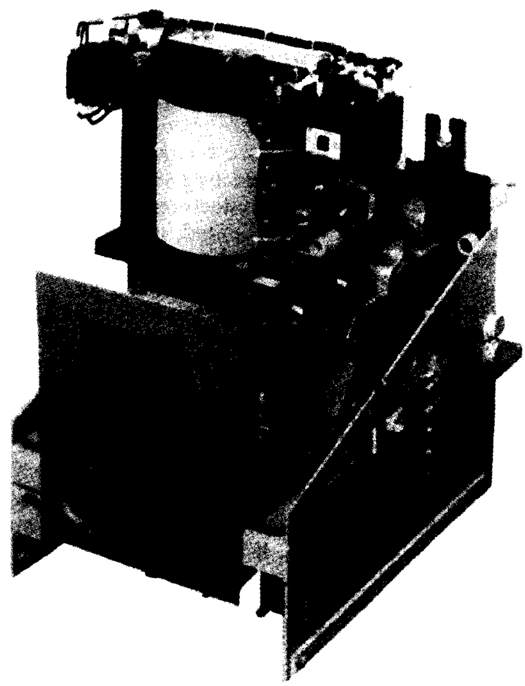


**Figure** 9.33 The fixed-mounting version of the circuit breaker illustrated in Figure 9.29 (Courtesy: George Ellison Ltd) breakers in the air-break category have similar current-interrupting capacities but, because they operate at much higher voltages, particular attention needs to be paid to the design of their arc control mechanisms. Something more sophisticated than the arc chamber used in the LV breaker is necessary if dimensions are to be contained to practical proportions. Accordingly, use is made of chambers in which the arc path follows a zig-zag, spiral or other form [4].

Also, because the arc-lengthening effect of any magnetic blow-out device is impaired when low inductive currents have to be interrupted, it is usual to assist the progress of the arc into its chamber by employing an *air puffer.* One such device uses afrair cylinder whose piston is actuated from the operating shaft of the breaker. The outlet port of the cylinder is connected through tubing to nozzles fitted on the moving contact arms. The geometry of the mechanism is so arranged that the nozzles direct blasts of air into the arc zone from below the contacts as they part [4].

Breaker size and weight accounts for the fact that horizontal withdrawal on floor-mounted rails is usual, and that single-tier switchboard arrangements are the recognized standard. Breakers of this type may be used in the 3.3 to 11 kV range. In practice, vacuum and $SF_6$ breakers now tend to predominate above 3.3 kV.

### 9.9.2 Moulded case circuit breakers (m.c.c.b.s)

A moulded case circuit breaker is a low-voltage switching and automatic protective device assembled in a moulded plastic housing. The nature of the sealed enclosure makes it a non-maintainable device. Since inspection of contacts cannot be made, replacement or, at best, limited re-use are the recommended actions after high fault current breaking.

An m.c.c. b is capable of clearing a fault in half the time taken by a conventional air-break circuit breaker of the same rating, but it cannot claim all the advantages of the a.c.b .. Its biggest limitation is that it is only a light-service device, and is incapable of repeatedly interrupting fault currents at its rated capacity.

However, because it is a versatile, low cost device it is likely to be used as the main output switch on small mobile generators. It may also be incorporated into load transfer switches of the type described in Section 9.7.4. More often than not it will be used as the feeder breaker in the power distribution sections of composite switchboards.

M.c.c.b.s are available in ratings from 100 A to about 2500 A. They are broadly classified by the type of trip unit fitted. At the lower end of the range, breakers usually have *thermal and magnetic trips* of the non-adjustable (fixed) type. The trip for each pole of the breaker consists of a thermal bimetal element giving inverse time-delayed overload protection. The magnetic element affords instantaneous short-circuit protection. On breakeR above about 225 A rating, thermal magnetic trip units are generally interchangeable within any given breaker frame size. In such cases the magnetic trip settings are adjustable. Some manufacturers offer low magnetic setting releases and solid-state trip devices specifically intended for the protection of generators against short-circuit.

Breakers used for motor or feeder circuits (where overload protection is affected by other downstream devices) may have only magnetic elements fitted-to give tripping at currents equal to or above the trip setting. Adjustment between about 2.5 to 10 times rated current is then possible. Trip elements are arranged to operate a common trip bar which opens all the poles in a multi-pole breaker. Shunt trip coils may be fitted to give remote tripping. After shunt trip operation the breaker must be reset before it is re-c1osed. Under-voltage releases are another option.

Solid-state overload tripping has become increasingly available. Its advantages include:

1. improved levels of accuracy and repeatability, compared with thermal magnetic trips;
2. an adjustable, narrow, and predictable operating band which helps in system discrimination (see the discussions in Section 9.12); and
3. a wide range of current adjustment, giving increased flexibility of application.

Care should be exercised when applying solid-state trip devices to loads having other than pure sinusoidal current wave-forms. Predictable operation may not be guaranteed in such cases [3]. On generator breakers the minimum short-time current setting should be just below the machine's short-circuit current level. For example, 1.5 times for a generator whose short-circuit current limit is 2 x f.l.c ..

The block schematic diagram of a typical solid-state trip unit is shown in Figure 9.34(a). The power required to operate the circuits and the magnetic trip coil is derived directly from the current transformers within the overload device - so that no external power source is necessary. The typical time current curves of Figure 9.34(b) show the relationship between the long-time, short-time, and instantaneous tripping characteristics.

Like other a.c.b.s, Imoulded case circuit breakers are *tripfree* switching devices. This means that if the manual operating toggle is held in the ON position, the breaker will stilI trip on overload or short-circuit. This is an essential safety feature for operating personnel. Motor-operated mechanisms may be fitted to give open, close, and reset control from remote locations.

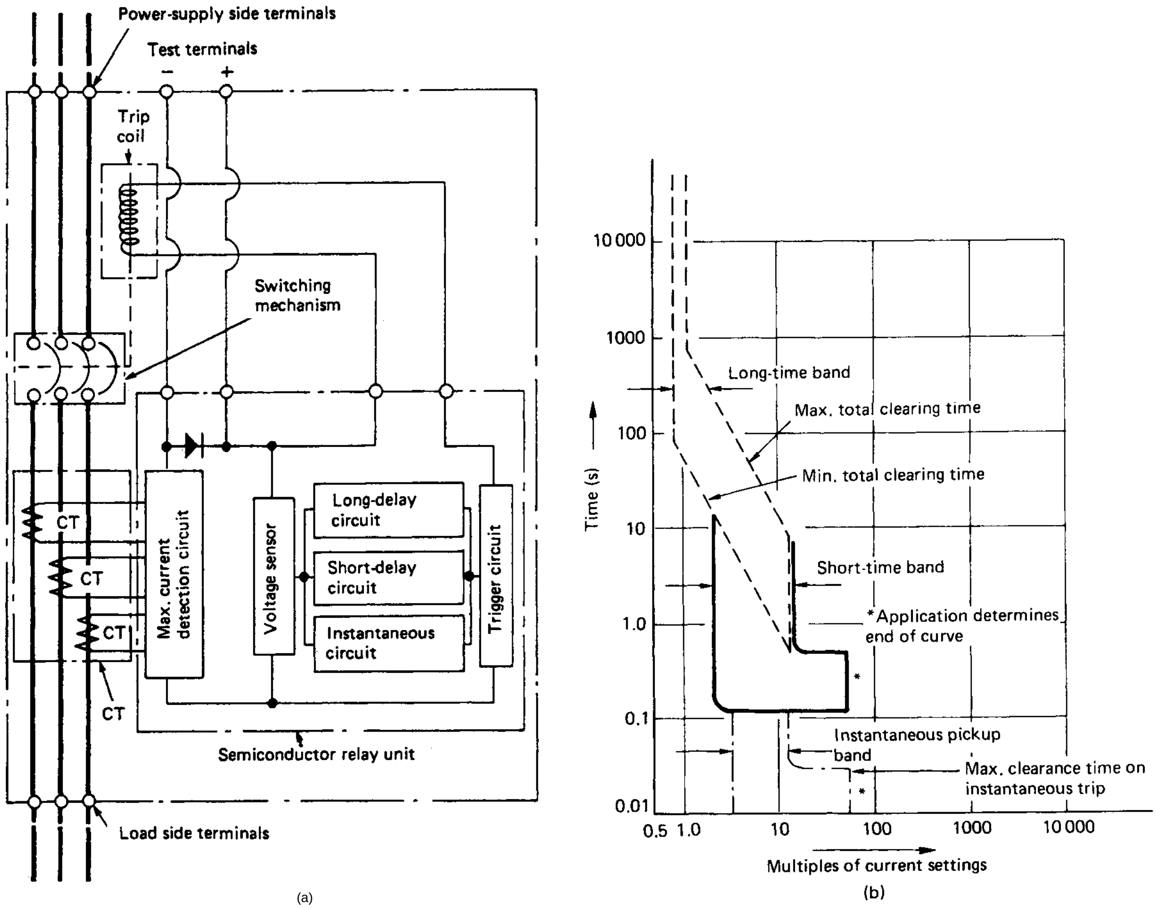



Figure 9.34 Block schematic. and time delay instantaneous time-current curves for an electronically controlled m.c.c.b. (al Block schematic of trip circuits (Courtesy: Mitsubishi Electric Corporation) (b) Typical time-current characteristics for solid state trip breaker

## 9.9.3 Current limiting breakers

Especially designed current-limiting a.c. b.s and m.c.c.b.s are available which have higher interrupting capacities than their 'standard' counterparts. Their salient feature is that they act in the same way as an h.Lc. fuse in limiting the let-through fault current and energy levels when a load-side short-circuit occurs. They achieve this by using ultra-rapid trip devices to cut off the prospective fault current at a level well below its peak value (see Figure 9.35). The breaker contacts are separated within a period of about one-quarter to one-half of a cycle after the short-circuit occurs. Looping the conductors attached to the main contacts assists in speeding-up contact separation. This is because the fault current flowing in opposite directions in the parallel conductor arrangement creates an electrodynamic

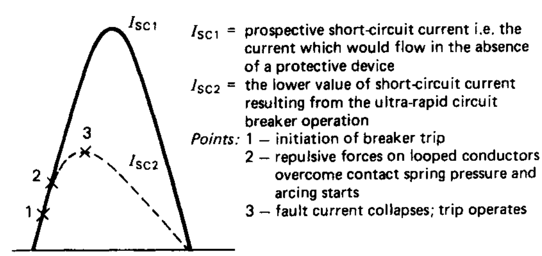



Figure 9.35 The high speed current-limiting a.c.b.'s current cut-off characteristics (Courtesy: Brush Switchgear Ltd)

repulsive force (proportional to the square of the current) between the conductors.

Breakers of this type also employ conventional thermaUmagnetic releases in addition to the current-limiting feature. Protection actions are then co-ordinated so that overload currents are cleared by the thermal trip, short-circuits of relatively low magnitude are cleared by the magnetic release, and high fault currents, above a predetermined point, are cleared by the ultra-rapid trip mechanism. The current-limiting feature is not affected when the thermal and/or magnetic releases function. Solid-state tripping devices may be used instead of the thermaVmagnetic type.

Current limitation offers the following advantages:

1. it enhances protection of associated apparatus (e.g. bus bars and conductors) by reducing the thermal and electrodynamic stresses placed upon them;
2. it can help in reducing the cost of an installation by lowering the performance requirements of switching apparatus located on the load side of the 'limiter';
3. it gives improvement in line- or source-side discrimination by reducing the short-circuit current (by the action of the 'limiter') on the load side; and
4. it provides the ability to interrupt high short-circuit currents, using smaller equipment.

On the debit side, the fast fault-clearance may cause transient over-voltages which could be detrimental to power system components and motors, in particular.

## 9.10 Vacuum circuit breakers

The heart of the vacuum circuit breaker (v.c.b.) is the *vacuum interrupter* or *vacuum switch.* It owes its effectiveness as a current interrupting device to the insulating properties of a vacuum. A comparison of the dielectric strengths of air, $SF_6$ and a vacuum is given in Figure 9.36.

The higher the degree of vacuum the better the dielectric strength. Most commercial equipment is designed for a 20-year life span, and a vacuum environment of $10^{-5}$ to $10^{-7}$ torr has been found to be consistent with the expected contact wear rate over such a period, for circuit breaker duty. *(Note:* the *torr* is the unit of pressure used in high-vacuum technology. It is equivalent to 1 mm of mercury and equals 133.3 N/m$^2$ or $1.33 \times 10^{-3}$ bar.)

### 9.10.1 The interrupter

Since pioneering work commenced in the 1920s, development has been directed to the problems of vacuum sealing and envelope evacuation, and finding suitable contact materials that include negligible gases but produce sufficient metal vapour to sustain a stable arc down to low current levels, and still withstand high current arcing without gross melting.

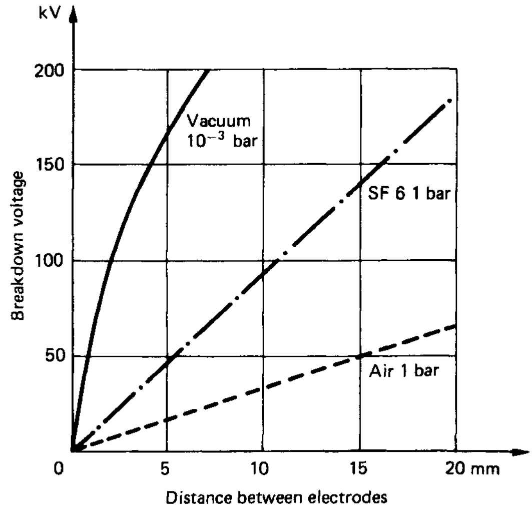



Figure 9.36 Comparison of dielectric strengths of air, $SF_6$ and vacuum

Several proprietary designs have emerged. AU, however, employ the same basic principles of operation and are essentially similar in concept. Figure 9.37 is the cut-away view of a typical interrupter. The main contacts are housed within a vacuum in a sealed ceramic or vitrified glass envelope. In the individual design illustrated, twin envelopes (E) are joined by metal seals and closed by metal end plates. One plate carries the fixed contact stem (G). The other carries a metal bellows (B), which provides a positive flexible vacuum seal to the axially-moving contact stem (N). Internal concentric metal shields (S) surround the contacts (F and M). The breaker operating drive is attached to the moving stem (N). Main circuit connections are made to G and N. Contact rating is affected by total contact pressure.

The bellows (B) is an important factor in the mechanical life of the interrupter. Its metal fatigue is proportional to the travel of the stem N, and to the number of switching operations. One end of the bellows is sealed to the end plate and the other to the moving contact stem. The atmospheric pressure outside the sealed envelope acts to close the butt contacts with a pressure related to the effective area of the bellows [14].

The internal metal shields (S) serve to protect .the inner surfaces of the envelope from the arc products (heat and metal vapour). They also control the electrical stress along the surface of the envelope when the contacts are open and voltage appears across the interrupter. Shield T protects the bellows.

Turning now to the contacts themselves. Two forms of interrupter have been developed. The first is applied to contactors calling for frequent making and breaking of motor starting and load currents. The second is used in circuit breakers where the

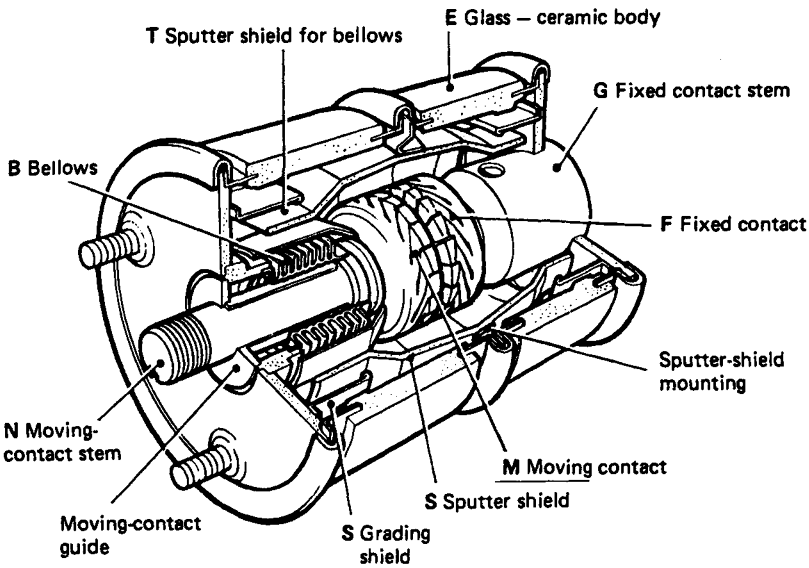



**Figure 9.37** Interior view of a typical vacuum interrupter (Courtesy: Brush Switchgear Ltd)

device is required to interrupt and make on large fault currents (albeit for a limited number of operations - measured in hundredths of those required on contactor duty), and must have a corresponding through-fault capacity. Not surprisingly, different contact materials are used in each case.

Contacts placed in a vacuum will tend to weld, even without current flowing, due to the purity of contact materials and the absence of any atmosphere to contaminate the surfaces [14]. To overcome this natural tendency, the contacts must be soft enough to be broken when they are required to be opened. The arc which forms on separation vaporizes on the surfaces of the contacts. This vapour then condenses on the contact surfaces when the current passes through a 'zero' and is interrupted.

The properties required of contact materials in circuit breaker application include [15]:

1. good mechanical strength and electrical conductivity;
2. good thermal conductivity - to assist rapid cooling of the arc roots;
3. sufficient metal vapour from low-current arcing to control *current chopping* (discussed later in this sub-section);
4. at the other end of the scale, limitation of metal vapour and thermionic emission from high-current arcing, to permit voltage recovery at current zero;
5. low weld and cold adhesion strengths at the contacting surfaces to give easy and consistent separation;
6. surfaces of sufficient smoothness to preserve the electric strength of the gap on contact separation; and
7. low and uniform erosion to give a long contact life.

Since no single metal has all these characteristics, mixtures have been evolved by manufacturers. These may range from alloys having copper as the basic material, to a sintered matrix consisting of a semi-refractory porous base infiltrated with a softer metal such as chromium or copper [15].

The interrupters used in contactors have plain-disc butt contacts and, because the switch actuating mechanisms provide a 'snatching' action, arcs up to 10 kA are naturally diffused and easily extinguished. Above this current level the arc, if stationary, concentrates towards a single spot on the contact surface, causing local overheating which cannot cool fast enough at current zero to prevent re-ignition of the arc. Merely increasing the size of the contacts is of little use because the overheating is local [15]. A different contact geometry is therefore necessary for v.c.b. interrupters where arcs in excess of 10kA peak must be extinguished.

One solution to this problem is to use contacts of the type illustrated in Figure 9.37. The design philosophy is to induce the arc to keep moving over the contact surface so that it remains diffused and local overheating is avoided. By doing this, and also changing the size of contact, it is then possible to increase the current interrupting ability of the switch.

Two contact forms may be employed, in both of which the current path is manipulated in such a way as to achieve self-induced electromagnetic movement of the arc. In the first, the contacts are modified discs with contacting hubs. Each contact has a regular pattern of slots curling outwards from its hub, producing a series of curved fingers. As the contacts open, an arc appears between the opposite hubs and moves on to the fingers. The current flowing in opposite matching fingers then produces a self-driving loop to commute the arc around the slotted peripheries. In the second form, the contacts are cup shaped. Here also a regular series of fingers is provided in the contacting rims - by means of slots cut at an angle to the axis. As the contacts open, the arc appearing between the rims is commuted around them by the action of the current flowing in opposite matching fingers. In both forms many moving parallel arcs are spread around the contacts at high currents.

The phenomenon known as *current chopping* occurs on any type of circuit breaker where the current is interrupted before its natural periodic zero (i.e when it is prematurely forced to zero). This abrupt change in the current level causes a surge voltage to be generated in any circuit containing inductance and capacitance. The magnitude of the surge will depend upon the value of the current 'chopped' and the power factor of the circuit switched. The voltage manifests itself as a damped oscillatory transient superimposed on the power supply wave-form. The frequency of the oscillations is also dependent upon the circuit parameters. (The reader's attention is directed to [16] for a fuller treatment on switching surges during circuit interruption.)

The wave-forms of Figure 9.38 [17] illustrate two hypothetical cases, one at zero power factor and the other at near unity. The same circuit impedances are assumed in each case (i.e the same transient amplitude) .

The fitting of surge suppression devices in sensitive network elements, or the improvement of system power factor (to as near unity as possible), are two of the methods used to minimize the detrimental effect of potential stresses. It is also possible to eliminate, or to reduce, current chopping in vacuum interrupters by using contact materials with high vapour pressures. Unfortunately, lowering the current chopping value also lowers the ultimate breaking capacity of the interrupter. A compromise has, therefore, to be reached in contact design for specific ratings and duties [17].

## 9.10.2 Examples of v.c.b.s

Turning now to examples of proprietary v.c.b.s. Early models designed to replace manufacturers' obsolescent oil-insulated breakers were constrained to follow the dimensional needs of existing fixed housings. Later, as v.c.b. s came to be increasingly accepted as an attractive alternative to the a.c.b., manufacturers began to develop more compact equipment, making no concessions to requirements for interchangeability with breakers working on different arc-quenching principles.

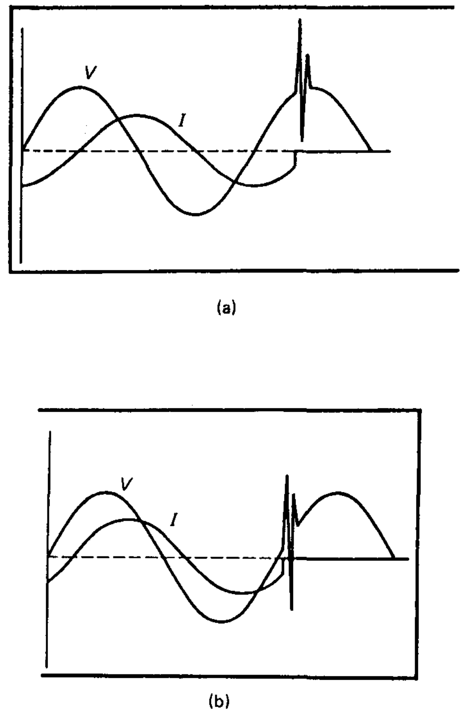



Figure 9.38 Voltage transients due to chopping the load current at the same amplitude (a) Close to zero power factor lagging (b) Close to unity power factor (Courtesy: *Electrical Review)*

Two basic forms are now used in indoor switchgear; the vertically-isolated, horizontally withdrawn type, and the horizontally-isolated type.

The former may be used with either single or double busbar configurations. A typical example is the Brush Switchgear type VMV equipment. The breaker is mounted in a folded steel carriage unit (see Figure 9.39). Vertical movement is effected by a scissor type jacking device. Interlocks prevent a breaker being inserted into its housing within the switchboard unless it is in the ISOLA TED position, and it cannot be closed unless it is in the ENGAGED or ISOLATED position. Also, it cannot be raised or lowered unless it is OPEN.

The fixed housing consists of two parts. The bottom housing into which the circuit breaker is inserted contains the safety shutters, selector mechanism, and earth connections. It also has a removable, hinged, flush-front door fitted with a window which coincides with the breaker's ON/OFF indicator. The top housing contains the instrument,

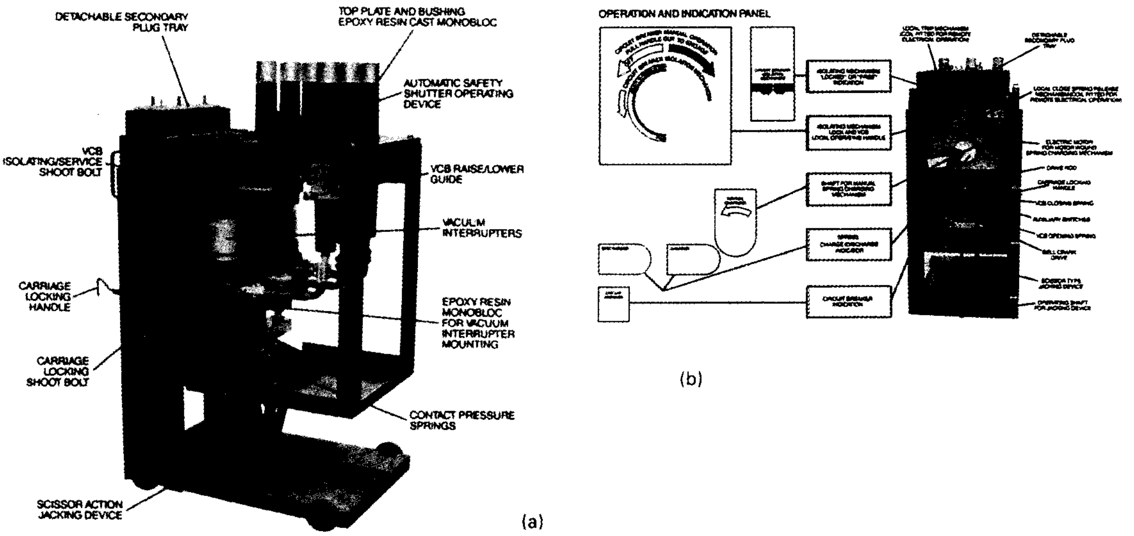



Figure 9.39 The carriage of a vertically-isolated vacuum circuit breaker (a) Carriage withdrawn from its fixed housing (b) Front view of unit with front covers removed (Courtesy: Brush Switchgear Ltd)

busbar, and current transformer chambers. When required, a further chamber may be added to accommodate protective relays and voltage transformers (see Figure 9.40).

Integral earthing is provided on each unit for both single and double busbar arrangements (see Figure 9.41). Single busbar units are fitted with three earthed contacts in front of the busbar spouts and with similar contacts to the rear of the circuit spouts. To earth the busbars, the breaker is raised to its ENGAGED height with the carriage forward of its normal service position. The breaker may then be closed to make a direct connection between the busbars and earth (through the v.c.b.). The 'circuit' side is earthed in a similar manner by raising the breaker in a position to the rear of its normal service position (see Figure 9.41(a).

The three carriage positions are labelled BUSBAR EARTH, NORMAL SERVICE, and CIRCUIT EARTH. Positive location of all three positions is achieved by means of a selector device situated inside the fixed bottom housing. This selector may be set to indicate the required position when the breaker carriage is withdrawn. The carriage is then re-inserted into the housing and should be stopped at the pre-selected position. In this position, and this one only, a 'shoot bolt' on the carriage moves across to engage a hole in the selector device (see Figure 9.39(a». The v.c.b. may then be raised. Padlocking facilities are provided for all positions and to restrict selection to any specified position.

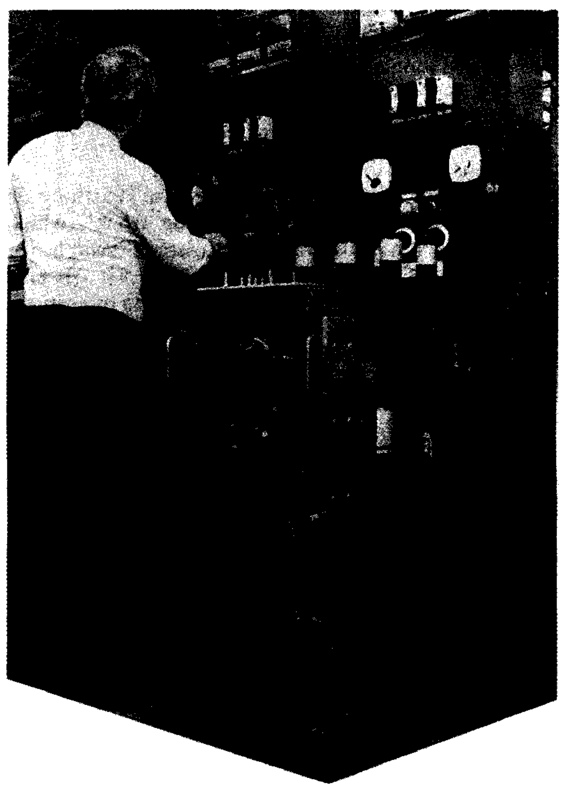


Figure 9.40 The v.c.b. carriage unit illustrated in Figure 9.39 withdrawn from its fixed housing and in the service 'free' position (Courtesy: Brush Switchgear Ltd)

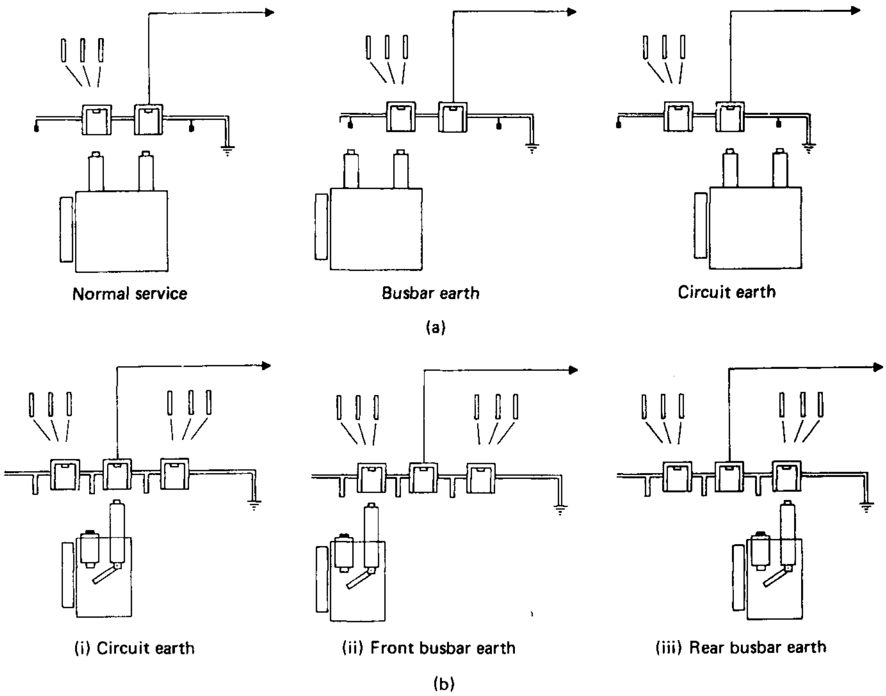



Figure 9.41 Integral earthing arrangements for busbars and feeder circuits on switchgear with vertical isolation (a) Service and earthing positions for single busbar units (b) Earthing positions for double busbar units using an Earthing Truck incorporating a fault-making air break switch (Courtesy: Brush Switchgear Ltd)

On double busbar units, integral earthing is achieved by means of an 'earthing truck', which incorporates a fault-making air-break switch for ratings up to 20kA, 12kV (see Figure 9.41(b)). This switch replaces the v.c.b. during earthing operations and uses a similar selector mechanism to that described above for the single busbar units.

An example of a horizontally isolated v.c.b. is shown in Figure 9.42. It is incorporated within the Brush Switchgear type VMH 12 equipment. A fully-rated earth switch, fitted with a removable handle, is operated from the front of the switchboard. Interlocking with the v.c.b. ensures that:

1. the earth switch cannot be operated when the v.c.b. is in the service position; and
2. with the earth switch closed, the v.c.b. cannot be inserted into its service position.

Additional interlocks prevent the breaker being 'closed' unless the carriage locking mechanism is in the LOCKED position. Also, the 'carriage lock' is only operable when the truck is in its SERVICE, ISOLATED or WITHDRAWN positions.

In common with most proprietary v.c.b.s, the units illustrated in Figures 9.40 and 9.42 may be fitted with a motor-charged or a manually-charged spring stored-energy mechanism, giving remote electrical or local mechanical operation. The very low operating energy of the breakers allows protective relays and instruments to be panel mounted in the switchboards, as shown in the illustrations.

Evidence of market acceptance of vacuum technology as a switching medium is provided by the fact that one of the leading manufacturers in the field (Siemens) produces some 11,000 triple-pole v.c.b.s per year, and that its production ratio of v.c.b.s to minimum-oil breakers is 9:1 [18].

## 9.11 Sulphur hexafluoride circuit breakers

Pressurized sulphur hexafluoride gas ($SF_6$) makes an excellent alternative to air as an interrupting medium in HV application. At a pressure of 0.9 bar above atmosphere, its dielectric strength is equivalent to that of high-grade switch oil.

It is a colourless, odourless, non-toxic, non-flammable, and chemically stable, electro-negative gas. The last-mentioned property makes it a good arc-quenching medium because its molecules readily adsorb the free electrons produced by an arc. At

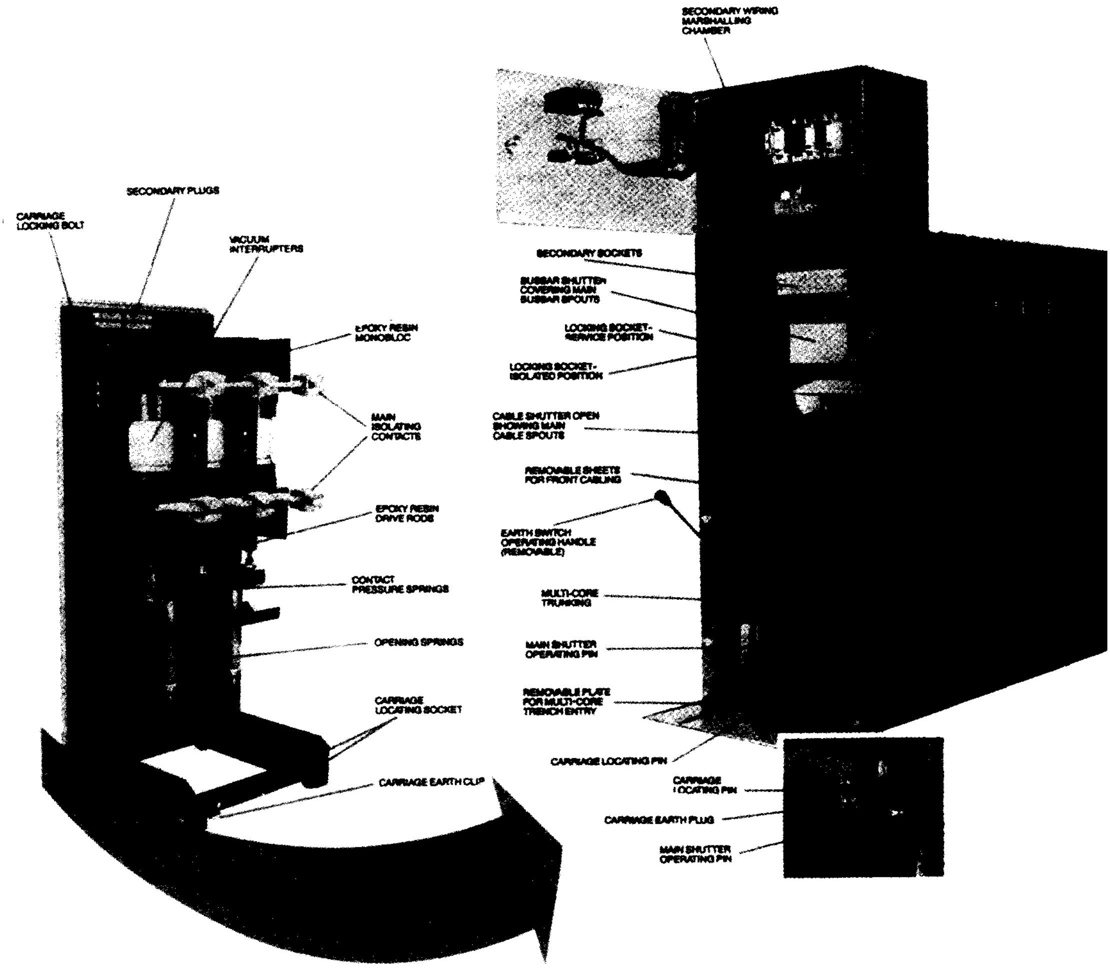



**Figure** 9.42 Vacuum switchgear with horizontal isolation (Courtesy: Brush Switchgear Ltd)

current zero the arc path is therefore quickly converted from a relatively good conductor to a very good insulator [6]. Also, at the temperature at which molecular decomposition *(dissociation)* occurs, the gas has a very high specific heat. The resulting high thermal conductivity provides good heat transfer from the arc and assists in the quenching process. The *dissociation products* following arc exposure largely recombine on cooling the gas. Any products that remain after arc extinction are usually adsorbed by filter packs provided within the breaker's enclosure (see Figures 9.44 and 9.46).

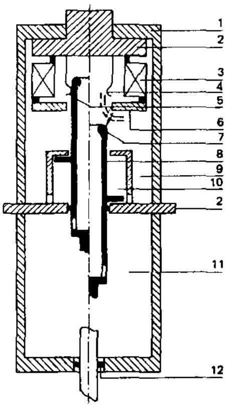
In the high voltage range we are considering (up to 15 kV), $SF_6$ circuit breakers are of the *self-extinguishing* type using a mechanically produced gas blast (a *puffer system)* and/or a magnetically rotating arc. The diagrams of Figures 9.43 to 9.47 illustrate the principles of operation and typical interrupter constructions.

### 9.11.1 Gas **blast or putTer type interrupters**

These use the forces created by the arc itself (or by the movement of the separating contacts) to generate the gas pressure required for arc extinction within a closed gas circuit.

The basic construction of the arc-quenching chamber of the first of our proprietary examples, the ABB type HB breaker, is shown in Figure 9.43. The chamber, which is filled with $SF_6$ gas, is subdivided into a pressurized space (9) and an exhaust space (11).

During an arc interruption, the stationary gas in space 9 is rapidly heated. At or near the dissociation temperature it expands significantly. This expansion is used to generate pressure. The purpose of the cylindrical coil 3 is to give rapid rotation of the arc around the main contacts. The way it does this is explained later in discussion of the rotating arc type



—— Magnetic flux lines
1 = Interrupting chamber
2 = Fixed contact
3 = Cylindrical coil
4 = Arcing fingers
5 = Contact fingers
6 = Annular arcing electrode
7 = Nozzle
S = Moving contact
9 = Pressurized space
10 = Blasting aid
11 = Exhaust space
12 = Seal against atmosphere

Left of centre-line: circuit-breaker closed
Right of centre-line: circuit-breaker open

Figure 9.43 The basic construction of an arc-quenching chamber of one proprietary type of SF. circuit breaker (Courtesy: ABB Ltd)

interrupter (see Figure 9.47). The effect of the arc rotation is to cause the gas in space 9 to be heated even quicker than it would otherwise have been. The heated gas flows through the moving contact (8) into the exhaust space 11, effectively blasting the arc axially in the nozzle 7. Gas flow, and hence its extinguishing influence, depends upon the current. The blasting aid (10) is so designed as to give intensive arc-blasting at high currents (i.e. short-circuit currents) and gentler blasting at low currents. This accounts for the good over-voltage behaviour of the breaker [19].

Figure 9.44 is a cutaway illustration of the type HB breaker, rated for up to 36 kV and 2500 A, and for short-circuit breaking up to 43.5 kA.

The second example is the Yorkshire Switchgear type YSF6 breaker illustrated in Figures 9.45 and 9.46. The moving portion of the unit assembly is a 4-wheeled truck which carries the circuit-breaking system, its operating mechanism, the moving isolating contacts, controls and indicators. As shown in Figure 9.45(b), all three breaker chambers and their associated isolating contact bushings are contained within a single cast resin moulding. The chambers are arranged in a trefoil configuration.

The truck is pushed into the fixed housing until it comes to a stop with the moving isolating contacts sufficiently clear of the fixed contacts to avoid discharge. The last few centimetres of travel (i.e. to contact touch and on to full engagement) is controlled by a detachable winding handle. Interlocks ensure that the moving element of the breaker can only be plugged-in or withdrawn when the circuit breaker is OPEN, and that the breaker can only be CLOSED when the moving portion is fully plugged-in or withdrawn.

Where switchboards are equipped with duplicate busbars or transfer earthing systems, a screw-jack elevating mechanism is employed to give alignment of the moving main isolating contacts with the appropriate stationary contacts on the fixed housing. Interlocking then ensures that the unit can only be plugged-in when it is correctly located vertically.

The breaker uses a motor-charged spring type operating mechanism incorporating an emergency manual charging facility. The motor may be arranged for local, remote or automatic control. The mechanism is so designed that if tripping is initiated during the 'closing' stroke, the contacts will continue to close and then immediately re-open. This ensures that a full volume of gas is available beneath the piston for successsful 'puffer' operation.

At 15 kV, the 1250 A rated version of the YSF6 breaker is capable of breaking 25 kA symmetrical current. For this voltage the rated pressure of the $SF_6$ gas within the interrupter chamber is 0.6 bar above atmospheric at 20°e. Total break time from application of tripping voltage to the instant of final arc extinction is of the order of 50 ms.

In ABB's type HB interrupter we saw that the gas pressure required to extinguish the arc was assisted by the heating effect of the rotating arc itself. The so-called blasting aid (item 10 in Figure 9.43) merely acted as an auxiliary puffer supporting the build-up of pressure at low currents and ensuring dependable current interruption over the entire breaking-current range. Gas flow, and hence the intensity of the cooling effect on the arc were dependent upon the current.

The YSF6's interrupter differs from this in that arc rotation is not employed, and reliance is placed on mechanical compression of the gas by a more conventional puffer system using the movement of the contacts themselves to pressurize the gas. The interrupter works on the principle of sweeping a specific volume of $SF_6$ gas axially along the arc to cool, de-ionize, and strip-off the outer layers of its plasma core until total current extinction is achieved.

The 'puffer' interrupters described above are said to be of the single-pressure, mono-blast type. They are not to be confused with those types to be found in EHV breakers which use duo-blast techniques and where the gas is directed at the arc in two opposite directions.

## 9.11.2 The rotating arc interrupter

This type of interrupter operates on the principle used in electric motor design, where Fleming's left-hand rule governs the space relationships of current, magnetic flux, and conductor motion when a current-carrying conductor is suspended in an electromagnetic field (see Figure 9.47). The arc at the fixed contact end rapidly transfers, under electromagnetic force, to a metal former within the interrupter coil, bringing the coil into the electrical

1 - Interrupting chamber
2 - Fixed contact
3 - Cylindrical coil
4 - Arcing fingers
5 - Contact fingers
6 - Annular arcing electrode
7 - Nozzle
8 - *Moving* contact
9 - Pressurized space
10 - Blasting aid
11 - Exhaust space
,2 - Seal against atmosphere
13 - Crank housing
14 - Operating shaft
15 - Tension rod
16 - Springs
17 - Rewind motor
18 - Manual rewind unit
19 - Adsorber

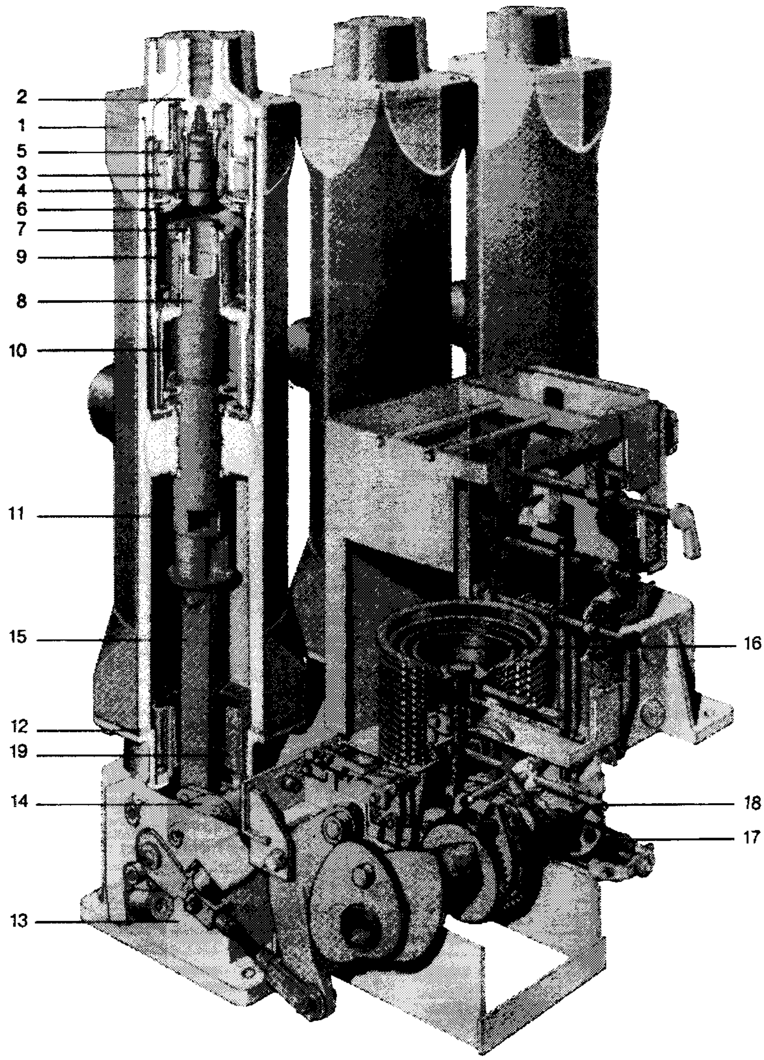



Figure 9.44 ABB series HB self-extinguishing SF. circuit breaker (Courtesy: ABB Ltd)

circuit. Once the coil is in circuit, the electromagnetic field produced by the current in it acts at right-angles to the arc column causing the arc to rotate at high speed within the coil former. This high speed rotation brings the arc into contact with cool $SF_6$ gas which extracts energy from the arc column and leads to extinction at the first available zero [20].

The contact and coil system shown in Figure 9.48(b) is that used by Brush Switchgear in its type PMR pole-mounted $SF_6$ auto-recloser. The nature of the interrupting process is such that it imposes none of the back-forces that are put upon operating mechanisms by the puffer type systems. Low stored-energy drives are therefore possible. The diagram of Figure 9.48(a) shows the operating mechanism used in the Brush Switchgear PMR unit. Closing is achieved by a HV solenoid connected across two phases of the incoming supply. During the closing stroke energy is stored in the spring - ready for a subsequent opening operation. This energy is 'held' by a latch which is released by a small solenoid when the unit is commanded to trip.

### 9.11.3 Gas insulated switchgear

In the late 1970s Siemens introduced a range of $SF_6$-insulated switchgear incorporating v.c.b.s. Since then other manufacturers have put similar equipment on the market. Such gas-insulated metal clad

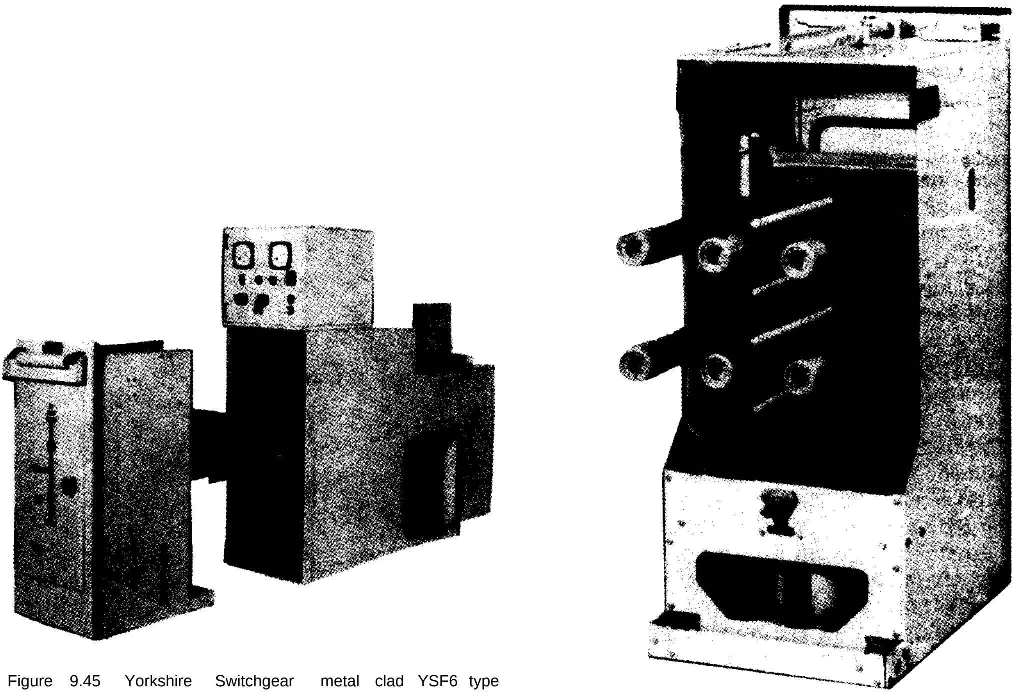
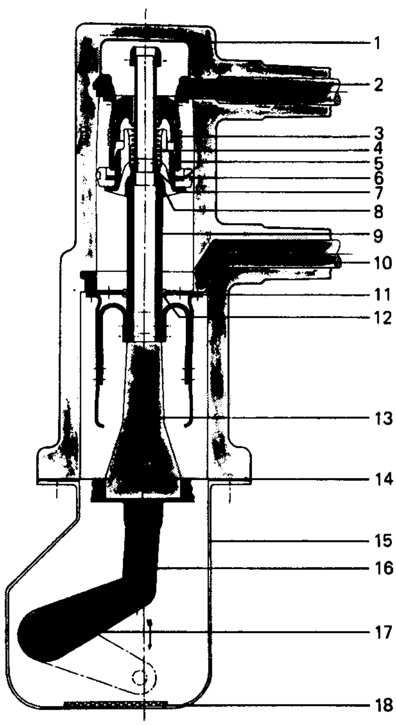


Figure 9.45 Yorkshire Switchgear metal clad YSF6 type circuit breaker. (Courtesy: Yorkshire Switchgear and Engineering Co. Ltd)



1. Cast resin enclosure
2. Upper isolating contact bushing conductor
3. Fixed main contact fingers (sprung)
4. Insulating nozzle
5. Compressor piston/moving main contact
6. Piston ring
7. Upper arcing electrode (spring loaded)
8. Lower arcing electrode
9. Main conductor rod
10. Lower isolating contact bushing conductor
11. Partition and moving connections support frame
12. Insulating bearing
13. Insulated drive link
14. Gas seal
15. Drive housing
16. Drive linkage
17. Input drive shaft with gas seal
18. Adsorbent filter pack

Figure 9.46 Construction, in diagrammatic form, of one phase of the type YSF6 breaker illustrated in Figure 9.45 (Courtesy: Yorkshire Switchgear and Engineering Co. Ltd)

switchgear (GIS) uses $SF_6$ as the insulating medium for the busbars and connections, and vacuum as the interrupting medium for the circuit breakers.. Widely applied in continental Europe, the concepl has not had equal acceptance in the United Kingdom for other than EHV equipment.

The sectional diagrams of Figure 9.49 illustrate one example of a proprietary treatment [21]. 1be ABB EAK switchgear system uses compartmented gas-tight sheet steel enclosures. Each compartment is fitted with pressure relief devices which limit the rise in pressure should an internal arc occur. Nominal working pressure is 0.2 bar. The permitted leakage rate is 1% per year and, at worst, gas may need to be 'topped-up' every five years. Metallic

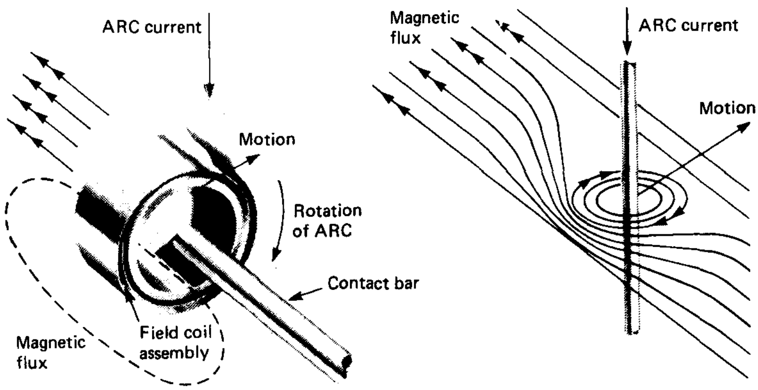
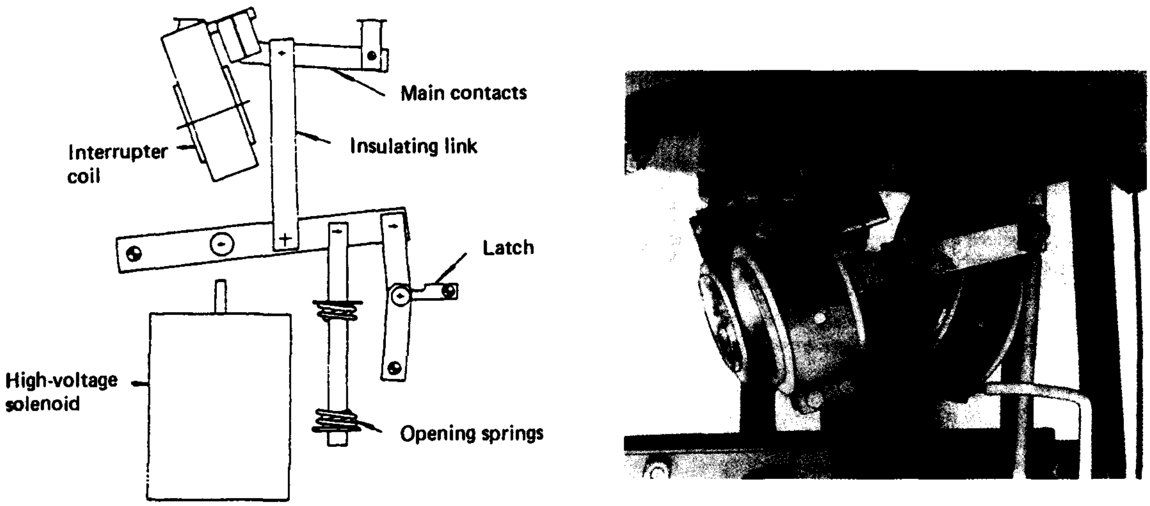



**Figure 9.47** Principle of operation of the rotating arc interrupter (Courtesy: Brush Switchgear Ltd)




(a) (bl

**Figure** 9.48 Interrupter coils and contacts arrangement in the type PMR auto recloser (a) The operating mechanism in diagrammatic form (b) Contact and field coil system within the circuit breaker (Courtesy: Brush Switchgear Lld)

filters fitted between electrically-related compartments permit both joint pressure monitoring and gas refilling. They also prevent internal arc faults spreading to adjoining compartments. Temperature-compensated pressure switches monitor the gas density.

The v.c.bs. are of the fixed (as opposed to the withdrawable) type. Using appropriate equipment it is possible to test the breakers with the gas compartment closed.

G.R. Jones [35] suggests that:

trends have been towards the self-pressurising and electromagnetic rotation type of interrupters, on account of their greater simplicity and in particular the dispensing with expensive and cumbersome operating mechanisms which carry heavy penalties with regard to operating power consumption. Also, ''' $SF_6$ offers advantages (over vacuum interrupters) of a choice of operating principles, reduced operating mechanism powers, and the fact that the end product is under the control of switchgear manufacturers - vacuum interrupters are only available to the switchgear manufacturers as a finished component which requires the fitting of a driving mechanism for conversion into a circuit-breaker.

## 9.12 Discrimination and co-ordination

*Discrimination* is the grading of the load current ratings of protective devices in a distribution system in such a manner that, when a fault occurs, only the device nearest the fault will operate. All other

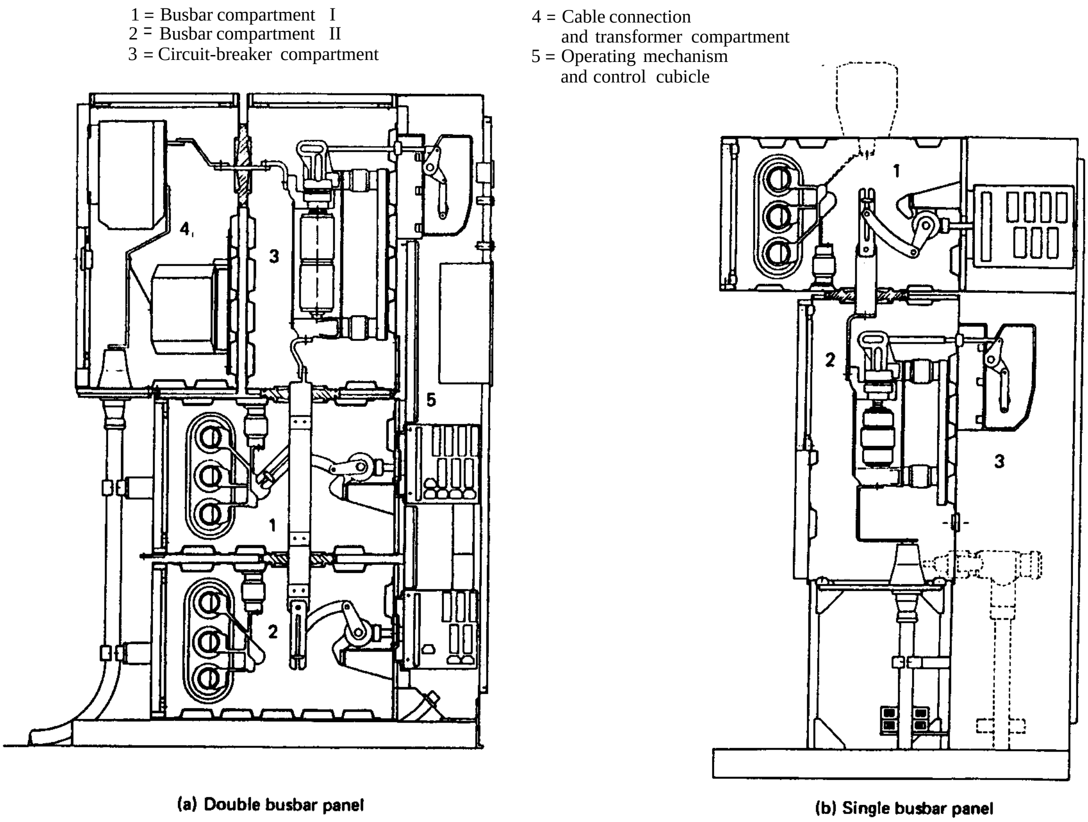



Figure 9.49 Type EAK medium voltage switchgear with v.c.b.s and $SF_S$ gas insulation (Courtesy: ABB Ltd)

higher-rated upstream devices (those nearer the supply source) should not have operated. This ensures that supplies are maintained to healthy circuits.

Effective discrimination between two series protective devices is obtained when the *major* device (the one nearer the power source) is unaffected by fault currents which are cleared by the *minor* (and lower-rated) downstream device. An important consideration in dealing with discrimination at high fault levels is the 'let-through energy' *(]2t)* permitted by devices. For example, to obtain positive discrimination between fuses the total let-through energy of the minor fuse must not exceed that of the pre-arcing value of the major fuse. In the same way, if circuit breakers are employed in series, the total *]2t* value for the major device must be higher than that for the minor device. Also, in order to guarantee discrimination between the breakers at current levels above the instantaneous trip setting of the major unit it is necessary for the latter to have a time-delayed tripping mechanism. *(Note:* In the term *]2t, ]* is the r.m.s. current (the short-circuit current) that passes through the device, and *t* is the time, iD seconds, during which the current is allowed to pass. This time may be the total operating time of a circuil breaker, or that of a protective relay and its associated circuit breaker, or the time that a fuse takes to blow. *]2t* gives a measure of the possible release of energy in a fault. Its dimensions are not those of energy. They only become so when multiplied by those of resistance (i.e. the resistance of the fault [21].)

Series connected overcurrent devices must haw: time-current characteristics that are so *co-ordinatd* as to ensure that selective tripping is achieved. In co-ordination studies, the characteristics of protective devices selected for their ability to meet load current and fault current requirements are plotted on log-log paper. It is important to ensure that the characteristic curves do not overlap and that there is a clear space or time interval between each of them (See Figure 9.51).

Because discrimination and co-ordination are quite complex subjects only a very brief treatment is possible here. (For more detailed coverage, atten-

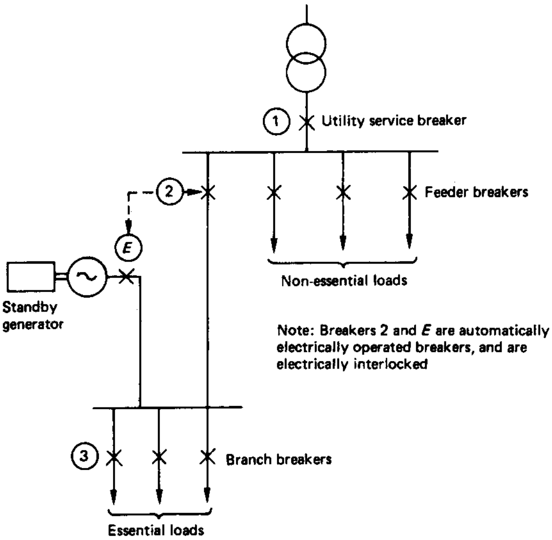



**Figure 9.50** Single-line diagram of a typical emergency generator system

tion is directed to the IEEE series of publications on 'recommended practices', listed in the references - [10] in particular. Co-ordination between direct-tripping devices and overcurrent relays is dealt with in Chapter 10 of this handbook). A simple example illustrating the principles of co-ordination must suffice for our present purposes.

It is worth mentioning here that one of two methods of tripping co-ordination may be applied in practice. The first is a *fully rated* system and the second is a *selective* system. Each affords a different degree of distribution service continuity.

In the *fully rated* system, breakers are rated for the maximum fault level at the point of their installation. All the breakers in the system are fitted with 'dual' trip devices - usually with long-time delay and instantaneous elements. Under normal circumstances the feeder breaker nearest the fault trips. However, if the fault is of sufficient magnitude to exceed the instantaneous trip setting of the main breaker, that breaker will also trip, and service continuity may be lost. This is not necessarily a *hardship* in some applications, where an entire process must be interrupted if one of its constituent operations is stopped. Because 'dual' trip devices cost less than 'selective' trip devices, the fully rated system is less expensive than the selective system.

A *selective* system is a fully rated system with tripping devices chosen and adjusted to provide the desired selectivity in the power installation. The breaker nearest the fault must open to isolate the faulted circuit, while all other breakers remain closed. Maximum service continuity is thus maintained to un-faulted parts of the installation.

In this system the main circuit breaker is fitted with long-time and short-time delay trips. It does not have an instantaneous trip. Feeder breakers are fitted with long-time delay and instantaneous trips. The latter ensure that the feeder breakers clear downstream faults before the short-time trip on the main breaker operates. Where additional discrimination is required with downstream branch breakers, the feeder breaker may be fitted with long- and short-time delay trips but have no instantaneous trip.

There is a third system which may be used, but which does not enjoy universal acceptance since it does not normally provide discrimination. This is the so-called *cascade* system. Here, only the main circuit breaker has adequate interrupting capacity for the maximum available fault current (current-limiting breakers are usually employed for the purpose). Downstream breakers are not rated to handle this level of fault current and must rely on the opening of the main (upstream) breaker for protection. The primary advantage of the system is that of low initial cost because it allows the use of low-fault-level downstream breakers. The 15th Edition of IEE Wiring Regulations normally requires the breaking capacity of a short-circuit protective device to be not less than the prospective short-circuit current at the point of its installation. However, it permits a lower breaking capacity device to be used if another protective device having the required breaking capacity is installed on the supply side (Clause 434-4), i.e. cascade back-up protection.

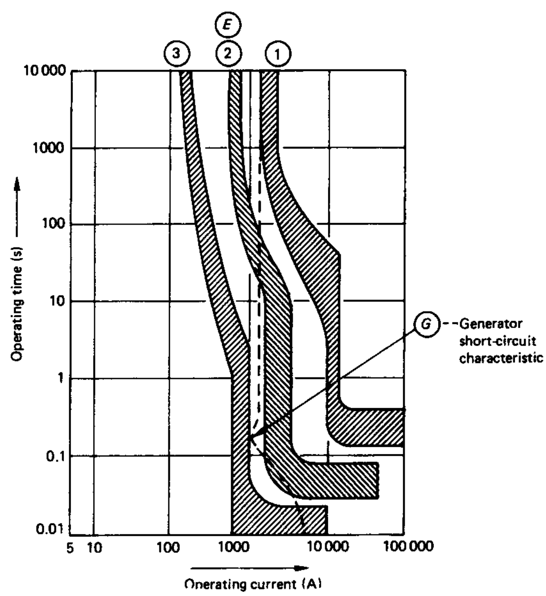



**Figure 9.51** Example of protection co-ordination for the system in Figure 9.50

In the single-line diagram of the emergency generator system shown in Figure 9.50, the series breakers 1 and 2 need to have time-delay in their short-trip regions, while breaker 3 must have an instantaneous trip to give effective co-ordination (see Figure 9.51). Similarly, the non-essential load feeder breakers must have instantaneous trips to co-ordinate with the utility service breaker 1 [22].

The fact that manufacturing tolerances must exist within the breakers, accounts for the 'envelope' form of the characteristics shown in the co-ordination plot of Figure 9.51. This means that, at a given current, a breaker 'will trip somewhere within the minimum and maximum clearance times represented by the thickness of its envelope. This is why it is important that there should be no overlapping of the envelopes if successful co-ordination is to be achieved between breakers fitted with direct-acting trips. A time interval should be maintained (at all current values) between the tripping characteristics of in-series breakers. Generally, a maximum of four LV circuit breakers can be operated in series. Until the advent of solid-state trip devices it was not possible to achieve selectivity between two breakers in series if both were equipped with instantaneous magnetic trips. With solid-state trip devices, instantaneous trip on downstream breakers can be achieved using zone selectivity to restrain the instantaneous trip on upstream breakers. This gives the fastest fault clearance for minimum damage without loss of selectivity [23].

Another point to note is that the emergency generator circuit breaker (E) must also be co-ordinated with the branch breakers (3 etc.). In the system under discussion the tripping characteristics of the generator breaker and the feeder breaker 2 are taken to be similar, both having the same nominal rating.

The emergency generator's excitation system is arranged to give sustained short-circuit current, at about 3 x f.l.c. (see characteristic G). Overheating of the generator windings is likely to result if a short-circuit is maintained for more than about 10 seconds.

The region to the left of, or below, a co-ordination curve represents an area of non-operation of the circuit breaker. Conversely, where a paired current-time co-ordinate falls in the region to the right of or above the curve, the circuit breaker will operate. A 3-phase 'bolted' short-circuit fault at the emergency load distribution board will, therefore, cause the generator breaker to trip well before 10 seconds. Similarly, a downstream 'bolted' 3-phase short circuit should result in the appropriate branch breaker tripping before the generator breaker operates.

The situation is not as clear-cut where unbalanced faults (such as line-to-line or line-to-earth) or arcing faults occur. They will all be of lower magnitude than the bolted 3-phase fault. In these circumstances the generator decrement curve will be different, and circuit breaker operation may be suspect. It is therefore advisable to provide the generator with some form of back-up protection, perhaps in the form of time-delayed over-excitation tripping (see Chapters 7 and 10).

We may summarize this discussion by stating that for a co-ordination study it is necessary to:

1. produce a single-line diagram of the power distribution system, showing all protective devices and the major or important distribution and utilization apparatus in the installation;
2. identify the degree of power continuity (or the criticality of loads) required throughout the installation;
3. define the operating current characteristics of each utilization circuit (e.g. normal and peak currents, etc.);
4. calculate the maximum short-circuit currents that are possible at each protective device location;
5. identify any special limiting requirements, such as the settings of utility service relays;
6. understand the operating characteristics and available adjustments of each protective device; before going on to
7. plot the time-current characteristic curves of all series devices on a single sheet of log-log paper. The characteristic curve of the smallest device should be plotted as far to the left of the paper as possible. Do not attempt to put too many characteristics on the one sheet; it only leads to confusion. Devices of different-voltage systems can be plotted on the same sheet, by converting their current scales to the same voltage basis (using the voltage ratios).

## 9.13 Enclosures

Indoor LV and HV switchgear are mounted in metal enclosures. The form of construction falls within one of two classifications: the cubicle type, and the metal clad type.

In the former arrangement, circuit breakers and auxiliaries are mounted in sheet steel cubicles, which are extendable on either side and are bolted together to form composite switchboards. The jig-built, rigid framework of each cubicle usually consists of standardized bolted members. Removable side cladding panels allow for future extensions. Front and rear access is provided by combinations of interlocked doors and removable panels. The circuit breakers may be of the fixed or of the drawout type. Main busbars are run in chambers above the vertical risers and adjacent sections are connected by links for extensions. Sealed inter-cubicle barriers may be fitted to contain any arcing products to individual cubicles. Typical arrangements of this type of switchboard are shown in Figures 9.20, 9.52 and 9.59.

The degree of segregation of functional equipment (from one another and from the busbars) may be pre-planned to satisfy one of the following requirements [24]:

1. no separation between circuits;
2. functional units separated from the busbars;
3. functional units separated from busbars and from one another (outgoing terminals and busbars may be in a common chamber);
4. functional units, including outgoing terminals, separated from the busbars and from one another (when combined with segregating barriers between the main horizontal busbars and vertical risers increased busbar security is obtained).

Metal clad switchboards are built in self-contained cubicle form. Several cubicles may then be placed side by side to build up large installations (see the illustrations in Figures 9.40 and 9.42). By definition (certainly in American practice) this type of equipment must incorporate circuit breakers of the horizontal or vertical withdrawable pattern. They must be compartmented so that each is completely separated from other apparatus. Safety shutters that close automatically when the breaker is withdrawn must be provided. All live parts should be enclosed in earthed, metal-encased compartments. These would include busbars, current and voltage transformers, control power transformers and cable terminations. Circuit instruments, protective relays and control switches may either be mounted on hinged front panels/doors or in separate chambers (as illustrated in Figures 9.40 and 9.42).

Enclosures should be designed to give protection against contact with the live and moving parts housed within them, and to protect internal devices against specified external conditions. The degree of protection provided is classified by BS 5420 (IEC 144). Enclosures are designated by a symbol consisting of the code letters IP, followed by two reference numbers which define the degree of protection. Additional letters may be used, after the code letters or after the reference numbers, to qualify methods of test, etc. The first numeral of the code (0 to 6) defines the protection against accidental contact and the protection of internal equipment against the ingress of solid foreign bodies. The second numeral defines the protection against the harmful ingress of moisture.

The British Standards Institution introduced BS5490 (IEC 529) in 1977, using the same Index of Protection (IP) system as the earlier BS 5420 and BS 4999 Part 20 (IEC 34-5: *Enclosures for electrical machines)* but differing only in minor details. It has a wider scope in that it relates to enclosures on all types of electrical equipment with rated voltage not exceeding 72.5 kV. The intention had been to

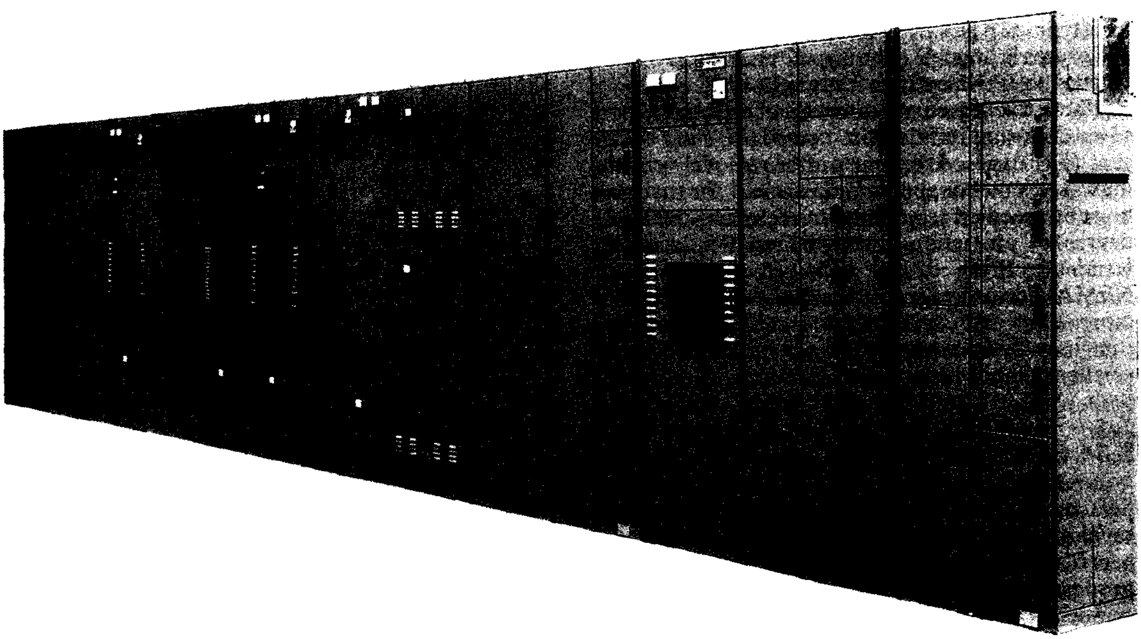


**Figure** 9.52 A typical modular cubicle design switchboard (Courtesy: George Ellison Ltd) rationalize the situation by withdrawing the older standards in due course. Much depends upon IEC action in this regard. Meanwhile, BS 5420 still continues to be applied to LV switchgear and controlgear enclosures.

Most indoor equipment will be designed to comply with IP 31, where protection is provided against:

- the ingress of solid foreign bodies having a diameter in excess of 2.5 mm;
- contact by the fingers with live or moving internal components (numeral 3); and
- water droplets falling vertically (numeral 1).

In the *indoor* context, the highest classification that is likely to be required is that corresponding with IP 55. This gives complete protection against:

- live or moving internal parts;
- harmful deposits of dust (ingress of dust is not totally prevented, but such quantities that do penetrate will not interfere with the satisfactory operation of the enclosed equipment); and
- water projected by jets from any direction under stated conditions.

In American practice enclosures are designated by type numbers which originated in the National Electrical Manufacturers Association (NEMA) codes. Type numbers for indoor, non-hazardous locations vary from 1 to 13 covering various degrees of protection from accidental contact and falling dirt (type 1) through hosedown and occasional submersion (type 6) to oil and coolant spraying and splashing (type 13) [25]. No direct comparison with IP enclosures is possible. The Type 2 enclosure roughly equates to IP31, and the Type 6 to IP55.

Where the degree of protection of an internal part of an enclosure differs from that of the main enclosure (e.g. exposed terminals after removal or withdrawal of functional units) the symbol for that part must be specified separately. In such cases the lower degree of protection is stated first. For example, terminals: IP 00, casing: IP 54. In the same way NEMA enclosures meeting the requirements of more than one type of external condition are designated by a combination of type numbers, the smaller number being stated first [25].

## 9.14 Power supplies

Switchgear embodying electrically operated current-breaking devices must have a reliable source (or sources) of control power for closing and tripping purposes. Supply security is less critical for closing power since alternative manual operation is often possible on the breakers under consideration.

Closing power may be obtained from storage batteries or from rectifiers fed from single-phase control power transformers (c.p.t.s). The former source is to be preferred, particularly when the primary power system is likely to be de-energized and when manual operation of circuit breakers is not possible or desirable.

Tripping power may be derived from:

1. storage batteries or a charged capacitor, for d.c. applications; or from
2. the primary, or protected, a.c. power circuit (via c.t.s where necessary) through direct-acting trips.

General distribution systems cannot be relied upon for tripping power supply because power outages are always possible and are likely to occur in emergencies when the protective system is most needed. Another point to consider when using power taken from the source feeding the switchgear is that a short-circuit may reduce the voltage level below that required to operate the breakers' shunt trip coils. The answer is to use d.c. tripping power as in 1 above.

Alarm monitoring for abnormal conditions on both tripping source and circuits is a general requirement [3]. The d.c. tripping circuits of protective relays should be segregated from those for other functions to avoid any possibility of 'sneak' circuits [26].

Where storage batteries are used it is important that adequate charging facilities are provided, and that maintenance routines are established and rigorously implemented.

Sealed gas recombination lead acid cell batteries are being increasingly applied for these duties. The long life, stainless steel encased, nickel cadmium types are reliable alternatives. They have very low open-circuit losses but require about 67% more cells than corresponding lead acid batteries. Standby periods of six hours are generally specified.

Control supply voltages may vary from between 24 and 250 V d.c. and from 110 to 440 V a.c. Choice is often governed by individual user preference.

Care should be taken in selecting battery boost-charge rates to ensure that the maximum permissible voltages of connected equipment is not exceeded. Also, the battery voltage in the discharged state must be above the equipment's minimum working voltage. Typically, upper and lower limits for 240--volt-rated breaker closing and tripping devices and control circuit apparatus would be 208 and 254 volts.

## 9.15 Instrumentation and metering

### 9.15.1 General

The instrumentation fitted to switchgear or associated control boards or desks should be designed to provide attendant staff with all the information needed on the plant's operating conditions. This would ideally include load levels and characteristics, load factors and energy consumption. The actual instrumentation provided for individual circuits in the power system will be governed by the operational importance of each element. Requirements for operational safety must be met. Plant maintenance should also be a consideration, and energy and time-elapsed meters can be sensibly employed to furnish information for this purpose.

Apart from the importance of overall aesthetic appearance it is important to ensure that a systematic arrangement of instrumentation is achieved. The aim should be to give easy appraisal and quick comparison of similar instruments on different circuits, and to facilitate rapid controlling action by attendant staff.

The excessive use of digital panel meters should be avoided. Where measured quantities vary rapidly they are difficult to interpret on a digital display. Composite switchboards may contain 50 or more instruments. The information displayed is more easily scanned and appreciated from analogue indicators than from digital ones. Attendants get accustomed to seeing the angles at which pointers (or neon plasma bars) are lying on analogue scales. Pointers not in their expected position are immediately flagged up in the mind. Efforts are then concentrated on correcting the indications by taking appropriate action. Displays in which digits are constantly changing all day lead to confusion and, after a period, the figures become meaningless [27]. Where parameter trends are required to be shown in analogue form, but precise and accurate check values are also required (e.g. frequency, power, load, and temperature), an instrument which has a digital display at the centre of an elliptical bar trend indicator (or a fan type display to represent a pointer) could be used.

When duplicate instruments are provided at control boards or at desks and consoles, they should be grouped in such a way as to permit easy identification for each power or feeder circuit. This can be done in several ways :

- by adequate spacing - horizontal separations being preferable to vertical;
- by marked outlines around each group; or
- by group colour patterning.

Labelling should be consistent throughout. For example, circuit titles above each group with individual labels below each instrument if necessary [28].

It is also desirable to have compatible scale formats. Avoid confusing combinations of circular-, quadrant-, and edgewise-scaled instruments. Where related electrical quantities, such as current or voltage, are required to be displayed side by side or one above the other, edgewise instruments should be considered, since they offer high stacking density where space is a limiting factoL

It is beyond our present scope to describe the mode of action or the design and internal construction details of measuring instruments and meters. This discussion will be confined to their application.

### 9.15.2 Instruments

*Accuracy*, which is defined as 'the closeness of an observed quantity to the defined or true value' (BS4778: 1979) is the limit of error to be expected in an instrument expressed as a percentage of its full-scale value, under reference conditions.

BS 89: 177 (IEC 51) classifies instruments in groups, using *class index* (CI) numbers, which correspond to the permissible percentage error at full-scale deflection for most (but not all) instruments [28]. CI numbers extend from 0.05 to 5.0.

A 1000 V full-scale Class 1.5 instrument (1.5 % accuracy) will thus have a permissible error of 15 V, which applies at any level of its scale reading. This means that at half-scale (500 V) the reading error could be 3 %, and 6 % at quarter-scale (250 V).

Switchboard and panel instruments are usually in the 1.0 to 5.0 classification. For normal industrial purposes Class 2.5 instruments with Class 1 instrument transformers, to BS 3938 (c.t.s) and BS 3941 (v.t.s), give the best compromise between cost and accuracy. Greater accuracy will be required (and is usually stipulated) for tariff metering instruments. A CI of 0.5, or even 0.2, may apply in such cases.

Where transformers are used for both measurement and protection purposes they will need to be rated to a class selected to match this dual need. The burden applied to them is then the total of instrument and protective relay burdens. It may be necessary to apply turns compensation to C.t.s to achieve the required measurement performance [26]. On smaller, unattended plants, Class 5 instruments with Class 3 transformers may be quite adequate.

It should be appreciated that variations from reference conditions (such as those due to temperature, frequency, the presence of stray magnetic fields, and wave-form distortion) may cause an instrument to exceed its permissible CI error rating.

Moving iron instruments using combined attraction and repulsion type movements to give long scales are most commonly applied in the measurement of a.c. (both current and voltage). These and air-cored or iron-cored moving coil dynamometer instruments respond to Lm.S. values of current and voltage. In this respect they are not susceptible to wave-form distortions which affect the accuracy of moving-coil rectifier instruments that are calibrated in Lm.S. for a pure sine wave only. Instruments using either built-in or separately mounted Lm.S. transducers are increasingly employed for the indication of active and reactive power, frequency, power factor, and a.c. current and voltage.

### 9.15.3 Energy meters

These are instruments which register the integral of the quantity of power used (be it active, reactive, or apparent power) as a continuous summation with respect to time. Energy measured may be in kilowatt-hours (kWh), in kilovolt-amp ere-hours (kVAh) or in kilovar-hours (kVArh). The most common form of meter uses an induction disc mechanism and the energy units are indicated on either clock dials or cyclometer rollers driven from the mechanism by gear chains. Solid-state energy meters are now also available and are increasingly applied.

The kVArh meter is effectively a kWh unit calibrated in VArs using a phase-shifting transformer to shift the potential applied to the meter through 90° electrical. It employs a ratchet-type assembly to prevent it from running backwards. The appropriate connections must therefore be made for recording lagging or leading power factor loads [3]. When metering polyphase systems a number of single-phase elements are mechanically arranged to drive a common register.

### 9.15.4 Demand meters

Energy meters record the total energy flowing through a circuit. Demand meters, on the other hand, measure the average rate of power flow over a period of time (typically 30 minutes). They are usually combined with watthour meters. The demand element is then driven from the watt hour element(s) to set a slave pointer at the highest kW for the timed interval. Alternatively, an independent thermally-driven pointer may be used.

Whilst tariffs are mostly based on active power (kW) demand, charges on apparent power (kVA) may be levied in order to encourage power factor improvement. Integrating instruments using either arithmetic sum or vector sum principles are available. The latter are preferred because the arithmetic sum instruments give higher indications if the power factor varies during the integration period or if the load is unbalanced - which is often the case [29].

### 9.15.5 Recorders

Recording instruments provide useful information for reconstruction of events and for registering operational patterns and indicating trends. In their multi-channelled form they give a time-sequenced record of events during disturbances and faults-particularly when they simultaneously monitor closing and tripping of key circuit breakers in the power installation.

### 9.15.6 Recommended instrumentation and metering

Table 9.2 offers a listing of the devices that should be considered for various incoming and feeder circuits. Useful optional instruments are identified by the letter '0'. Notes on some of the factors to be considered follow the table.

## 9.16 Control systems

### 9.16.1 General considerations

Control systems for diesel generator plant are required to perform the three functions: control, protection, and indication. They should be designed to give a comprehensive indication of the state of a generator plant at all times and to provide the means for modifying that state. Equipment for this purpose would therefore include:

- measuring instruments;
- condition indicators;
- protective relays;
- alarm annunciators;
- prime mover and generator regulating controls; and
- command signalling devices to engines and switchgear.

Mention has already been made (in Section 9.15) of instrumentation for electrical power circuits. Engine governing and automatic voltage regulation have been discussed in some detail in Chapters 6 and 7, and protective relaying and alarm annunciation will be discussed in Chapter 10 which follows.

The wide range that is possible in the size and complexity of plants calls for a flexible and economic approach to each control system requirement. Solutions are often dictated by the qualifications of operating and maintenance staff. Small unsophisticated plants where only very elementary logic circuits are required, may best be served by systems based on well-proved, reliable, and rugged electromechanical relays. In developing countries this technology is fairly widely understood by operating staff whose primary training and experience tends to be in the diesel engine field. Relays have the distinct advantage of being easily seen to be either operative or not. Also, because of their slow operating speed, they may be used in extremely (electrically) 'noisy' areas with little fear of maloperation. In single-running small plants control operations are simple and usually only involve engine starting and fuel control. A few relays can do the whole job and the cost of alternative, solid-state, electronic systems cannot be justified. Essential engine instrumentation and fault monitoring may be provided as part **of** the 'control package', mounted on or near the prime mover.

**Table** 9.2 Circuit instrumentation

| *Circuit* | *Instruments and meters* |
|---|---|
| 1. Small individual running generators | Voltmeter & selector switch<br>Ammeter & selector switch<br>3 Ammeters (0)<br>Wattmeter<br>Frequency indicator (0) |
| 2. Large individual running generators | Voltmeter & selector switches<br>3 Ammeters<br>Watthour meter<br>Frequency indicator - see Note (iii)<br>VArmeter [or Power Factor indicator (0)]<br>[See Note (i)] |
| 3. Parallel running generators | 3 Ammeters<br>Wattmeter<br>Watthour meter<br>VArmeter [or Power Factor indicator (0)]<br>[See Note (i)]<br>Elapsed-time meter<br>1 set of synchronizing instruments per installation, comprising:<br>Synchroscope (with sync. lamps)<br>2 Voltmeters<br>Frequency indicator<br>[See Note (ii)] |
| 4. Incoming utility supply feeder | Voltmeter & selector switch<br>Ammeter & selector switch<br>Wattmeter<br>VArmeter [or Power Factor indicator (0)]<br>Demand meter (0) [see Note (iv)] |
| 5. Plant [or consumer] feeder | Ammeter & selector switch<br>Voltmeter & selector switch (0)<br>Wattmeter (0)<br>Watthour meter [Demand attachment (0)]<br>[See Note (iv)] |

*Notes*
(i) Power factor meters may sometimes be substituted for VArmeters, but as they develop low torque at low load they are prone to reading errors below 25% of rated current. Also, they only monitor the pJ. of one phase at a time. This may lead to erroneous conclusions if the phase loads are dissimilar and if only one reading is taken [3]. Power factor calculated from kW and kVAr values always provides a more reliable and accurate indicator.

(ii) Synchronizing instruments may be mounted on a swivelling frame on the end of a composite switchboard. Only one set of instruments is necessary for each switchboard. In large multi-generator installations it is advantageous to have more than one, placed as near as possible to the circuits to be synchronized, to facilitate accurate reading. Double-movement voltmeters and frequency meters may be used. Any incoming generator, before being paralleled to the main busbar, should be connected (by plug or switch) to the 'incomer' movements of the voltmeter and frequency indicator. The second movements of both instruments are permanently connected to the busbars.
(iii) The deflectional type frequency indicator, incorporating a pointer, should be used in preference to the lower cost, 'vibrating-reed', mechanical type. More so, where larger generators are supplying frequency-sensitive loads.
(iv) It is good practice to design-in test blocks for portable instruments (and recorders) which may be used to make periodic checks where permanent instrumentation is not fitted.

Control systems have three main components:

1. Input devices: pushbuttons, control switches or sensing devices responsive to pressure, speed, temperature, electrical quantities, etc.
2. Logic or control units: relays or equivalent two-state devices, which receive information from the input devices, sort it out, make the necessary decisions, and then pass these on to the output devices.
3. Output devices: solenoid valves, actuators, relays or contactors, motors, etc.

Control systems may be represented by the block diagram shown in Figure 9.53.

Electromechanical relays (EMR) have certain inherent disadvantages, such as inconsistency in operating times due to changes of coil resistance, and the effect of harmful environments on contact wear and tear - calling for frequent inspection and periodic adjustment. Relays and their contacts tend to become less reliable when not in use. This must be of concern where plant is on standby duty and where logic circuits may involve upwards of 50 relay contacts.

### 9.16.2 The background to electronic controls

Electronic control systems using digital techniques were introduced in the 1950s. The elementary circuits used (known as *gates)* allowed information to pass, or not pass - according to the type of input and the state of the circuit itself. Four different circuit configurations were used as 'building blocks' to construct total systems. They were OR, AND, and the inhibition-type gates, NOR and NAND.

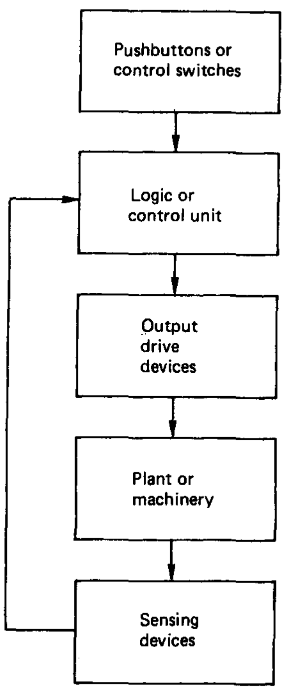



**Figure 9.53** Block diagram defining a control system

Standard circuit modules were built up from transistors and diodes, together with conventional electronic components such as resistors, capacitors, and chokes. These modules were then encapsulated in plastic materials or potted in epoxy resins to give full protection from environmental hazards such as dirt, corrosion, and vibration. They were either mounted on printed circuit boards or plugged into hard-wired bases, to give a system build. The modules were not capable of being repaired. Failure meant replacement. Unfortunately, the higher cost (compared with the conventional EMR systems) was the major barrier at that time to their full acceptance in generator controls - although they had wide application in industrial process and drive systems.

The logical extension of these discrete-component modules was the integrated circuit (IC) elements introduced in the 1960s. ICs are circuit modules, all the components of which are produced from a single small chip of silicon crystal. Typically, a standard IC consisted of two, four-input NOR gates in one encapsulated 'chip' the size of a transistor. Again, they were not repairable items.

Within a very short period of time IC technology advanced even further with the development of the field-effect transistor which can be produced in large quantities on a monolithic semiconductor chip. This led to:

- *medium scale integration* (MSI) of components, where a complete sub-system or system function was fabricated as a single microcircuit containing 12 or more equivalent gates or circuitry of similar complexity; and then to
- *large scale integration* (LSI) giving major sub-systems consisting of 100 or more gates [30].

Very large scale integration (VLSI) devices have been made possible by complementary metal oxide silicon technology (CMOS) in which the control electrode of a device is insulated from its active region by a layer of silicon oxide.

The large-scale commercial production of modules employing integrated circuit techniques **has** given the control engineer greater flexibility in system design using standard hardware. The more complex multi-generator controls are now likely to comprise a central process controller, interfaced with digital and analogue input/output sub-systems built up from integrated transistor logic. These sub-systems may, in turn, interface with switch or relay contact inputs, transducer inputs, engine *start/* stop signals, drives to instrumentation or recording equipment, and links to VDUs and to printers or which events and alarms may be recorded for subsequent analysis.

Since, for anyone manufacturer, the production volume of such control systems is likely to be no more than 100 a year, design tends to be based on specialized, commercially available, one-board microprocessors rather than on in-house designs from IC level upward. Also, microprocessor-based systems afford greater flexibility in their operating mode. Identical hardware designs may be used in a number of applications by merely changing the configured program. This has distinct advantages in production, commissioning, and maintenance. Also, where a bus-oriented architecture is employed (i.e. where all inputs and outputs are connected to a separate input/output bus structure) the system is easily expandable.

### 9.16.3 Typical proprietary systems

Control specifications will depend upon the. operational requirements of the plant. The following examples detail the features of typical microprocessor-based systems. They serve to illustrate the different proprietary approaches to meeting a specification calling for the automatic starting and stopping of generators in a multi-unit installation operating into an independent common busbar system. Each manufacturer has its own unique design solution for the same requirement.

The first equipment described is the Brush Electrical Machines' *Prismic* control system. The block diagram of Figure 9.54 shows its configuration.

The system would, typically, comprise a racked assembly of the central processor (CPU) card and the interface cards which condition the input and output signals. The CPU contains an INTEL 8085 microprocessor and peripheral components, and also buffers the address, data and control buses which provide access to the interface cards. An integral power supply is contained within the rack. The interface cards perform a variety of functions which may include:

1. a digital input card for accepting switch and circuit breaker status, or similar inputs;
2. an analogue input card for accepting transducer inputs from load or similar inputs;
3. a transducer card for accepting voltage and current signals, and performing internal active and reactive power calculations;
4. a preset constant card for site adjustment of system parameters;
5. a digital output card to initiate circuit breaker operation, prime mover start/stop, and annunciator signals, etc.;
6. an analogue output card to drive instrumentation or recording equipment; and
7. a serial output card to provide an RS 232C link to VDU, printers, etc.

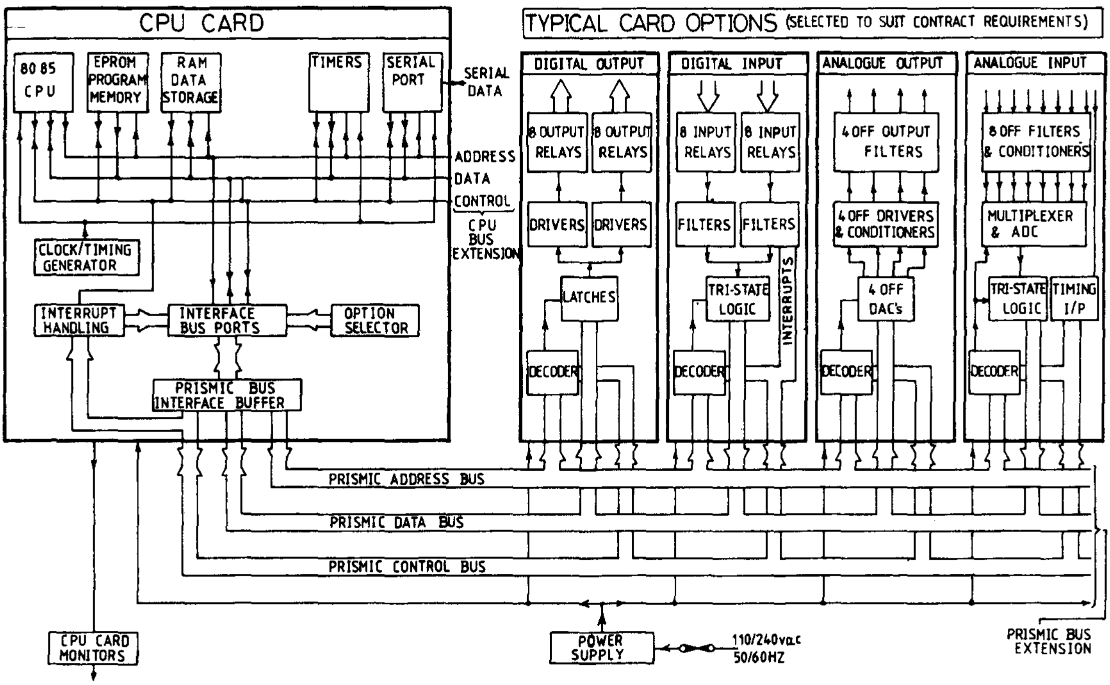



**Figure 9.54** Block diagram of the 'Prismic' control system (Courtesy: Brush Electrical Machines Ltd)

A typical system interface diagram is shown in Figure 9.55 below.

*Prismic* may be used to automatically control a number of generators operating either in an isolated power system or, in conjunction with a utility supply, in a peak lopping mode (see Chapter 8). Among the features offered are:

1. Continuous monitoring of the system capacity and load so that, when the 'spinning reserve' in the plant (i.e. the difference between capacity and the load, at any given time) falls below a preset level for a predetermined period, another generator is started. A reduction in generator running hours is obtained by the later starting and earlier stopping of generators. When the spinning reserve is being calculated, the rating of the generators may be compensated for ambient temperature (or for overdue maintenance) to obtain full use of a set's capacity.
2. The ability to drive instruments which display the total load, the total capacity with temperature derating, and the spinning reserve. Where an installation contains utility feeders, the spinning reserve is not easily calculable by a plant attendant - more so when the generators are all of different sizes and when derating factors have also to be computed. In manned stations these *Prismic* indicators can be the basis for an attendant's decision to start or stop generators.
3. Alarm signals for spinning reserve 'critical', and 'excessive'. The former pre-warns of an impending overload/load shedding situation. The latter warning is activated when the spinning reserve greatly exceeds one set's capacity (e.g. 1.5 to 2 times). Both signal levels are site-adjustable.
4. Selectable starting and stopping sequences for each generator in the system. This enables the running hours on each set to be controlled to suit preventive maintenance schedules. If an incorrect duty sequence is selected, or if the order in which the sets run goes out of sequence, an alarm is initiated. Should a generator fail to start or to synchronize, the next set in the duty sequence is started and an alarm is given. The faulty set is added to the *Prismic* memory and is not used again until it has been switched out and back into a 'valid' duty selection.
5. The ability to select a minimum number of running sets, irrespective of load demand. This is particularly useful in marine applications for when ships are docking or manoeuvring in close waters.

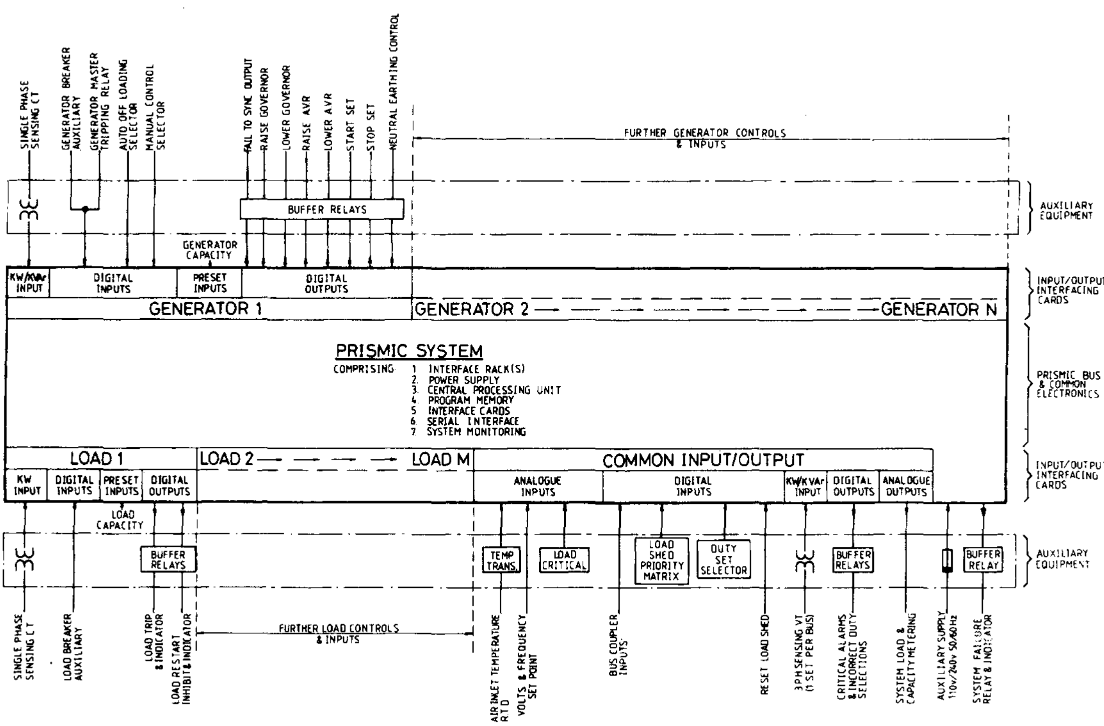



**Figure 9.55** A typical 'Prismic' system interface diagram (Courtesy: Brush Electrical Machines Ltd)

6. The ability to fulfil an automatic mains failure or black start function when powered from a station battery. The microcomputer may then be used:
   (a) to start generators in sequence;
   or, where individual synchronizing facilities are provided,
   (b) to start all the available generators and synchronize them together to rapidly build-up capacity.
7. An adjustable generator run-on period. Where turbo-charged engines are involved it is advisable to arrange for generators to be run lightly loaded, and then off-loaded for a short period of about 4 minutes before they are stopped. This is to allow them to cool down. Off-loading is conducted in a controlled manner. The governor and automatic voltage regulator settings of those sets remaining on the busbar are adjusted in order to minimize system disturbance.
8. Active and reactive power sharing controls. These function to ensure that all generators operating in parallel with each other, or with a utility supply, take their correct proportionate share of the total kW and kVAr loads. The requirements during peak lopping will differ from those in the base load (or isolated system) mode.

   (a) *Peak lopping:* once an 'incoming' generator is started and synchronized with the busbars its governor datum point must be raised until the desired output is produced by the set. Similarly, because the reactive output from the generator will have remained low (and will probably have changed to leading VAr generation), it is necessary to raise its automatic voltage regulator's (AVR) datum point by an amount appropriate to the proportion of lagging kVAr output required to be produced by the generator. The generators may either be controlled to hold the utility feeder demand at a maximum level or they may be operated, at an efficient output, with the utility demand being less than the maximum level. For example, generators may be programmed to take at least 50 % of their rated capacity, initially, and have any furtQ,er loading restricted until the utility demand again reaches the maximum level. Such an arrangement would ensure that the generators are run at a reasonable efficiency, yet also make best use of the utility supply.
   (b) *Base load:* as in (a) above, it is necessary for the governor and AVR data on incoming machines to be raised. However, without the stabilizing effect of an 'infinite' utility supply, raising the governor datum will tend to increase the busbar frequency. To restore it to nominal, all the other machines on the busbars must have their governor data settings reduced. Likewise, busbar voltage is increased when the incoming set's AVR datum is raised. To compensate for this, the data settings of the AVRs on all the other sets on the bus must be reduced. A further consideration is that governors and AVRs may have droop characteristics, i.e. speed and voltage fall with increasing load. The load sharing controls must therefore arrange to compensate for this by raising each governor and AVR datum point as load increases and lowering them as load decreases. They do not act quickly enough to affect inherent governor and AVR stability. The droop characteristics are essential for good stability during transient load conditions.

   These topics are discussed, in some detail, in Chapters 6, 7 and 8.
9. Load shedding. When generators are operating in parallel, an undesirable condition could arise if one was 'lost' due to a serious fault. If the remaining units can not cope with the sudden overload, they might begin to stall in cascade - with an eventual total loss of supply.

   The equipment overcomes this problem in the following way. The microprocessor continuously monitors each set's master fault relay for the first indication of a machine or prime mover fault. The control system's memory is also being continuously updated with details of the reserve capacity and the size (and distribution) of the load. Within milliseconds of a fault being detected, and before the generator circuit breaker trips, the failing generator's capacity is subtracted from the reserve in order to determine the size of overload which will result. The microcomputer now decides on the number of non-essential loads which need to be tripped to prevent a system overload. Within 20 ms of fault detection, trip signals are given to the appropriate output feeder breakers. Meanwhile, the failed generator's circuit breaker is still not fully open. Such speed of response cannot be approached by conventional electromechanical load tripping techniques. The sudden loss of a set thus causes minimal disturbance to the power system. Under certain conditions, a *gradual overloading* of the system may take place. For example:

   - the temporary overloading of running generators, whilst an incoming machine is being started and synchronized; or

- the duty incomer fails to start or synchronize; and a replacement is being started, and will soon be on load; or
- all available generators are in use, and the load has increased beyond system capacity.

In each case, the overload should not be excessive and full use of the overload rating of the generators must be made to provide time for the corrective action to be taken. The microcomputer calculates the system load from the generator outputs and compares the total with the total generator capacity. If an overload persists for a preset time interval sufficient non-essential load is tripped to remove the overload.

Another situation in which load shedding is necessary is when *system frequency falls* below the controlled level for more than a short period - suggesting a system overload without any obvious symptoms. The condition may be the result of a number of factors. Typically, a fuel blockage preventing a prime mover from giving its rated output. *Prismic* responds to such a condition by tripping one load per interval of an under-frequency trip timer until the power system frequency recovers.

Following load shedding sequences, the plant can be re-accelerated or reconnected as the system capacity recovers. The microcomputer then operates in the reverse manner to load shedding, by reconnecting or permitting load to be reconnected, once the reserve capacity is adequate for each load.

An installation may contain one or more heavy loads which, if suddenly impacted onto a power system, may cause overloading. The microcomputer, having checked the running generator capacity, gives a closing signal to the feeder breakers only when total capacity is sufficient. If necessary, a further generator would be started and synchronized to the busbars before connection of any heavy-load feeder(s) is permitted.

10. Preferential load shedding. Loads can be tripped in a timed sequence and in a descending order of priority designated on a matrix plug board which may be reset on site. The microcomputer works down the matrix priority, assigning load values and keeping a running total until a value is reached which, once tripped, will clear the overload.

    An alternative, and more economic approach is to assign a fixed value to each load feeder and dispose with the feeder monitoring feature. This is valid when the feeders present a reasonably constant load. However, there is a risk that one load more than the necessary minimum may be tripped during shedding.

The illustration in Figure 9.56 shows *Prismic* equipment applied in a shipboard installation.

Figure 9.57 shows, in block diagrammatic form, the function of a typical fully automatic load demand control scheme for multiple diesel generator set installations. Not all the functional blocks may be provided or required in every proprietary system, and hardware design and arrangements will vary from one manufacturer to the next.

The single-line diagram in Figure 9.58 shows one manufacturer's schematic for an automatic synchronizing and load sharing system on a three-generator shipboard installation. The 'blocking key switch' provides the means of inhibiting the generator's start functions so that the machinery is made safe for routine inspections and maintenance work.

The Powercenter AP600 marketed by Petbow Limited is another example of a proprietary system. It is designed for the automatic control of up to six generators operating in base load or load-lopping duty. Briefly, it uses:

- A common 'programming control module' (CPM) which contains facilities for selecting the duty sequence of the sets, operational and system mode control selector switches, and total load measuring equipment.
- Plug-in control boards which give:
  - automatic starting, sequence control, and stopping for each set;
  - sequencing commands, and selection of automatic or manual paralleling;
  - load sharing control, and controls to ensure a proportional rate of speed change;
  - set controls and alarms.

By providing each set with its own synchronizer, load level discriminator, load sharing unit, and speed controller, total system integrity is enhanced and greater security of supply is obtained.

The illustration in Figure 9.59 is of an AP600 system applied to four 600 kVA peak lopping generating sets designed to run in parallel with a 10 MW utility supply. The switchboard is shown undergoing witness tests at the manufacturer's works prior to despatch to Malaysia. The system's common programming control module (CPM) is in the third-from-left section of the board.

The reader should not conclude that only automatic controls can be considered for multiple set installations. On the contrary, there is much to be said for installing manually-controlled systems where staff are trained and possess the necessary skills in the operational techniques required. All too often, however, such systems are prone to maloperation due to carelessness or inadequate operator training. In any event, all well-designed automatic systems should include manual override facilities to provide alternative control in emergencies.

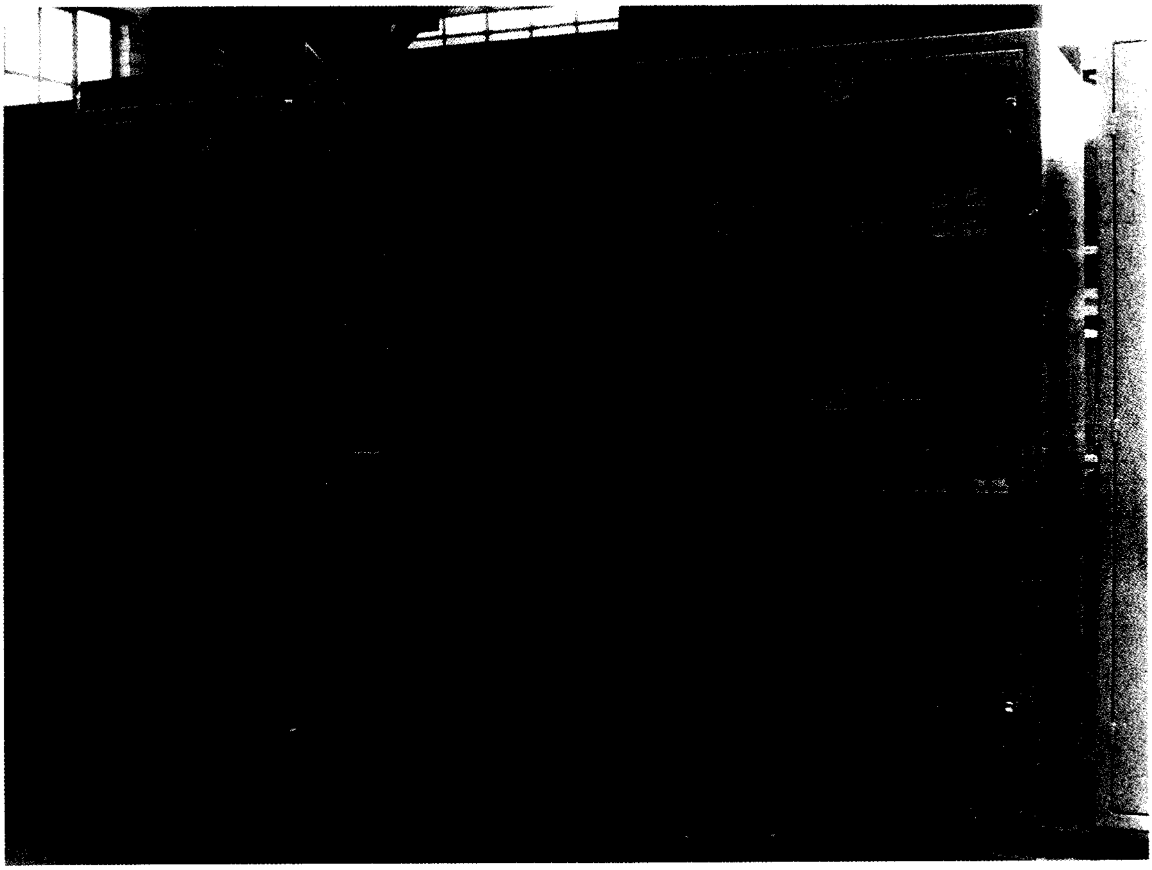


**Figure 9.56** A nine generator set control panel for the Shell MSV 'Stadive', using two 'Prismic' systems for power management (Courtesy: Brush Electrical Machines Ltd)

### 9.16.4 Centralized control

It is possible to provide serial links to input/output units at remote locations (e.g. to a centralized control room in a power station or on board ship). This may be by cable. For very remote reception and transmission of signals, modems and standard telephone lines or radio links may be employed.

Where several power stations operate into a regional network, it is then possible to have each controlled by a local microcomputer under the overall command of a central controller. Each local controller must have the capability of keeping its plant operating should the central unit fail. An example of this is the application of *Prismic* controls in the power management of generators distributed on three interconnected oil platforms. Data gathering and routine control of each platform's generators is performed by local *Prismic* units. A master microcomputer then manages the overall generation on the three platforms. Communication between local and master units is by a VHF radio link. Should this link be lost, each platform reverts to independent control.

Another example of remote control and intelligence gathering is the use of modems to connect regional centres by telephone lines to remote terminal units (RTUs) in unmanned telecommunication stations. The RTUs use digital and analogue input/output modules to interface with the stations' generator controls, alarms, and instrumentation, permitting periodic test running and providing fault read-outs.

### 9.16.5 Controlgear location

On manned or partially-manned plants, it is important that attendants are presented in a clear and unambiguous manner with continuous information on the status of the plant. On the simplest single

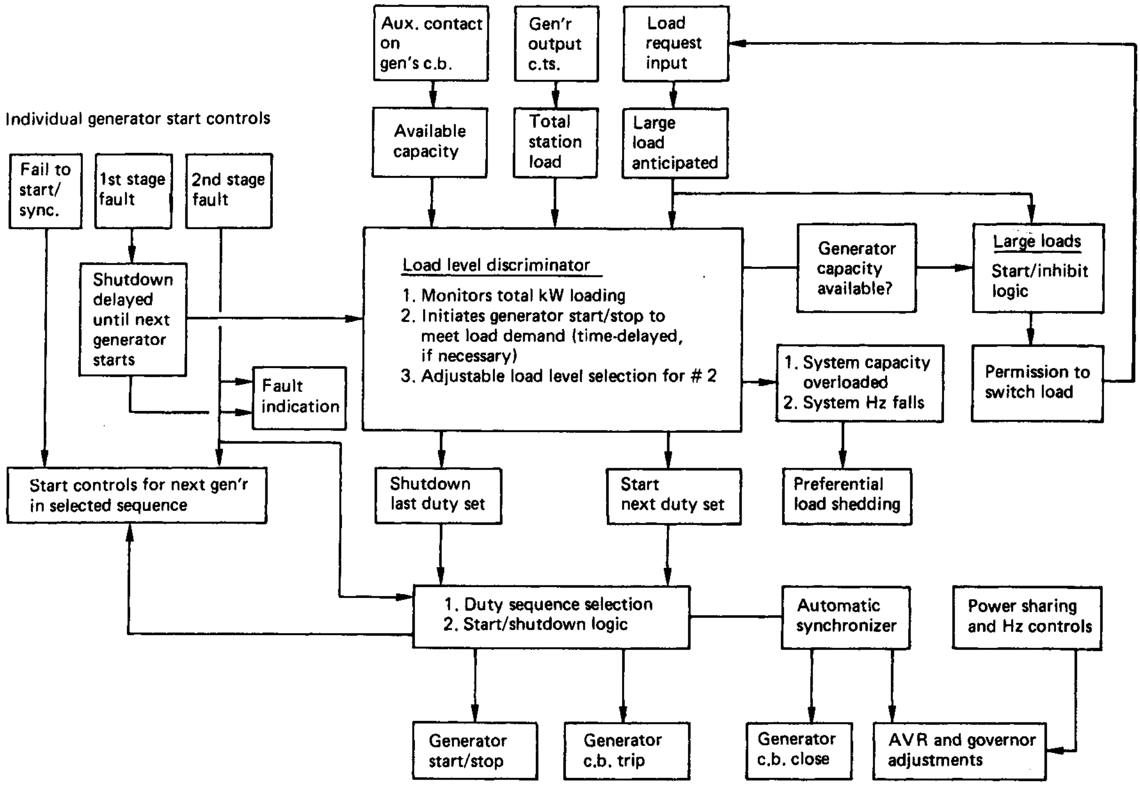



**Figure** 9.57 Block diagram of the functions in a typical load demand scheme for a multi-generator installation

generator installations, instrumentation and logic controls are usually incorporated within the switchgear cubicle (which may be set-mounted on the smaller units) to give convenient operation of the plant from one location. On the more complex multi-generator systems, since the adjustments on one machine affect all others in parallel with it, simultaneous observation of all the effects of any one action is essential. Where only two or three generators are involved individual switchboards, arranged as for the single generator, may suffice - provided that they are placed as close together as possible, and preferably in a quiet location away from the noise of running machinery.

Where adequate observation of a greater number of switchboards is difficult from one vantage point, it is advisable to use a control desk placed some distance in front of a composite switchboard. This desk may be used to house the generator regulating and control equipments, while instruments and switchgear indicators are retained on the individual switch cubicles. Where size and cost of an installation permits, a mimic diagram, representative of the complete power plant and its feeder networks, may be incorporated into the control desk (see Figure 9.60). Alternatively, the diagram may be fitted into a separate panel surmounting the composite switchboard. It should include pilot lights and semaphores to represent switching devices, such as circuit breakers, bus couplers, and isolators; and miniature indicating instruments to cover feeders, and generator output conditions [31].

## 9.17 Related standards

The purpose here is to list and briefly outline the scope of the key British Standards applicable to the manufacture, design, specification or operation **of** switchgear and controlgear apparatus, as described in this chapter. References in parentheses are those of corresponding standards published by either the International Electrotechnical Commission (lEe) or by the European Committee for Standardization (CEN). The referenced document is not necessarily identical to the British Standard, but has varyiD~ degrees of agreement with it.

In the last decade a considerable rationalization **of** switchgear standards has taken place in the United Kingdom. This has resulted in a significant

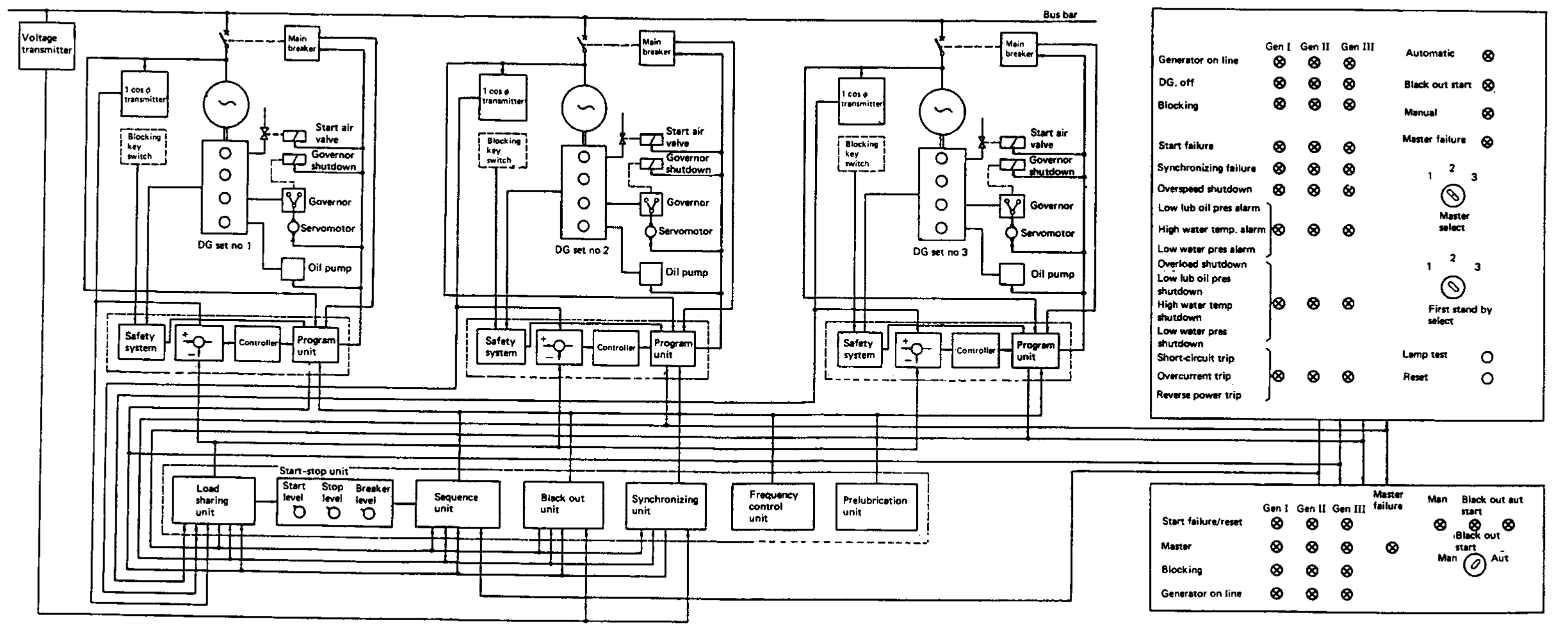



**Figure 9.58** Line schematic of an automatic synchronizing, load sharing scheme for a 3-generator shipboard installation (Courtesy: SELCO)

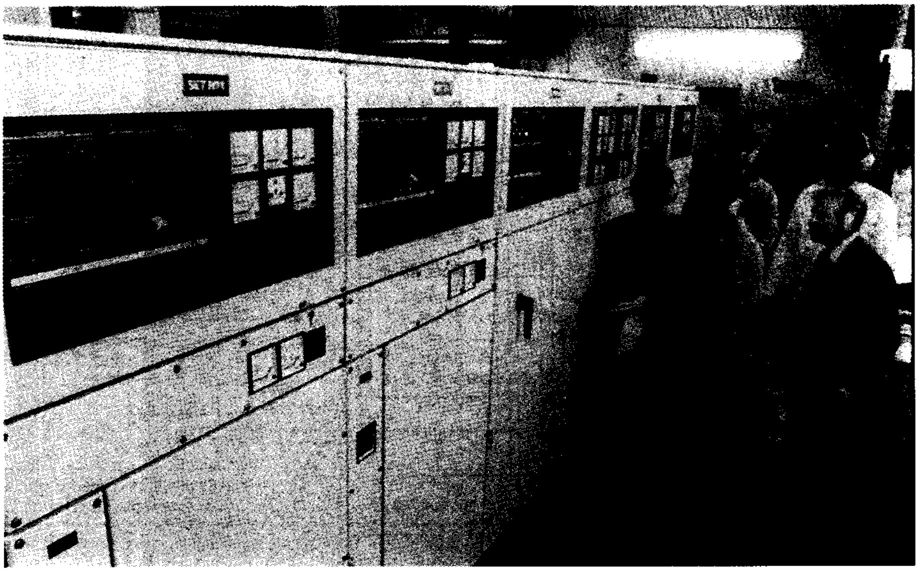


**Figure** 9.59 A four generator set cubicle suite, incorporating switchgear and control gear, on test at the manufacturer's works (Courtesy: Petbow Ltd)

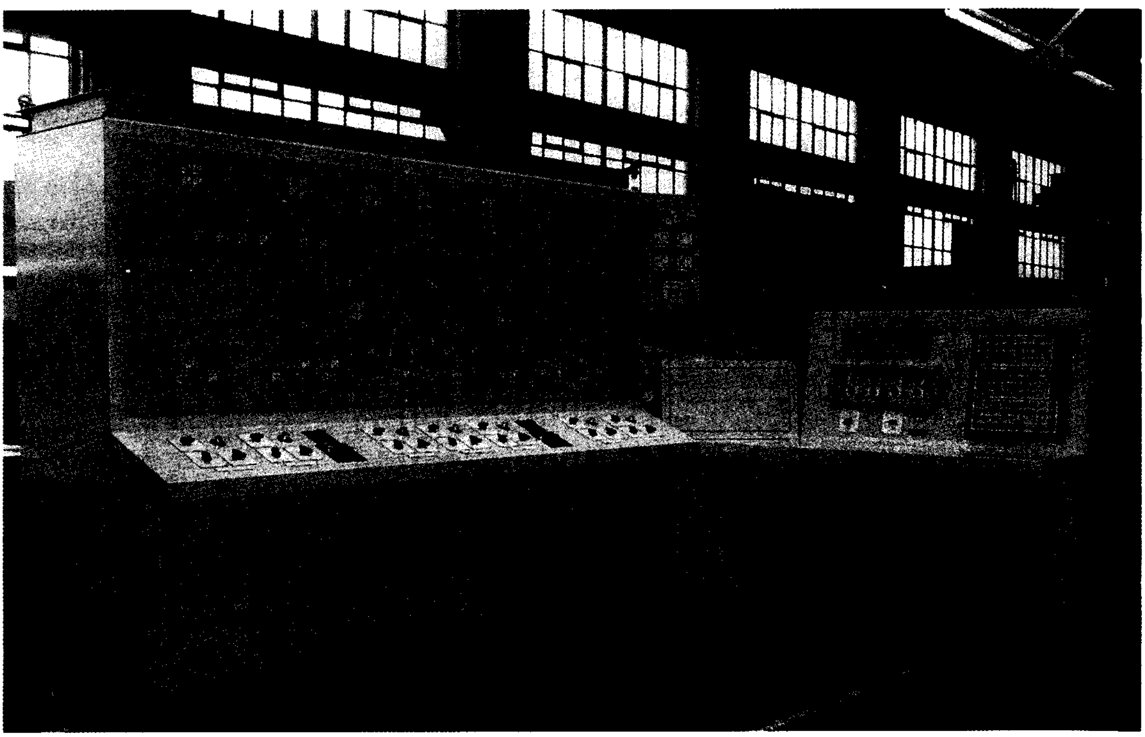


**Figure** 9.60 Mimic and alarm panel for the Britoil 'Clyde' platform, incorporating 'Prismic' power management, kW/kVAr sharing, and load shedding of a seven generator, three bus section, seventeen feeder system (Courtesy: Brush Electrical Machines Ltd) alignment with the IEC standards and harmonization with CENELEC (the European Committee for Electrotechnical Standardization) EN documents. For example, in 1977 two British Standards were introduced (BS4752 Part 1 and BS5419) to replace no less than seven separate, earlier standards for switching devices.

Applicable American Standards are comprehensively listed in the references in Chapter 9 of ANSI! IEEE Std. 141-1986, and in Section 5 of IEEE Std. 241-1983 (see the reference section at the end ofthis chapter). Some of the major organizations concerned with developing and co-ordinating electrotechnical standards in North America are now members of the various IEC commissions. Standards in the USA and Canada are, therefore, in the process of being harmonized with those of the lEe.

### 9.17.1 Switchgear and control gear - general

BS 5486 Part 1 (lEC 439-1) - *Low voltage switchgear and controlgear assemblies: General requirements.* It covers definitions, electrical characteristics, service conditions, design, construction and tests of assemblies, and classifies fault-withstand capabilities.

BS 5227 (IEC 298) - *A. C. metal-enclosed switchgear and controlgear of rated voltage above* 1 *kV and up to and including* 72.5 *kV.* It covers definitions, rated values, design and construction, and specifies tests for voltage after erection on site. The vacuum (Figure 9.40 and Figure 9.42) and the $SF_6$ switchgear equipment (Figure 9.45) described in this chaptet" conform with this standard.

BS 5472 (EN 50 005) - *Specification for low voltage switchgear and control gear for industrial use. Terminal marking and distinctive number. General rules.* This details the terminal marking to be used. The 'distinctive number' is a convention indicating the switching capacity.

There are also standards, in the form of Codes of Practice, which recommend the procedures to be followed in the operation and maintenance of switchgear. Particular attention is given to the precautions to be taken to secure the safety of personnel. Among these are BS 6423 which deals with the maintenance of switchgear (and controlgear) for voltages up to 650 V, and BS 6626 relating to equipment operating at voltages above 650 V and up to 36kV.

BS 5559 (IEC 445) - *Specification for identification of apparatus terminals and general rules for a lUliform system of terminal marking, using an alphanumeric notation.* It applies to the terminal marking **of** units such as machines, control equipment and ronductors.

BS 5490 (IEC 529) - *Specification for degrees of protection provided by enclosures.* It classifies the degree of protection provided on *all types of electrical equipment* where the rated voltage does not exceed 72.5 kV. It brings together the requirements of two older standards BS 4999 and BS 5420, which dealt with rotating machines and LV switchgear, respectively, and it covers a broader range of enclosures than either of those standards. BS 5420 may still be quoted in some equipment specifications and it is as well to know of its existence.

BS 5420 (IEC 144) - *Specification for degrees of protection of enclosures for switchgear and controlgear for voltages for up to and including 1000 V a.*c. *and 1200 V d.c*.. It classifies the ability of enclosures to protect against contact with live or moving parts inside, ingress of solid foreign bodies and ingress of liquid, and gives proving tests.

BS 4099 - *Specification for colours of indicator lights, push buttons, annunciators and digital readouts.* It comes in two parts. The first (lEC 73) specifies colours and establishes a convention for their use in indicator lights and push buttons. Part 2 relates to flashing lights, annunciators and digital readouts.

### 9.17.2 Circuit breakers

BS4752: Part 1 (IEC 157-1, IEC 157-1A) - *Specification for switchgear and controlgear for voltages up to and including 1000 V a.c. and 1200 V d.c.: Circuit breakers.* It gives the general requirements for all types of circuit breaker (including moulded case breakers) and covers definitions, rated values, service conditions, and tests.

The following observations are pertinent:

1. Rated values must be given by the manufacturer for:
   - current,
   - voltage,
   - making capacity (kA peak),
   - breaking capacity, at a stated voltage (kA r.m.s. sym.),
   - short-time current for 1 s or 3 s (kA r.m.s.), and

   opening and total break times should be declared.
2. It is important to determine on what basis the current rating has been assigned. Manufacturers have the habit of giving open air ratings. The user must be satisfied that the device, as fitted in the switchboard enclosure, has an adequate thermal current rating (in site ambient conditions) for the circuit it switches. The following example will illustrate this point.

The Ellison Type GEA 20 a.c.b. (illustrated in Figure 9.29) has an IEC 157-1 open air rating at an average ambient of 35°C, peaking at 40°C over a 24-hour period, of 2000 A. To determine open air ratings at different site ambient temperatures the following factors must be applied.

| *Site ambient temp* ("C) | *Multiplying factor* |
|---|---|
| 20 | 1.09 |
| 25 | 1.06 |
| 30 | 1.03 |
| 40 | 0.97 |
| 45 | 0.94 |
| 50 | 0.90 |

The manufacturer's recommended ratings for this frame size, when double-tiered in various IP enclosures and at a site ambient of 35°C, are determined by applying the following factors.

| *Enclosure class* | *Multiplying factor* |
|---|---|
| IP21 | 0.90 |
| IP31 | 0.875 |
| IP41 | 0.725 |
| IP51 | 0.725 |

*Example:* What would be the rating of a GEA 20 frame breaker double-tiered within an IP 41 enclosure, and used in a site ambient temperature of 40°C?

The factor for IP 41 is 0.725
The factor for 40°C is 0.97
The overall derating factor is therefore (0.725 x 0.97) = 0.703

The maximum load current that can be carried at 40°C and in an IP 41 enclosure is therefore 2000 x 0.703 = 1460A.

*(Note:* Similar de-rating procedures will apply to moulded case circuit breakers. Manufacturers' data should be consulted for specific details.)

Vacuum and $SF_6$ circuit breakers must comply with BS5311 (IEC56) - *Specification for high-voltage alternating current circuit-breakers.* In it, the rated short-circuit current is characterized by two values measured at the instant of breaker contact separation. They are:

1. the average of the r.m.s. values of the a.c. components in all phases; and
2. the percentage value of the maximum d.c. component in any phase.

The making current of a breaker is specified as the peak asymmetrical current measured at the first peak after a fault initiation. Its value is 2.5 times the r.m.s. value of the a.c. component of the breaker's rated short-circuit current. For example, the peak making current of the $SF_6$ type YSF6 breaker illustrated in Figure 9.45 is 62.5 kA, i.e. 2.5 times its 3-second short time current rating of 25 kA at 12 kV.

The percentage value of the d.c. component is calculated for a circuit having an *X/R* ratio of 14 and at a time equal to the minimum circuit breaker opening time plus one half-period of power frequency. Considering a circuit breaker rated at 25 kA for 50 Hz operation with a minimum opening time of 30 ms, its tested parameters would be [26]:

a short-circuit breaking current of 25 kA r.m.s. with a d.c. component of 51 %, and a making current of 62.5 kA peak.

### 9.17.3 Other power switching devices

BS5424: Part 1 (IECI58-1) - *Contactors.* It covers the classification, characteristics, conditions for operation and construction, tests and current ratings for different utilization categories. It should be noted that contactors to IEC standards will not necessarily comply with the standards of countries in North and South America. NEMA (the National Electrical Manufacturers Association) and CSA (the Canadian Standards Association), for example, require larger creepage paths and clearance in air than IEC standards, at the same rated voltage. Thus, a device constructed for 500V a.c. to IEC standards may only be used on 300 V to satisfy USA and Canadian standards. Similarly, IEC 158 permits a 20°C higher temperature rise on current-carrying parts. IEC devices are therefore physically smaller than the equivalent HP-rated NEMA devices [32].

BS 5419 (IEC 408) - *Specification for air-break switches, air-break disconnectors, air-break switcll disconnectors and fuse-combination units for vohages up to and including 1000 Va.c. and 1200 V d.c..* It thus covers LV isolators, switchfuses and fuse-switches (see Sections 9.7.1 and 9.7.2) and includes definitions, classification, characteristics, marking, standard conditions for operation, construction and tests.

BS 5253 (IEC 129) - *A. C. disconnectors (isolators) and earthing switches of rated voltage above 1 kV.* It gives definitions, rating, design and construction, rules for selection and maintenance, and defines type and routine tests.

BS 5463 (IEC 265) - *Specification for a.c. switches of rated voltage above 1 kV.* This again covers definitions, service conditions, design and construction, and gives type and routine tests.

In the context of British practice, the above standards are currently applicable. However, the IEC's Technical sub-committee 17B, which deals with LV switchgear and controlgear, is revising all the specifications within its sphere of activity. Existing IEC standards will now be combined into a six-part standard - IEC 947. Parts 2-6 cover specific devices, as shown in the following table [33]. Part 1 explains the general rules of the standard. It is expected that a new British Standard will be derived from IEC 947, in due course.

| *IEC947 Part No.* | *Devices* | *Previous IEC* | *BS* |
|---|---|---|---|
| 2 | Circuit breakers | 1EC 157, | BS4752 |
| 3 | Switches, disconnectors, switch-disconnectors, fused combination units | IEC408, | BS 5419 |
| 4 | Contactors | IEC 158, | BS 5424 |
| | Starters | IEC292, | BS 4941 |
| 5 | Control circuit devices (push buttons, pilot lights, etc.) | IEC 137, | BS4794 |
| 6 | Multiple function devices (combination of products for special purposes) | | |

Clark [33], in acknowledging that the new standard will eliminate the cross-references previously necessary, suggests that the implications for switchgear manufacturers, installers and end-users are considerable. Testing requirements are more stringent in many cases, and failure to meet the new parameters may well lead to familiar products being derated. The all-embracing term *Isolator* will no longer be accepted. Isolating devices now become *disconnectors* or *switch-disconnectors* - the essential difference being that a *disconnector* does not have an appreciable breaking capacity.

## 9.18 Certification of switchgear and equipment

User specifications may contain a clause such as:

> All switchboards are to be designed to meet BS 5486 Part 1: 1986 Class 3 classification .... and equipment shall be of a type that has been tested at these ratings and classification, and covered by a certificate issued by a member of AST A, KEMA or similar.

ASTA is the Association of Short-circuit Testing Authorities (Inc.). Formed in 1938, it has among its objectives:

- the co-ordination of the type testing of electrical power transmission and distribution equipment, and
- the issuing of certificates based on the satisfactory performance of type tests under the direction of independent AST A observers.

Initially, it operated in the HV field but since 1968 its membership has widened to include stations concerned with the testing of LV equipment. In addition to certificates covering satisfactory performance under short-circuit condition, the Association also issues certificates of conformity with the complete requirements of National and International standards.

Following the EEC's directive of 1973 calling for the harmonization of LV electrical equipment (known as the 'low voltage directive' - LVD), AST A was nominated by the United Kingdom as one of four bodies authorized to assess equipment compliance with Article 2 of the LVD.

ASTA is also a founder member of the 'Short-circuit Testing Liaison' (STL) - an organization which provides a forum for international collaboration between testing organizations. STL's basic aim is the harmonized application of IEC recommendations to the type testing of electrical power equipment. Among its members are: N.V. tot Keuring Van Elektrotechnische Materialen (KEMA), Arnhem, the Netherlands; Gesellschaft fur Elektrische Hochleistungsprufungen (PEHLA), Frankfurt, West Germany; Centro Elletrotechnico Sperimentale Italiano (CESI), Milan, Italy; and Ensemble des Stations d'Essais a Grand Puissance Fran<;aises (ESEF), Clamart, France [34].

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# 10

# Prime mover and generator protection

**Contents**

## 10.1 Introduction

The amount of protection to be applied will be largely governed by economic considerations, and determined by the size of the generator, its importance in the installation it serves, and the costs associated with downtime. Every well-designed power system has inherent *passive protection,* i.e. it has in-built reliability. One may add to this a measure of *active protection,* such as that provided by relays and pressure, temperature, and vibration actuated switches, etc. Such protection should be designed to enhance reliability.

To provide protection against every conceivable fault may merely introduce unnecessary complexity into protective gear. Besides being prohibitively costly, it could detract from overall system reliability, especially if the potential unreliability of the protective devices is higher than that of the equipment it is intended to protect. As always, compromise is necessary. Only the most likely and potentially dangerous faults must be considered and protection provided to cope with them.

The extent of protection will depend on the voltage, the rating, and the role of the machine. The form of the protection will also be governed by whether the installation is locally or remotely operated. For example, where an installation is continuously manned alarms only may suffice for certain fault conditions. On the other hand, for remotely-controlled or partially-manned systems automatic shutdown would be essential for even the least critical failures.

Again, the generator may be a key unit or it may be just one of several providing base power to a network, either directly or through step-up transformers. In the latter case any justification for the maximum possible protection must always be weighed against the effect the shutdown or long term outage of a single generator will have on the system's operation.

## 10.2 Prime mover protection

In a short treatment such as this, it is not intended to describe the numerous protective systems applied to engines ranging from the smallest high-speed units to the largest slow-speed types. Protection equipment extends from simple alarm devices to complete data logging systems, and various options are provided by engine manufacturers. The prime considerations in the selection and application of protective systems must be that they are well engineered, are fairly straightforward (i.e. easily understood by operating personnel), and that they employ well-proven and thoroughly reliable devices.

Mechanical, hydraulic, pneumatic, and electrical systems are available, providing reliable control and operation. In the case of electrical systems, it is important that they derive their power from a SOurce other than the generator driven by the protected prime mover.

Any list of the strategic temperature, pressure, speed, and flow parameters to be monitored in engine systems cannot be exhaustive, and the engine manufacturer's advice should be sought on the extent of protective insurance to be taken. Equipment investment, the nature of the installed plant, and the load it serves will largely determine the extent of protection to be applied.

Regardless of engine size, there are certain essential operational parameters that must be monitored. These are:

- lubricating oil pressure;
- coolant temperature; and
- speed.

Other characteristic functions that may be covered, depending upon the particular prime mover used, are:

- lubricating oil temperature;
- lubricating oil level in the sump;
- differential pressure across lubricating oil filter( s);
- jacket water temperatures at outlets from individual cylinders;
- jacket water pressure or flow and make-up tank levels;
- raw water temperature, pressure and flow;
- injector and/or nozzle cooling water temperature, pressure and flow, and make-up tank level;
- fuel pressure;
- differential pressure across fuel filter(s);
- stored fuel levels;
- starter battery condition;
- starting air pressure;
- charge air temperature and pressure;
- exhaust temperatures (including before and after a turbocharger if one is fitted);
- engine vibration;
- bearing temperatures.

Abnormal operating conditions are detected by sensors whose output signals are fed into alarm! shutdown logic circuits. Various combinations of indicative and protective action are then possible:

1. alarm only (visible and audible);
2. simultaneous alarm and shutdown;
3. two-stage - i.e. alarm before shutdown.

Which one is used will depend on the plant's operational mode. Whether alarms only would suffice or whether instantaneous shutdown is required depends very much upon how closely the plant is attended and on the nature of the load it supplies. For example, 1 would only apply to continuously manned plant; and 2 would be more appropriate for unmanned machinery. System 3 may be applied in either context. It offers power plant attendants the chance to identify the reason for the first-stage alarm condition. Should they fail to rectify the situation, the second stage of protection will operate to automatically stop the engine. For an unattended multiple-generator plant or in an unmanned machinery space (the VMS of marine parlance) the first-stage alarm signal may be used to 'mobilize' another generator and, hopefully, have it connected to the busbars before an overload condition is imposed on other running units.

Alarm systems are usually electrically powered since sirens, bells and lamps are convenient means of signalling fault conditions. Shutdown systems may be operated electrically, pneumatically, hydraulically, or by direct mechanical action. Engines may be shut down using one of several methods to stop the fuel supply. These include:

- stopping the action of the fuel pumps themselves;
- acting directly into the engine governor system (see Chapter 6);
- shutting off the air supply to the engine;
- holding the exhaust valves open (4-stroke engines only).

Examples follow of some of these methods and of the sensors used: we shall consider each of the engine's primary systems and look at some typical safety devices and their application in proprietary schemes.

### 10.2.1 Lubrication system

This is arguably the key factor in the efficient and reliable operation of any prime mover. In-service difficulties are usually indicated by fall in oil pressure. Reasons are varied and may include [1]:

1. Low oil level. The oil near the surface of any sump is considerably aerated during engine operation. Partial loss of pump suction is thus possible, leading to persistent reduction in pump delivery pressure.
2. Obstruction of, or air leakage into, pump suction.
3. Choking of a full-flow filter. An appreciable pressure drop can occur across such a filter if the element becomes choked by oil-insoluble matter.
4. Dilution of the oil by fuel. Any appreciable contamination will give a marked reduction in the viscosity of the lubricating oil and hence in delivery pressure. The effect is common in engines using direct injection, and is usually progressive.
5. Defects on the discharge side of a pump. Apart from breakdown of the pump itself oil pressure collapse may result, for example, from the cracking or severing of an oil connection or failure of a main or big-end bearing. Another possibility is incorrect operation of the pressure relief valve, e.g. spring failure, stuck open, or wrongly set.

Whatever the reason, oil pressure levels will fall more quickly at the far end of the engine oil header where the pressure is naturally lower. This is the obvious place to site any oil pressure sensor. Sensors may take various forms, the commonest being the pressure switch. There are three basic types; diaphragm, bellows, and piston-actuated devices. If the first type is employed care must be taken to select a unit whose diaphragm is oil-resistant. Nitrile and beryllium copper are among the materials that are employed. In the second type of device the bellows may be mounted either within or external to the body of the unit. Suitable materials are copper alloy and stainless steel. The piston-actuated type is prone to erratic operation or jamming in the presence of mineral deposits or insoluble contaminants. A point to watch for in selection is that the instruments are unaffected by the vibration frequencies and amplitude levels expected in the particular application.

A feature of some instruments is their ability to carry two microswitches (see Figure 10.1) operating at the same or different pressure settings within the range of adjustment provided. This enables a single device to perform the dual function of high/low pressure alarm signalling. An instrument employing two diaphragms, bellows, or pistons may be used to detect the difference between two pressures (e.g. across a filter element, see item 3 above). A microswitch is actuated at a predetermined difference in the two applied pressures.

Some indicating instrument manufacturers offer mechanical gauges (for the measurement of press-

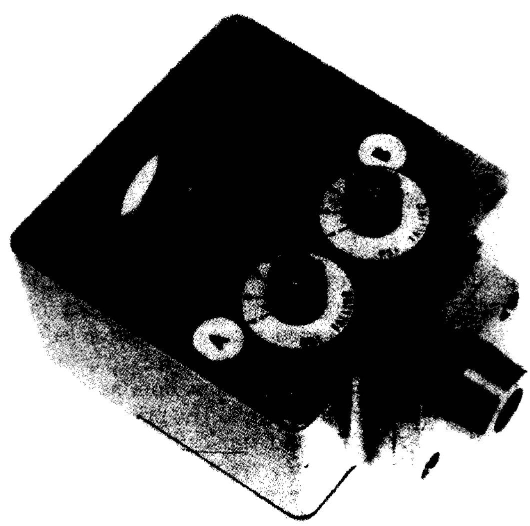


Figure 10.1 Diaphragm-operated pressure switch with two microswitches (Courtesy: The Pyropress Engineering Co. Ltd)

ure, temperature, levels, etc.) fitted with adjustable high and/or low limit contacts. A typical example is the Murphy *Switchgage* illustrated in one of its pressure reading forms in Figure 10.2.

On larger engines, particularly those whose pistons are oil cooled, temperature switches may be added to the lubricating oil protection circuits to detect excessive temperature conditions. Detection of temperature by probes fitted to sumps is unsatisfactory. Considerable temperature variations are likely to exist, according to depth and positioning of the sensing probes.

The switch contacts of all the protection devices mentioned above are light-duty rated and, as such, are unsuitable for the direct switching of the highly inductive coils that are used in shutdown devices such as solenoid valves and actuators. Interposing 'amplifying relays' are necessary in such cases.

Protection logic must be arranged so that the oil pressure circuits are inhibited whilst the engine is started and run-up.

### 10.2.2 Cooling systems

Problems with cooling circuits inevitably result in high engine temperatures. Commonly applied protection devices are temperature switches and indicating gauges with integral limit contacts. Both may incorporate two-stage contacts to give alarm and shutdown signals. The temperature switches are available in bulb-and-capillary, and direct immersion forms. *Thermowells* or pockets may be employed which are either screwed into a line fitting or welded into a pipe to accommodate the stem or bulb. This obviates the need to drain lines when a switch is removed. It should be obvious that the sensing element should be completely immersed in the coolant in order to ensure accuracy in operation. Care should also be taken to route capillary tubing clear of any heat radiating sources such as exhaust systems. False readings may otherwise result.

All the instruments contain a bellows element and operate on the pressure-sensing principle. The sensing element (stem or bulb) contains a measured liquid fill. Any change in temperature about this element causes expansion or contraction of the liquid. The resulting movement is transmitted directly by a push rod to snap action microswitches. Figure 10.3 illustrates a typical stem type temperature switch with cover and screwed pocket removed.

Air-cooled engines employ cylinder head temperature sensing to give protection against high engine temperatures. The sensing bulb may be fitted into a screwed socket or a boss in the cylinder head. On the smaller air-cooled engines where it is not possible or feasible to monitor cylinder head temperatures, the pressure flow generated by the cooling air fan or blower may be measured. This also provides detection of fan belt failure.

On large engines very useful additional protection is given by a low pressure sensor positioned in the inlet to the engine's coolant system. If coolant circulation failure occurs this pressure sensitive device operates before any temperature rise is detected [2].

### 10.2.3 Engine speed

It is essential that an engine is protected against overspeed, particularly where independently-mounted governors (e.g. of the hydraulic or electro-hydraulic type) are fitted - with the attendant risks of broken or disconnected control linkages. Any overspeed governor or sensor should be entirely independent of the normal governing mechanism,

Figure 10.2 A pressure indicating gauge with adjustable limit contacts (Courtesy: Frank. W. Murphy Mfr. Inc.)

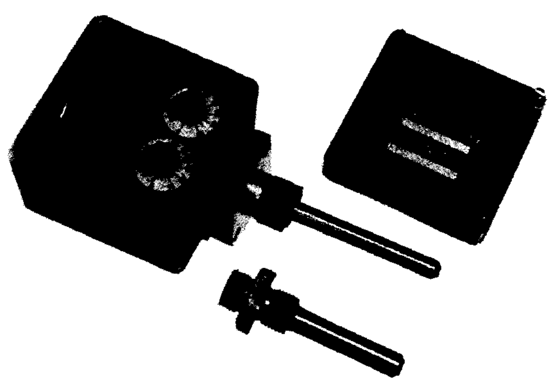


Figure 10.3 A stem type bellows-operated temperature switch incorporating two microswitches (Courtesy: The Pyropress Engineering Co. ltd)

i.e. it must employ a separate drive. Furthermore, it should be arranged to cut off fuel by some means distinct from the normal control gear. For example, it can act to override the governor control and close the injection pump rack. In this way operation of the overspeed protection is guaranteed even though the fuel pump control gear may have jammed or broken, putting the normal governor out of action [3]. Overspeed protection (usually set at about 120% of rated speed) must always be arranged to stop the engine instantaneously. Some engines employ centrifugally-operated overspeed governors which override the independent governor controls to close the injection pump rack when an overspeed condition occurs.

Where it is required to operate electrical control circuits in response to changes in rotational speed (e.g. isolating engine starting circuits at firing speeds when under remote or automatic starting conditions, and detecting rated speed), in addition to providing overspeed protection, a centrifugal speed switch of the type shown in Figures 10.4 or 10.5, may be employed. Both switch types offer a variety of drive possibilities.

The operating mechanism in the first unit illustrated (the *Pyropress* type C142) takes the form of a speed-sensitive, spring-loaded .;entrifugal governor for each of the switch actions controlled - up to four in number. The governors actuate snap-action microswitches through suitable linkage. When the unit is connected directly to a driving shaft the spring coupling shown in the illustration should be used.

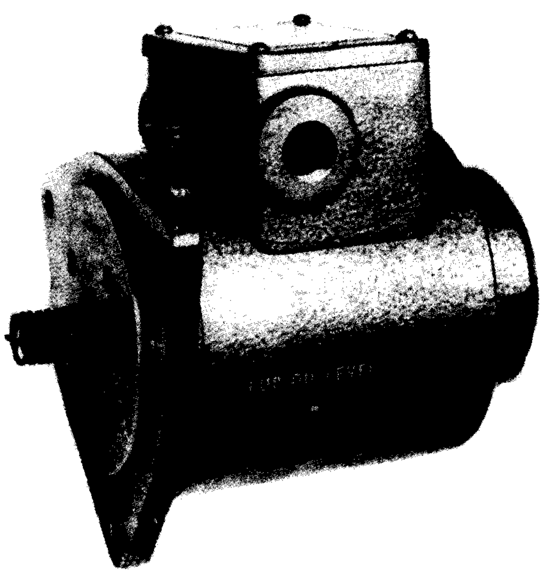


Figure 10.4 Example of a speed switch with individual centrifugal elements for each switch action (Courtesy: The Pyropress Engineering Co: Ltd)

The unit whose internal construction is shown in Figure 10.5 is a *Synchro-Start* three-element switch. As the driving speed increases two centrifugal weights extend, causing the plunger to contact the toggle plate. The bearing on the end of the plunger absorbs the thrust load and permits it to rotate without wear on the toggle plate. Precision protrusions on the plate actuate the three snap-action switches.

Yet another form of speed switch is the electronic type. Again, it can provide multiple switching points for control circuits as well as engine overspeed. The signal source for the switch may be:

1. a magnetic probe mounted at the engine flywheel ring gear, whose output is a function of the gap between the pick-up and the gear teeth, and the peripheral velocity of the gear, i.e.

   pick-up frequency

   $$= \frac{\text{No. of teeth} \times \text{gear shaft speed in rpm}}{60}$$

2. a tacho-generator;
3. the output frequency of the main generator.

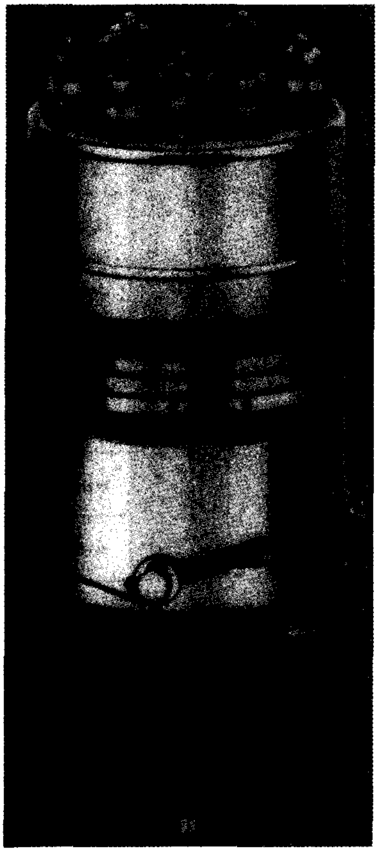
### 10.2.4 **Fluid** level monitoring

Reference has been made, in the characteristic functions listed earlier in this section, to monito~ make-up and service tank levels and lubricating oil level in the engine sump. We shall now consider some typical devices used for the purpose.

*Sump ai/level*

Figure 10.6 shows examples of devices that are used for monitoring lubricating oil level in wet sump systems. The two Murphy instruments illustrated are oil level sight gauges with adjustable limit switching capability. Both are conveniently mounted off any crankcase capable of being spot-faced and tapped - as the typical installations show. The model L-100 in illustration (a) has an adjustable low-limit switch which closes if the oil level drops to where the hinged float touches the low-limit screw. The type L-129 (illustration (b» offers adjustable low- and high-limit contacts. In its standard form it uses single terminals for each limit setting (as does the L-100). One side of the switch contacts is earthed to the instrument case. External alarm circuits must therefore have one line of their d.c. supply (usually the positive) earthed. The L-129 is also available with completely isolated switch contacts.

A range of combined oil level regulator and safety switch is marketed by the same company (see Figure 10.7). These devices are designed to automatically replenish the crankcase oil from adjacent oil storage



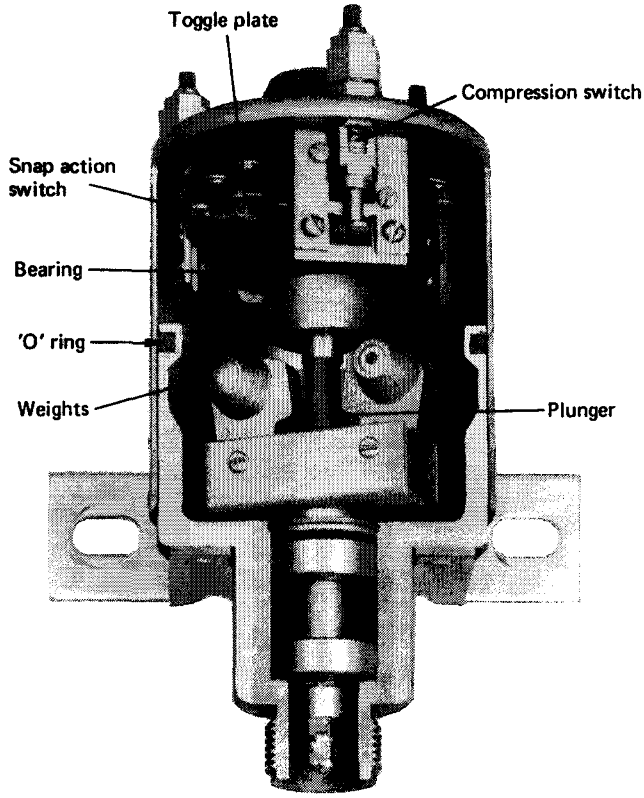



**Figure** 10.5 A three-element speed switch with field adjustable switch points (Courtesy: Synchro-Start Products Inc.)

reservoirs. They incorporate a 'thumb' valve which ensures rapid and accurate oil metering. A typical application is on remote and unattended telecommunication sites, where engine driven generators may be required to run for periods of up to 1000 hours without routine attention.

## *Coolant and fuel oil level*

Dual purpose gauges may be used to indicate levels in radiator headers and also to trigger alarms if levels should fall to low-limit set-points.

A switch-only device marketed by T.A.V. Engineering provides simple yet reliable coolant level sensing for radiator header tanks. It employs an encapsulated reed switch housed in a central stem. The switch is actuated by a circular magnet moulded into an annular plastic float that is free to slide vertically on the stem. Should the coolant level drop to a predetermined level the reed switch is activated to give a warning or shut-down signal.

Where fuel oil service tanks are filled by automatically controlled electric motor driven pumps it is usual to provide high- and low-level alarm indication. The signals may be derived from float actuated switches. A neat design is that of the Bayham R & G type 1710 unit which employs a float arm that is mounted within the tank and which is connected through a glandless magnetic coupling to a snap action mercury switch fitted to a pad on the tank's outside face. This arrangement prevents any fuel leakage that is otherwise apt to occur at interface connections between float arm and switch mountings.

Particular care is necessary with unattended or partially-manned power plant, where liquid fuel systems are concerned. Every reasonable precaution should be taken to minimize fire risk. We shall be discussing fire detection and extinguishing systems in some detail when we deal with installation design in Chapter 13. In the present context, however, it is worth mentioning that one of the major risk areas is an engine's fuel injection piping which carries fuel

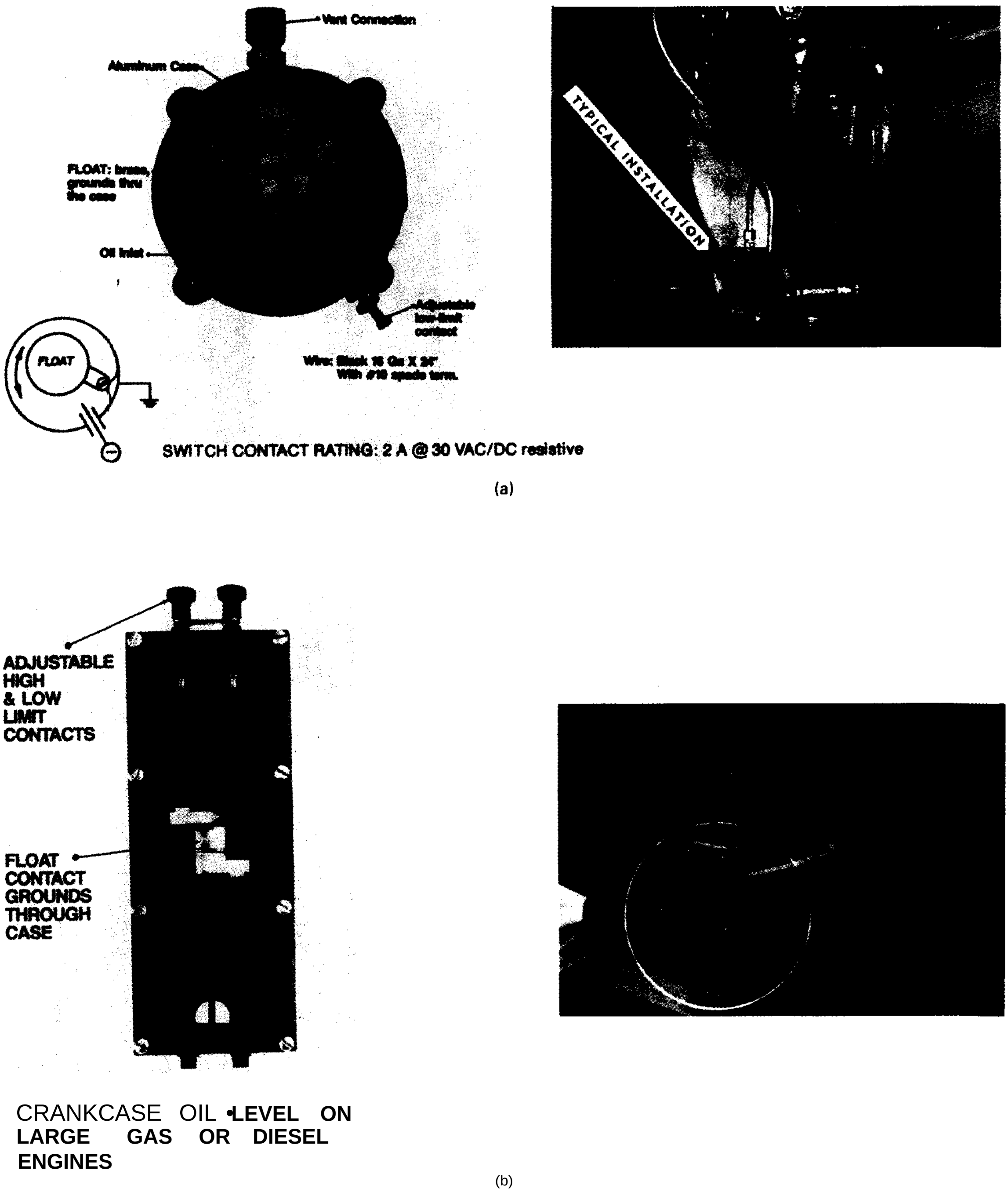



**Figure 10.6** Examples of monitoring devices for lubricating oil level (Courtesy: Frank W. Murphy Mfr. Inc.)

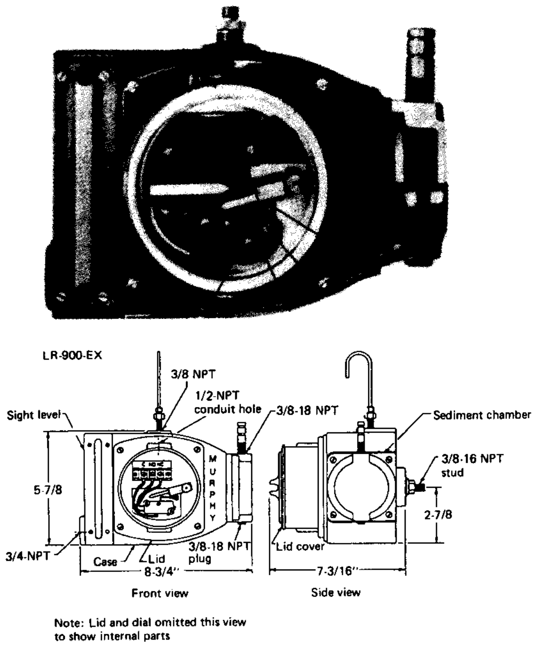



**Figure 10.7** The flameproof model of a combined oil level regulator and safety switch (Courtesy: Frank W. Murphy Mfr. Inc.)

oil at high-pressure between the pump and the injector. It is subjected to severe vibration and unless adequately supported and clamped along its route length, is susceptible to failure. Such failure may range from a minor leak to a complete pipe fracture. If the consequent oil spray reaches the exhaust manifold or a turbo-charger body a severe fire hazard results.

In the early 1970s engine manufacturers W.H. Allen designed and fitted fuel-pipe fracture protection equipment to engines installed in unattended machinery spaces in ships. This is still a standard feature of their S37-G heavy-fuel engines. Each high-pressure fuel pipe (and its end connections) is completely encased within a strong, sealed, flexible sheath which is longitudinally compressible to facilitate access to the connections (see arrangement diagram (a) of Figure 10.8). Leakage from any of the high-pressure fuel pipes is contained within the sheath and is drained to a common manifold from where it is fed to a drain tank equipped with a level switch. This arrangement considerably reduces the fire risk by giving warning of any fault in the fuel injection piping. For less stringent requirements the seal at the fuel pump end of the injector pipe may be omitted. Any fuel contained within the outer sheath is then allowed to drain down over the fuel pump into a gully in the engine housing, and is collected in a drain tank [4].

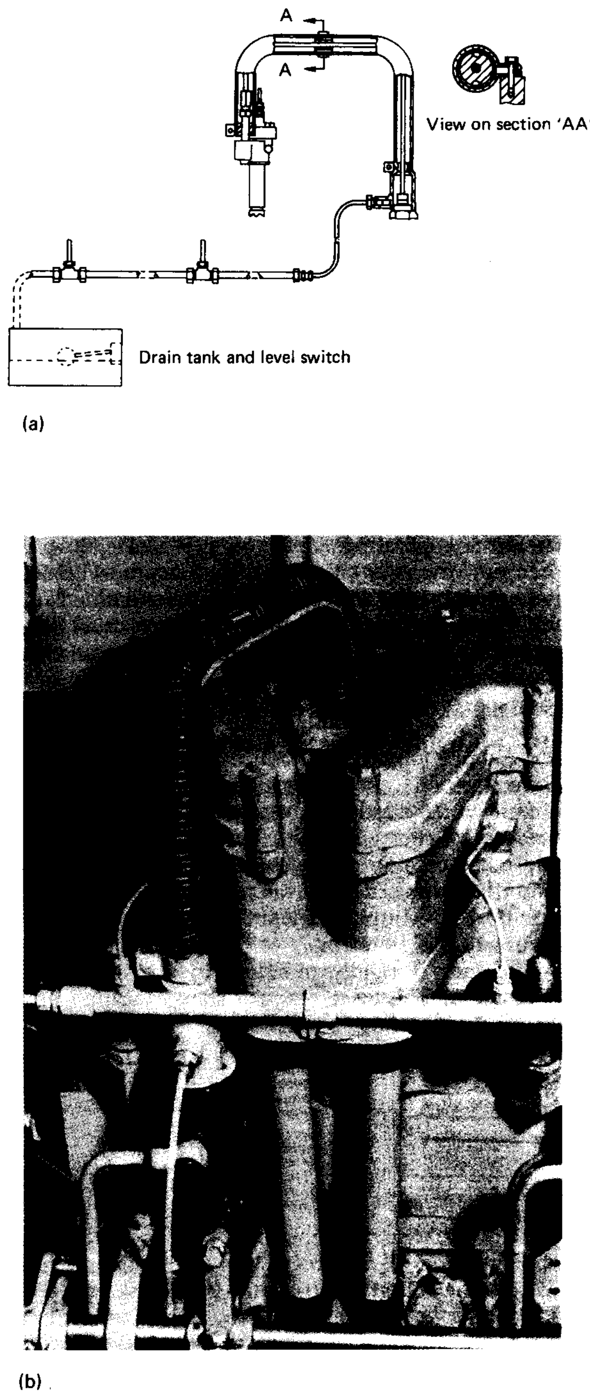



**Figure 10.8** Fuel pipe fracture protection equipment (a) Full injection pipe sheath arrangement (b) Close up of cylinder head showing fuel injection pump and injector with fuel pipe fracture protection sheath and piping to drain tank (Courtesy: NEI Allen Ltd)

The Southampton-based company Giro Engineering Ltd markets a range of rigid sheathed fuel pipe kits for some 30 manufacturers' engines. Each of the *Duoline* fuel pipes consists of a high pressure fuel injector pipe contained within a rigid, tubular steel, outer sheath firmly locked onto special end fittings. In the event of failure fuel is retained in the sheath and piped away along the gap between the concentric pipes to an alarm tank. Since each pipe is only marginally bulkier than a single-pipe system existing pipe routes and clamping points are usually used. Special indicators may also be fitted to show the exact location of failure. Some engine manufacturers provide the *Duoline* system as standard equipment. Others offer it as an optional item.

### 10.2.5 Flow monitoring

On the larger water-cooled engines it is useful to have some means of verifying that the coolant circuits are operating satisfactorily. We have already seen how use may be made of a pressure switch in the engine's inlet to detect coolant circulation failure. Other deviceii commonly applied are visual flow indicators, flow alarm switches, and instruments that combine both functions.

### 10.2.6 Engine-generator vibration

Detection of excessive vibration is particularly desirable in unattended or partially manned machinery spaces. Switches sensitive to abnormal oscillation in any plane of motion may be installed and used to stop the prime mover when excessive vibration occurs. The Murphy series VS-2 switch shown in Figure 10.9 is an example of one such device.

The unit is rigidly mounted to the monitored equipment. The inset diagram shows location and positIOning for the most effective protection on generating plant. The switch is 'armed' by pressing the reset push button which moves the tripping latch to a position where the holding power of the permanent magnet is sufficient to keep it in a 'latched' position. The air-gap is factory preset to 0.01 inches (0.25 mm) for minimal shock. Adjustments are made by moving the armature linearly toward or away from the holding magnet. This is done by using the slotted sensitivity adjustment screw. A malfunction in the reciprocating or rotating parts of the protected plant (see also generator rotor faults in Section 10.3.2 of this chapter) may result in abnormal shocks or vibrations. Should this happen, the sliding inertia mass in the instrument causes the armature to separate from the adjustment rod and break the magnetic coupling. The switch contacts are then actuated.

The switch is adjusted so that its contacts are not actuated during start-up and normal operating conditions. This is most easily done by turning the adjusting screw in its 'more sensitive' direction until the switch trips. The screw is then turned in the opposite direction (in about 45" increments) until the switch does not trip.

### 10.2.7 Engine shut down

Mention has already been made of the methods used to effect shut down. We shall now consider some of these in more detail.

#### *Electrically operated devices*

One of these is the solenoid-operated fuel shutoff valve. A typical example is the Murphy series SV valve illustrated in Figure 10.10, which operates on 12, 24 or 32 volt d.c. It should be placed in the fuel

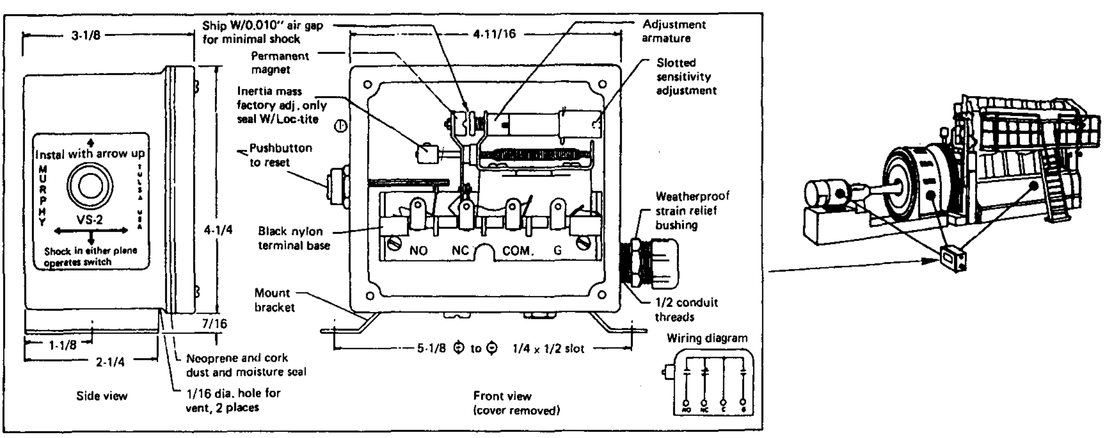



**Figure 10.9** Vibration switch (Courtesy: Frank W. Murphy Mfr. Inc.)

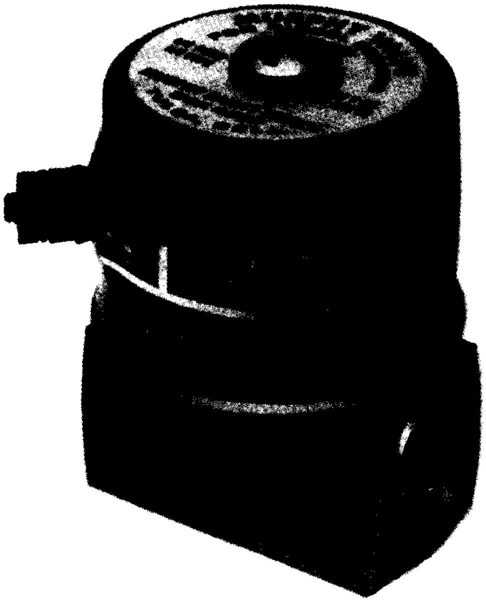


**Figure 10.10** Solenoid-operated fuel shut-off valve (Courtesy: Frank W. Murphy Mfr. Inc.)

supply line as close as possible to the fuel injection pump and after the final fuel filter. It may be arranged for either 'energized-to-stop' or 'energized-to-run' configurations. In the latter arrangement activation of engine-mounted safety switches would cause the supply to the solenoid to be interrupted - by contacts in the shut-down relay of the protection circuit. The valve closes and cuts-off the fuel to the engine. A check valve may be fitted in the excess fuel line to the service tank to prevent the injection pump siphoning fuel back through the line. This ensures that the engine shuts down quickly.

Not all engine makers will permit shut down by fuel cut-off. Where the method is sanctioned, use is usually restricted to mechanically governed engines. The following points should be noted [5]:

1. The valve should only be used as a means of emergency shut down. If used as a regular means of shut down, fuel aeration could lead to starting problems.
2. The engine is likely to run-on for a considerable period after valve operation.
3. Care must be taken when fitting the valve to ensure that contaminants are not introduced into the fuel system.

This form of shut down *must not* be used on hydraulically governed engines. Operation of the valve will result in loss of governing and a dangerous *run-away* condition. We have established (in Chapter 6) that external solenoid shut-down valves are used for the smaller hydraulic governors. Their sole purpose is to drain the governor's control oil into the engine sump. They are *not* used as fuel shut-off devices.

The preferred method of stopping mechanically governed engines is to operate the stop lever on the fuel injection pump. This is done by electrical, hydraulic, or mechanical type actuators. The shut-down arrangement should be of the *fail-safe* type, i.e. engine shut-down should take place automatically in the event of actuator power supply failure. The usual arrangement is for the actuator to hold the stop lever in the *run* position against a return spring.

The term *fail-safe* can have different connotations. For example, when it is applied to emergency generators in ships the vital consideration is not the generator itself but the vessel it safeguards. In these circumstances, failure of the control supply to a shut-down device should not be allowed to jeopardize the ship's safety, especially when it is manoeuvring in close waters. Engine protection in such cases is arranged to operate in an *energized-to-shut-down* mode.

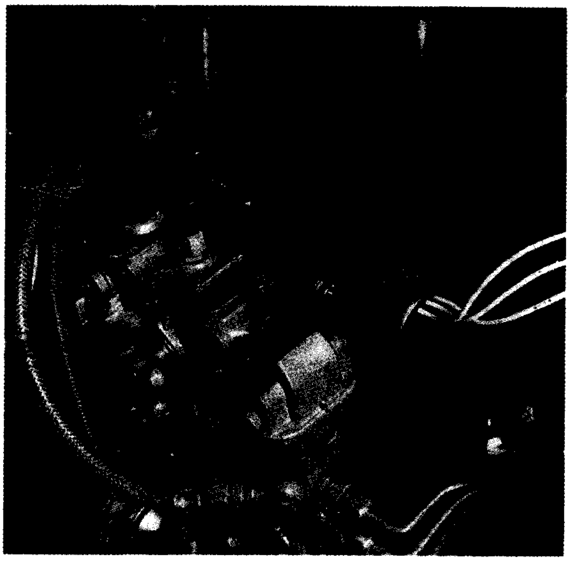
The normal shut-down device on mechanically-governed engines is the d.c. solenoid actuator. The cut-away illustration in Figure 10.11 is of a unit which has two working coils. Both are initially energized to give the high pull-in force required. The self-contained, heavy duty, double break switch disconnects the lower resistance *pull-in* winding, on completion of the plunger stroke. This leaves the higher resistance, continuously rated *hold-on* coil in circuit. This coil provides the necessary force to hold the injection pump's stop mechanism in the run position. Typical currents and forces for a 24 V d.c. solenoid of this construction are:

- a pull-in current of 23 A;
- a hold-on current of 0.3 A; and
- pull and hold force ratings of 75 N and 180 N at 25 mm, respectively.

The upper illustration of Figure 10.11 shows the application of this type of shut-down solenoid to a proprietary engine.

It is important that any linkage used with dual-coil solenoids is free of binding during the plunger's movement. The plunger must be allowed to complete its travel into the solenoid body. This ensures that the internal switch automatically disconnects the low resistance (short-time-rated) pull-in coil. Otherwise excessive heat is generated within the solenoid body and this may cause irreparable damage within a very short time (over 30s). The solenoid's mounting must be sufficiently strong to withstand the pull forces and all likely vibrations and shocks. Well designed systems will include an overload device (such as a miniature circuit breaker), to protect the solenoid.

The auxiliary terminal shown in Figure 10.11 may be used for a number of purposes, for example, to



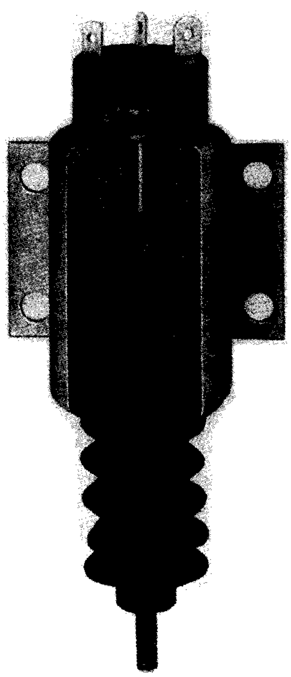


**Figure 10.11** A dual-coil construction solenoid actuator (Courtesy: Synchro-Start Products Inc.)

indicate that the plunger is properly seated after pull-in or to give a *sequencing* signal to the engine's control logic.

### *Non-electric systems*

A typical example of a hydromechanical system is that shown in Figure 1O.12(a). It uses engine lubricating oil to 'arm' a snap-action, spring-actuated shut-down device. This is directly connected to the fuel pump control lever or to an intake air shut-off valve. The trip actuates on falling oil pressure. A third option is a fuel shut-off valve, which gives immediate shut down when installed in *'pressure-time'* fuel injection systems of the type used on *Cummins* engines. If the valve is fitted to engines with conventional jerk pump fuel systems overspeed sensing *must not be used.*

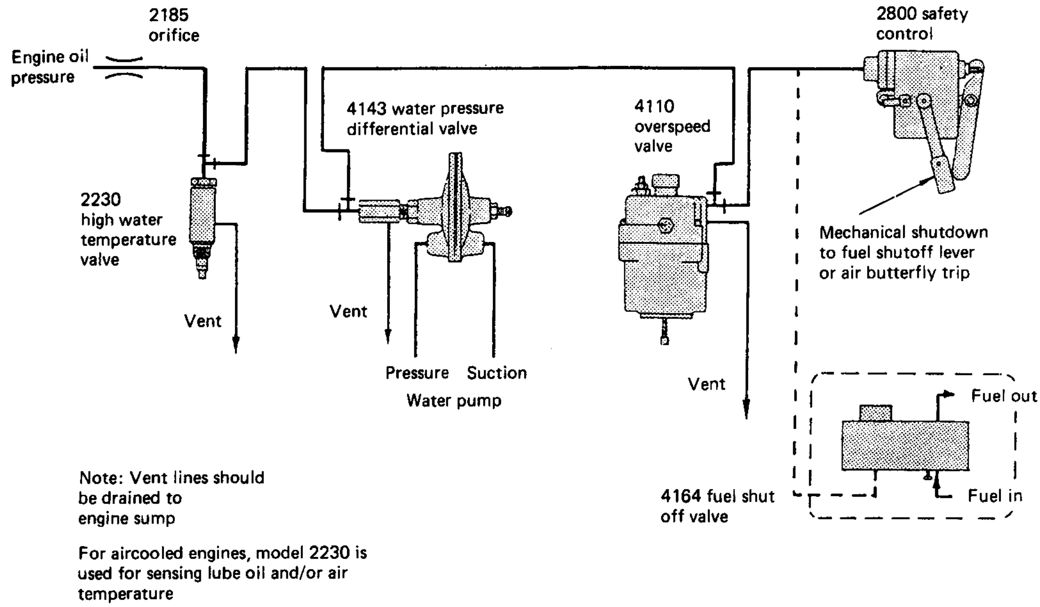
The handle of the 2800 safety device is connected to the fuel pump control lever or to an air butterfly in the intake air system. Before starting the engine the 2800 arm must be cocked and latched in the 'fuel-on' position. When engine lubricating oil pressure rises to a preset level the latch drops out and the device is 'armed'. When engine oil pressure falls to the preset point the 2800 trips and stops the engine.

The other protective sensors shown in Figure 1O.12(a) are essentially vent valves which drop oil pressure at the 2800 when dangerous conditions occur. They are arranged to vent oil back to the engine sump when activated. The system is 'fail safe' because breakage of an oil pressure line or excessive oil leakage or a plugged orifice will cause engine shut down.

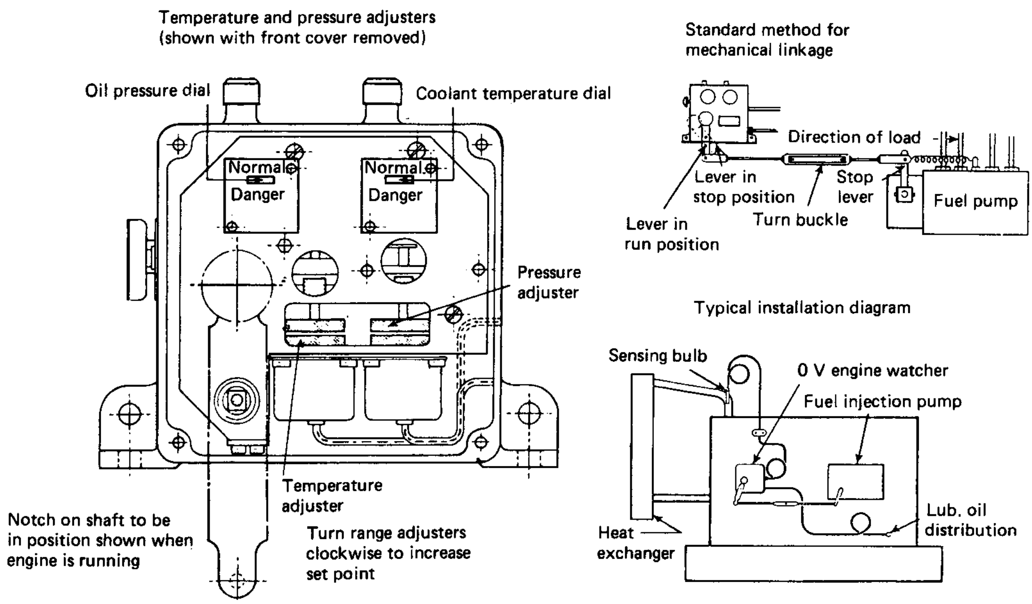
The 4143 differential pressure valve is designed to protect the engine against a blown radiator hose or excessive cavitation in the jacket coolant system. When coolant drops to dangerous levels most temperature sensors will not detect the condition until it is too late. This is because the sensing element does not respond in air or steam pockets as fast as it would with the scrubbing action of jacket coolant flow. The 4143 should be adjusted to vent oil in the safety shut-down system at a pressure differential slightly below that which occurs at low-idle engine speed. There are right and wrong ways of piping the sensing devices into the system, and the manufacturer's literature should always be consulted.

Another proprietary unit often used on the smaller engines is the type OV equipment marketed by Teddington Industrial Equipment (see Figure 10.12(b)). It incorporates a latch which operates through linkwork to lock the injection pump's stop lever in the 'run' position. The latch may be released in anyone of three ways:

1. manually, by means of a push button on the unit;
2. by a pressure-sensitive capsule housed within the unit and influenced by engine lubricating oil pressure;
3. by a temperature-sensitive capsule, also incorporated within the unit and influenced by coolant temperature.




(a)




(b)

**Figure 10.12** Examples of non-electric shutdown systems (a) A hydro-mechanical safety shutdown system (Courtesy: Amot Controls Ltd) (b) A mechanical shutdown system (Courtesy: Teddington Industrial Equipment Ltd).

The capsules are set to release the latch at specific pressures and temperatures. When the latch is released an external spring on the unit returns the control lever to the 'stop' position and closes the fuel rack. The cause of shutdown is indicated on one of two dials mounted on the unit.

Mention has already been made of the use of an intake air butterfly valve as an effective shut-down device. An engine will stop if it does not receive sufficient oxygen to burn the fuel. One of the worst hazards on engines operating in areas where inflammable gases are likely to be present (e.g. oil refineries and off-shore oil rigs) is engine overspeeding due to ingestion of these gases. In such conditions, even when the diesel fuel supply has been cut-off, the engine will continue to run and the governor is unable to control the speed. The inflammable gases passing along the air inlet manifolds act as a fuel. There is also the real danger of the ambient gas cloud surrounding the engine being ignited by the passage of flame from the engine cylinders (through the air inlet) as the valves 'bounce' on an overspeeding engine. Another cause of engine 'runaway' is overfilling of oil-bath intake air cleaners.

A device that may be used to provide *automatic* overspeed protection in such circumstances is the shut-down valve marketed by Chalwyn Equipment. The principle of its operation may be explained by reference to Figure 10.13. The unit, which contains a spring-loaded poppet valve, is fitted upstream of the air inlet manifold and is actuated by the pressure differential across it while the engine is running. This gives a valve closing force which is restricted by springs. The tension of these springs can be adjusted to give closure only when engine speed exceeds the desired level. Closure is instant and automatic.

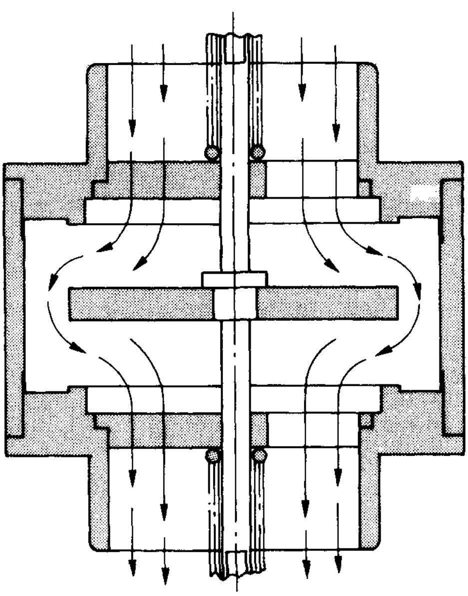


**Figure 10.13** Air intake shut-off valve (Courtesy: Chalwyn Equipment Ltd)

The valve is held in its closed position by the partial vacuum created in the air inlet manifold as the engine stops. Once the engine has stopped the vacuum is dissipated through normal engine clearances and the springs reset the valve automatically. The engine is then ready for restarting.

An anti-flutter mechanism is fitted to the smaller versions of the valve. This consists of a spiral adaptor on which the valve moves. It ensures valve stability and prevents premature closure due to valve fluctuation when used on single and odd-cylinder engines.

### *Dual-fuel and gas engines*

Dual-fuel engines are stopped by cuting-off both gas and pilot diesel fuel supplies. Spark ignition engines are stopped by earthing or interrupting the ignition circuit, and shutting-off the gas supply.

### 10.2.8 Some examples of monitoring and annunciator equipment

Where multiple alarms and/or shut-down protection are to be provided it is well worth considering the use of proprietary systems. A 'buyer's guide' is quite out of the question here and the examples that follow are merely intended to illustrate what can be done.

The ideal installation would provide for the control and condition monitoring of the power plant from one central location. Figure 10.14 illustrates this point. The spacious control room accommodates suites of panels which allow control of engines and generators. Facilities include synchronizing, remote switching, generator protection and comprehensive alarm and fault indications.

Use has been made of multi-channel alarm annunciators for each of the four generators installed. Annunciators of this type are available from a number of manufacturers. Typical examples are illustrated in Figure 10.15. That shown at (a) is a Highland Electronics type MPAS 40 microprocessor controlled system which can cater for up to 26 alarm channels. It is possible to include both prime mover and generator alarm functions in the one annunciator panel.

The Murphy Series ST alarm panel (illustration at 10.15(b)) is also designed to cater for all applications where normally-open or normally-closed sensor switch, or protection relay, contacts are used. Units in the range can cater for 5 or 10 alarm points.

The Modex Automation engine control/alarm unit illustrated in 10.15(c) is available in manual and

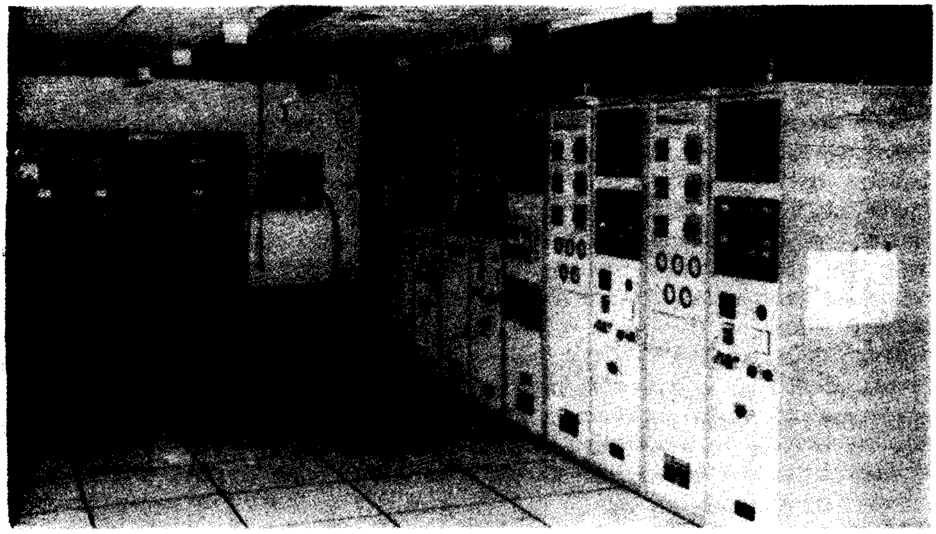


**Figure 10.14** Engine instrument and alarm panels in the control room of a Pacific island power station (Courtesy: NEI Allen Ltd)

automatic start versions, catering for low oil pressure, high engine temperature, failed to start, charge fail, and overspeed alarm conditions.

The *Autostop* Unit (Figure 10.15(d)) is one of several modules in a diesel engine control system marketed by *Selco.*

At the other end of the scale, the Pyropress MU2000 series system provides a comprehensive automatic condition monitoring and status indication facility. Continuous monitoring of up to 21 variables is possible. Inputs may be derived from temperature, pressure, speed, current, power and phase angle transducers. Each input channel can have one or two independently adjustable setpoints whose status is indicated by LEDs (light emitting diodes). These, and the channel levels, may be digitally displayed at any time. Analogue retransmission of any or all channels (to drive meters and/or recorders at remote locations) is an optional feature.

Each of the systems in the Pyropress range requires a common control module. This houses power supplies, digital meter readout, and other common functions (see the top left-hand section of the unit illustrated in Figure 10.16). A module is required for each input measured. Unused spaces are blanked-off. Alarm and shut-down systems require an additional *common circuits* module. A *group alarm* module provides the user with additional relay outputs for any setpoint or group of setpoints. A maximum of eight contact outputs is available from each group alarm module.

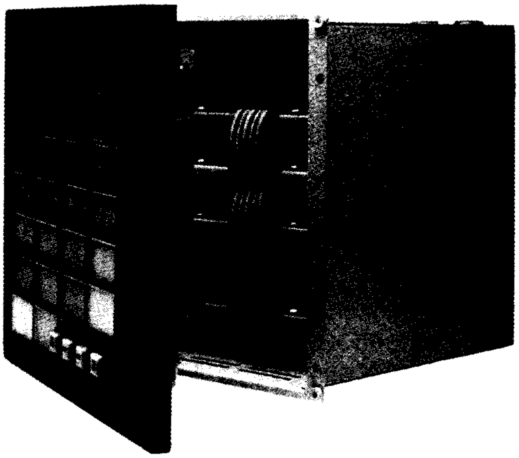
## 10.3 Protective relaying

BS 142: Section 1.1 *Glossary of protection relay terms* defines a protection relay as 'an electrical relay designed to initiate disconnection of a part of an electrical installation, and/or to operate a warning signal, in the case of a fault or other abnormal condition in the installation'. Protective relaying is concerned with the application of these relays to elements of systems in such a manner as to effect their prompt disconnection when undesirable conditions (such as short-circuits) occur in them, or when they begin to operate in an abnormal manner, i.e. when their dynamic functions exceed design parameters.

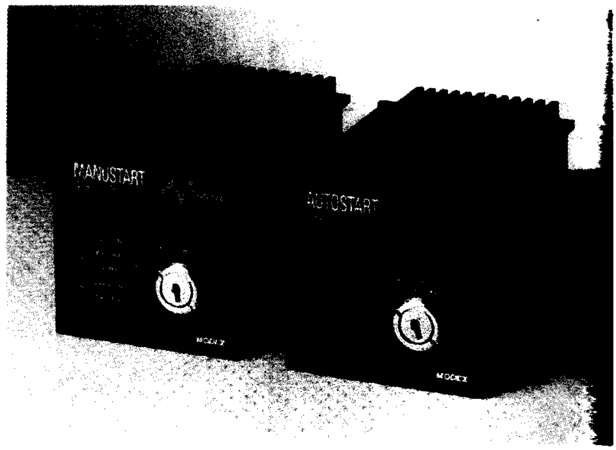
### 10.3.1 Philosophy of application

A protective relaying system should be capable of detecting a network element failure or an abnormal condition within the element with a speed commensurate with the particular power system's requirements, and then operate the minimum number of circuit-breaking devices to isolate the defective element from the network. The advantages of speedy isolation are:

1. Prevention, or at least minimization, of damage to the isolated element to reduce the downtime and expense related to its repair and so permit its restoration to normal service in the shortest possible time.



(a)

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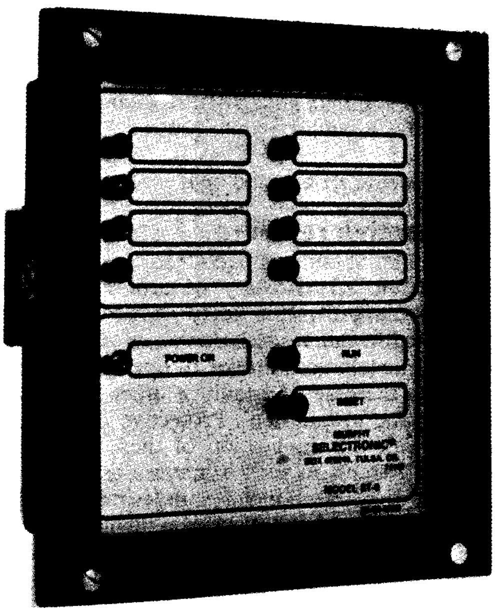
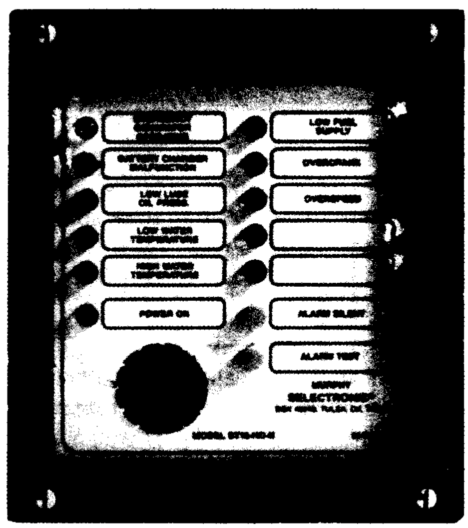
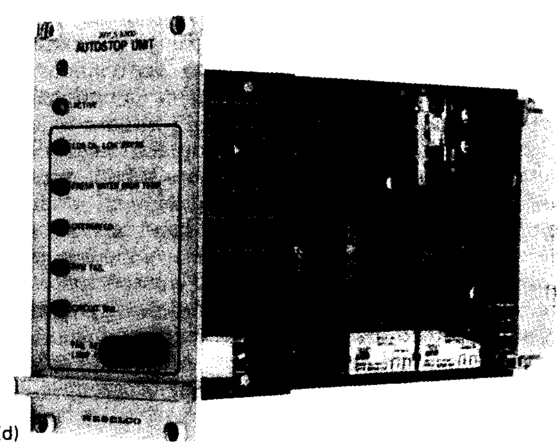







(d)

**Figure 10.15** Examples of monitoring and annunciator equipments ((a) Courtesy: Highland Electronics Ltd (b) Courtesy: Modex Automation (c) Courtesy: Frank W. Murphy Mfr. (d) Courtesy: Selco)

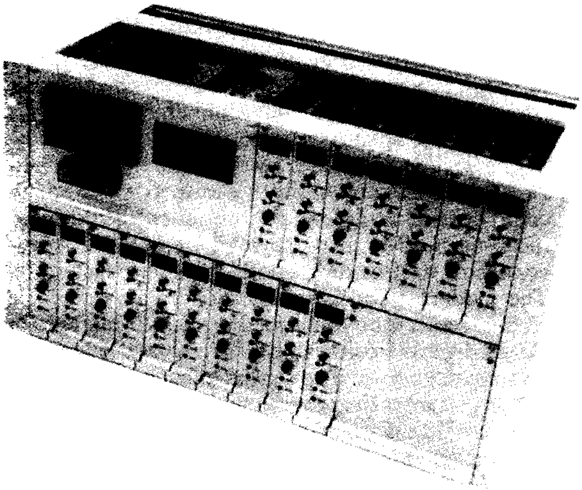


**Figure 10.16** Plant condition-monitoring system (Courtesy: The Pyropress Engineering Co. Ltd)

2. Minimizing interference with normal operation of the overall power system or of any dedicated end-process that may be associated with the loss of the isolated element.

This latter aspect of protective relaying is of special significance where reliability of service is of paramount concern to power system users. The speed with which protective devices operate therefore has a· direct bearing on continuity of service to the otherwise healthy parts of the power system. Rapid fault-clearing will keep generators and motors stable and help them 'ride through' any momentary system disturbances [6]. During a short-circuit paralleled generators will tend to lose synchronism if a fault is allowed to persist.

The essential attributes of any well-designed protective relaying scheme must therefore be:

1. *Sensitivity.* The ability to detect and initiate operation against the minimal variation in a dynamic function.
2. *Selectivity,* which relates to a relay's ability to recognize a fault condition in the zone or in the item of plant which it is intended to protect, and to operate only into those zones, and in that sequence, which the protective system design envisaged. It should be capable of ignoring faults arising in other zones. Some devices are inherently selective and others are not. Selectivity is achieved [7] by:

   - comparison of measured values on both sides of a protected item;
   - current and impedance grading; and
   - time grading.

   More of this later, when we discuss particular devices.

   Wherever possible, protective relaying should be so arranged that one zone's protection takes over from another's, should the latter's devices fail for any reason. This is known as overall back-up protection and is discussed in more detail later in this Section.
3. *Speed,* which as we have just seen is essential when removing a failed element from a network. In this context, the characteristic embraces both the initiating and the corrective action taken; that is, the time for a breaker to operate and to isolate the circuit must be included.
4. *Reliability.* The capability of a protective device to perform repeatedly and accurately within its design limits. It implies certainty of operation and that all extraneous causes will not jeopardize this assurance.

## 10.3.2 Relay types

These fall into two categories:

1. the electromechanical; and
2. the solid-state (electronic) type, using either digital logic or microprocessors.

Electromechanical relays take many forms, of which the most common are the *attraction* and the *induction* types. Attraction type units work on the solenoid principle with a plunger being drawn into a magnetic coil. They work satisfactorily on both d.c. and a.c. Therein lies one of their limitations when used for overcurrent protection. They act so fast that they trip on the d.c. offset or transient peak rather than on the actual setting which is much lower. This characteristic, known as *'transient overreach',* should be taken into consideration when setting relays of this type [8].

The more commonly used relay is the induction disc type which is of similar construction to an integrating a.c. energy meter. It works on the same principle as an induction motor. Magnetic fluxes cause eddy currents to flow in a metallic, nonmagnetic rotating disc. The torque so produced causes the disc to turn - in an identical principle to that used in a conventional domestic meter. After a predetermined angle of rotation the disc is arranged to trigger a trip mechanism. Variations of current and/or voltage signals, and the use of varied flux distribution patterns and damping arrangements, offer many permutations in operational characteristics. It hasn't the application limitations of the attracted-armature relay and its versatility accounts for its wider use in relay schemes.

The advent of semi-conductor devices such as the transistor and the thyristor resulted in the development of solid-state relays. They offer alternatives to electromechanical relays for most relaying applications. Not only are they physically smaller than their electromechanical counterparts but they are also faster-acting and give improved performance. They may be used in conjunction with electromechanical devices provided the design of such composite schemes makes due allowance for their disparate time-delays. A further advantage of static relays is the lower burden imposed on current transformers - typically, 0.5 VA at setting current, for an overcurrent relay, compared with the 3 VA of the induction disc types. Because of their resilience and very low mass they are also able to withstand far greater levels of mechanical shock and vibration - a very considerable advantage in respect of transportation and site erection.

Because they are static devices (apart from the final output elements, which are electromechanical relays) they require less maintenance. However, when considered in the context of diesel generating plant, fault diagnosis and repairs are probably beyond the capability of on-site maintenance personnel, particularly in the least-developed countries where the technology associated with electromechanical relays is more likely to be understood by the competent electrical technician.

On the debit side static relay components are prone to damage in high-humidity environments unless they are encapsulated. Also, transistors and thyristors are sensitive to transient voltages (arising from switching operations) which may be injected into the protection equipment either directly, through metering transformers, or by electric or magnetic field induction. This is also a significant consideration where a communications link is employed in a protective scheme. Any electrical *noise* and extraneous *signals* are a potential hazard to the *security* and correct operation of the system [9].

Protection relays usually operate directly into the trip circuits of circuit-breakers. Use is often made of auxiliary or intermediate electromechanical relays to provide higher switching power on the tripping contacts or to multiply the number of circuits affected by the operating signal.

The design of static protection initially developed as single or dual quantity measuring relays which could be used as direct substitutes for electromechanical units. The earliest relays employed semiconductor devices such as silicon planar transistors. The modem trend is to use digital gate and logic techniques, custom-built medium scaled integrating (MSI) digital circuits, and memories and microprocessors, to give widely programmable multi-function relays that meet the requirements of complex power systems [10]. Examples of proprietary relays are given in Section 10.5.

Analogue input signals from measurable power system quantities (such as current, voltage, phase angle and power) are converted to digital form and are measured and compared with reference 'setting' values. The resultant signals are processed either by digital logic or by a microprocessor (see the simplified block schematic of Figure 10.17). Discrete logic can perform a number of relatively simple operations in parallel. A microprocessor can handle highly complex logic tasks but is not ideally suited to parallel operation [10].

### 10.3.3 Transformers in protective relaying

Current transformers (c.t.s) and voltage or potential transformers (v.t.s) are combined with relays and circuit-breakers to provide the blocks upon which a protection scheme is structured. Their purpose is to

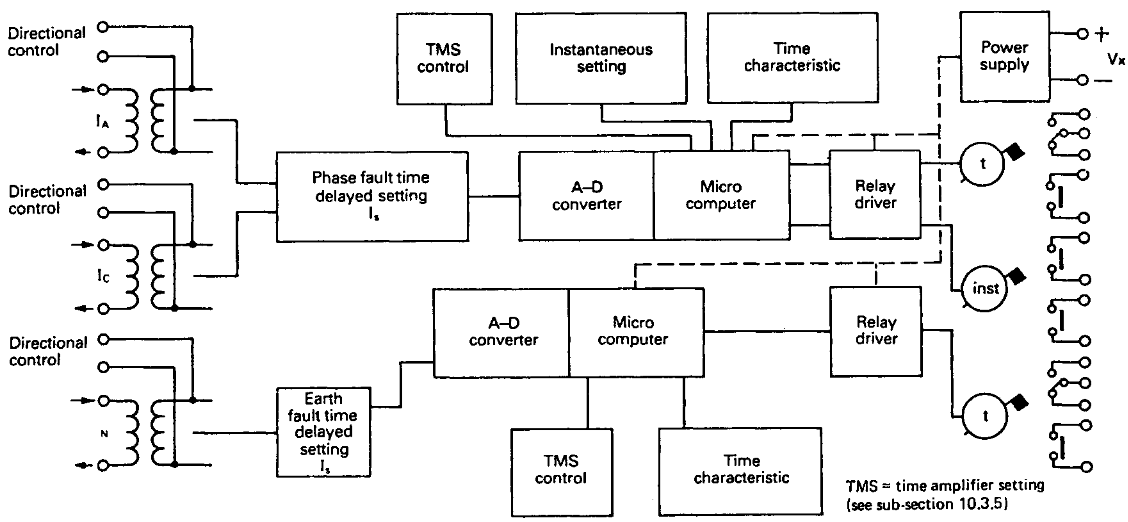



**Figure 10.17** Block diagram of 2-phase and earth fault type MCGG relay with phase instantaneous element (Courtesy: GEC Alsthom Measurements Ltd)

isolate the protection circuits from the higher voltages of the main power networks and to change the network working currents and voltages to values suited to the protection relays. Primary and secondary windings are electrically separated and the only coupling between them is that of magnetic flux.

We can only deal here with those features and that terminology which are of significance in our present discussion ..

## *Current transformers*

These may take several forms. Those of direct interest to us are of the air-cooled *bar primary* and the *wound primary* type. The latter have particular application to lower primary currents. As the description implies bar primary C.t.S use the cable or busbar of the power network circuit as the primary winding. The secondary winding is completely insulated and is permanently assembled on a core of rectangular or circular shape. This format is also referred to as a *window-type* or a *doughnut* C.t. in American practice where a bar-type or in-line transformer is taken to be one which has a primary bar conductor permanently mounted in the core window, and to which the network conductor or bus bar is connected [6, 8].

The wound primary type C.t. has primary and secondary windings insulated from each other and assembled on the one core. By definition they are classed as high reactance. They are less accurate than the bar primary type C.t.s and are not allowed for high accuracy (Class X) duty.

British Standard BS 3938: *Current transformers,* which is related to IEC 185, specifies C.t.S for use with electrical measuring instruments and electrical protective devices and gives guidance on their application and use. The standard defines classes of accuracy for protective c.t.s. Each class is associated with a *limit of error.* In all practical transformers their current ratios differ from their theoretical (turns) ratios and their *phase angle* (i.e the angle beween primary and reversed secondary-current phasors) diverges from the theoretical 180° due to the iron losses within them. These errors are referred to as the *ratio* and *phase angle* errors, respectively. For Class 5P and lOP c.t.s the limit of error is 5 % and 10%, and takes account of both phase angle and ratio error. The 'P' refers to 'protection' as opposed to 'measuring'. 5P is employed for sensitive protection (such as differential schemes) and also where protection co-ordination requires relays to be set close to each other. lOP is used where a 10% error is acceptable. Limits for Class *X* devices are not explicitly stated [11].

Two other terms commonly associated with protective transformers are *burden* and *output.* The burden is the *load* connected to the secondary winding and is expressed as ohmic impedance at a certain power factor. It should be noted that this power factor is *not* the power factor of the system network being protected. *Rated burden* is thus the impedance of the secondary circuit when carrying the rated current at a stated power factor. The *output,* on the other hand is the *J2Z* product expressed in volt-amperes (VA).

The smallest operational errors are to be expected when transformers are loaded to between 50 and 70 % of their rated burden. Rating plate burdens may be exceeded in exceptional cases (e.g. 125% indefinitely and 150% for about 15 minutes) without damage to the transformer, but accuracy will be affected when this happens. The error is doubled when the load is doubled.

The accuracy classification should be just high enough to provide an adequate supply to the connected load. The higher the class, the greater the cost of the transformers. Where there are many circuits on one project the cost of over-specifying may become significant. The main consideration for LV and HV switchgear is space, which is always limited. Accommodation difficulties can result if c.t.s are over-specified.

Preferred secondary current ratings are 5 A, 2 A and 1 A. Where long circuit leads cannot be avoided voltage drop considerations will dictate the use of 1 A rated secondaries.

A current transformer operates as a low-impedance device and its secondary circuit should always be *closed* through series-connected relays and/or instruments. If the load circuit is opened high-voltage peaks can occur in the secondary winding. This will put insulation at risk and overheat the transformer core. In theory, a short-circuiting switch should be provided for the winding. It should be arranged to be closed when no low-impedance loads are connected in the circuit. In practice, it is never fitted since any withdrawable component (such as a protection relay fitted in a drawout case) has automatic shorting at the case terminals, and on hard-wired circuits it is assumed that wires will not be disconneceted deliberately while on-load.

While BS 3938 offers guidance on the use of c.t.s for the dual purpose of measurement and protection, it is extremely difficult to produce a C.t. capable of efficient use for both purposes. It is only in those instances where the simplest forms of protection and instrumentation are used (e.g. a direct-acting overload device in series with an ammeter) that the dual-purpose role can really be justified [11].

## *Voltage transformers*

These are made for specific primary voltages. For voltages up to 15 kV they are usually of the cast-in-resin, dry type.

British Standard BS 3941: *Voltage transformers* (IEC 186) defines performance requirements and gives guidance on applications. Preferred secondary voltages range from 11O/v'3, for earth-connected v.t.s, to 220 V/phase. Operation up to 120% rated voltage is possible while still maintaining accuracy. Above this level overheating could occur. As in the case of c.t.s, the permissible error limits determine the accuracy classification. Voltage transformers for protective service are classified as either 3P or 6P, having voltage ratio errors limits of ±3 % and ±6 %, respectively.

Practice differs on the use of fuses in protective V.t. circuits. Where they are employed on the primary side of transformers they are only intended to clear a potential primary winding short-circuit caused by insulation failure. They will not protect against overload on the secondary side. Even a short in the secondary will not give sufficient primary current to blow the fuses. Low voltage fuses should be fitted in all secondary circuits which are not earthed.

Readers will find Section 15 in [6]; Section 17 in Item [3] of the Bibliography; and Section 4 in Item [4] of the Bibliography of particular value in obtaining an understanding of American practice on instrument and control transformers. The appropriate American Standard for instrument transformers is ANSUIEEE C57.13 - 1987.

### 10.3.4 Co-ordination

We have discussed in Chapter 9 the need for incorporating selective tripping (discrimination) in distribution networks using circuit-breakers and fuses. The aim must be to ensure that only the protective device *before* the network fault trips. Branch circuits of the same or higher level should not be affected. This is achieved by arranging for devices nearer the power source to have progressively higher trip current settings and longer fault-clearance times. The same principle applies to relay protective schemes.

The time-current characteristics of the protective devices to be co-ordinated should be plotted and compared on a single sheet of log-log graph paper. This systematic approach will help in the choice of the right devices to achieve the desired selectivity. Computers are increasingly used in the analysis of power systems. Software for overcurrent grading and the programming of relay curve plotting is becoming more widely available for unit protection schemes [12].

Co-ordination margins between breakers and fuses have already been dealt with in Chapter 9. When overcurrent relays are used, either with other relays or with breakers and/or fuses, clear time-margins should be provided between all protective devices in a co-ordinated system. Breakers and fuses have *band* characteristics to allow for manufacturing tolerances whereas overcurrent relays have *line* characteristics. When selecting for co-ordination it is therefore necessary to ensure that the correct edge of a band characteristic is used. If a relay is downstream of a *banded* device, the lower limit of the band is used. The converse applies for relays upstream and nearer the power source.

The drawback with fuses, miniature circuit breakers, and some moulded-case breakers is that their short-circuit trip characteristics are not adjustable. This can be a serious drawback on installations where prospective short-circuit fault levels are likely to change. For example, where power is provided by mutiple generators the value of fault current will depend upon the number of generators in service at the time the fault occurs. Ideal selectivity is only obtained by using protective devices that give adjustable sensitivity or variable operating times or, better still, a combination of both.

### 10.3.5 Overcurrent relays

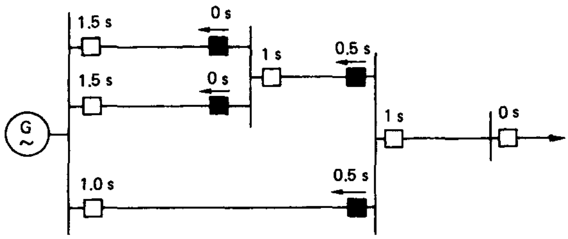
The overcurrent relay is by far the simplest type of functional protective device. Its purpose, as its description implies, is to operate when more than a predetermined amount of current flows in the portion of the power network which it protects. There are two basic types:

- instantaneous; and
- time-delayed.

Theoretically, the instantaneous relay is designed to operate with no time delay, immediately measured current exceeds the relay's current setting. In practice, operating times may vary from about 1 cycle to about 10 cycles of power frequency, depending on the relay construction, i.e. whether it is of the solid-state or the electromechanical type.

Where overcurrent relays are used in several series steps it is necessary to maintain a time margin between them. A margin of 0.25 to 0.4 s, at maximum fault current is typical. This allows for breaker operating time, relay overtravel, variations in the manufacturing tolerances of c.t.s, and a safety margin [6]. See Figure 10.18 for a network fed from one end. Note that the final-circuit relays are set for instantaneous operation. Stouppe [6] suggests that all overcurrent relays other than those applied to network incomers should incorporate instantaneous attachments and time-delay elements. This will help achieve overall selectivity where several in-series protection steps are used and still maintain reasonable operating times at the circuit-interrupting devices nearest the power source.

Before going on to discuss the various time-delayed characteristics we shall consider the setting adjustments provided on the relays. The first is a current (or *plug)* setting. The term *plug* derives from the fact that on an electromechanical relay the




■ = Directional overcurrent relay (DOC); trips only if fault is in the direction indicated (see sub-section 10.4.1)

□ = Overcurrent time relay

**Figure 10.18** Protection for a network fed from one end showing typical time settings

tappings on the current coil are brought out to a plug setting bridge (see Figure 10.19). A plug is inserted in this bridge to select a current setting at which the relay will start to operate. Equally or unequally spaced coil taps can be provided for a number of adjustable steps to give, typically, 50 to 200 % of the rated current output (i.e. the *energizing quantity*) of the protection c.t. The plug bridge may be replaced on certain relays by a knurled knob giving current adjustment against a graduated multiplier scale. On solid-state relays the setting control may be made on measuring boards mounted on the relay frontplate. See Figure 10.21(b) where the boards are identified by $I_S$ ($= \Sigma \times I_N$). $\Sigma$ is the sum of all the switch positions and $I_N$ is the relay's rated current in amperes. Setting ranges are, typically, from $0.5\,I_N$ to $2.4\,I_N$, in $0.5\,I_N$ increments.

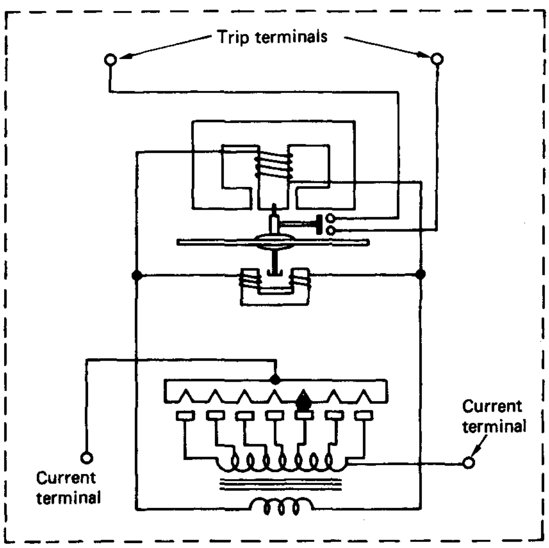



**Figure 10.19** Connection diagram for an induction disc type overcurrent relay

The second adjustable setting is that for time and is referred to as the *time multiplier setting*. On induction relays the adjustment may be made through a knurled moulded disc (rotated against a graduated time multiplier scale) which moves the back-stop controlling the travel of the disc. This varies the time that the relay contacts take to close for given values of fault current. Time multipliers are usually between 0.1 and 1.0. A typical family of time-current characteristics for an induction disc relay is shown in Figure 10.20.

On static relays the time multiplier control may be provided on measuring boards of the type illustrated in the relay of Figure 10.21(b). There it is identified by $xt = \Sigma$, where $\Sigma$ is the sum of all the switch positions. The range of multiplication may be from 0.5 to 1.0 in 0.025 steps.

Figure 10.21 shows typical setting features for induction disc and static type relays. The current setting plug bridge and the time multiplier disc are readily identifiable in illustration (a), which is of a GEC Measurements CDG series induction relay withdrawn from its casing and without its mounting chassis. Illustration (b) is the nameplate of a static type MCGG relay from the same manufacturer and

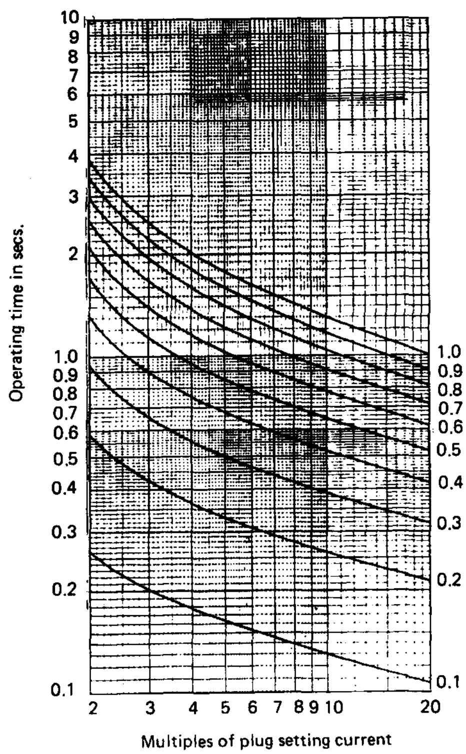
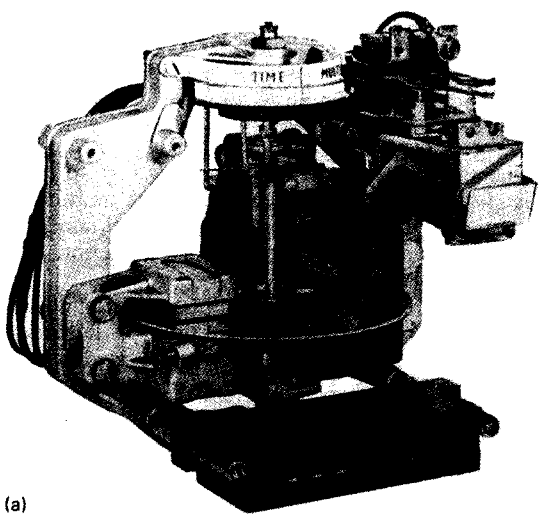
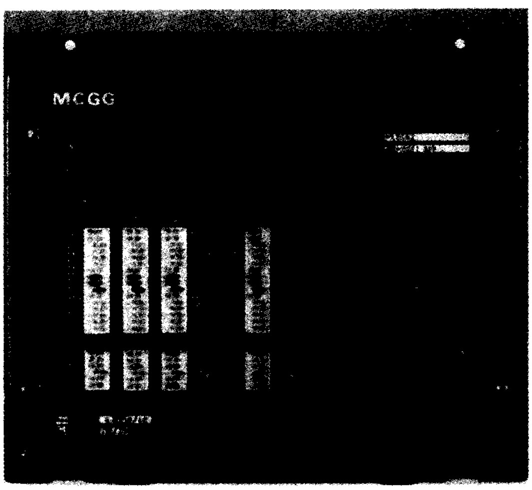



**Figure 10.20** Typical time/current characteristics on an induction type overcurrent relay (Courtesy: GEC Alsthom Measurements Ltd)


(a)



(b)

**Figure 10.21** Setting features for typical overcurrent relays (a) Induction disc relay (b) Modular static relay (Courtesy: GEC Alsthom Measurements Ltd)

shows the measuring boards for current setting ($I_s$) and time setting ($xt$). The board identified by $I_{INST}$ is the current setting control for the relay's instantaneous time element. When all switches on the board are set to the left (zero), or when the lowest switch is set to infinity (regardless of the positions of the other five switches), the feature is rendered inoperable.

## *Time-current characteristics*

The operating times of overcurrent relays may be made to vary in such a way that they are reduced for higher values of fault current, i.e. to vary inversely as the current flowing through the relay increases. Figure 10.22 compares the various characteristics that are obtainable from electromechanical relays which use heavily damped induction discs to increase time delays. Equivalent characteristics may be obtained from static relays. Figure 10.23 shows those available from the delayed element of the type MCGG which is illustrated in Figure 10.21(b). The obvious advantage of this facility is that a standard relay may be ordered before detailed system co-ordination studies have been completed.

Definite minimum time (DMTL) relays have been successfully used as the main form of protection (or as back-up to the main protection) on generator schemes. Inverse definite minimum time (IDMT) characteristics more closely match the thermal performance of machines and offer better time-grading capability.

On those installations where long feeder lines exist there will be reductions in fault-current level as distance from the power source is increased (see Chapter 9). Since the operation time of the DMTL relay changes little with current variation it is not the ideal choice in such cases. The *very-inverse* relay is particularly suited to such applications. BS 142 defines it as one having a time/current relationship in the form: $t \propto (I - 1)^{-1}$. It will be seen from the characteristic of Figure 10.22 that operating time is approximately doubled for a reduction in current from seven to four times the multiplier setting. This permits the use of the same multiplier setting for several relays in series [13].

The *extremely inverse* characteristic relay (whose operating time is almost inversely proportional to the square of current ($t \propto (I^2 - 1)^{-1}$) is best applied to those feeder distribution circuits which are likely to be subjected to the peak-current surges of switching operations.

Typical examples are rural feeder lines where automatic reclosers are used to restore service after transient faults [12, 13]. It is a requirement that the auto-recloser opens before fuses blow in the circuits to the consumers. If the fault in a consumer circuit persists the auto-recloser is arranged to lock in the closed position. This gives the appropriate protective fuse time to isolate the fault. In these circumstances it is important that upstream overcurrent relays are selectively time-graded with all downstream fuses. The long time-characteristic of the extremely inverse relay is ideal for such discrimination.

Overcurrent relays are not cheap devices. They represent a costly alternative to the simple direct-acting overload devices described in Chapter 9. Because of their inaccuracy and calibration difficulties the latter devices are not easy to co-ordinate into any but the simplest protection schemes. The price gap beween them and the overcurrent relay has been successfully bridged by the development of

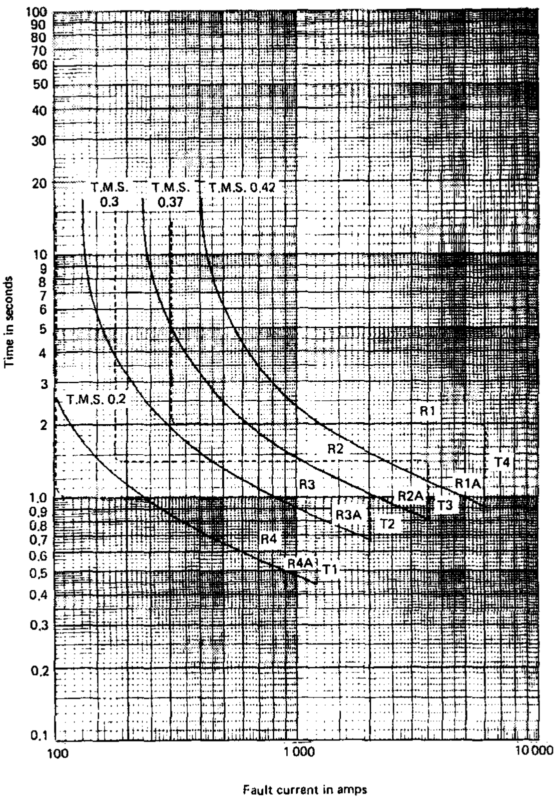



**Figure** 10.22 Comparative characteristics of definite time relay and inverse definite minimum time relay (Courtesy: GEC Alsthom Measurements Ltd)

more sophisticated designs of magnetic and solid-state direct-acting devices. While they may not quite match-up to the accuracy and close calibration tolerance of the inverse-time relay with definite minimum time (IDMTL), they provide similar characteristics and allow a considerable measure of co-ordination and discrimination. Their use has been largely linked with the modern low-voltage, air-break circuit-breaker [11].

## *Voltage controlled relays*

Unfortunately, one of the difficult areas of overcurrent relay application is in generator protection. This is because of the tendency of a generator's sustained fault current to be low if its automatic regulator is out of service and if no current-forcing circuitry is employed (see Chapter 4). Also, under fault conditions busbar voltage falls to a level lower than that obtaining on normal overload.

*Voltage controlled overcurrent relays* which incorporate an instantaneous undervoltage unit are designed to cater for these conditions. They do this by employing two operating characteristics, either of which may be 'selected' by the undervoltage relay which monitors the busbar voltage. In overload conditions when busbar voltage is near normal the relay operates on a long IDMT characteristic (see Figure 1O.24(a)) to match the generator's thermal characteristic. Under fault conditions, when the busbar voltage falls, the relay operates on a standard IDMT characteristic, permitting it to be time-graded with other IDMTL relays in the system.

An alternative technique is employed on *voltage restrained overcurrent protection,* where the IDMT characteristic of the relay is modified continuously according to the voltage at the machine's terminals. See Figure 1O.24(b).

## *Protection zoning*

On the larger power systems each item of equipment forms a zone. These zones are arranged so that they overlap as shown in Figure 10.25. Each is protected by what is termed a *unit system of protection,* which operates only on the occurrence of a fault within its own zone. It must remain stable under conditions arising from through-faults.

Non-unit systems (e.g. those where overcurrent relays are used in a time-graded discrimination scheme) will respond to faults beyond the actual zone of protection. Normally, relay(s) in the faulty zone will clear the fault before those in other zones operate. Should the relay(s) in the faulty zone fail to operate, those in the non-unit-system zones will. This is referred to as *overall back-up protection [14].*

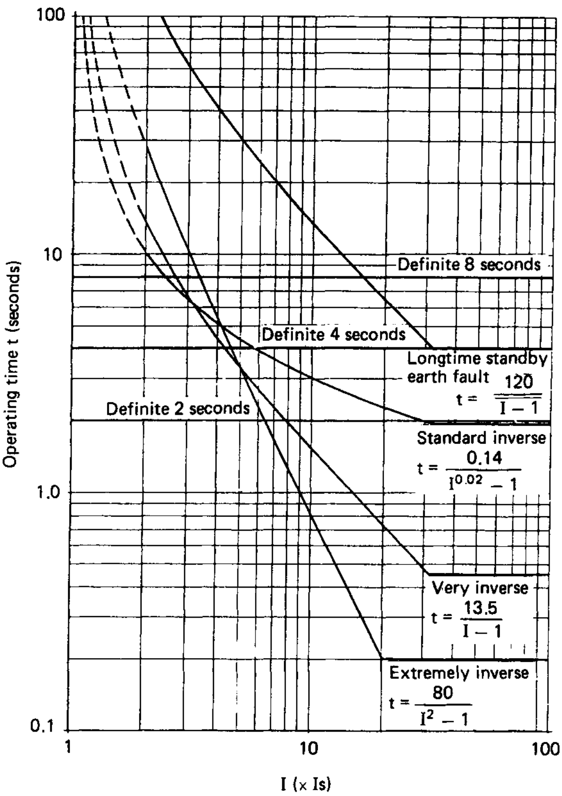



**Figure 10.23** Operation time characteristics of a time-delayed overcurrent element in a static modular relay (Courtesy: GEC Alsthom Ltd)

Within the zones themselves two categories of protection may be applied:

1. Primary protection, which is the 'first line of defence', and operates to remove only the faulted element from the total network.
2. Standby or 'last resort' protection, which uses relays to isolate network elements by either operating the same circuit-breakers as the primary protection or by tripping breakers in adjacent zones to disconnect a greater portion of the power system.

It will be noted from Figure 10.25 that each power network item (generator, generator-transformer, transmission feeders, etc.) is interconnected to the network through circuit-breakers. Because the zones overlap any failure in a region where overlap occurs will result in the operation of more breakers than the minimum necessary to clear the fault. If there was no overlap, failure in the regions between zones would not be covered and no breakers would trip. Overlap is the lesser of two evils [15]. In practice, the extent of overlap is limited so that the operation of too many breakers is avoided.

Although primary protection is mainly concerned with complete or partial short-circuits (between phases and to earth) it also covers abnormal conditions such as persistent overload on thermally rated plant, rotating machines, transformers, and reactors. The response in such applications need not be as fast as that required to remove a short-circuit. Nevertheless, in most applications the fastest possible primary protection is beneficial.

Standby relaying is usually provided for added protection against short-circuits only since they are the commonest cause of failure in power systems. Indeed, experience indicates that standby protection for other than short circuits is not economically justifiable [15].

Readers will also encounter the terms *restricted* and *unrestricted* zones. These are defined later in sub-section 10.4.1.

## 10.4 Generator protection

We shall now examine those fault conditions that can occur on a generator in service, and discuss the relay protection equipment that may be applied in each case.

- Stator winding faults
- Rotor faults
- Over- and under-voltage
- Over- and under-frequency
- Overload
- Unbalanced loading
- Loss of excitation
- Failure of prime mover
- Loss of synchronism

Before we do this it is as well to mention, for the benefit of a broad-based readership, that the diagrams which follow will not use the *device function numbering system* commonly applied to protection engineering schemes. The reader needs to be aware of the system, however, and an abridged list of those functional numbers which may relate to engine-generator protection schemes is given in Appendix D.

*Device numbers* indicate the operational function of the device. They had their origin in American practice, where they are mainly used in the context of control equipment associated with switchgear. They are also applied to other electrical diagrams and specifications. BS 3939: *Graphical symbols for electrical and electronics diagrams - Guiding principles* has adopted the numbering scheme originally introduced in America by the National Electrical Manufacturers Association (NEMA) in its standard SG-5 in 1959 *(Power Switchgear Assemblies* Part 8) and later issued by the American National Standards Institute (ANSI) in their document ANST

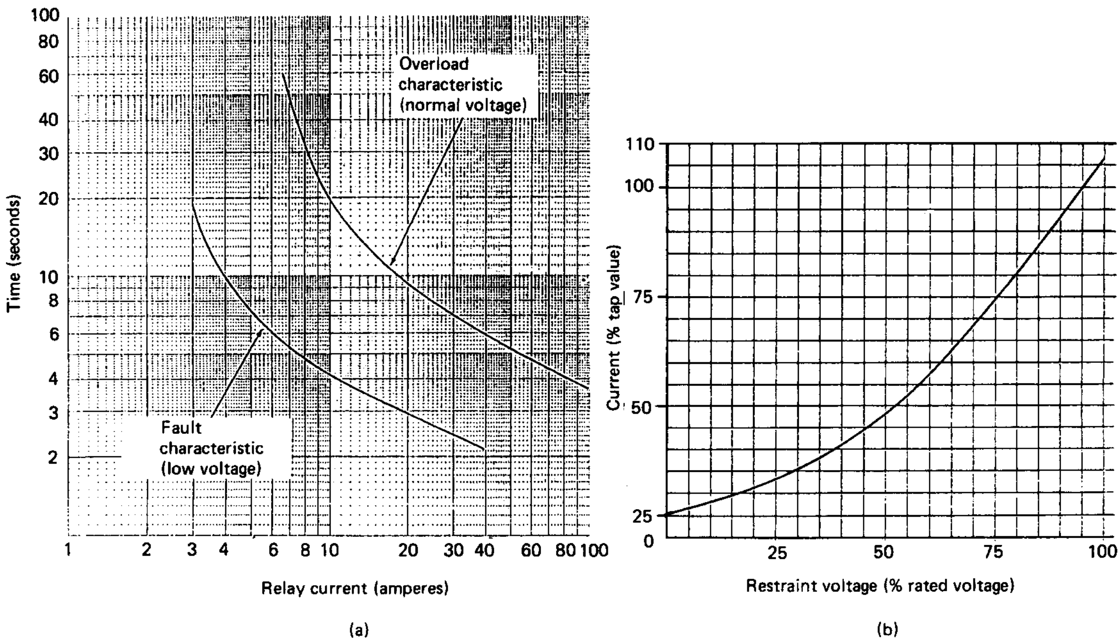



**Figure 10.24** Typical characteristics for voltage controlled and voltage restrained overcurrent relays (a) Voltage controlled relay – set at 100% (5A), with time multiplier setting (TMS) of 1.0. (b) Operating characteristic of voltage restrained relay, with TMS = 1.0 (Courtesy: GEC Alsthom Measurements Ltd)

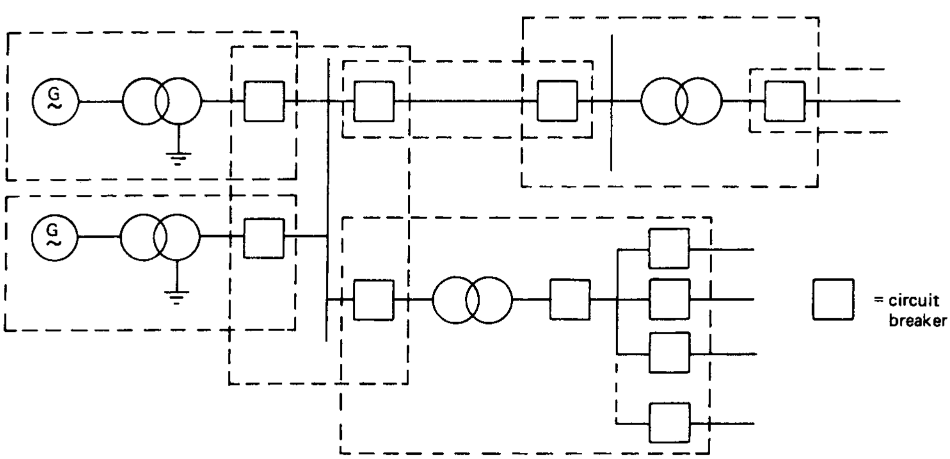



**Figure 10.25** Zones of protection in a power network

C37.2 -1979, *Electrical Power System Device Function Numbers.* There are minor differences between the British and American documents in certain functional titles and definitions but in each case the 'intent' of the device is the same.

### 10.4.1 Stator winding faults

Any fault caused by insulation failure within the windings of a machine will only exist within the machine itself. Opening the main output circuit-breaker will not protect the windings. Of course it is important that any breaker between generator output terminals and system busbars is opened in order to prevent other generating plant in the network feeding into the faulty machine. If the generator's main field continues to be energized the e.m.f. generated internally will maintain the fault current. One of the first actions must therefore be to quickly remove the excitation supply to the main field. This is a relatively straightforward procedure on machines employing d.c. exciters, or on certain forms of static excitation where the main field is fed through sliprings on the rotor shaft (see Chapter 3 Figure 3.5). The rate at which the fault current is reduced is then dictated by the speed with which the magnetizing flux decays within the machine.

Where 'brushless' excitation is employed one can only act to remove the a.V.r. fed supply to the a.c. exciter's field winding. The aggregrate time-constants of the excitation system in such cases means that the flux decay time is longer and, consequently, so also is that of the fault current decay. It is possible on machines of the type described in Figure 3.34 of Chapter 3, which have 'buck and boost' a.c. exciter field windings, to use the regulation field winding (that providing the subtractive or bucking effect) to help speed up the process but its influence can only be marginal.

Stator winding faults may develop through failure of insulation between turns of a winding, between phases, or between phases and earth. Interturn faults are difficult to detect and protect against. Roe [8] describes a scheme that may be employed where generators use a parallel-circuit winding (i.e each phase has two windings in parallel). With this form of construction a 'jumper' connects the parallel windings together at the halfway point. Its purpose is to carry the small circulating current that flows due to the inequality that exists between the windings. The method described detects any increase in the circulating current caused by short-circuits between turns on one of the paralleled windings of a phase. Because the circulating currents are only of the order of 0.005 times rated current, low-burden extremely inverse overcurrent relays with specially designed (split-phase) c.t.s are required. Close liaison is necessary with the generator manufacturer and particular attention must be paid to winding connections and external leads. The engineering effort and expense involved in such measures will rarely be justified, especially when it is realized that most interturn faults will quickly develop into earth-faults and may be cleared by the stator earth-fault protection. There remains the possibility, however, that extensive damage could arise if the interturn fault occurs at the winding ends before it develops into one detectable by other protection [16].

While phase-to-phase faults usually evolve from interturn faults, they may occur without any such preliminary. Once breakdown in interphase insulation begins it inevitably leads to an immediate earth-fault. The damage caused to the stator by the short-circuit current can be considerable. It is very unusual to have a phase-to-phase fault clear of earth.

#### *Forms of earth-fault protection*

The basic forms of earth leakage or earth-fault protection using single relays are shown in Figures 10.26, 10.27 and 10.28. Diagram (a) of Figure 10.26 illustrates the use of a core-balance transformer (c.b.t.). The three phase conductors are passed through the ring core of the transformer which carries a detector winding (or sensing coil). Under balanced conditions the currents in the three phases vectorially sum to zero. Any out-of-balance or *residual* current resulting from the earthing of a line conductor sets up a flux in the ring core. This flux links with the detector winding and induces a voltage within it which energizes a fault relay preset to pick-up at a certain level. In another form of c.b.t. the ring core is provided with three primary windings to which the line conductors are connected.

Diagrams (b) and (c) illustrate alternative methods of applying the residual current detection principle in earth-fault protection. They use individual c.t.s in 3-wire and 4-wire circuits, respectively. Current balance under normal circuit conditions is between the secondary currents in the c.t.s. In arrangement (a) it is the fluxes in the ring core of the c.b.t. that are balanced.

Diagram (d) illustrates how a single relay may be used for earth-fault detection. The relay is operated from a C.t. inserted in the neutral-earth connection of the generator. It is important to realize that all these forms of protection do not protect against open circuit in a line, i.e. *single-phasing* [11].

#### *Neutral earthing*

The methods most likely to be used in the installations under discussion are:

1. Solid earthing, which is normal British practice for low voltage systems below 600Y.

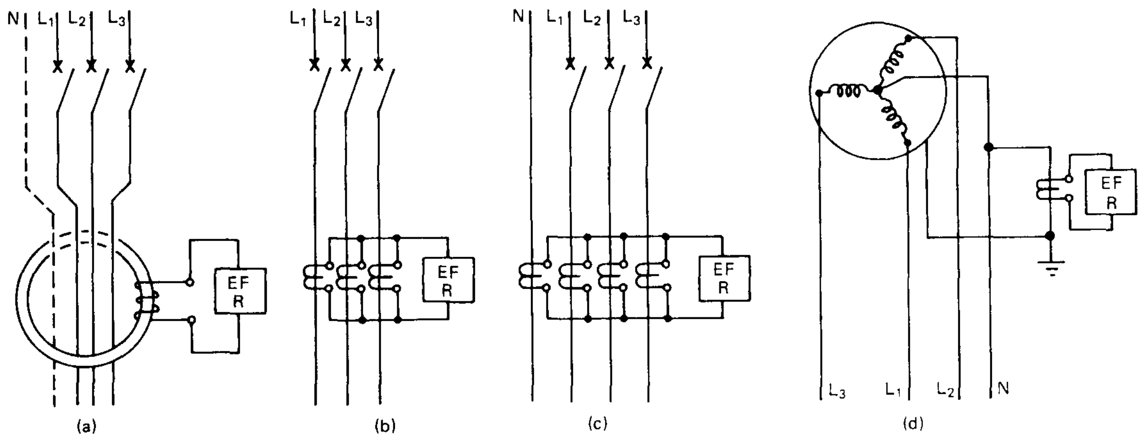



**Figure 10.26** Basic forms of earth-fault protection using single relays

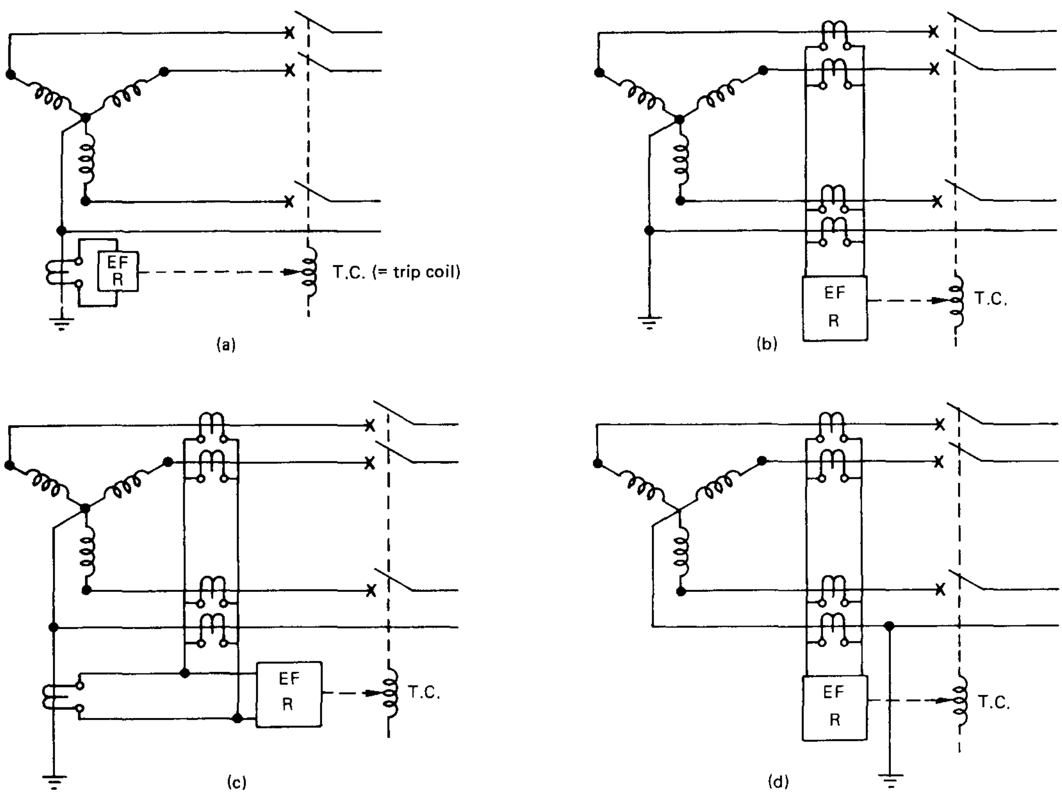
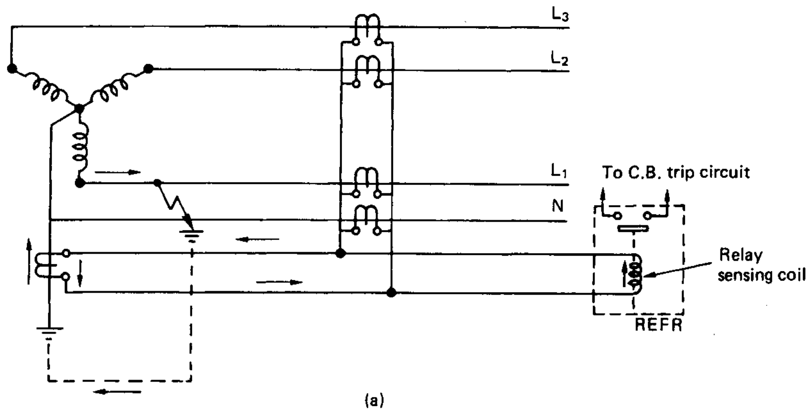



**Figure 10.27** Earth-fault protection on a 4-wire output generator (a) and (b) Unrestricted earth-fault protection schemes (c) and (d) Restricted earth-fault protection schemes



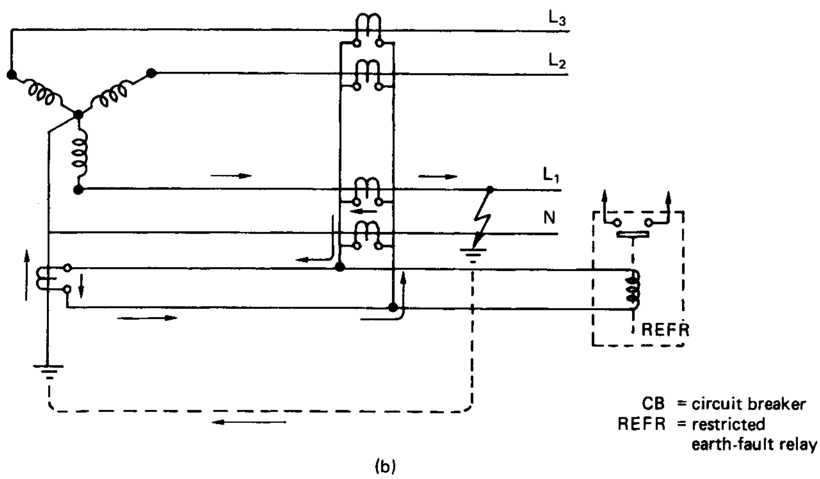




**Figure 10.28** The principle of restricted earth-fault protection (a) Fault within the zone (b) Fault outside the zone

2. Low-resistance earthing for systems between 1kV and 15kV, employing either metallic grid or liquid type earthing resistors. In European practice reactors of corresponding ohmic value are often employed.

The intention in both methods is to provide a solidly-earthed system. The purpose of the low resistance in method 2 is to limit the earth fault current either:

1. to full load current, for convenience of C.t. ratios and co-ordination of protection; or
2. to approximately 100A - being the minimum order of current that will still allow discrimination using core balance c.t.S to achieve the required sensitivity; or
3. to approximately 5A - being the minimum that can still be detectable although not allowing discrimination between zones.

Occasionally, HV systems involving generators are solidly earthed. The main reasons for earthing low voltage systems are:

- to stabilize the voltage of the system with respect to earth;
- to ensure that the voltage between any phase and earth does not normally exceed the phase voltage of the system;
- to anchor the neutral point of the system so that its voltage potential does not fluctuate;
- to allow the system protection to operate in case of fault between any phase and earth;
- to decrease hazard to human life.

Earth resistances of less than 1 0 may be obtained in favourable soil conditions (using earth plates, mats or driven electrodes in parallel arrangements). BS Code of Practice CP 1013 *(Earthing)* recommends a value of 10. Even in relatively high-resistivity soils it is possible to achieve values of the order of 2 to 50.

In this discussion we are concerned only with the engineering of protective systems. The objective is to insert sufficient resistance in the neutral earth path to limit fault currents to levels that minimize damage to plant while ensuring that current magnitudes are adequate for detection by, and operation of, protective relaying; but these are not the sole criteria.

Where on-site generators are employed the power source's earthing impedance is just one element of the earth fault loop for final circuits at the most distant points of the consumer's installation. The lEE Wiring Regulations give values of the maximum permissible earth-fault loop impedance (Zs) for all the conventional types of protective devices used in such final circuits. Due regard should be paid to the needs of the installation, as a whole before finalizing the power source's earthing arrangements.

Readers will encounter references to other forms of earthing such as high-resistance earthing, and earthing through arc suppression coils and through voltage transformers. These are special methods which are not associated with the size of generator or the operating voltage levels that concern us. Briefly, they may be considered to give an *insulated neutral* and offer the advantage that a system may continue in service after a first earth-fault occurs. Locating such a fault can be difficult. If a second earth-fault (i.e. on another phase) occurs, one has a phase-phase-earth fault. This can cause considerable damage if one of the earth faults is not cleared immediately.

Choice of earthing method is dictated by the network's operational requirements such as those of power and lighting loads, of continuity of service, and of safety and cost. International marine regulations, for example, permit the use of both isolated and earthed neutral systems for all vessels except tankers. Earthed systems are forbidden in tankers. Choice, however, is almost inevitably for isolated systems - in order to avoid loss of vital services should a single earth-fault occur [17].

## *Generator earth-fault protection*

When earth-fault protection is applied to a generator circuit it should be of the type known as *restricted* earth-fault protection. The term implies that there is full discrimination between earth-faults external to the protected zone and those that occur within the zone. The alternative configuration known as *unrestricted* protection implies that no such discrimination is given. Any earth-faults occurring well outside the immediate circuit to which the protection is applied may cause unnecessary opening of generator circuit-breakers. All of the schemes illustrated in Figure 10.26 are classified in the unrestricted protection category.

Figure 10.27 compares basic forms of both types of protection applied to 4-wire generator systems. Diagram (a) shows the simplest arrangement and covers all zones from the generator windings to the final circuits in the load network. Regardless of where the earth-fault occurs, the return current path to the generator neutral must always pass through the c.t. and therefore operate the earth-fault relay (e.f.r.). Diagram (b) is for an arrangement that monitors faults in the load network only and does not detect earth-faults in the generator windings. Note the relationship between the earthing point in this diagram and that in diagram (d). Diagrams (c) and (d) indicate the different arrangements necessary for restricted earth-fault protection. The location of the neutral earthing point in relation to the protection c.t. in the neutral conductor determines whether 4 or 5 c.t.s are employed.

The principle of restricted earth-fault protection is explained in Figure 10.28. The secondary current of the C.t. placed in the star-point-to-earth connection is shown (in diagram (a)) as circulating entirely through the eJ.r.'s sensing coil. This is not strictly true as a proportion of the current will divide through the secondaries of the four line c.t.s. The current drawn by these four 'idling' C.t.Sis excitation current. It is related to the voltage generated by the working (the fifth) C.t. at the point of common connection and the C.t. magnetization curve. The magnitude of this current is very small compared with the earth-fault relay's setting. The overall sensitivity will be decreased, but only by a small amount - e.g 10%. High impedance relays are used. A stabilizing resistor may be necessary in order to prevent relay malfunction on heavy through faults.

We shall now consider the application of earth-fault protection to single and multiple generating plants operating in various modes. Combining the arrangements of Figures 1O.27(b) and 1O.27(d) we can derive a scheme that provides earth-fault protection in all zones for a single base-load generator installation [18]. The operation of relay e.f.r.a. in Figure 10.29 indicates the presence of a fault in the machine's windings. Relay eJ.r.1. covers for faults developing in the load network. Any signal from eJ.r.a. should be used to shut down the prime mover and trip the output circuit-breaker or contactor. Action should also be taken (especially on the larger generators) to suppress the excitation circuit. For faults in the load network it is only necessary to trip the circuit breaker. The generator may continue to run if deemed desirable.

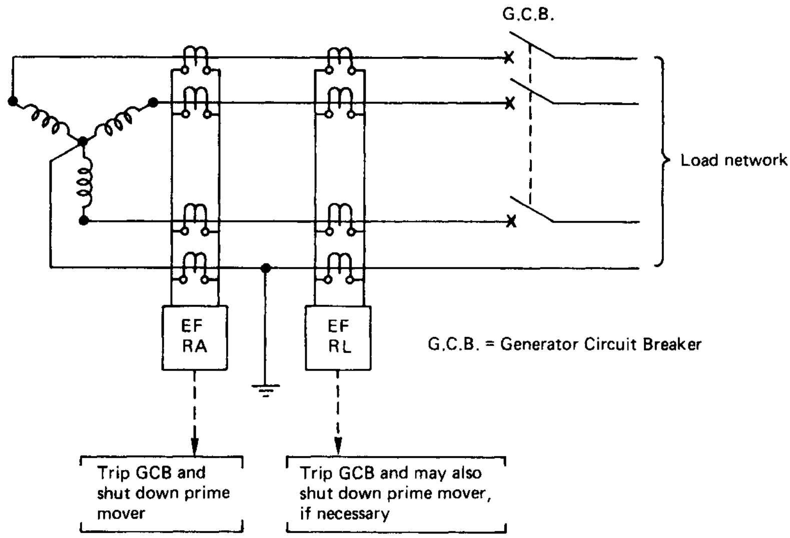



**Figure 10.29** Earth-fault protection in all zones for a single generator

Schemes fQr multi-power source systems may use the arrangement shown in Figure 1O.27(d). It is equally applicable to installations where a single generator operates in standby to a utility supply and to installations which contain multiple generators. Anyone, or a combination of all, of the arrangements in (a), (b) and (d) of Figure 10.27 may be used for non-paralleled multiple generators utilizing 4-pole breakers or contactors.

Special precautions are necessary, however, where multiple power sources operate in parallel or employ 3-pole output switching devices. Simultaneous earthing of the neutral conductor at more than one point with respect to the c.t.s is proscribed. This is because there can be no guarantee as to which return path the fault current will take.

A scheme that meets all the requirements for parallel or non-parallel running generators is shown in Figure 10.30 [18]. It uses 3-pole contactors or circuit-breakers. Relays e.f.r.a. and e.f.r.b. give restricted earth-fault protection for the generator windings. Relay e.f.r.1. protects the load network zone regardless of which generator is operating. A signal from this relay should be arranged to trip outgoing load feeder contactors or circuit-breakers.

Operators of private standby generating plant in the United Kingdom need to be aware of the Electricity Supply Company's regulations relating to the use of multi-pole changeover switching devices. Much will depend upon the method of earthing applied to the installation. Until the relaxation of regulations in 1965 all Area Boards in the United Kingdom provided a single neutral earth at their substation distribution transformer (many still do to this day). This requires 4-pole switching to be used (see also Figure 10.31). Where a relaxation has been applied and the use of *protective multiple earthing (p.m. e.)* or *multiple earthing of the neutral (m.e.n.)* has been permitted, 3-pole switching is usually satisfactory. It is a requirement of p.m.e. that the neutral is earthed not only at the Supply Authority's end but also at the consumer's end of the distribution network. Also, that all extraneous and exposed conductive parts (e.g. metalwork) within a consumer's premises shall be bonded together and to the neutral.

Figure 10.31 shows typical protection configurations using 3- and 4-pole switching arrangements. In both cases relay e.f.r.a. provides restricted protection for the standby generator windings and e.f.r.1. gives unrestricted protection to the load distribution network - regardless of supply source. The latter relay should be arranged to trip both supply source contactors.

Figure 10.32 shows a simplified arrangement for 4-pole switching using one earth-fault relay to give unrestricted protection in all zones, but only when the standby generator is supplying the essential loads. No protection is given when the utility supply feeds the site loads (see also Figure 10.33).

Anxious to standardize on a scheme that would cater for both non-p.m.e. and p.m.e. systems (since non-p.m.e. systems were being increasingly converted to p.m.e. in its area) the United Kingdom's East Midlands Electricity Board produced a code of practice in the mid-1970s. This devised a common arrangement for both systems permitting the use of 3-pole, electrically and mechanically interlocked changeover contactors.

The salient features of the scheme, reproduced in Figure 10.33, are that the installation's bonding is in accordance with the lEE Wiring Regulations and

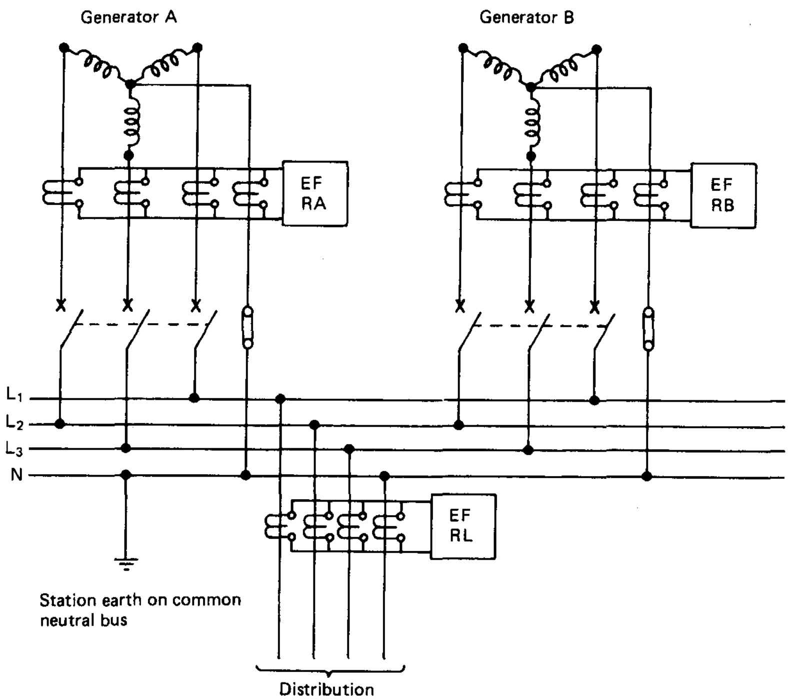



**Figure 10.30** Multi-generator plant with earth-fault protection in all zones

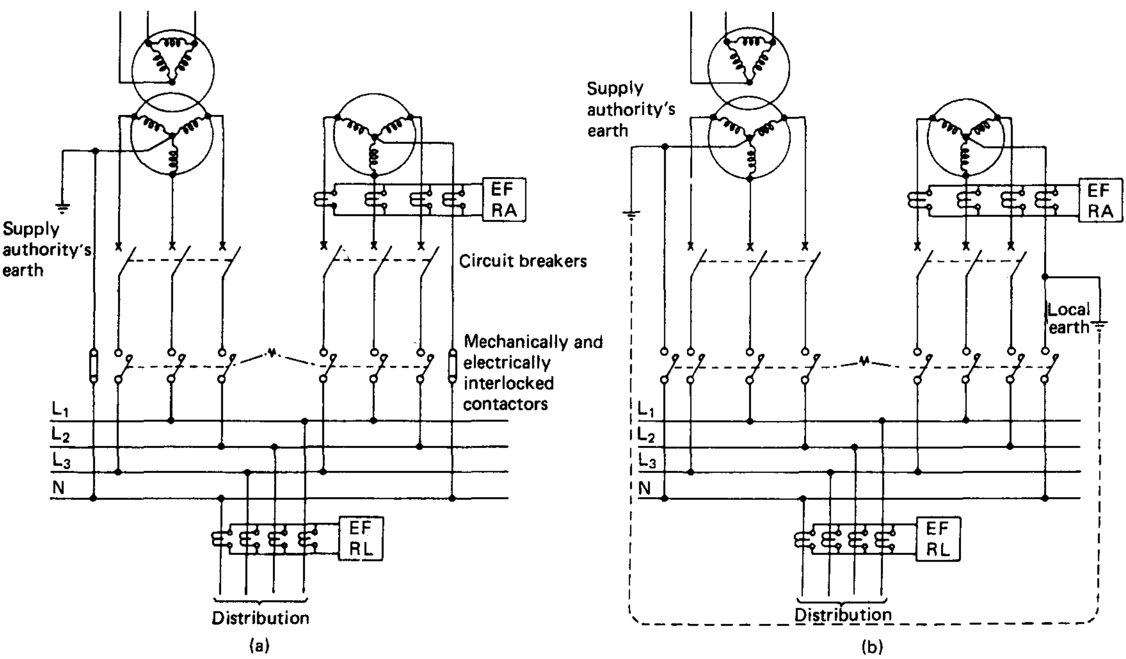



**Figure 10.31** Standby-to-mains generator supply with 3-pole and 4-pole switching, giving restricted and unrestricted earth-fault protection

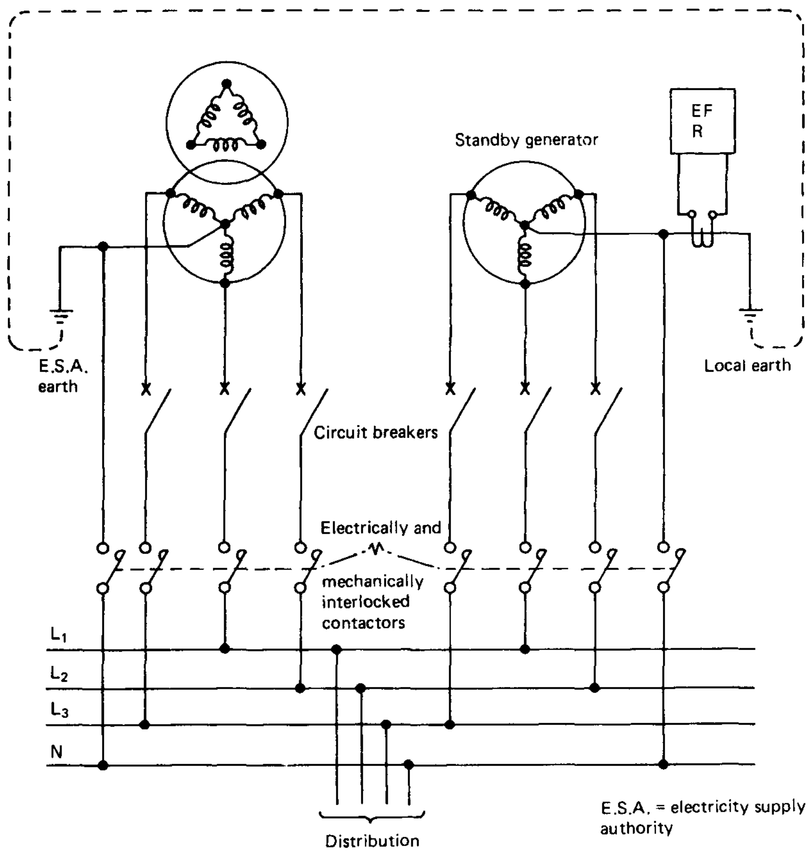



**Figure 10.32** Unrestricted earth-fault protection in all zones only when the standby generator feeds the load.

restricted earth-fault protection is provided for the standby generator zone. The generator's neutral is connected to the consumer's earth bar through a core balance c.t. All the phase conductors are threaded through the transformer. Restricted protection is therefore given for all earth-faults on the generator and between it and the core balance transformer (c.b.t.). *(Note:* for the larger sizes of generator with large diameter cables it is more convenient to use four c.Ls as in the arrangements of Figure 10.31.)

The relay operated by the c.b.L performs the following functions:

1. trips the controlling contactor to the essential load network;
2. stops the generator prime mover.

If prime mover shutdown is not provided the standby generator's neutral must be switched along with the three phases - i.e. a 4-pole contactor must be fitted. This is because a 3-pole contactor would not interrupt the fault-current circuit which would continue to be maintained through the fault-to-earth and earth paths.

A *standby* earth-fault relay designed to give backup protection for earth faults on the generator is shown as an optional extra. It is necessary to incorporate a time delay into this relay in order to give discrimination with fuses or other earth-fault protection devices in the load distribution sub-circuits.

The schemes shown in Figure 10.31 are equally applicable to plants operating in parallel with a utility supply - typically, in peak lopping installations (see Chapter 11). Since it is usual to interconnect the neutrals of utility supply and generator(s) for the parallel-running mode, 4-pole switching is unnecessary. Three-pole arrangements are the norm.

Three-pole switching can result in malfunctions of protection if both of two sources of supply (e.g. utility transformer and local generator circuits) have a neutral-to-earth connection. In such cases, if the parallel neutral/earth paths could cause malfunction of the standby (or back-up) earth fault protection, 4-pole switching should be employed.

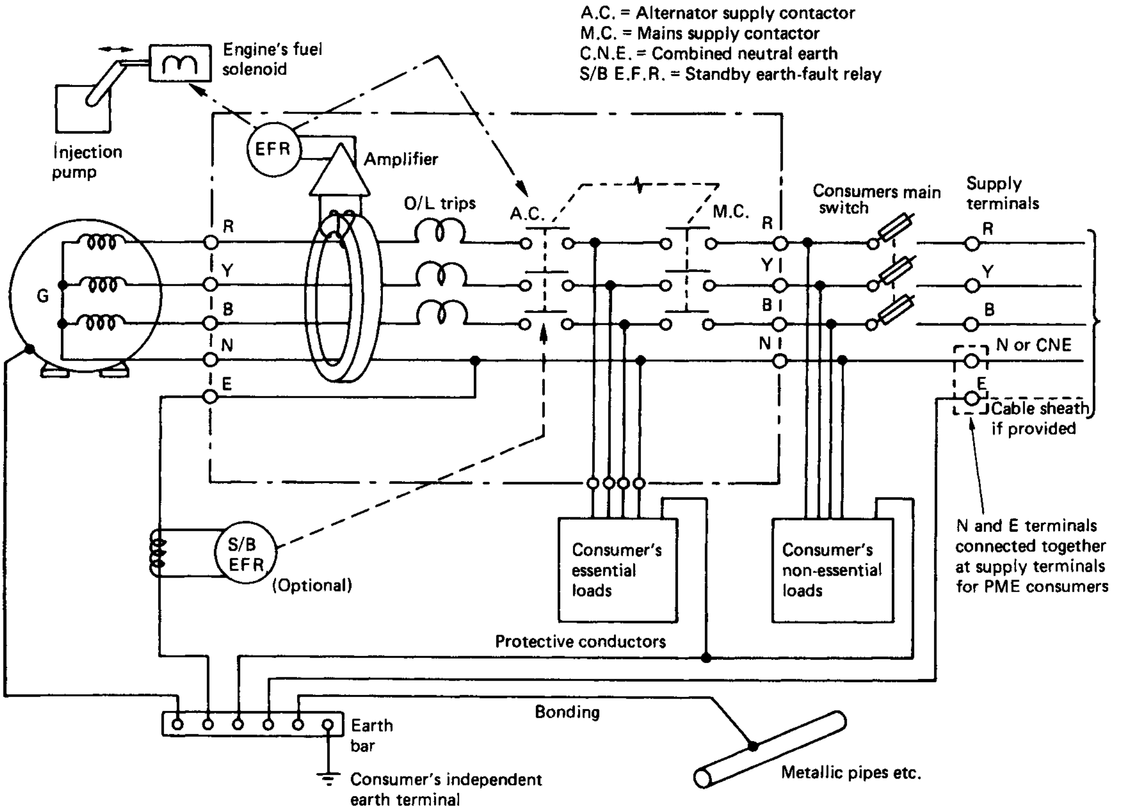



**Figure 10.33** Standby generator scheme suitable for p.m.e. and non-p.m.e. installations using 3-pole changeover contactors

The overcurrent relay has been discussed in some detail in Section 10.3.5. It is fairly common practice, where the minimum earth-fault current is less than the normal full-load current, to combine two overcurrent and one earth-fault element in a single triple-pole relay. The connections are as those shown in Figure 10.34. The centre element is usually the earth-fault one. Elements may have combinations of time-delayed and instantaneous operation.

It is very important when using this arrangement **to** ensure that the current transformers operate well below their saturation levels under all fault conditions. That is, they should have sufficiently high *bee-point* voltages [14]. (The knee-point voltage is defined in BS 3938 as the point on the magnetization curve at which a 10% increase in excitation voltage produces a 50 % increase in excitation current.)

The reader will come across the term *directional relays.* In their overcurrent form they are not applied to generator zones and are more suitable for the protection of ring mains, parallel feeders, paral**lel** transformers, and transformer feeders. They should not be confused with 'power directional' relays (see Section 10.4.8). Directional relays respond to the phase relationship between the current flow and a reference voltage, which is fed to an additional voltage element within the relay. They will only operate when an overload or short-circuit current flows in the desired direction.

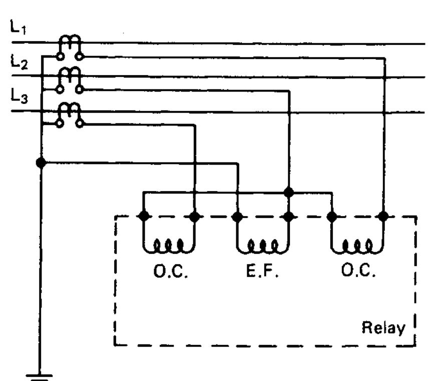



**Figure 10.34** Schematic for triple element combined overcurrent and earth-fault relay

The schemes we have just discussed give technically sound and economically viable solutions to the problem of internal earth-fault protection for small low-voltage machines (and indeed are basic to the protection of larger machines). Their fault clearance times tend to be too slow for the higher voltage, larger output, and more expensive machines. Serious consideration should be given to the use of a truly unit-type protection (described in the next sub-section) for machines:

- above 1 MVA;
- above 5 kV; or
- above 500kVA at 2.2kV and higher.

## *Differential protection*

Often called *balanced* or *Merz-Price* protection, it uses the most selective of relaying principles. It works on the basic proposition that, under healthy conditions, the current entering into a protected section (a winding, in our case) is identical in magnitude and phase angle to that leaving it. Current transformers of equal ratio are located in the input and output lines of the protected section and are connected by pilot wires to a current sensitive *(differential)* relay.

The single-phase diagram of Figure 10.35 depicts the basic principle of the circulating-current system. During normal conditions in the protected zone

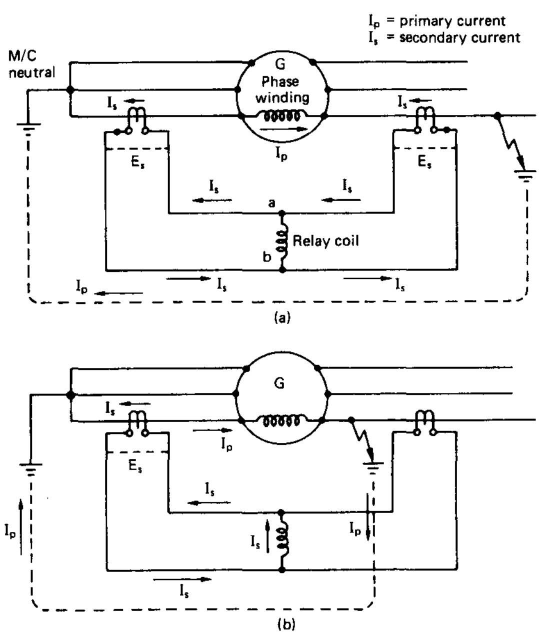



**Figure 10.35** The principle of circulating current protection (a) In normal conditions or for an external fault (b) For internal fault condition

(diagram (a)) no current flows through the relay's operating coil which is connected across the equipotential points a and b in the pilot-wire loop. A similar situation applies when a fault occurs outside the zone. The direction of the circulating current in the 'differential' loop is unchanged since the primary current entering and leaving the C.t.s is of the same magnitude and in the same direction. The system is therefore insensitive to load current changes and to any through-fault currents (i.e. it is stable for all conditions outside the zone).

If an 'internal' fault occurs within the protected zone between the two c.t.S the equality of input/output currents (i.e. the current balance) is disturbed. See diagram (b) in Figure 10.35. The secondary current flow in the right-hand C.t. is zero. The only current flowing in the relay coil is that from the left-hand c.t. The relay operates when the magnitude of this current exceeds the relay's pick-up setting.

Figure 10.36 shows the connections for a generator's differential protection scheme. It consists of two sets of high quality c.t.s with similar characteristics, connected to the three elements of a circulating-current relay. Note the need to have all six ends of the stator windings brought out to the machine's terminal box. The c.t.s should not be used for any function other than that of differential protection, because unequal secondary loading may occur [11]. Despite this precaution it is quite possible for supposedly identical sets of c.t.s to give slightly differing ratios when subjected to high asymmetrical through-fault currents. Such currents, which have a marked d.c. component (see Figures 4.33 to 4.36 of Chapter 4), can cause the transformers to reach saturation level. Any variations in the magnetizing characteristics of the C.t.S will then result in some unbalance current (or spill-current) flowing through the relay winding, even though the fault may be external to the protected zone.

There are ways of ensuring stability under these conditions. One method is to use a so-called high stability circulating current relay. This is a voltage-operated high impedance relay set to operate at a voltage slightly higher than that developed by the current transformers under maximum external fault conditions.

Because of its high speed and immunity to a.c. transient currents the high stability relay is more usually applied to small and medium sized generators. Larger machines (and directly connected generator-transformer units) may employ another method known as *biased differential protection.* It is particularly suited to those circumstances where c.t.s on the line side of a generator are likely to have dissimilar characteristics to those on the neutral side of the windings.

The *bias slope* (see Figure 10.37) of a relay is defined as the ratio:

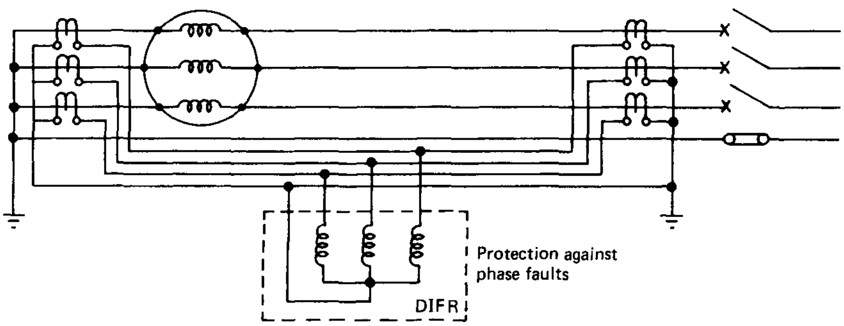



**Figure 10.36** Circulating current (differential) protection applied to a 3-phase generator

$$\frac{\text{increase in current through the spill circuit to cause operation}}{\text{increase in through current}}$$

The contacts of 'biased' relays are arranged to close only if the differential current for a corresponding through current falls within the relay's operating region, i.e above the bias line setting. The setting of the relay is the minimum current (expressed as a percentage of generator rated current) which will trigger the relay.

The percentage bias is a fixed parameter defined at the minimum current setting as:

$$\frac{\text{spill current}}{\text{through current}} \times 100$$

The characteristics depicted in Figure 10.37 include that for a relay with a 10% bias. A generator, typically, requires 10% values for both setting and bias. The upper curve in Figure 10.37 therefore gives a very satisfactory relay operating characteristic for all but the smallest generators.

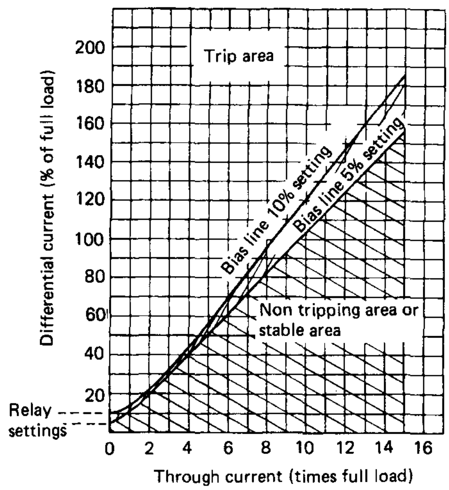



**Figure 10.37** Operating characteristic of a percentage biased differential relay (Courtesy: GEC Alsthom Measurements Ltd)

Solid state relays are widely applied in bias differential schemes. Restraining and differential operating voltages are compared in transistorized comparator stages to operate into output units of the attracted armature type. Such relays (e.g. GEC Alsthom Measurements type DTH 31 and P & B Engineering type PBSD 3A5 16) may also incorporate second harmonic restraint features to inhibit operation by the normal inrush currents produced when transformers directly connected to generators are first energized. Descriptions are outside the scope of the present discussion, which must be confined to system principles only.

When a generator is directly connected to a step-up transformer without any intervening switchgear it is normal practice to include both generator and transformer in the one differential protection scheme. One set of C.1.s is then placed at the generator neutral end of the zone and the other in the transformer HV lines before the circuit breaker - as shown in Figure 10.38. Notice that the c.1.s are connected in star at the generator neutral end and in delta at the transformer HV side. This is done in order to compensate for the 30° phase shift introduced by the delta-star step-up transformer. Because the power transformer usually has tap-changing facilities it is extremely difficult to match both sets of protective c.1.s for all voltage ratios. The differential protection schemes applied to generator-transformer units should therefore always be of the percentage biased type.

The star-point of the HV side on the power transformer is likely to be earthed through a neutral resistance. It is therefore normal practice to include

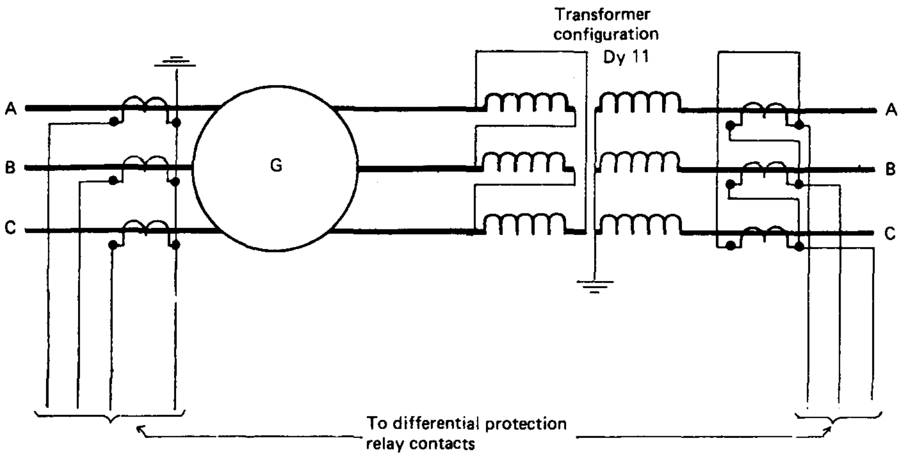



**Figure 10.38** Current transformer connections for overall differential protection of a directly connected generator-transformer unit

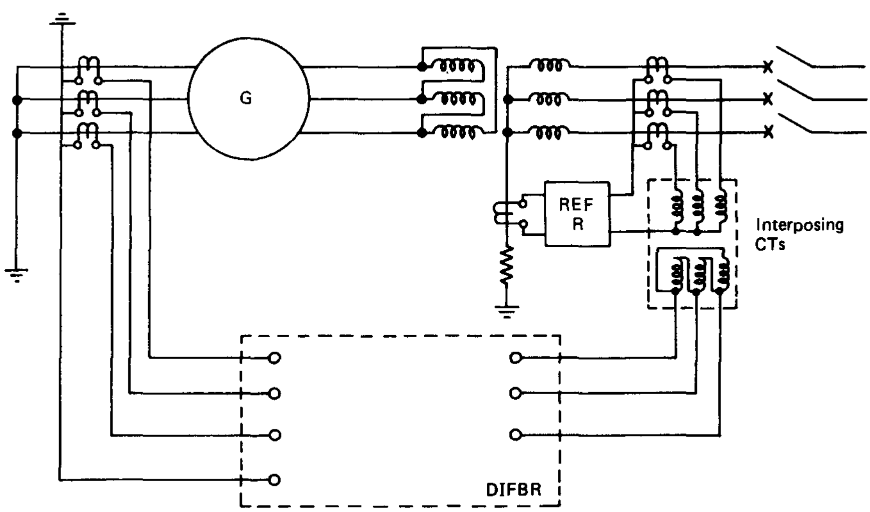



**Figure 10.39** Combined overall biased differential and restricted earth-fault protection for a directly connected generator-transformer.

a restricted earth-fault relay (as shown in Figure 10.39). It is also necessary to time-delay the operation of the differential protection in order to cope with the high inrush magnetizing currents of the power transformer. Where this is unacceptable use may be made of a percentage biased relay with second harmonic restraint features - as discussed above.

None of the schemes described in this and the previous sub-section give 100% protection of the stator winding against internal faults. There is no difficulty in detecting an earth-fault near the generator output terminals. The earth-fault voltage and hence the current flowing to earth is sufficient to ensure reliable operation of protection equipment. This is especially true when the neutral-to-earth resistance ensures that the magnitude of the fault current is greater than that of the machine's full-load current (i.e greater than 1p.u.). The situation is markedly different if an earth-fault occurs near the star-point of the stator winding. The voltage behind the fault is then usually insufficient to create a relay-energizing current greater than its setting value.

The percentage of generator winding protected depends both upon the magnitude of fault current that the neutral resistance (more strictly, the impedance) is designed to pass, and upon the setting of the relay. The two must be correlated to obtain the optimum stator protection. Where a generator is connected directly to a load the value of the earthing resistance $R_N$ is usually chosen to be about 1 p.u. This means that 1 p.u. phase voltage is measured across it when rated full-load current flows through it. Given a resistance of 1 p.u. and a differential protection relay setting of 20 % of the generator's full-load current, an earth-fault 20 % distant from the star-point would create just sufficient fault current to trip the relay. In other words, 80 % of the stator winding is protected. Reducing the relay setting to 5% would give 95 % of the winding protected; and so on.

If the neutral resistance ($R_N$) were reduced to, say, 0.9p.u. with a relay setting at 20%, an earth-fault 18 % distant from the star point (i.e. 0.9 x 20) would just be detectable. Protection would therefore be afforded to 82 % of the winding. Figure 10.40 [14] illustrates the argument.

It can be shown [14] that $x$, the position of the fault from the star-point, expressed as a fraction of the whole phase length (i.e the unprotected fraction of the phase winding) is given by:

$$x = kI_sR_N/V_{ph}$$

where $I_s$ is the relay setting, in amperes;
$k$ is C.t. current ratio;
$V_{ph}$ is the phase voltage;
$R_N$ is earth resistance value, in ohms;
$kI_s$ is the setting of the protective system measured on the *primary* side of the C.t. (i.e the primary fault setting).

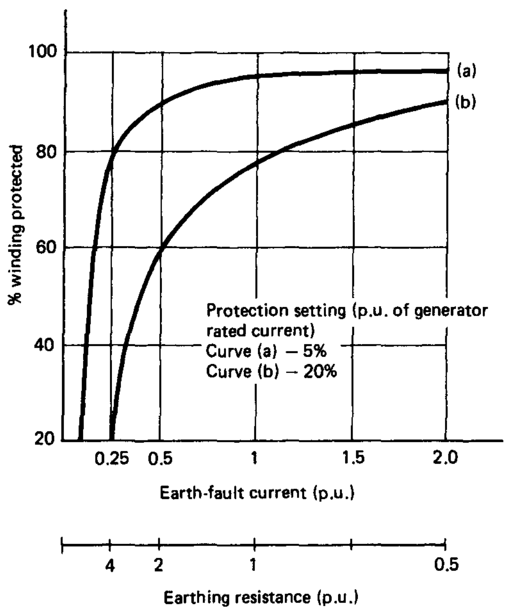



**Figure 10.40** Percentage of generator winding protected against earth-faults

Furthermore, if all these quantities are expressed in per-unit terms (of the generator's rated current), the relationship for $x$ becomes:

$$x = I_{s.pu} \cdot R_{N.pu}/V_{ph.pu}$$

Figure 10.40 is drawn for the case of $V_{ph.pu} = 1$.

### 10.4.2 Rotor faults

In modern practice it is usual for the generator's main (rotor) field circuit to be fully isolated from earth. The presence of a single earth-fault due to insulation failure does not jeopardize the machine. A second earth-fault some physical distance from the first would, however, short-circuit a major part of the field winding. If this does not take the machine out of service it will certainly cause magnetic unbalance in the rotor and possible bearing damage.

On machines in which excitation is affected through shaft-mounted brushgear it is possible to employ direct detection methods using, for example, a potentiometer across the field winding, with a centre tap connected through a sensitive moving-coil relay to earth. Alternatively, d.c injection techniques are employed where, in the presence of a fault, current flowing in a bias circuit is detected by a sensitive balanced-armature relay or by a moving-coil relay. a.c. injection methods are also applied, but any schemes that introduce currents in the main shaft should not be entertained as they are likely to accelerate bearing failure [8].

Generators in the range we are considering are more likely to be of the 'brushless' type. Direct access to the main field will not be possible so that any of the fault detection techniques just described are out of the question. We have considered in Chapter 3 (Section 3.3.2) some of the methods that may be used to detect rotating diode failures. An open-circuit on anyone of these devices (or a single earth-fault on the winding, for that matter) would produce little change in excitation level. Alarm indication only would suffice in such circumstances. A short-circuited diode is more serious. The resulting magnetic imbalance will tend to cause abnormal vibration in the machine. This can be detected by a vibration monitor. Action should then be taken to unload the machine or to take it out of service.

### 10.4.3 Over and under-voltage

Protection against abnormal voltage conditions is not often applied to generators. Over-voltage can be produced by overspeed or by automatic voltage regulator failure. It may overstress generator winding insulation but is more likely to endanger connected sensitive loads such as computers and communication equipment.

The most commonly applied relays are of the solid-state type in which the input signal is rectified to give a proportional d.c. voltage which is compared with a preset reference voltage. The resultant of this comparison is fed, via a transistorised amplifier, to an electromechanical output relay. Instantaneous and time-delayed versions are available.

Settings must be selected to allow for network transients (e.g. due to load switching) but to trip the machine before dangerous voltage levels are reached. Where generators are operating in parallel it is necessary to discriminate between healthy and faulty units. Because over-voltage results from excessive excitation a protection system operating on combined over-voltage and high exciter field current may be used [19]. Due allowance must be made for the range of excitation in normal operation (i.e. from zero, on load removal, to maximum when field-forcing on load switching or short-circuit). Under-voltage settings should similarly take account of the voltage dips that are expected during load switching.

Where voltage surges are likely to be induced by lightning discharges, on lines external to the generating plant surge protection should be considered - especially where vacuum breakers or contactors are used with the larger and higher voltage machines.

### 10.4.4 Over- and under-frequency

In most instances the prime mover will be fitted with an independently-acting overspeed device (see Section 10.2.3). This is usually set at about 15% above normal speed. Over-frequency protection is then quite unnecessary as far as the generator itself is concerned. However, some specialized loads are prone to damage if operated at other than design frequency. Frequency relays are arranged to trip the load breakers when the supply frequency drifts outside predetermined limits.

On single generator installations overloading will result in frequency drop. The problem is that if no action is taken to alleviate the situation, the machine's a.v.r. continues to boost excitation to compensate for loss of speed. If the condition is allowed to persist rotor overheating can occur. Most modern a.v.r.s are fitted with under-frequency protection but these circuits are designed to operate at low speeds and are only meant to protect the generator against engine idling conditions. Under-frequency relays may be used to initiate load-shedding by tripping selected load breakers in multiple steps with a time-delay between steps. A stability study would determine the frequency settings required at each step [8].

Frequency relays may be of the solid-state type or of the polarized sensitive balanced-armature type (such as the GEC Alsthom Measurements type FMG), where the relay has three separate windings. The operating and restraint windings are energized through series circuits tuned to resonate at frequencies on either side of the setting. The third winding provides a small bias in the restraint direction to prevent transient operation if the supply is switched on at a frequency close to the relay setting. On the under-frequency relay the operating winding is tuned to a frequency below the setting, and the restraint winding to a frequency above the setting. As supply frequency falls the current in the restraint winding decreases whilst that in the operating winding increases - as its tuned circuit approaches resonance. The over-frequency relay is similar in operation except that the tuned circuits are reversed.

The solid-state versions give greater accuracy but, because they use square-wave pulsing controls, their measuring logic can be adversely affected by harmonics in the input wave-form. Low pass filters fitted between the protection v.t. secondary and the relay are therefore required when the total harmonic distortion exceeds 5% of the fundamental frequency.

### 10.4.5 Overload

On partially-manned or unattended sites it is necessary to include protection against prolonged overloading. We have established elsewhere (Chapters 2 and 3) that diesel generating sets rated to ISO standards are capable of meeting 10% overload conditions for periods of 1 hour in any 12 hours of continuous operation. Fuel systems are so arranged that once an engine operates beyond the 10% overload region supply is restricted by preset control or *fuel-limiting* stops. Load increases that call for fuel amounts beyond this limit merely result in the engine's speed falling below the governor control setting. This not only results in engine overheating and high pressures on its bearings but it also raises generator temperature. In the previous section we discussed the use of frequency relays to detect the reduced speed condition and to initiate the appropriate load-shedding actions.

In Section 10.3.5, we considered the merits of the modern direct-acting overload devices linked with low-voltage switchgear and suggested that they afforded adequate protection on the smaller installations. On larger base-load installations serious consideration should be given to the use of frequency and/or IDMTL overcurrent relays. The latter may be voltage restrained to give better discrimination in overall system protection schemes.

Other devices which may be used on the larger machine installations are:

- temperature relays; and
- power relays.

*Temperature relays*

A number of resistance temperature detector (RTD) elements may be embedded into the machine windings during manufacture. The RTD elements may be of platinum or copper - 100nand 10n resistance, respectively. They are strategically positioned by the machine manufacturer to detect hot-spots and localized heating, such as that caused by short-circuited laminations within the stator. Each RTD element forms one limb of a balanced Wheatstone bridge. Change in the resistance of any element as a result of its temperature rise unbalances its bridge circuit. The resultant voltage is amplified and is compared with a common voltage reference corresponding to the preset temperature trip level of the relay.

In the six-point relay illustrated in Figure 10.41 all the comparator outputs are fed via a relay driver to a multi-input OR gate which energizes the output relay if one or more RTD elements exceeds the trip setting. The output relay is also energized if any of the six input channels are open-circuited. Light emitting diode (LED) indicators show the 'normal' and 'tripped' conditions for the relay and also which of the inputs are exceeding the trip level. Adjustment of the trip point is by a multi-turn potentiometer accessed from the front panel. Temperature is adjusted by SOCper turn. Since no visual readout is given it is prudent to seal the setting and mount the relay within the control gear enclosure. This will militate against the operator who may be tempted to raise settings when under pressure to maintain operations.

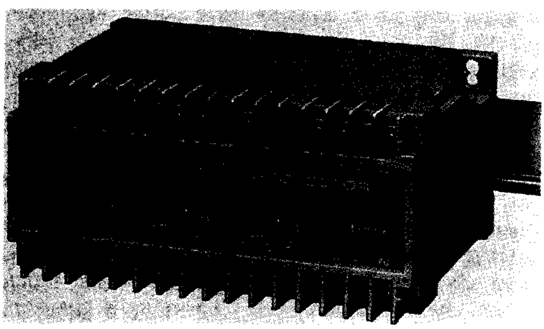


**Figure 10.41** A six-channel input temperature trip relay (Courtesy: Crompton Instruments Ltd)

*Power relays*

In these relays power is computed from current and voltage signals, taking due account of the phase relationship between the signals. For true power (watts) the relationship is governed by the characteristic quantity $I \cos\phi$, whereas reactive power (VArs) is proportional to $I \sin\phi$. The capacity of a power system is expressed in volt-amperes (its apparent power) which is vectorially expressed as:

$$\text{kVA} = \text{kW} + \text{kVAr} = |VI|\,(\cos\phi + \sin\phi)$$

The relationships between the three forms of power is dealt with more fully in Chapter 4. It will help in our present discussion to think of watts being put into the system (in the form of torque) by the prime mover, and that VArs required to support the voltage and transport the watts through the system are put in by the generator's a.v.r. Power relays may be connected for either watts or VAr measurement by a simple rearrangement of the voltage and current connections across (and in) the power system lines. By virtue of its sensitivity to phase angle the power relay is inherently directional in operation. This characteristic is very useful when it comes to sensing loss of prime mover power - as we shall see in a later sub-section (10.4.8)

For high speed applications electromechanical induction-cup and solid-state relays are suitable alternatives. A single relay is sufficient for balanced conditions on three-phase, 3-wire or 4-wire systems. Where unbalanced loads are likely a relay must be employed on each phase or a triple pole unit must be used.

### 10.4.6 Unbalanced loading

All faults other than those involving all three phases of the system will give rise to unbalanced currents. These may be resolved into positive-, negative-, and zero-sequence components. The relative values and the relative phase angles of these *fictitious* components of current will vary from one asymmetrical fault condition to another.

While faults external to the generator should be quickly cleared by circuit protection, any failure of remote protection to operate or of related circuit breakers to trip would result in the faulted circuit(s) remaining connected to the generator. We are concerned here with the effects that sustained external faults which have not been cleared by the appropriate protection will have on the generator.

The worst condition for the machine occurs on those faults that give rise to negative phase sequence (n.p.s.) currents in the stator windings. These are phase-to-phase faults (between lines) and phase-to-neutral faults (or line-to-earth, where the neutral is earthed).

The n.p.s. components of the current rotate in a direction counter to the d.c. field system of the generator. This produces a stator flux which cuts the rotor at *twice* its rotational velocity and induces double-frequency currents in the field system and in the rotor body. The resulting eddy currents may be very large and cause severe overheating of the rotor – especially at those points where the circulating eddy current is concentrated by the winding slots of cylindrical rotor machines. Heat concentrates in parts of the coil binding rings and surface fusion has been known to result [10]. The heating effect is less marked in salient pole constructions, particularly those employing laminated poles and heavy amortisseur windings (see Chapter 3). The presence of the damper windings has a powerful limiting effect on the double-frequency currents in the field system.

The measure of the machine's tolerable thermal overload is given by a constant factor (A. Allen, 1987, personal communication) which is the product:

$I_2^2 \times t$

where $I_2$ is the negative sequence component (p.u. of the generator's rated current) and '$t$' is in seconds.

Generator manufacturers nominate this factor from design calculations. Values, typically, fall in the range 4 to 60 seconds. If n.p.s. current flows in the generator and the $I_2^2t$ product exceeds the manufacturer's stipulated value, damage can be expected. Higher values of n.p.s. current can be tolerated for short time periods and, conversely, small values can be tolerated for long periods.

In addition to the $I_2^2t$-withstand factor, generator manufacturers stipulate a maximum value of n.p.s. current that can be withstood continuously (i.e. where the $I_2^2t$ heat input to the machine is small enough to equal heat lost over an an identical time period). This value ($I_{2_c}$) is, typically, between 0.2 and 0.4 p.u. for salient pole machines. The values quoted for both $I_2^2t$ and $I_{2_c}$ are based on the generator being fully loaded prior to the n.p.s. current flowing.

Typically, if a line-to-line fault were to occur, the high value of n.p.s. current resulting from this unbalance fault must be cleared within 5 seconds to ensure that the rotor is not damaged. A relay which is sensitive to n.p.s. currents and which has an inverse square law characteristic matching the $I_2^2t$ thermal withstand of the machine should be arranged to disconnect the machine before damaging internal temperatures are reached. The relay should, preferably, be arranged to initiate an alarm to alert attendants when a low level of n.p.s. is first detected. Action should be taken to trip the generator breaker if the unbalance condition persists or if the level of n.p.s. current rises.

The output from a network which gives an a.c. output voltage proportional to the negative sequence current is fed into the relay. See Figure 10.42 for the block schematic of the GEC Alsthom Measurements type CTN static relay. This voltage is rectified, smoothed and fed into the squaring circuit of the main measuring element, the definite time delay circuit, and the alarm element.

The output from the squaring circuit is proportional to the square of the input voltage ($I_2^2$) and is applied to the main timing circuit to give the required relationship between $I_2^2$ and the relay operating time $t$.

The voltage to which the timing capacitors ($C_6$ and $C_7$) are charged depends upon the voltage applied from the squaring circuit. This means that even if the n.p.s. current is less than the relay setting, the timing capacitors will partly charge and reduce the relay operating time when the current exceeds the setting time. This feature simulates any pre-heating of the machine caused by the low levels of n.p.s. current that could be present during normal running conditions.

The timer output is selected by a 16-position time multiplier selector switch (K 1). When this output exceeds the reference voltage it provides one of the inputs to a two-input AND gate. The other input comes from the definite delay timer which is activated by the timer starter circuit when the n.p.s. current exceeds the relay setting ($I_{2S}$). When both inputs to the AND gate are present the hinged armature output relay is energized.

The starter and timer for the alarm circuit are very similar to those of the definite time delay circuit except that a 5 s delay is provided. The starter circuit triggers the timer when the n.p.s. current exceeds the alarm setting. The alarm setting is adjustable between 70% and 100% of the main relay plug setting. The relay is energized from an auxiliary d.c. supply. A regulator drops the supply voltage to a level acceptable to the circuitry.

We have already established that the relay operating time when n.p.s. current is present should be equal to the thermal withstand time of a generator carrying the same amount of negative sequence current. We have also seen that a machine's withstand approximates to $I_2^2t$ – a constant, K. In practice, for currents just above the continuous withstand capability of $I_{2c}$, the time given by the above expression is much lower than the actual withstand time of the machine. This is because of natural heat loss from the machine. This fact is taken into consideration when selecting a relay operating characteristic to match more accurately the actual withstand characteristic of the machine. The time/current characteristic of the CTN relay is given in Figure 10.43.

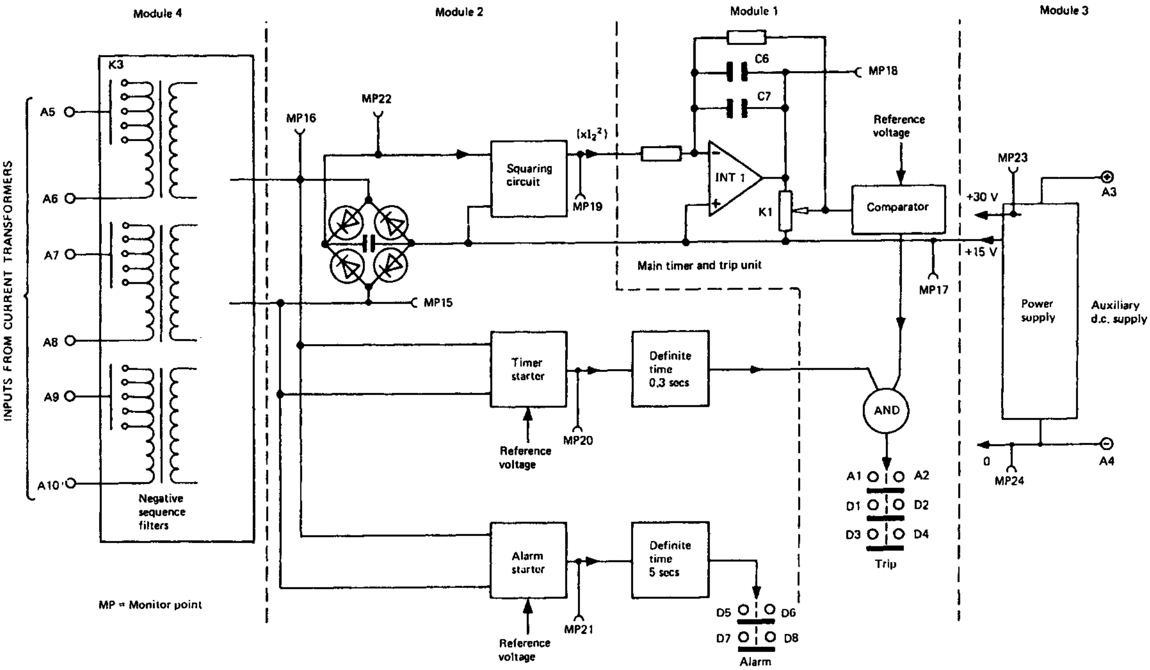



**Figure 10.42** Block schematic diagram of a negative phase sequence current relay (Courtesy: GEC Alsthom Measurements Ltd)

### 10.4.7 Loss of excitation

Loss of excitation in a generator can be caused by:

- a failure within the main field system (as discussed in Section 10.4.2);
- a failure in the a.V.L; or
- failure within main and/or auxiliary exciters in the excitation chain.

The condition is readily detected by an undervoltage relay on a single machine feeding a load network. When the generator is one of several running in parallel, or if it is connected into an 'infinite system' such as a utility supply, loss of excitation may result in the machine losing synchronism. It then runs asynchronously as an induction generator deriving its excitation from the reactive stator current provided by the power system. The magnitude of this reactive current may well exceed the rating of the generator so that its stator windings are overloaded. Additionally, the slip frequency currents induced in the rotor damping windings will cause abnormal heating of the rotor [16]. Asynchronous operation will not damage the machine immediately. Conventionally cooled machines should be capable of operating at full load in this mode for about 5 minutes.

Failure of a.v.r. supply to the exciter field may be easy enough to detect but main rotor field circuits are not so easily monitored on machines with brushless excitation schemes (see Sub-section 10.4.2). One of the methods employed on parallel operating machines is to detect the presence of excessive kVAr flow from the system busbars to the machine. This may be done with a directional power relay of the type we shall be discussing in more detail in Sub-section 10.4.8. A simplified block connection diagram is shown in Figure 10.44. The reader should note the difference between the quadrature connections required for the input energizing quantities (voltage and current) when reactive power is monitored and those required when the relay is used as a 'true power' device (Figure 10.46). The external connections reflect the different current/voltage relationships that apply in each case (i.e. kW = $VI \cos\phi$; kVAr = $VI \sin\phi$). The relay energizing quantity for kVAr measurement must therefore be $I \sin\phi$, and $I \cos\phi$ for kW. In a belt-and-braces approach a second power relay with a 30° internal phase shift is sometimes employed to provide a power factor measurement based on reactive power flow. In this configuration, if both the kVAr flow and the shifted-phase kVAr flow exceed the settings of the respective relays, the machine is immediately taken out of service.

Another method used takes account of the fact that when a generator loses synchronism the quantity that changes most is its impedance measured at the stator terminals. Loss of excitation will result in

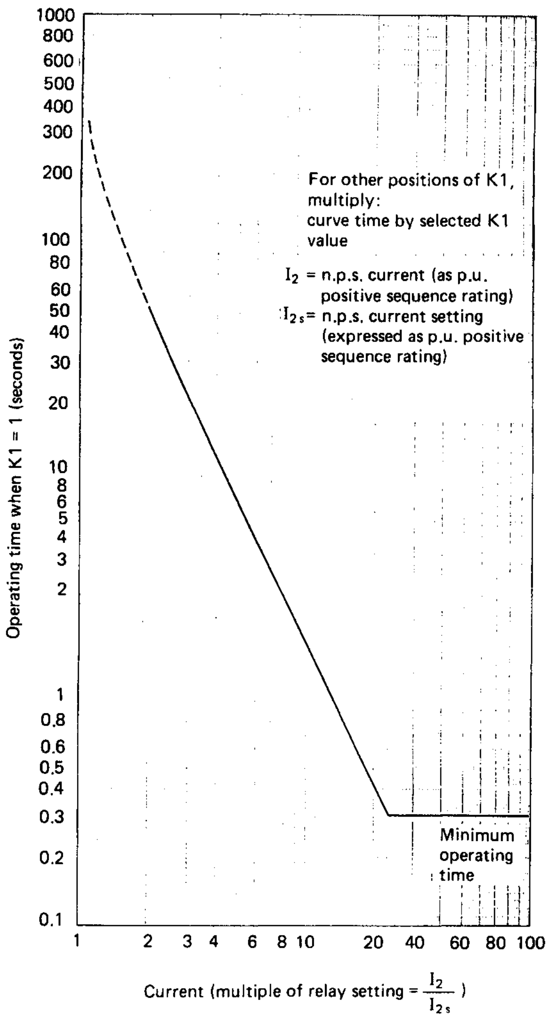



**Figure 10.43** Operating time/current characteristic of the relay shown schematically in Figure 10.42 (Courtesy: GEC Alsthom Measurements Ltd)

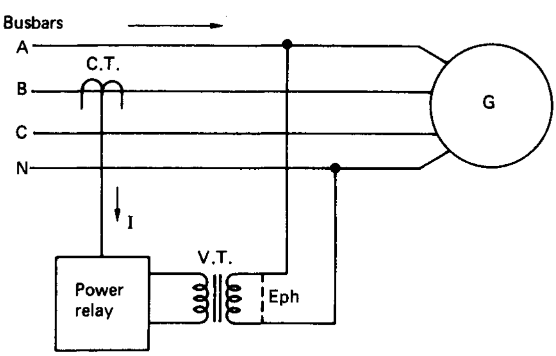



**Figure 10.44** Directional power relay connected for VAr measurement (see Figure 10.46)

the machine's terminal voltage falling while the current begins to increase. The apparent impedance of the machine therefore decreases and its power factor changes. An *impedance relay* may be used to detect this change from normal load value. These relays can be constructed to give various *R-X* characteristics. Application theory is fairly complex and must be outside the scope of our discussion. Attention is directed to [9] and [16] for further reading on the subject.

The most common relay characteristic is the *circular offset mho* shown in Figure 10.45. The offset and the diameter of the circle of the relay characteristic are both adjustable. The relay is usually set so that the offset is equal to half the generator's transient reactance ($X'_d$) and the diameter of the characteristic is equal to the direct axis synchronous reactance ($X_d$). When the machine experiences a loss of field its terminal impedance moves into the negative reactance area. The relay operates as soon as the operating-point locus moves inside the circle – the relay characteristic setting. The impedance phasor is drawn for lagging currents at heavy and light loads ($I_a$ and $I_b$, respectively).

Loss-of-excitation protection schemes are usually arranged to shut down the failed generator if adverse field conditions persist for a predetermined time.

### 10.4.8 Failure of prime mover

Should the prime mover fail (say, due to fuel problems) while a generator is running in parallel with others or with a utility supply, the generator will 'motor' and will draw power from the system into which it is connected. Diesel engines are less

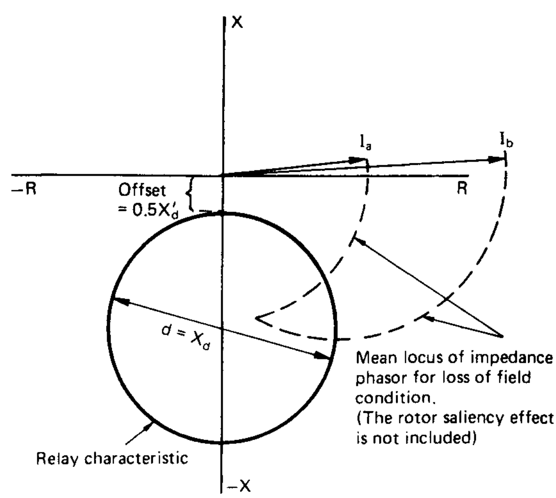



**Figure 10.45** Offset mho impedance characteristic for a generator loss-of-excitation protection scheme

susceptible to damage caused by generator moto:ing than some other types of prime mover. Nevert'1e-less, some means of detecting the reverse power flow is necessary, especially to protect against 'inverted' running should mechanical seizure occur on the prime mover (e.g. bearing heating leading to closure of fuel valves).

Selection of the proper protection depends upon the amount of power that is required to drive the prime mover when no fuel is supplied. For diesel engines this, when expressed in terms of a percentage of the full-load nameplate kW rating, is of the order of 25 % for 4-stroke engines and between 15 and 20 % for 2-stroke engines. These figures may be very much lower for well run-in engines. In all cases, the engine manufacturer should be consulted for actual values.

Protection is provided by a directional *(reverse power)* relay set to operate at a level lower than the predetermined motoring power of the prime mover. Typically, this is below 10 % of machine rating. The sensitivity of the chosen device depends upon the generator's application. In some applications, such as on marine power systems, maintenance of supply is such a critical requirement that only large (but safe) amounts of reverse power would be sufficient cause for tripping a generator. On others the generator may be tripped at very much lower levels. Relay sensitivity may then be limited only by the need to avoid nuisance tripping during synchronizing operations or during transient load changes.

The true power taken by the generator on inversed running should be monitored. Due account must be taken of the power factor of the current drawn from the system. This may be either lagging or leading depending upon the excitation level of the failed machine. A true 'wattmetric' relay having accurate quadrature adjustment must be used. Unlike directional relays for *fault* power applications the reverse power relay should not be fitted with phase angle or low voltage compensation [16].

In most cases, single phase power measurement suffices because loss of prime mover torque affects all three phases equally. True power (kW) is measured by voltage taken from line to neutral and current is measured from the same line. Where the neutral connection is not available three phase voltage sensing, or a power relay with an in-built 30° voltage phase shift, may be used.

Suitable protection relays may be of the electromechanical (induction cup) type or of the static type. An example of the latter is shown diagrammatically in Figure 10.46. It measures $I \cos \phi$, on the not unreasonable assumption that voltage may be regarded as constant and balanced. The relay has a definite time characteristic, ensuring that maloperation does not occur due to momentary power reversals during synchronizing or during power swings on the system. The unit uses a phase sensitive bridge to produce an output which is amplified and compared with an adjustable d.c. level to give the settihg range *(Ps),* in multiple steps - between 3 %

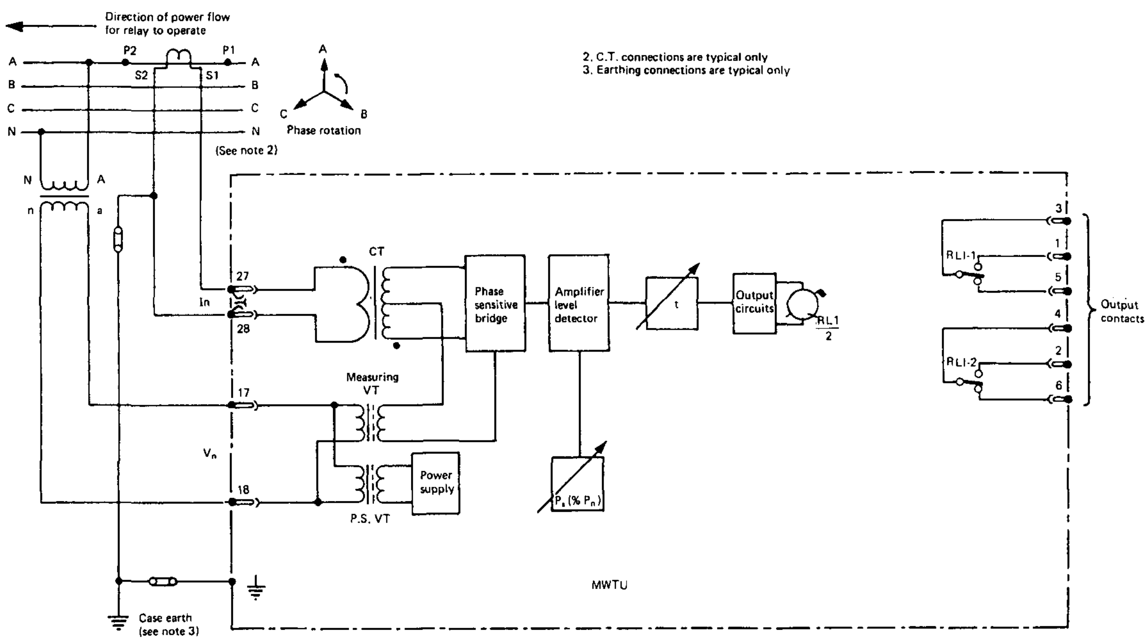



**Figure 10.46** Block schematic and application diagram for a static reverse power relay (Courtesy: GEC Alsthom Measurements Ltd)

and 30 % of the nominal power. The output from this level detector controls a timer with a continuously adjustable range up to lOs. The relay is self-powered from the measuring voltage transformer. An alternative version is available for phase-to-phase V.t. connection.

### 10.4.9 Loss of synchronism

Severe system faults or operation at high load levels with leading power factor (and hence a relatively weak field) may cause a machine to pull out of synchronism. The generator and its prime mover are subjected to violent torque oscillations. Synchronism can be regained if the load is quickly reduced. If this fails it would be necessary to take the machine out of service. The alternative is to remove the machine's excitation to make it run asynchronously. This immediately removes the power oscillations. Reclosing the excitation at a low value will then allow the machine to resynchronize smoothly [9]. The *pole-slipping* that can occur with such system disturbances results in a flow of *synchronizing power* (see Chapter 8) which reverses in direction twice every slip cycle. This is the cause of the violent oscillations.

One convenient and reliable method of pole-slipping protection uses measurement of the magnitude, direction, and rate of change of load impedance relative to the generator's terminals. If satisfactory unit discrimination is to be achieved a great deal of care needs to be exercised in designing and setting pole-slipping protection which is based on load impedance measurement. The application of offset mho-type relays to this form of protection requires fairly complex analysis. The techniques involved are outside our present scope. Pole slipping protection is seldom applied to diesel generating plants. If used, it is usually only on the very largest systems.

## 10.5 Typical protective relaying schemes

Having described the protection equipment that may be applied for specific fault conditions, we shall now examine typical schemes for single and multiple generator installations. These are not meant to be definitive as system needs will vary. Experienced guidance should be sought in obtaining the best and most economical packages for any proposed installation. In some cases a client's specification will dictate the relaying requirements. This should never imply finality in design terms. A contractor's own study, based on his specialist equipment manufacturers' recommendations, may suggest a different approach which could well satisfy the 'sense' of a client's overall requirements. If this is so, the alternative proposals should be defined and the information on which they are based should be declared.

Where plant is to be unattended the aim should be to provide automatic protection of both generator and prime mover against all harmful conditions. Where attendants are present automatic shut-down could result in the unnecessary removal of generator(s) from service for those abnormal conditions which may be corrected by attendants. Opinions will differ as to which conditions should be left to the action of attendants.

Table 10.1 (in Sub-section 10.5.4) offers guidance on the monitoring and protective features to be provided for generators. Consideration must always be given to the cost and functional importance of the plant when determining needs. The objective must be to provide the minimum of protection consistent with adequate coverage of all conditions that are liable to cause damage or affect the continuity of supply [6, 10].

In the discussions that follow we shall start with the very basic standby-to-utility generator, then expand this to consider parallel running machines feeding isolated loads, and finally consider the protection of peak-lopping and cogeneration plants. In each case the aim is to recommend the basic features that should be applied and those which should be considered.

### 10.5.1 Single generator protection

The single line diagram of Figure 10.47 defines the minimum protection for a single standby unit which is isolated from the utility supply by some form of changeover switching (see Chapter 11, Section 11.3). The protection consists of a three-element. voltage controlled overcurrent relay for phase-to-phase and phase-to-earth protection. A separate earth-fault relay provides back-up phase and earth-fault protection for systems where the machine's neutral is solidly earthed. The overcurrent relay will also provide back-up to the distribution network. That is, it will detect faults external to the generator and trip its breaker should other protective devices in the network fail to operate or fail to clear the faults quickly enough.

Multi-purpose protection equipment based on microprocessors is now widely available. They are easily activated and set by the user for his specific application. The Asea Brown Boveri (ABB) Series SPAG units are typical examples. Designed for stand-alone, small and medium sized stationary and mobile generating plants, they offer a number of functional modules giving flexibility in the design of operational schemes for various applications. System reliability is enhanced by self-supervision features, including self-diagnostics. Functional modules include:

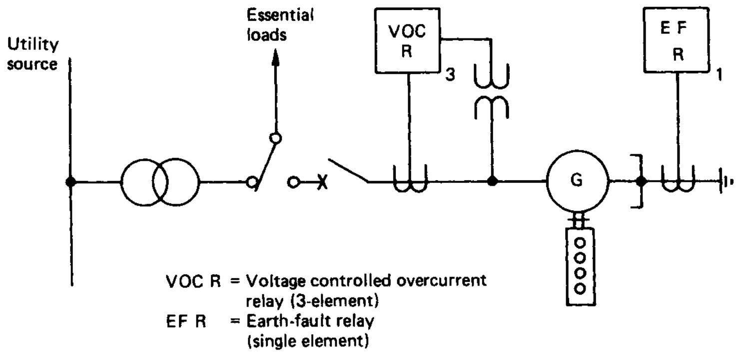



**Figure 10.47** Single-line diagram of basic protection for a standby generator

- overvoltage and undervoltage;
- overcurrent;
- reverse power; and
- earth faults.

Direct numerical display is provided for setting values, voltages, load currents, memorized fault data, indications and status information.

### 10.5.2 Multiple generator plant

When two or more generators are operated in parallel the protection requirements are enhanced to include a reverse power relay for each machine and some means of synchronizing and paralleling the generators to the busbars. Figure 10.48 shows the basic protection required for a two-unit configuration.

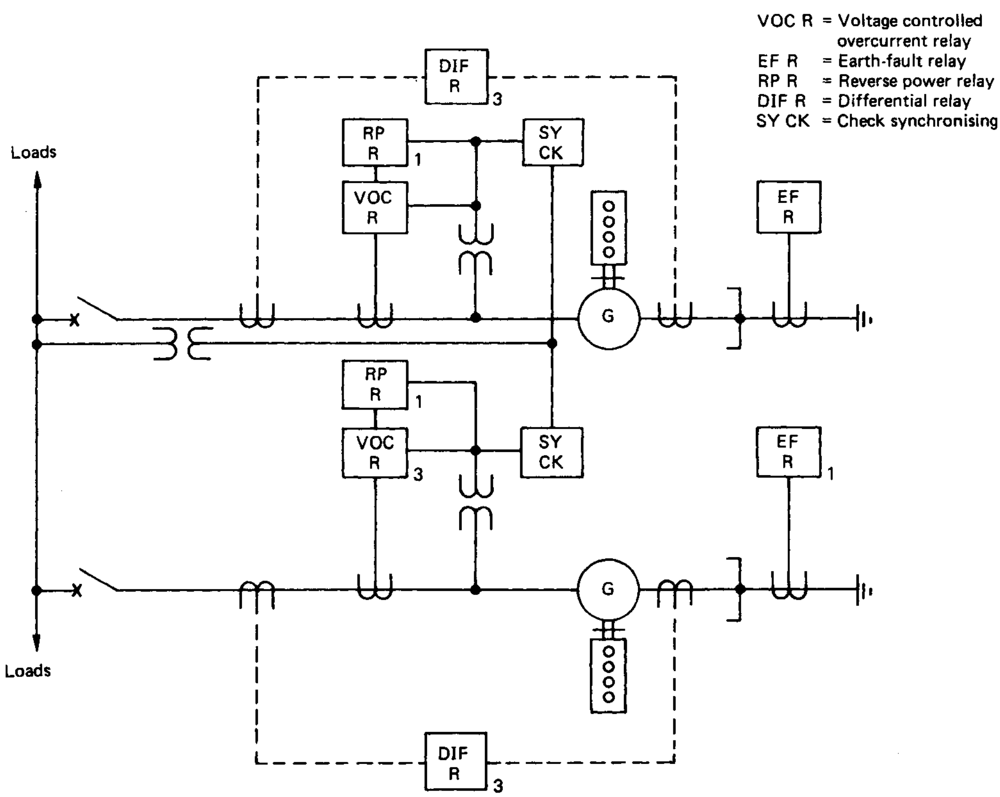



**Figure 10.48** Basic protection for parallel-operation generators

The differential protection scheme has been shown as an option but one which should be seriously considered for those installations where larger unit-size machines are employed (see Sub-section 10.4.1). Choice of the synchronizing device will be determined by the operational needs of the plant. If the installation is permanently manned and generators are started and stopped infrequently the synchronizing of incoming machines may be supervised by check relays. These verify that the proper system conditions exist before breakers can be closed. Where frequent synchronizing operations are the norm or where remote control is provided, it may be necessary to use automatic synchronizing relays for each machine. These are then arranged to interact with the generator's excitation controls and the engine's governor to give voltage and frequency matching. They also automatically compute the correct advance angle before giving a closing signal to the generator circuit breaker. See Chapter 8 for more details of check- and auto-synchronizing devices.

Multi-functional relays specifically designed for the protection of parallel-running generators are also widely available. One such equipment is the P & B Engineering type PBSG 310 relay shown in Figure 10.49. The relay package includes three plug-in measuring units (shown on the right of Figure 10.49). Unit PBCP 3B2 caters for reverse power and dual-stage over-voltage protection. The reverse power function includes a time-lag feature. Units *PBCI* 3B3 are used for high- and low-set overcurrent protection and for load shedding. The overcurrent units can be set to give either definite or inverse time characteristics.

### 10.5.3 Parallel operation with a utility supply

We shall now consider the protection requirements for in-plant generators and utility tie lines in peak-lopping and co-generation schemes .

Additional protection to that already defined for a standby generator scheme (discussed in Section 10.5.1) will be required. It is essential that the generator is removed from service as quickly as possible for any faults developing within the plant itself or within the utility's feeder to the plant. Should a fault develop within that portion of the utility's network which is associated with the consumer's plant the feeder must be the first to be

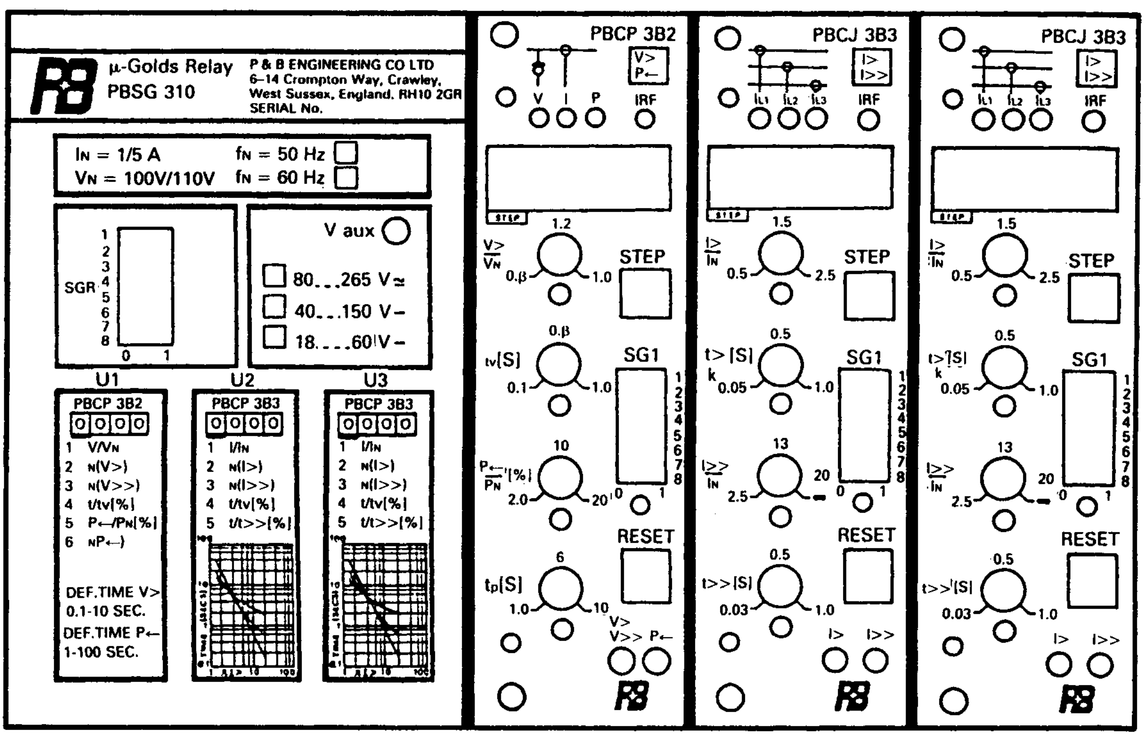



Figure 10.49 An example of a multi-function generator protection relay (Courtesy: P & B Engineering Co. Ltd)

interrupted and the last to be restored. Most utilities will expect the consumer to pay for the additional protection required to remove in-plant generators from the affected line.

The majority of private generation systems are connected to a radial feeder. Any fault in that feeder or in the substation associated with it is effectively a step change in the generator's load. The generator will attempt to support the connected load and also supply the fault current. The machine overloads and prolonged voltage and/or frequency dips will result. The under-voltage and under-frequency relays of Figure 10.50 are included for this purpose. They should be arranged to disconnect the generator from the faulted zone. Over-frequency detection guards against engine governor failure, and under-voltage against generator excitation control failure.

It is a requirement of many Supply Authorities that in-plant generators are totally isolated before the tie-line breaker is closed. It is then usual to inhibit closure of that breaker by placing the voltage relay contacts in series with the breaker's closing coil contacts. Automatic synchronizing facilities capable of adjusting generator speed and voltage will reduce the time required to re-establish the utility supply to the plant.

Any protective devices included in the plant's generating system will need to be approved by the Supply Authority. Also, its personnel will require right of access to the consumer's protective equipment for periodic calibration and tests.

Those co-generation schemes which employ induction generators will not require synchronizing equipment since the generators usually draw their excitation VArs from the utility. Voltage and frequency are controlled by that source. When the utility supply is disconnected the induction generator's terminal voltage decays rapidly. In other words, it needs the utility system in order to generate an output (see Chapter 11, Section 11.3.4).

Operation of the under-voltage relay is delayed so as to cater for system voltage dips due, for example, to the starting of large motors elsewhere in the utility-fed network. The time-delayed output of the relay trips the in-plant generator breaker. Over-voltage relays may act to instantaneously trip the generator circuit breaker. The frequency relays serve to isolate the plant generator when the utility supply fails.

A point worth noting is that capacitor banks are commonly employed by industrial consumers for power factor correction on their premises. These are shown in the single line diagram of Figure 10.51. They will provide continued excitation (VArs) to the induction generator. This being the case, the generator's output voltage and frequency will be a

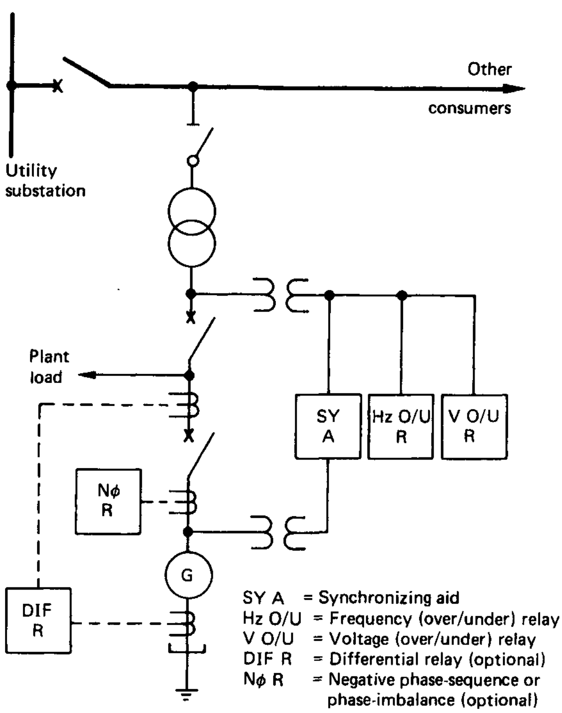



**Figure 10.50** Basic protection for parallel operation with a utility

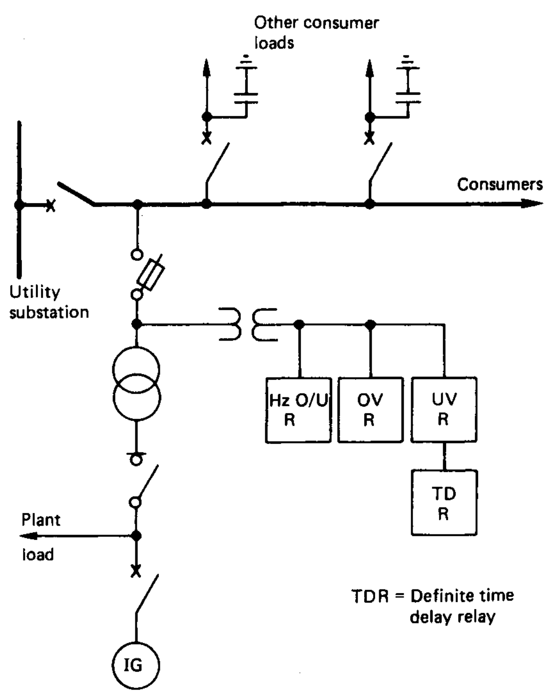



**Figure 10.51** Protection for an induction generator in a cogeneration scheme

function of prime mover torque and of the total load imposed by the consumer's installation plus that of other consumers tied to the utility's radial feeder. The condition will be detected by frequency and under-voltage relaying and the induction generator will be tripped.

Reference is made in the next chapter (Section 11.4.4) to the Electricity Council's Engineering Recommendation G 59 *(Recommendations for the connection of private generating plant to the Electricity Boards' distribution systems).* In our context, it lists the objectives for the protective equipment to be provided by the *private generator.* These are summarized as:

1. to inhibit connection to the Board's supply unless all the latter's phases are energized and within agreed protection settings;
2. to disconnect the generator when a *system* abnormality results in deviation of voltage or frequency at the point of supply;
3. to disconnect the generator on loss of Board's supply;
4. to ensure automatic disconnection (or alarm indication where competent attendance is available) of the in-plant generator when failure of any supplies to the protective equipment inhibits its correct operation.

G 59 goes on to indicate the minimum protection necessary for both HV and LV supply arrangements. This includes the detection of:

- over-voltage
- under-voltage
- over-frequency
- under-frequency
- loss of mains

It acknowledges that other protection may be required, and may include the detection of:

- neutral voltage displacement
- overcurrent
- earth fault
- reverse power

The rider is added that if automatic resetting of the protective equipment is used there must be a built-in time delay in order to ensure existence of a *healthy* supply for a continuous period of 60 s. The automatic reset must also be inhibited for faults on the *Private Generator's* installation. Staged timing may be necessary where more than one generator is involved.

### 10.5.4 Relay application guide

Table 10.1 lists the recommended protective features to be applied to generators. It is not practicable to cover every application. Consideration must be given to the cost and functional importance of the plant when determining the protective measures required for lower rated machines.

The selection column classifies the protection systems as follows:

a recommended for general application
X where required

In practice, one relay can be used for several functions. For example, one triple pole overcurrent relay may be used for both phase and earth fault protection.

*Notes:*
(1) With HV generators.
(2) Only when continuous operation on unbalanced load is likely.
(3) For parallel running generators.
(4) Not usual below 100 kW, or in non-critical applications.
(5) Usually applied: (a) above 1 MVA;
(b) above 5 kV;
(c) above 500kVA at more than 2.2 kV.
(6) On generators equipped with static excitation but not on brushless machines.
(7) For protection against external overload and reduced cooling, e.g. high ambient temperatures or dirty air filters. Usually fitted to machines above 5 MVA.

## 10.6 Related standards

Reference has been made in this chapter to the following British Standards. Entries in parentheses are the corresponding and/or technically equivalent international standards.

BS 142: Part 1: Section 1.1 (IEC 50(446) - *Glossary of protection relay terms*
BS 3938 (IEC 185) - *Current transformers*
BS3941 (IEC 186,IEC 186A) - *Voltage transformers*
BS 3939 (IEC 617) - *Guide for graphical symbols for electrical power, telecommunications, and electronics diagrams*
CP 1013 - *Earthing*

## 10.7 References and bibliography

### 10.7.1. References

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2. Kates, *E.l.* and Luck, W.E. *Diesel and High Compression Gas Engines,* 3rd edn, American Technical Society, (1.974)

**Table** 10.1 Choice of a.c. generator protection systems

| *Protection systems* | *Selection* | | |
|---|---|---|---|
| | *Classification* *Above 1 MVA* | *Below 1 MVA* | *Section reference and (Notes)* |
| Short-circuit | 0 | 0 | 10.3.5 |
| Overcurrent | 0 | 0 | 10.3.5 |
| Overload | X | X | 10.4.5 |
| Stator earth fault | 0 | X | 10.4.1 (1 & 4) |
| Restricted earth fault | 0 | X | 10.4.1 (1 & 4) |
| Unbalanced load | X | X | 10.4.6 (2) |
| Reverse power | 0 | 0 | 10.4.8 (3) |
| Over-/under voltage | X | X | 10.4.3 (4) |
| Over-/under frequency | X | X | 10.4.4 (4) |
| Loss of excitation | X | X | 10.4.7 (1 & 3) |
| Differential | X | X | 10.4.1 (5) |
| Rotor earth fault | X | X | 10.4.2 (1 & 6) |
| Winding over temperature | X | X | 10.4.5 (7) |


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4. Allen fuel-pipe fracture protection equipment. *Apex,* No 6 March, NEI Allen Ltd (1971)
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6. Stouppe, R.L. Jr. System protection and coordination. Chapter 12 of *Switchgear and Control Handbook,* edited by Robert W. Smeaton, McGraw-Hill, (1977)
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17. Bailey, A.C. Transportation: ships. Chapter 31 of *Electrical Engineer's Reference Book,* 14th edn, edited by M.A. Laughton and M.G. Say, Butterworth, (1985)
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19. Ames, R.L. Marine a.c. generating systems. *LSE Engineering Bulletin,* 12(1), January (1972)


### 10.7.2 **Bibliography**

The reader is particularly referred to:


1. *The J&P Switchgear Book* listed under Reference [11]
2. The three volumes which make up the Electricity Council's publication listed in Reference [16]
3. IEEE recommended practice for electrical power distribution for industrial plants - the so-called 'Red Book', IEEE Std 141-1987, The Institute of Electrical and Electronics Engineers Inc. and distributed by Wiley-Interscience, a division of John Wiley & Sons Ltd

4. IEEE recommended practice for the protection and coordination of industrial and commercial power systems - the so-called 'Buff Book', IEEE Std 242-1975, The Institute of Electrical and Electronics Engineers Inc.
5. Recommendations for the connection of private generating plant to the Electricity Boards' distribution systems. Electricity Council Engineering Recommendation G 59.
6. The installation and operational aspects of private generating plant. Electricity Council Engineering Recommendation G 26.
7. Notes of guidance for the parallel operation of private generators with Electricity Boards' low voltage networks. Electricity Council Engineering Recommendation G 4711.

Also, useful information on related topics is obtainable from equipment manufacturers, GEC Alsthom Measurements brief guide *Generator protection* (publication R-5061A), and *Relay application guide* (publication R-5582), are typical examples.

The journals and specialist-conference publications of learned societies report on the latest advances in design and engineering practices. For example, the lEE's Conference Publication 272 December 1986 includes the following papers:

(a) Enhancing control and protection for improved plant reliability.
(b) Combined solid state system for protection, automation, measurement and tele-transmission in MV switchgear.
(c) Protection against reverse and under-power conditions by modern electronic relays.
(d) Computer-aided design of industrial protection coordination with assessment of relay settings under transient conditions.
(e) Microprocessor-based power system protection schemes.

ing describes the detonation in a gas engine cylinder due to over-compression of the air-gas mixture before sparking. The octane number is analogous to the cetane number of a distillate fuel oil. Both relate to the ignition quality of a fuel.

Jones [15] advises that a 'mean octane number' calculated from those of the various constituents in a gas is not always a good guide to a fuel's ignition quality. The heavy fractions in the gas can give rise to detonation where the mean number might suggest that no problem exists. This particularly applies to turbocharged engines where compression pressures are high. Also, because most engines of this type are charge cooled, the temperature of the air-gas mixture entering the cylinder is critical. If heavy fractions are present in the gas the inlet manifold air temperature must be kept low.

## 12.9 Lubricating oil

The many tasks that a lubricating oil has to perform within an engine were discussed in Chapter 1 (Subsection 1.7.1). When selecting oils for service requirements one needs to take account of the conditions that exist between engines of different speeds and piston connections. For instance combined cylinder and bearing lubrication is used in high-speed and medium speed trunk piston engines, whereas separate lubrication of cylinders and bearings is customarily applied to low-speed, crosshead type engines. Cylinder lubrication conditions can be particularly severe in those engines which use the combined system. The period between engine overhauls will largely depend on the rate of cylinder wear and the condition of the cylinders themselves [16].

Modern oils fur engines are of the mineral type, manufactured from crude oil (see Figure 12.1). Most are now refined using solvent extraction processes, in which undesirable compounds are selectively dissolved and removed [17]. Further processes follow, such as refrigeration prior to dewaxing and clay filtering, to give a rationalized range of oils from the one refinery. These oils are then blended and compounded with additives to give the many grades and special properties needed for engine duty.

### 12.9.1 Properties of lubricating oils

The chief properties of lubricating oils measurable by physical and chemical laboratory tests are listed below. The first nine are common to those of liquid fuel specifications (see Section 12.5) and the tests used to determine them are similar. We shall consider the significance of the properties in relation to engine lubrication.

1. viscosity
2. relative density
3. carbon residue
4. ash content
5. sulphur content
6. water content
7. pour point
8. cloud point
9. flash point
10. acidity/alkalinity
11. demulsification number
12. insolubles content
13. diesel fuel diluent
14. foaming
15. oxidation stability

*Viscosity*

This is perhaps the most important of the oil properties since it determines the effectiveness of the oil film separating moving and rubbing surfaces. It controls the load-carrying ability and affects the friction and wear of bearings, governs the oil's sealing effect and the rate at which the oil is consumed [6].

While every attempt is made to standardize on the use of kinematic viscosity (cSt) in oil specifications, the arbitrary (flow time) units of Saybolt, Redwood and Engler still persist within the industry. Also, the Society of Automotive Engineers (SAE) viscosity classifications continue to be widely applied.

Devised initially for the automotive industry, the SAE system uses numbers which represent a range of viscosity at given below-zero temperatures for the lower viscosity oils and at 100°C(212°F) for those of higher viscosities.

The oil grades are classified in the order of their viscosity (see Table 12.1). The viscosity of the six thinner grades (carrying the suffix W for 'winter') is the *dynamic viscosity*, at sub-zero temperatures- expressed in centipoise (cP). That for the four

**Table 12.1** SAE Grades for engine oils

| *SAE Number* | *Max. viscosity (cP) at °C* | *Kinematic viscosity at 100°C* Min. | Max. |
|---|---|---|---|
| 0W | 3250 at −30 | 3.8 | – |
| 5W | 3500 at −25 | 3.8 | – |
| 10W | 3500 at −20 | 4.1 | – |
| 15W | 3500 at −15 | 5.6 | – |
| 20W | 4500 at −10 | 5.6 | – |
| 25W | 6000 at −5 | 9.3 | – |
| 20 | – | 5.6 | <9.3 |
| 30 | – | 9.3 | <12.5 |
| 40 | – | 12.5 | <16.3 |
| 50 | – | 16.3 | <21.9 |

### *Cloud point*

This is being replaced by the *cold filter filling point* (CFFP). Both are indicative of the temperature at which wax begins to crystallize from the oil. They have no significance during normal running.

### *Flash point*

Most lubricating oils have sufficiently high flash points (typically 150°C closed) to eliminate fire hazard during handling and storage. Flash point has no significance in relation to the oil's performance in an engine.

### *Acidity/alkalinity*

The measure of an oil's acidity or of its alkalinity is given by its *neutralization number.* The neutralization value of an acid oil (its *acid number)* is expressed in milligrams of potassium hydroxide (KOH) necessary to neutralize 1 gram of oil, i.e. it is expressed in mg KOH/g. The term *total acid number* (TAN) is an indication of the total acidic constituents of the oil, i.e. the combination of organic and inorganic acids present. The *strong acid number* (SAN) is a measure of the oil's inorganic acidity only. The difference between the two numbers (TAN and SAN) represents the organic acidity and is a good indicator of the acidic 'weakness' of an oil and of the effects of some additives. Highly-refined straight mineral oils contain very small amounts of acidic matter and may have a neutralization number of 0.10 or less [19].

The *total base number* (TBN) is a measure of the alkalinity of an oil. It is determined by titration of the oil with hydrochloric acid or perchloric acid ($HClO_4$). The result is expressed as that amount of acid necessary to neutralize 1 gram of the oil. Unused oils containing dispersant additives are usually alkaline. Reduction in alkalinity when in use is a measure of the depletion of such additives in an oil [17].

The neutralization number of a used oil is higher than when it is new. This is because the oil oxidizes in service and organic acids are produced. The neutralization number does not distinguish between corrosive and non-corrosive acids. It is not, therefore, a measure of the corrosive tendency of an oil [6].

Some engine manufacturers may advise that oil is drained and renewed when its neutralization number exceeds a stated level. Gunther [19] suggests that the more appropriate yardstick is the *rate* at which the oil reaches that level, and that '... a decided rise in neutralization number, accompanied by an increase in viscosity and other pertinent changes, is an indication that a serious condition has been reached, or is being approached'. One needs to correlate the history of the engine's operational oil changes with the charge-oil's immediate (tested) condition in order to determine the best action to be taken, i.e. either replace the oil charge or continue for the present.

### *Demulsification number*

The demulsification number of an oil is the time (in seconds) required for an oil which has been emulsified with water to separate under defined test conditions. The emulsification may be achieved by stirring or by steam blowing.

Modern mineral oils possess good properties of water separability. They will lose this property when contaminants are allowed to enter the oil and remain there indefinitely. If water is present in a service oil' carbon dioxide from the air will combine with it to form a weak acid (carbonic acid). This results in a sludge which could add to the emulsification properties of the oil. Any tendency to emulsify is increased by the presence of combustion products in the lubricating oil. Since emulsification permits oil to retain water particles it is undesirable for the following reasons [19]:

1. it leads to lubricant deterioration;
2. it could cause mechanical failures (because oil is displaced by water in frictional areas);
3. it may cause rust and corrosion; and
4. it could cause the lubricant to 'foam'.

### *lnsolubles content*

Tests (typically BS 2000: Part 143 and IP 143) are applied to used oils to determine the amount of contamination present. In the first part of the test precipitation by normal heptane is used to give a composition of inorganic, carnbonaceous, and asphaltic matter. The asphaltenes are extracted from this composite using a solvent and they are weighed after the solvent has evaporated. The remaining residue then consists of inorganic and carbonaceous matter. The inorganic element contents are determined (as 'sulphated ash') by using the test method of BS 2000: Part 163 and IP 163, in which the residue is heated to free it from its carbon matter. The sulphated ash may be further analysed by chemical or spectographic methods [17].

The nature of lubricant insolubles is fairly complex. Van HeIden and Hengeveld [21] report that extensive research has shown that the two major constituents of oil contaminants in large residual-fuelled engines are combustion soot and calcium sulphate. They quote a typical analysis for extracted separator sludge as showing 20 % soot, 65 % inorganic calcium salts and 10 % hydrocarbons, with the remainder comprising degraded additives and other inorganics. These inorganics might include, for example, metallic wear debris, corrosion products, and inorganic contaminants from external sources.

They conclude [21] that' ... lubricant contamination is becoming more severe with modern highly-rated engines, widespread use of residual fuels and trends to reduce oil consumption'; and, since '... engine cleanliness is related to oil contamination and the fouling rate seems to be proportional to insolubles concentration, ... this can provide some guidance to engine builders to set limits to maximum tolerable contamination levels'.

### *Diesel fuel diluent*

It is possible to get dilution of lubricating oil by fuel leakage into the crankcase but it can also occur by loss of fuel from multi-hole injection nozzles. The effect is progressive. The best safeguard against undue dilution is to maintain the fuel injection equipment in good order [17]. One immediate remedy is to change the oil or to drain off part of the charge in use and top-up with fresh oil. It may be desirable to use a heavier grade oil for the top-up [16].

Any appreciable contamination of the lubricating oil by fuel causes a marked reduction in the viscosity of the oil and hence its delivery pressure [16]. Determination of the degree of dilution by a comparison of the viscosities of used and unused oil is, however, unreliable. Far more dependable methods are, to compare the boiling point distributions in the two oils by gas chromatography [17], or to compare their flash points.

### *Foaming*

An oil which has air entrapped within it will *foam* (or froth) when it is churned. The air may enter the oil in many ways. Gunther [19] cites several, including:

- through the intake of an unsubmerged pump;
- situations where oil is discharged into a sump at a point above the oil surface; and
- splash lubrication systems, where oil breaks up into small droplets.

In dry sump systems (see Sub-section 1.7.1 of Chapter 1) the scavenge pump must have a larger capacity than the circulating pump in order to ensure that the sump remains 'dry'. At times, therefore, the scavenge pump is likely to be drawing in some of the atmosphere of the crankcase together with oil. When system pressure is reduced the air entrapped in the oil expands and causes foaming [17]. New oils have a tendency to foam more rapidly than used oils. Also, the greater an oil's viscosity the greater the likelihood of foaming.

The rate at which bubbles on the surface of an oil break-up depends upon the surface tension of the oil. Some additives (such as dispersants) and contaminants increase surface tension and may intensify frothing. All oils will foam. *Anti-foam agents* (additives or suppressants) may be included in an oil to prevent formation of a stable foam. Small concentrations of silicones (typically polymeric organic siloxanes) are used for the purpose. The concentrations need to be small (less than 0.001 %) because one does not want to reduce the surface tension too much and so diminish the oil's lubricating property. The 'foam-breaking' agents allow the small bubbles that form on the oil's surface to combine and form larger ones which then break up more readily [9].

Oils are aerated under standard conditions in sample tests. The volume of foam produced immediately after cessation of air-blowing is then compared with that which remains after the sample has settled for ten minutes. The test is repeated on a further sample at elevated temperature [17].

### *Oxidation stability*

The *oxidation* of any substance implies the combination of oxygen with that substance or the removal of hydrogen from it. This process takes place in lubricating oil and changes occur within the oil due to the presence of entrained air (or water). It is perhaps the most important of the internal contamination processes which affect the service life of an oil.

Oxygen in the air combines with the hydrocarbons of an oil to form aldehydes, which then convert into organic acids. The process is accelerated by an increase in temperature, by aeration, and by the presence of catalytic metals. These conditions are inherently prevalent in RIC engines. For example:

- high combustion temperatures;
- aeration caused by the splashing effect of crank mechanisms;
- water due to condensation from combustion; and
- the presence of catalytic copper and ferrous metals. The oxidation effect is more pronounced when the surfaces of such metals are fresh, and are being worn [19, 20].

The organic acids resulting from the oxidation produce various harmful effects. Those acids that are more volatile (i.e. those with low boiling points) will attack bearing and other surfaces causing pittage corrosion. Those with high boiling points react with the oil to produce sludges, gums and carbon residues. These products may be soft or hard, depending upon engine temperature and the relative proportions of the organic acids.

The sludges are deposited in sumps, in oilways, on filters and strainers, and in heat exchangers. The gums form in the combustion chambers and adhere to piston rings and grooves, valves and valve chambers. In their more extreme form, the 'sludges' appear as hard varnishes or lacquers (thin layers of converted varnish) which cause valve and piston ring sticking and even valve burning. The effects of carbon residues have been discussed earlier and in Sub-section 12.7.1.

There are many oxidation tests that may be conducted in laboratories. Each has been devised to simulate different service conditions. Results, therefore, cannot be directly compared. (Lansdown [18] suggests that the method of IP 176, *Oil oxidation and bearing corrosion test* (Petter Engine Test) is most suitable for engine oils.) More reliance is placed on actual engine tests.

### 12.9.2 **Additives**

Straight mineral oils are no longer able to meet the operating conditions imposed on modern engines. Consequently, lubricating oils must now have a range of chemical compounds added to them to improve their quality and performance beyond that which can be achieved by refining alone. A very brief description follows of some of the main *additives.*

#### *Corrosion and rust inhibitors*

Corrosion inhibitors act to form a protective film that adheres to (or is adsorbed on) metal surfaces, or they may act to break the chain reaction of oxidation and acid formation. See also below. Typical compounds are organic amines and *soaps* such as calcium, sodium or barium sulphonates.

The purpose of rust inhibitors is to provide a thin film of oil on engine surfaces during operation and shutdown periods. The essential feature of the compounds used is their high polar attraction to metal surfaces, giving a *plating* action. They include metal sulphonates, amines, fatty acids and metallic soaps of fatty acids [19].

#### *Oxidation inhibitors*

Oxidation inhibitors (or anti-oxidants) are used to prolong the useful life of an oil. They act to prevent, retard or modify the oxidation process, and to inhibit corrosion of bearing and metal surfaces. They may do this in different ways. Those that compete with the oil for oxygen (i.e. act as 'decoys' for any environmental oxygen) are known as *preferential anti-oxidants.* They are expendable. When they are 'spent' the *oxidation stability* of the parent oil reverts to its base characteristic. The subsequent service life of the charge then depends upon the oil's basic qualities.

The so-called *metal deactivators* (also called anticatalysts and passifiers) serve to neutralize the catalytic acti(pn of any metal particles suspended in the oil and form a barrier, or protective coating, over those engine surfaces which are in contact with the lubricating oil.

Metal salts, sulphur and phosphorous compounds, and amines are some of the ingredients of anti-oxidants.

Rust inhibitors and those additives designed to reduce engine wear, also have a passivating effect on catalytic metal surfaces. Conversely, oxidation inhibitors also act as corrosion inhibitors.

#### *Detergents and dispersants*

The term detergent implies a cleaning agent. It relates to products used in solution for washing or cleaning by action other than by simple dissolution. Detergents are metal soaps soluble in oil. They do not correct the cause of oxy-product development and only act to prevent its build-up on clean surfaces exposed to lubricating oil. Detergents do not remove existing dirt deposits from dirty surfaces. They may be more accurately described as *detergent-dispersants.*

The {unction of a dispersant is to keep contaminant particles isolated from each other. In other words, it acts to keep the fine particles in suspension within the oil mass. This may lead to difficulties with choking of fine-particle filters. The normal filters used in engines are unlikely to give trouble [17].

Contaminant particles in suspension are preferable to their being deposited on engine parts. Dispersant oils do look dirty in use. The suspended dirt is fairly harmless even though the lubricating qualities of the oil may not be enhanced by its presence. Dispersant oils can be safely used until their recommended change period is reached. The periodicity of oil changes is materially increased by the use of detergent-dispersants and anti-oxidants.

Organo-metallic salts, such as salicylate ester salts, are the usual additives for high operating temperatures, while polymer compounds are generally used for low temperature conditions.

#### *Viscosity-index improvers*

These are high molecular weight polymers which act to reduce the rate of change of viscosity with temperature. They raise the viscosity of an oil by a greater proportion at higher temperatures than at lower temperatures. In so doing, they ensure good oil circulation at low temperatures and maximum viscosity at high temperatures. VI improvers are used in multigrade oils meeting SAE requirements.

#### *Pour-point depressants*

Paraffinic base oils are usually de-waxed as part of the refining process. The process is costly and if the de-waxing is too severe there is a danger of removing desirable constituents. In practice, a combination of de-waxing and adding selected *depressants* is used. The depressant materials are complex polymers of high molecular weight.

When a paraffinic lubricating oil is cooled below its pour point it coagulates because the wax separates out to form a congealed matrix of needle-shaped crystals. This matrix acts as a sponge to hold the oil. Some pour-point depressants function by surrounding the wax crystals with a protective coating, thus preventing them linking up to form the matrix. The viscosity of the free oil is not affected.

Some viscosity-index improvers also function well as pour-point depressants. Their mode of action is somewhat obscure. They appear to modify or guide the growth of the wax crystals in a three-dimensional mode around a nucleus, so preventing the interlocking matrix from being formed [17].

#### *Foam depressants*

Anti-foaming agents function to reduce the surface tension of an oil, thus releasing any air entrained in it. They are usually high molecular weight silicone polymers (such as the polymethyl siloxanes) in concentrations of less than 0.001 %.

### 12.9.3 Oil specifications

We have discussed the SAE system of classification in a previous Sub-section (12.9.1). We shall now consider the specifications that are commonly quoted in lubrication practice.

The American bodies API, ASTM and SAE have co-operated in producing a classification of lubricating oils by type of use in both gasoline and diesel engines. Those applicable to the latter are:

CA - for light duty service with high-quality fuels;
CB - for moderate duty service by naturally aspirated engines operating on lower quality fuels with higher sulphur content;
CC - for moderate to heavy duty service by pressure-charged engines; and
CE - for severe duty service typical of turbocharged engines in high speed, and low speed, high output duty.

Lubricant manufacturers market their products under brand names (e.g. Shell *Rotella TX* and Silkolene *Hardwick).* They issue data sheets which describe the typical properties of the product. These give prospective users a yardstick by which a particular brand may be assessed for intended service.

It is customary for engine manufacturers to co-operate with oil refiners in undertaking thorough engine test programmes on various brands of oil in several kinds of service. They then issue reference lists of the specified oils to be used consistent with the duty and rating of an application and the fuel which it is intended to use.

If a plant operator should need to consider an unlisted oil he must compare the properties of the brand he intends using with those of one, or more, of the approved brands on the engine manufacturer's list. Lubricant data sheets should be used for such comparisons. Better still, the operator should ensure that the oil has an official certificate of conformance for the appropriate specification designated by the engine manufacturer. Any change effected should always be followed by a careful monitoring of the new oil's performance in the engine's systems.

Among the widely accepted specifications are the American military specification MIL-L-2104, and its British equivalent (the DEF-2101 series) issued by the UK Ministry of Supply. Modifications to both specifications are denoted by a letter suffix: B, C, D, etc.

The American companies Caterpillar and General Motors were the first to devise extensive test programmes for the evaluation and approval of lubricants for use in their engines. Much of the subsequent military standardization was based on the earlier work of these two companies. Often-quoted specifications are those derived by the Caterpillar Tractor Company - its Series 1, 2 and 3 oils, designated Cat 1, etc. Later designations generally have the higher performance levels. It is outside the scope of this chapter to give full details of the many standard engine tests, and their associated specifications. Those readers who wish to study the topic in some depth should make [17] or [20] their starting point.

## 12.10 Corrosion inhibition in transit and storage

It is prudent to arrange for engines to be given temporary protection against atmospheric corrosion during transport or storage. Practical measures include:

1. the application of impervious coatings to insulate internal surfaces from their environment; and
2. the use of chemical inhibitors to reduce corrodibility of such surfaces. In particular, to reinforce oxide films so that they can persist and suppress further reaction even in the presence of moisture.

Combinations of both are possible and are effectively used on engines for storage periods of 12 months or more [22].

Typical 'temporary' protectives are the Shell Ensis Engine Oils. They are available in various viscosity grades and are applied by using the correct grade in place of normal lubricating oil for a short period before engine lay-up. They contain additives which neutralize the acids formed during fuel combustion.

Their compatibility with service lubricants means that no flushing procedures are necessary and they may even be retained as the service lubricant in some types of engine until the first scheduled oil change.

Fuel systems may be treated by using a special 'calibration fluid' as a fuel. The fluid is left in the fuel lines during lay-up.

The cooling system too should be treated with a mixture of water and an inhibitor (such as Shell Dromus Oil B).

The engine to be treated is run until it is thoroughly warm. It is then stopped, drained of lubricant and coolant, and refilled with the recommended protectives. The fuel filter housings and any integral service tank are drained of fuel and the fuel system is primed with the calibration fluid. The engine is run for a short period and allowed to cool after it is shut-down. Additional protective lubricant is then sprayed into inlet and exhaust manifolds - care being taken to seal all open flanged joints with well-seated, and gasketed, blind flanges. Unpainted external surfaces should be swabbed with a protective (such as Shell Ensis Fluid 260) which has dewatering properties and will give a thick film coating (about 0.01 mm) of medium-hard consistency. A drying time of about four hours is recommended in temperate climates.

## 12.11 Referenced standards

Listed below are those UK standards, issued by the British Standards Institution and the Institute of Petroleum, to which reference has been made in this chapter. Corresponding International (ISO), European (EN) or Institute of Petroleum (IP) standards are shown in brackets. The extent of their agreement with the British Standard varies. Some are completely identical and have dual-numbering. Others have substantial technical equivalence, with differences perhaps in wording and presentation.

BS 526 - *Definitions of the calorific value of fuels*
BS 1179 - *Glossary of terms used in the gas industry*
BS 2000 - *Methods of test for petroleum and its products*
- Part 12 *Heat of combustion of liquid hydrocarbon fuels*
- Part 15 *Pour point of petroleum oils*
- Part 34 *Flash point by Pensky-Martens closed tester*
- Part 57 *Smoke point of kerosine*
- Part 61 *Sulphur in petroleum products (bomb method)*
- Part 71 *Kinematic viscosity of transparent and opaque liquids and calculation of dynamic viscosity*
- Part 107 *Sulphur in petroleum products (lamp method)*
- Part 123 *Distillation of petroleum products*
- Part 143 *Asphaltenes in petroleum products (precipitation with normal heptane)*
- Part 154 *Detection of copper corrosion from petroleum products by the copper strip tarnish test*
- Part 163 *Sulphated ash from lubricating oils and additives*
- Part 170 *Flash point by the Abel apparatus (non-statutory method)*
- Part 218 *Calculation of cetane index of diesel fuels (range* 55 *and above)*
- Part 219 *Cloud point of petroleum oils*
- Part 230 *Pumpability test for industrial fuel oils*
- Part 364 *Calculated cetane index of diesel fuel oils (range below 55)*

(*Note:* these BS 2000 Parts have correspondingly-numbered equivalents in standards issued by the Institute of Petroleum; for example, Part 163 is identical with IP 163.)

BS 2869 - *Fuels for non-marine use*
- Part 1 *Specification for automotive diesel fuel (class A 1)*
- Part 2 *Specification for fuel oil for agricultural and industrial engines and burners (classes A* 2, C 1, C 2, D, *E, F,* G *and H)*

BS 3156 - *Analysis of fuel gases* (this is a multi-part standard which deals with:

- determination of: the main combustible and inert constituents,
  the minor constituents, and
  the combustion characteristics of common fuel gases;
- the separation of constituents by chromatographic analysis; and
- determination of the constituents and characteristics of gases at pressures above 1.7 bar.)

BS 3195 - *Methods for sampling petroleum products*
- Part 1 (ISO 3170 and ISO 1995) *Light hydrocarbons: manual sampling*

BS 3804 - *Methods for the determination of the calorific value of fuel gases*
- Part 1 *Non-recording methods*

BS 4231 (ISO 3448) - *Classification for viscosity grades of industrial liquid lubricants*

BS 4382 (ISO 3735 & IP 53) - *Method for determination of sediment in crude petroleum and fuel oils (extraction method)*

BS 4385 (ISO 3733 & IP 74) - *Method for determination of water in petroleum products and bituminous materials (distillation method)*

BS 4450 (EN 7 & IP 4) - *Determination of ash from petroleum products*

BS 4451 (ISO 4262 & IP 14) - *Method for determination of carbon residue of petroleum products (Ramsbottom method)*

BS 4699 (IP 189 & IP 190) - *Methods for determination of density or relative density of petroleum and petroleum products (pyknometer methods)*

BS4714 (ISO 3675 & IP 160) - *Method for laboratory determination of density or relative density of crude petroleum and liquid petroleum products (hydrometer method)*

BS5379 (EN 41) - *Determination of the sulphur content of petroleum products by the Wickbold combustion method*

BS5580(IS05165&1P41) - *Dieselfuels-determination of ignition quality-Cetane method*

BS 6188 (EN 116 & IP 309) - *Method for determination of cold filter plugging point of diesel and domestic fuels*

BS MA 100 - *Specifications for petroleum fuels for marine oil engines and boilers*

*(Note:* A related specification is that of ISO 8217 - *Petroleum products - Fuels (class F) - Specifications of marine fuels)*

IP 336/86 - *Sulphur in petroleum products by energy dispersive X-ray fluorescence (non-dispersive X-ray fluorescence)*

## 12.12 References and bibliography

### 12.12.1 References


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by the Institution of Diesel and Gas Turbine Engineers and Fuel and Metallurgical Journals Ltd., September (1988)

22. *Shell Temporary Protectives for Corrosion Prevention*, Shell International Petroleum Company Limited (1972)

### 12.12.2 Bibliography

The text-books listed in the references have been used in the preparation of this chapter. Those which are recommended as starting points for research by the reader are:

1. For fuel oils: [4, 5 and 7].
2. For gaseous fuels: [12 and 14]. The latter is particularly recommended for its explanation of the digestion process and the engineering requirements of digesters in the production of bio-gas. Not included under the references is a work by M. Medici entitled *The Natural Gas Industry*, Butterworth, (1974), which is targeted at a wide readership but presents specialized knowledge on many aspects of the industry.
3. For lubricants: (17, 18, 19 and 20]. Another useful text-book, on the wider subject of tribology, is that edited by J. Halling entitled *Principles of Tribology*, The Macmillan Press Ltd, issued in paperback in 1978. The contribution by R.B. Howarth on Lubricant properties and testing (Chapter 9) is of particular interest in this context.

Other useful sources of information are:

1. The house journals and technical literature of the major engine manufacturers and oil companies [10, 16 and 22].
2. International trade journals and magazines specializing in prime-movers and engine-powered equipment such as *Diesel Engineering, Diesel and Gas Turbine Worldwide, High Speed Diesel Report* and *European Power News.*

# 13 Installation and commissioning

**Contents**

## 13.1 Introduction

This chapter deals first with the layout and structural aspects of power plant installations, emphasizing the need for good foundations. It then goes on to examine the major auxiliary systems giving recommendations on design and location.

A section dealing with cabling describes cable constructions, cable ratings, and methods of installation and termination. It concludes with an explanation of the classifications used in specifying fire-performance cables.

The general rules governing safety of personnel and equipment are then discussed under the subject headings earthing, fire protection and lighting.

Finally, the need for a thorough commissioning programme is considered, and typical check-lists are offered based on a step-by-step approach to the exercise.

## 13.2 Plant categories

For our purposes we may conveniently sub-divide generating plant into two installation categories:

1. stationary plant; and
2. mobile or transportable equipment.

Applications in either category may include base load, peak lopping or standby duty, as defined in the introduction to Chapter 5.

Stationary plant implies a permanent installation supplying power, for example, to rural electrification schemes, small townships and communities, and industrial or commercial facilities. Mobile or transportable equipment is that used to supply power on a short-term or temporary basis. Housed within purpose-built weatherproof enclosures or in ISO type freight containers, they may be mounted on commercial vehicles, trailers, and barges to give easy mobility. Enclosures for military equipment may be designed to accommodate so-called mobilizers, which are demountable, wheeled running gear units. In their transportable form the housings (or bases) of the power plant may be provided with lifting facilities enabling transportation by road, rail or sea, air freightage, or even helicopter lift. In the case of the ISO containerized equipment jack leg lifting is also possible by means of proprietary ISO leg equipment.

### 13.2.1 Stationary plant

We need to consider, in this category, the housing of plant in existing or in specially constructed buildings. D.S.D. Williams [1] advises that

> in either instance, it should be axiomatic that the plant be housed in a manner worthy of it. It is foolish, economically, to house high-class machinery in a ramshackle structure, yet many seem to think that four walls (sometimes fewer) and a roof of sorts are all that is necessary. The building should be simply but well constructed; it should, in fact, be a model of good construction for whatever building material is used in it. There are no restrictions as to material except that the whole structure should be as free from combustible material as possible.

*Plant layout*

The size of a power station or of a plant room is determined by the number and the rating of the generators to be installed, and by their requirements for auxiliary services. In addition to the engine-generator assemblies there will be switchgear and distribution and control gear, engine starting equipment, fuel service tanks, provisions for fuel and lubricating oil storage, engine cooling systems, exhaust silencing equipment, and (on the larger engines) lubrication and fuel systems external to the engine. The internal layout should be such that the basic requirement is to construct a station building around the machinery [2].

Normally, the plant supplier is not involved in the station design but is very concerned with the layout of the plant within the building. His approval should be sought before any proposed arrangements are finalized.

Building designs are carried out with a variety of professional and contractual relationships. Commonly this involves architects, consulting engineers, main contractor and sub-contractors. It is essential that effective co-ordination is established early in the plant design process. The following general considerations should be noted [3]:

1. Often the extent of co-ordination problems only becomes apparent when design detail is well under way. It is important to establish a sequence of design tasks for all parties concerned which progressively leads to more detailed work without nullifying earlier work.
2. The zoning and routeing of services, and well-planned plant and system layouts will minimize co-ordination problems.
3. Most co-ordination must be done *before* installation begins. This ensures that those builder's work details which are needed early in the construction programme are well established before plant installation commences.

It is important that adequate space is allocated in the designed layouts for functional requirements such as plant attendance, routine cleaning, inspection, maintenance, and repair of the plant and associated auxiliaries. This is in addition to the dimensional requirements of the plant and equipment. The use of grid planning systems in the design will help in the task of co-ordinating building fabric and auxiliary services, and in the integration of one service with another. A three-dimensional grid may be necessary where extensive cross-overs occur or where large elements such as exhaust pipes and ductwork have to be accommodated [3].

It is prudent to provide for future expansion. Growth may be in the form of a larger unit to replace the original or of additional units (in multi-generator plant) to cater for increased load. A removable end wall offers one way of providing for future plant room expansion.

Ideally there should be a clear floor space of at least three metres all round each generating set, regardless of its size, to facilitate maintenance. This distance may be reduced to two metres if the user is prepared to sacrifice convenience of overhaul for reduction of space. On multi-engined stations there should be sufficient headroom for installation and service gantry cranes - one for large lifts of between 10 to 30 tonnes and a smaller unit of about 2-3 tonnes capacity. Height to the underside of the common crane rail girder should be such that the distance between the bottom of the hook on the larger crane (when fully raised) and the floor level is sufficient to clear the installed engines and allow for their erection and dismantling. Typically this height would be about seven metres for stations with 1.5 MW medium speed engines.

On smaller installations with just one or two generators the alternative provision of a load-bearing beam above the centre line of each engine would suffice. Lifting tackle with manual or power operation may be attached to each beam which could be an integral part of the building structure. Sufficient floor space should then be provided at the generator end of each unit to allow for the setting down and removal of major components. Figure 13.1 gives the floor area and height requirements recommended by the Building Services Research and Information Association (BSRIA) for individual standby generators in the range 50-625 kVA - in Technical Note TN 4/79: *Space allowances for building services*

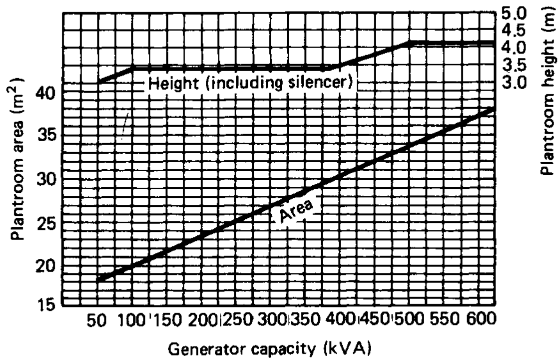



**Figure 13.1** Floor area and height for standby generators (Courtesy: The Building Services Research and Information Association (BSRIA))

## *Structures*

In many cases standby generator installations will be an integral part of commercial or industrial premises. Plant rooms are normally located on an external wall or external to a main building. The fabric of the enclosure is likely to be the same as that of the main building, e.g. brick or concrete walls (or combinations of these materials), and aluminium or steel cladding with insulation barriers.

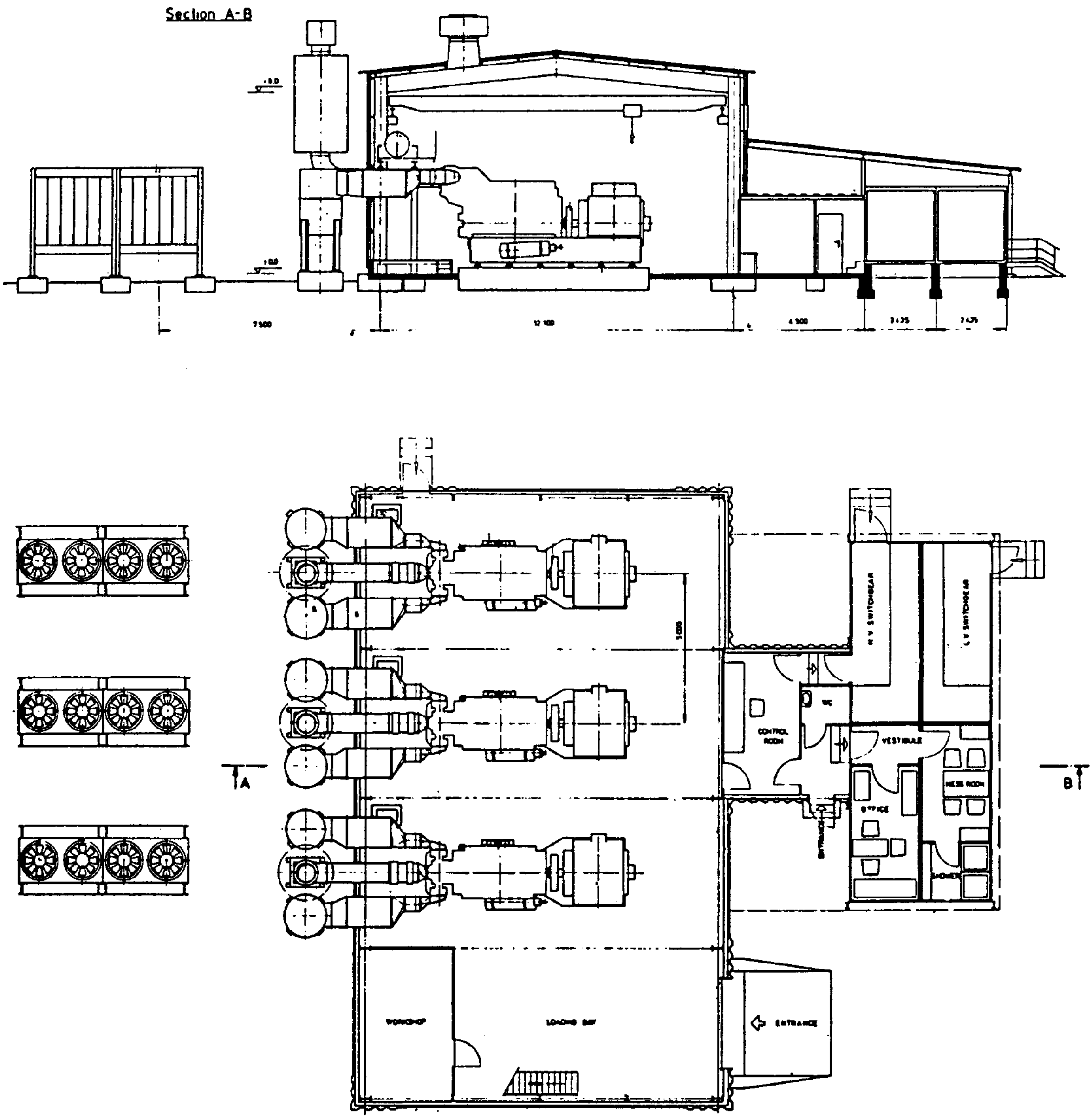
There will be a wide choice of building materials for the larger power stations. Factors affecting choice would include the need to meet local planning authority requirements in terms of environmental compatibility, cost, and intended life of the plant. Buildings will be constructed around a structural steel framework. Designs will vary to suit the particular machinery layout, and may include [4]:

- a machinery hall with a basement for auxiliaries;
- the provision of annexes to the main hall for auxiliary equipment, control room, offices, social amenities, service workshop and stores. The annexes may be on the same level as the machinery hall or sunk at a lower level.

The power station elevations in Figure 13.2 illustrate some of the possible arrangements.

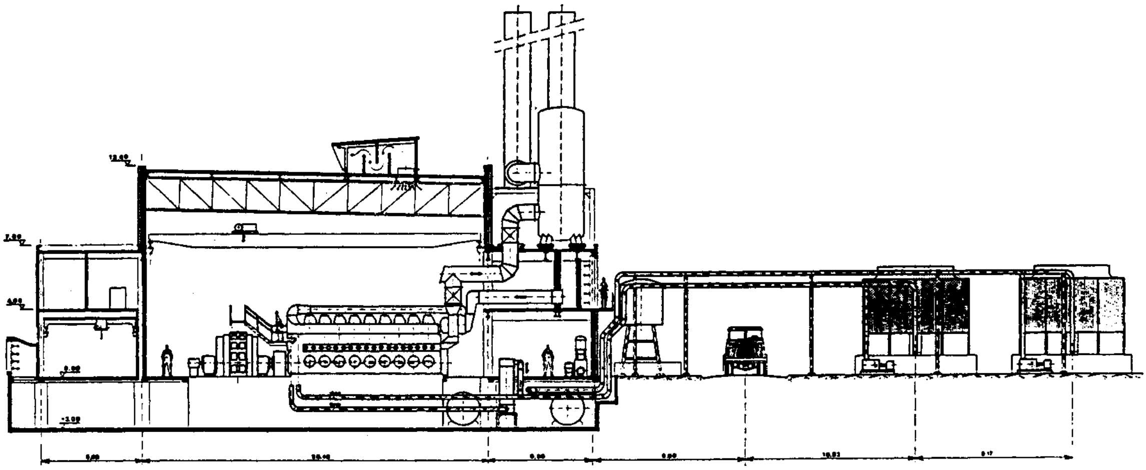
The scheme of diagram (a) is typical of a small-scale power station of about 5 MW capacity using high speed or medium speed engines. Machinery hall and annexes are on the same level. The building envelope may be of prefabricated modular construction allowing easy erection on site and permitting extension to accommodate additional generators at a future date. Substantial benefits may be obtained by using ISO container modules for the annexes. These would be fitted out at the manufacturers' works and house, for example, HV and LV switchgear, control centre, workshops, stores, offices, mess rooms and other amenities, and would be air conditioned where appropriate [5]. (See also Figure 13.5.)

Diagram (b) illustrates an arrangement on a large 100MW power station in Bastia (Corsica) [6]. Note the provision of a basement for the bulkier service auxiliaries. The cost of the basement is small because site excavation had to be carried out for the foundation blocks. The main advantage is that it provides a 'clean' machinery hall floor by eliminating the need for service trenches. The main pipework runs are located in the basement and are only brought up to the engines at the required positions. Access to the basement equipment is by removable chequer plating or grating. The ideal layout would

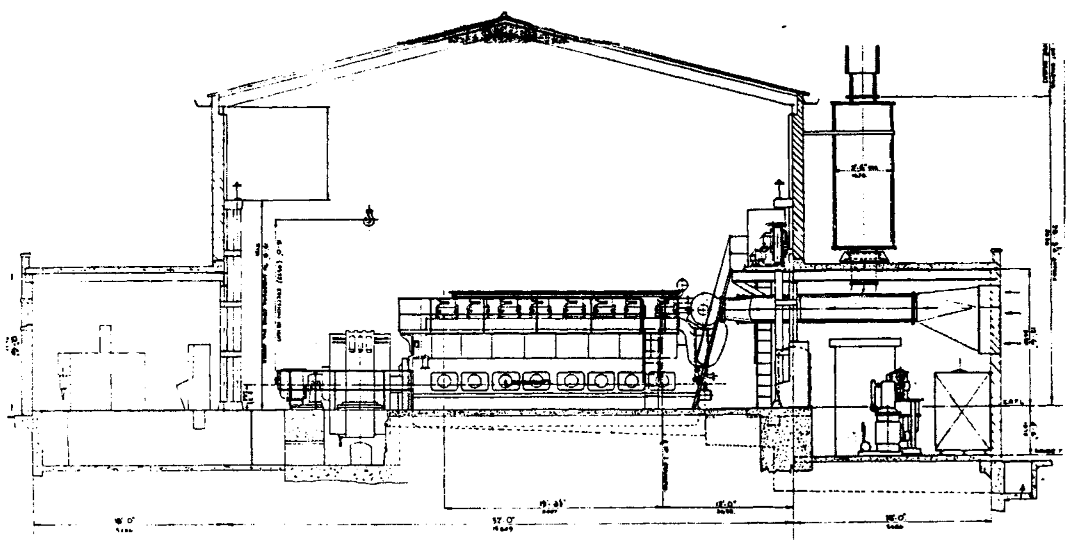



(a)

**Figure 13.2** Typical power station layouts and structures (a) A 5 MW modular diesel generating station with machinery hall and annexes on the same level. (Courtesy: MAN B & K AG)



(b)



(c)

**Figure 13.2** Typical power station layouts and structures (contin.) (b) Elevation of a power station housing eight MW generating sets and incorporating a basement for the bulkier service ancillaries. (Courtesy: NEI Allen Ltd) (c) Elevation of a power station with a sunken auxiliaries annexe - an alternative to the arrangement of layout (b). (Courtesy: Mirrlees Blackstone (Stockport) Ltd) allow for removal of equipment by the station gantry crane.

A station with a sunken auxiliary annexe is shown in diagram (c) (4). The need to provide sufficient height for removal of the lubricating oil cooler stacks without raising the annexe roof and complicating the exhaust and air trunking runs in so doing, led to the idea of lowering the annexe floor. Removal of the heavier components from the auxiliary unit assemblies is effected by a light crane rail fitted over the centre line of the assemblies. The external trench in the extreme right of the diagram carries the raw water pipes to the annexe and the distillate and heavy fuel pipes from bulk storage and transfer pumps. Connecting pipework to the engines is in service trenches within the main hall.

A feature of the design is a services gallery running along one wall. This accommodates the distillate fuel service tanks, water make-up tanks and the exhaust valve cage/injector nozzle cooling unit. The latter uses treated water and must be sited at a level higher than the engines to obviate the possibility of vapour-locking when a generating set is shut down. Where the manufacturer's engines are required to run on heavy fuel the pre-centrifuge and the service tanks are housed, as shown, in the annexe.

It may be possible in some stations to adapt the use of conventional *piperacks* to afford not only structures for carrying service pipes around the plant room, but also to provide a protected location for ancillary equipment. The piperacks may be fabricated from steel or concrete and steel, and would consist of connected goalpost-shaped frames *(bents)* on top of which the pipes are rested. Electrical conduit and trunking, cable trays, and lighting and other fixtures may then be fitted to the vertical members of the frames (the stanchions). The piperacks may be of single- or double-deck construction. Engine auxiliary plant, and fire-fighting and first-aid stations can then be located under the piperack (7).

In the mid-1970s one British company introduced a novel form of prefabricated modular-construction power station which was capable of being erected and put into operation within two to three weeks of arrival on site [8]. The concept is illustrated in Figure 13.3.

Unit dimensions were calculated to permit containerization for shipment. Single module buildings were made from three modular bays (each 8m x 6m x 4m high), and double units from six bays. Optional features were service workshops and office suites. Generating sets were mounted on independent base units which slotted into cutouts in the building base and were skidded in and out of the building through holes in the walls which fitted the radiator housing (see Figure 13.3(a)). Each base unit carried a supporting structure on which exhaust silencer and pipework were mounted, as well as a half-ton lifting device for engine maintenance purposes. The building base was fitted with chequer plate flooring and service ducts and also contained a 4000 litre fuel service tank. In recent years increasing use has been made of modified ISO standard

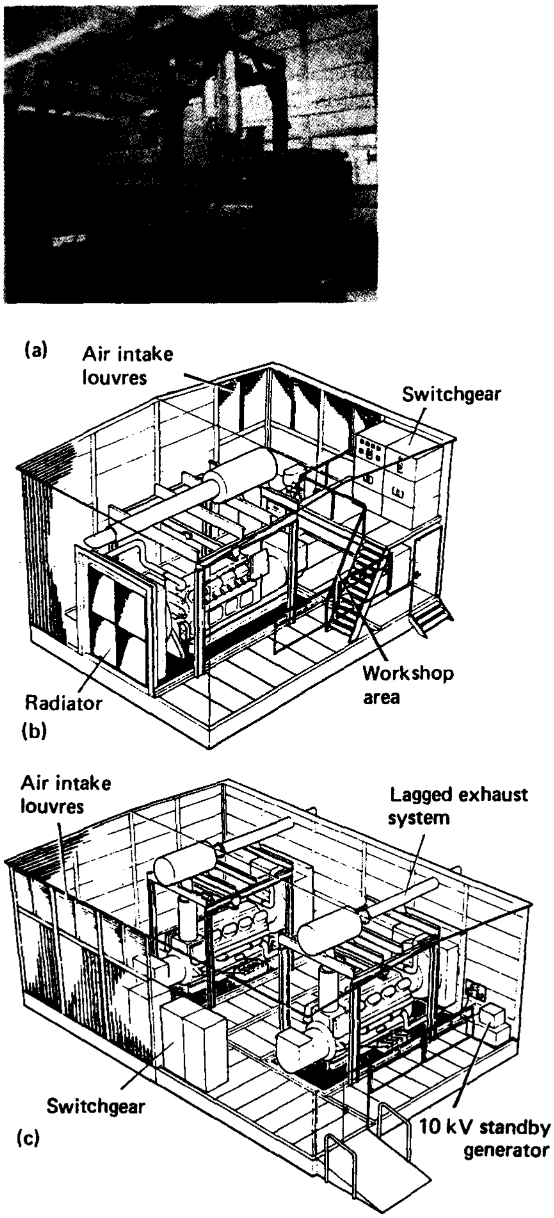



**Figure** 13.3 The concept of the prefabricated, modular construction, power station (Courtesy: International Power Generation) (a) Diesel-generator unit (850kVA, 50Hz) mounted on a base unit carrying a supporting structure, on which exhaust silencer and pipework are mounted; and incorporating a lifting device for engine maintenance purposes (b) 850kVA generator in a single module with workshop (c) Two 850kVA generators in a double module freight containers as housings for power plant. These can be rapidly assembled on site to give small-scale power stations in applications such as remote construction projects (see Sub-section 13.2.2).

### 13.2.2 Mobile and transportable equipment

A great variety of vehicle or trailer mounted sets are commercially available, ranging in output from 1 kW to about 3 MW. The majority employ high speed engines of both the air-cooled and the water-cooled type. The largest units incorporate medium speed vee-form engines running at l000rpm. The ventilation requirements for air-cooled machines (see Section 13.3) demand particular care in the design of acoustic enclosures.

It is important that trailers comply with any national regulations governing their use on public highways. In Europe type approval for compliance with E.E.C. standards covers such aspects as limiting dimensions, laden weights related to the brakes fitted, lighting, reflective marking, and variations of wheel load.

The many advantages of the ISO container accounts for its popularity with transportable plant manufacturers. It is available in several standard sizes. That most commonly used is the lC, a so-called 20 ft unit, whose leading dimensions are 6058 mm long, 2438 mm wide and 2439 mm high. Alternative unit lengths are: 10 ft (2991 mm), 30 ft (9125 mm) and 40ft (12 192 mm) - all in the standard width of 2438 mm, and heights of either 2438 or 2591 mm.

Housing plant in containers offers many advantages:

1. structural robustness allowing for the minimum of site foundation preparation (see Section 13.5);
2. easy lifting and handling, giving the mobility benefits afforded to ordinary freight containers throughout the world. The power unit is effectively its own packing case;
3. thermal and acoustic treatment is fairly easily undertaken;
4. the power equipment is fitted, commissioned and tested at the manufacturer's works so that on-site commissioning requirements are minimized.

Manufacturers have exercised a great deal of ingenuity in the use of containers for packaging plants for self-support stations. Typical applications are illustrated in Figures 13.4 to 13.8 which follow.

The majority of power containers marketed by MTU-Mercedes since the mid-1970s have found application in sparsely populated regions where they have been used (often in multiples of five) to provide power to townships and communities not served by utility power grids. They employ the manufacturer's compact 396 series of vee-form engines operating at either 1500 or 1800 r.p.m. Separate power distribution containers accommodating multiple input/output modular cells may be used to distribute the generated power to consumers. Figure 13.4 shows the layout of a power unit based on the ISO lC container (6058(L) x 2438(W) x 2439(H)). Maximum nominal ouput is 1 MVA at 50 Hz.

The container is acoustically treated. Free-field sound levels of the order of 75 dB(A) at 7 m and 72dB(A) at 14m are typical. Cooling and combustion air is drawn in through the splitter-type silencer (8). Engine-generator heat radiation causes an approximate 5°C rise in cooling air temperature. This air is forced into atmosphere by the fan cooler (3) and the splitter-type ventilation silencer (10). The gate flaps (14, 15) are opened before the generating set is operated. They also function to provide:

- additional rigidity during transit;
- splash protection;
- upward deflection of generated noise;
- dust and foliage protection;
- rapid dispersion of exhaust gases;
- a ramp for roll-inlroll-out of the generating set.

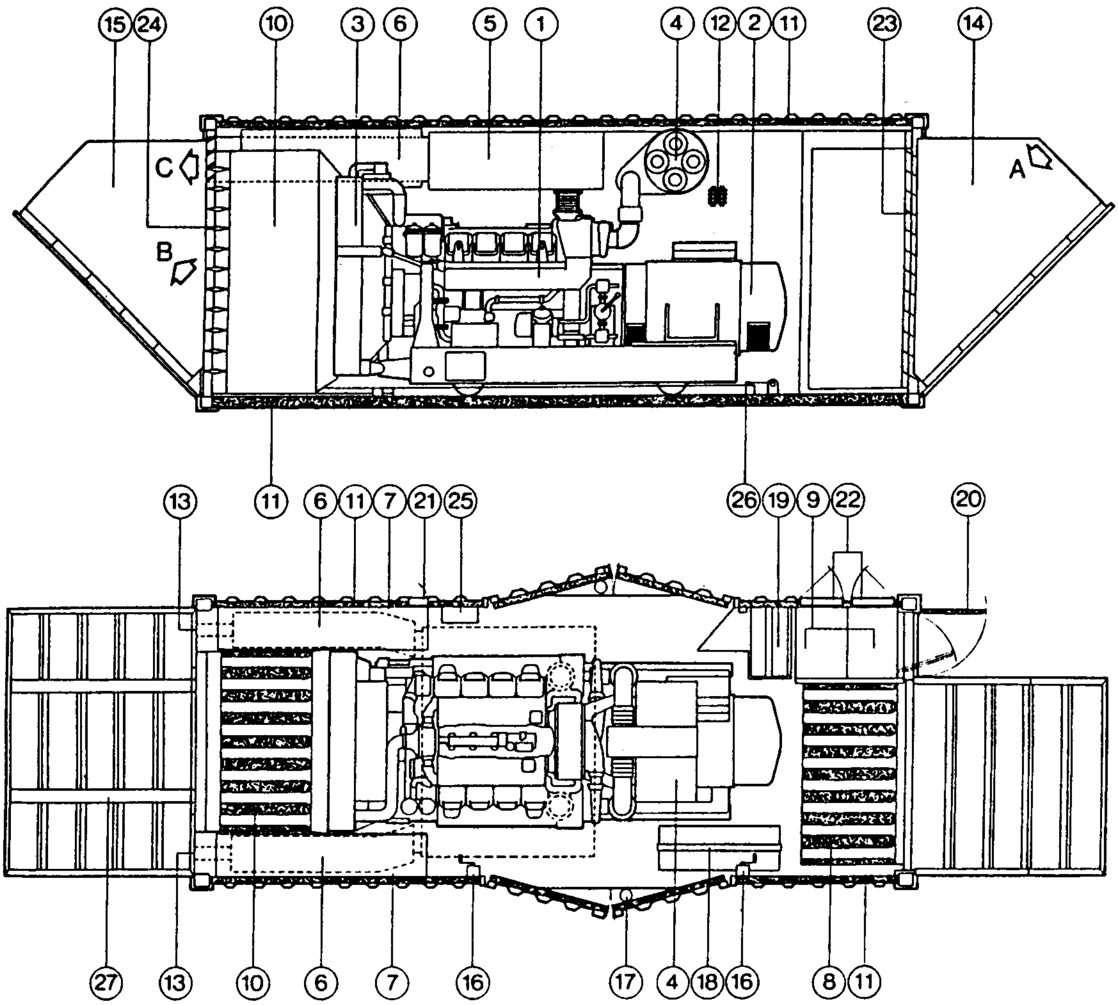
An excellent example of a portable power station package is that illustrated in Figure 13.5, which typifies the modern application of containerized plant. The installation is a Pet bow *Powercenter* supplying power and hot water to a l000-bed hotel complex.

The station comprises three 720kVA 400/230V generators driven by Cummins 12-cylinder KTA38Gl diesel engines, each installed in 20ft ISO containers. A 40 ft container which houses the switchgear, distribution board, and the fully automatic synchronizing and load sharing equipment links the three generator housings together. All containers are sound-proofed to give sound levels of 70dBA at 7m.

All sets are arranged to start when public supply voltage falls below (adjustable) preset limits. The control panel suite houses two 5000 A circuit breakers for supply changeover switching. Power is transmitted to the hotel complex at 3 kV through two 1 MVA step-up transformers.

The CHP system makes use of engine heat exchangers and radiators to provide a heat output of 470 kW (28 MJ/min) from each generator on a three-loop system.

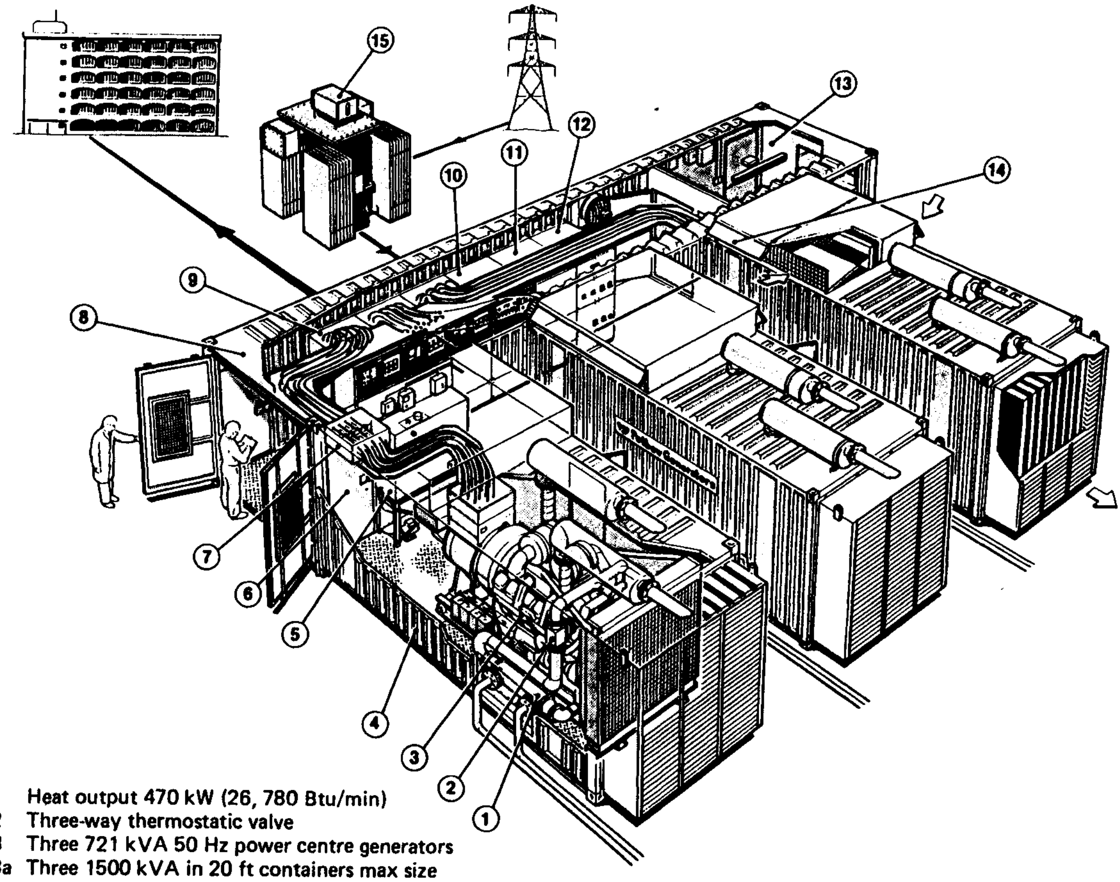
An example of containerization applied to telecommunications is that shown in the illustrations of Figures 13.6 and 13.7 for a IOkW VHF-TV transmitting station in North Africa. The multi-container building in the foreground of Figure 13.6 houses the transmitter equipment and includes dummy loads, de-humidifiers and the air-conditioning equipment necessary to maintain internal temperatures at about 20°C. Offices, social amenities and storage




1 Diesel engine
2 Alternator
3 Fan cooler
4 Dry-type air filter
5 Exhaust silencer
6 Exhaust duct, insulated
7 Fuel tank
8 Splitter-type intake silencer
9 Switchgear cabinet
10 Splitter-type ventilation silencer
11 Sound proofing interior lining
12 Lighting diagonally opposite (4 x a.c., 2 x d.c.)
13 Exhaust outlet with flutter flaps
14 Air intake flap with detachable side plates (open during operation, closed in transit)
15 Ventilation flap with detachable side plates (open during operation, closed in transit)
16 Cable winch to operate intake and ventilation flaps
17 Fire extinguisher
18 Battery
19 Battery charger
20 Access door to control panel
21 Fuelling flap
22 Flaps for power and control cables
23 Weather louvre, with bird screen
24 Weather louvre, motorized
25 Fuel feed unit (with automatic/manual selector)
26 Eyelet for tackle line
27 Guide rail

A = Air in
B = Air out
C = Exhaust gas out

**Figure 13.4** An MTU-Mercedes power plant housed in an adapted ISO 1C container and powered by an MTU 396 engine (Courtesy: Butterworth and Co. (Publishers) Ltd)



1 Heat output 470 kW (26, 780 Btu/min)
2 Three-way thermostatic valve
3 Three 721 kVA 50 Hz power centre generators
3a Three 1500 kVA in 20 ft containers max size
4 Three 20 ft ISO containers, soundproofed
5 Three fuel tanks 8 hour capacity with auto transfer
6 Bulkhead soundproofed interconnecting doors
7 Output cable link chamber
8 One 40 ft soundproof ISO container
9 AP600 auto sync. auto mains failure system
10 Common control panel
11 Incoming mains bus chamber
12 Distribution switchboard
13 Personnel compartment, soundproofed and air conditioned
14 Air inlets, adjustable vents
15 2 MVA 11 kV stepdown incoming transformer

**Figure 13.5** A 2 MVA, combined heat and power, portable power station package (Courtesy: Petbow Ltd)

facilities are also located within this complex. Sun-roof assemblies were used to supplement the in-built solar rejection properties of the linings provided on all the containers. The standby generator for the station is housed in the 20 ft container in the background. Figure 13.7 is a ground-level view of the site showing the pad-mounted mains supply transformer for the station and behind it the standby generator house and the bulk storage fuel tank.

Figure 13.8 illustrates a mobile radio transmission system with integrated power facility. Separate compartments are provided in the unit on the left for transmission and studio equipment. The trailer on the right carries a generator housed in an acoustically-treated enclosure, together with cable drums and eight sectionalized fibreglass antenna poles complete with stay wires and the tools necessary for their assembly and erection on site.

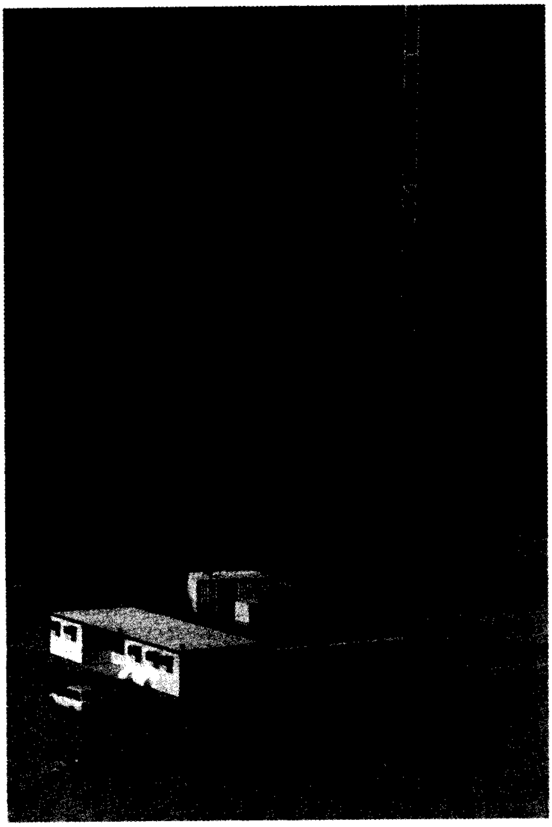


**Figure 13.6** A 10 kW VHF-TV transmitting station illustrating the ISO containerization of transmitter and standby power equipment (Courtesy: Incomtel Ltd)

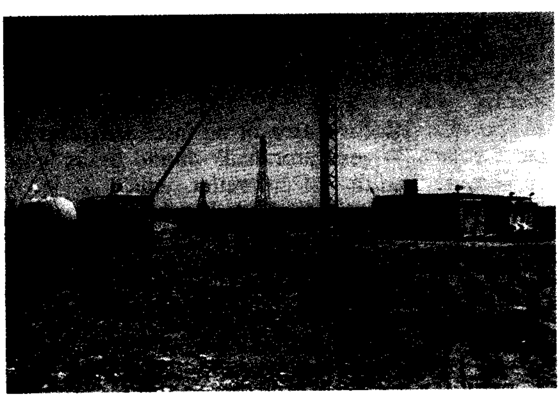


**Figure 13.7** A ground-level view of the transmitting station shown in Figure 13.6 (Courtesy: Incomtel Ltd)

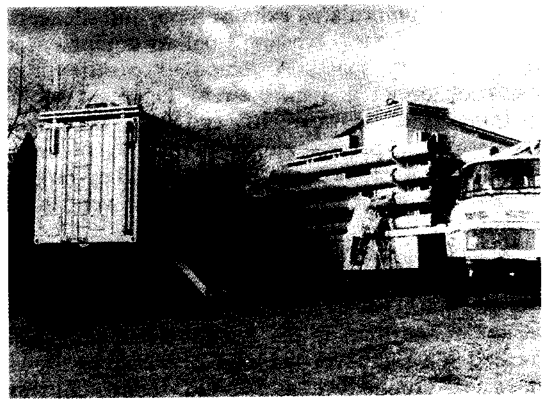


**Figure 13.8** A mobile, radio transmission system. The trailer on the left carries ISO containerized transmission and studio equipment ; that on the right, the power generation and ancillary equipment (Courtesy: Incomtel Ltd)

Broadcasting organizations require mobile systems of this kind for:

- providing emergency services;
- providing services in case of damage at fixed stations which are out of operation due to fire, earthquakes or similar occurrences;
- undertaking surveys for the planning of future stations; and
- providing temporary services, in otherwise poorly covered areas, for special events or contingencies.

## 13.3 Ventilation and aspiration air requirements

Generating plant installations require adequate quantities of air for:

- combustion;
- cooling; and
- ventilation.

The air requirements for combustion have been discussed in Section 1.7 of Chapter 1. Induction systems should be designed to supply clean air to the engine at, or as near, site ambient temperature as is possible and with the minimum of restriction. Where air to engine intake filters is drawn from within the plant room (and not directly from outside the building through ductwork) the ventilation system should be designed to cater for this.

Both engine and generator carcases radiate heat. Approximately 8 % of the generator nameplate $kW_e$ rating is dissipated in such heat. It is therefore necessary to make provision for constantly renewing the air supply to the plant room in order to prevent undue temperature rise within it. Consideration should also be given to the need to remove the heat rejected by uninsulated exhaust pipes and silencers, and by other heat-producing auxiliary equipment in the machinery space. A temperature differential (between outlet and inlet air to the plant room) maintained at between 10° and 15°C is usually satisfactory. Approximately $9 m^3/hr/kW_e$ of air is required by 4-stroke engined plant and $11 m^3/hr/kW_e$ by 2-stroke plant for combustion and ventilation purposes.

In those installations where engine cooling is by means of radiators external to the building (see Figure 13.2(a» or by closed circuit heat exchangers, air outlet apertures in the generator hall should be located at a high level and inlet air should be drawn in as near ground level as possible - consistent with the requirement to avoid pulling dust, rainwater or snow into the operati'ng spaces. Avoid areas where obstruction is possible, e.g from parked vehicles. Ideally, the air should be drawn in at the generator end of the installation. This ensures that near-ambient air is made available to the generator's cooling system. See Figure 13.9. The movement of air by convection alone may suffice in some installations. If in doubt use extractor fans.

The following formula may be used to calculate the air required to remove rejected heat from machinery spaces in which engines are cooled by remote means [9]:

$$V = (Q)/0.07242\ \Delta T$$

where $V$ is the air needed to remove the heat (in $m^3$/min)
$Q$ is the total heat to be removed (in MJ/hour)
$\Delta T$ is the permissible temperature rise in the machinery space (in °C)

The total heat figure ($Q$) should include that rejected by all machines (including auxiliaries) and associated heat exchangers expected to operate concurrently.

One may use the following data for rough estimations of values for $Q$:

1. heat rejected by engine and generator carcases 0.30 MJ/hr/$kW_e$;
2. heat loss per linear metre from uninsulated exhaust systems:
   (a) for exhaust pipes 7 kJ/hr/$kW_e$;
   (b) for exhaust silencers 250 kJ/hr/$kW_e$;
3. heat rejection from heat exchangers 0.05 MJ/hr/$kW_e$;

where $kW_e$ is the nameplate rating of the generating set.

Where the cooling radiator is mounted on the generating set's bedplate an aperture should be positioned in an external wall directly in line with the air flow through the radiator. One has two choices on air flow direction. The radiator's cooling fan may either be of the suction ('puller') type or of the pressure ('pusher') type. Figure 13.9 shows the preferred pressure type air outlet. Pusher fans are usually capable of providing sufficient air flow to remove all heat rejected by the engine, generator and short runs of uninsulated exhaust pipe.

In the simplest arrangement the radiator's outside face may be placed not more than 200 mm from the aperture in the plant room wall. The 'free' or effective area of the aperture (accounting for fitted weather louvres) should be at least equal to the frontal area of the radiator. Recirculation of hot air must be avoided and it is preferable to use a flanged duct between the radiator and the wall opening. The length of the duct should be kept to a practical minimum. A short section of treated canvas or rubberized canvas should be included in the duct run to cater for expansion and to give flexibility where generating sets are fitted with anti-vibration mountings. Recirculation of hot air is also possible if air discharge and air inlet apertures are too close together.

Ducts should be designed to minimize restriction. They should have sufficient cross-sectional area to ensure that back-pressure does not exceed 12 mm water gauge. If a long run of duct is unavoidable the cross-sectional area will need to be increased, as also will the free area of the louvred aperture in the external wall. In the context of back-pressure, prevailing wind directions should be considered when planning vent locations. Winds will restrict air flow if they blow directly into an air vent. In coastal locations winds may change direction through 180" during the course of a day. In such cases a wind break some 2 m high and 3 m from a radiator outlet aperture will alleviate airflow restriction.

In emergency generator applications it is desirable to reduce heat losses from the plant room while the machine is at standstill. Inlet and outlet aperture louvres may be motorized to automatically move into the open position when the generator is started. Alternatively, where the air blast radiator is of the pressure type, the outlet louvres may be gravity operated. Louvred apertures should be fitted with screw-fixed or welded birdguards on their internal faces.

The total effective area of all inlet apertures to plant rooms or generator halls should be at least 50 % more than that of the outlet vents.

Where aspiration air is ducted to an engine's inlet manifold (or turbocharger) from an externally mounted air cleaner, care should be taken to ensure that the total restriction at the engine's intake point does not exceed the values permitted by the engine maker. See Sub-section 1.7.1 of Chapter 1 and Figure 13.2(c). Where bends are employed they should be of the 90° long-radius type. Returns which change air flow direction through 180° should be avoided at all costs.

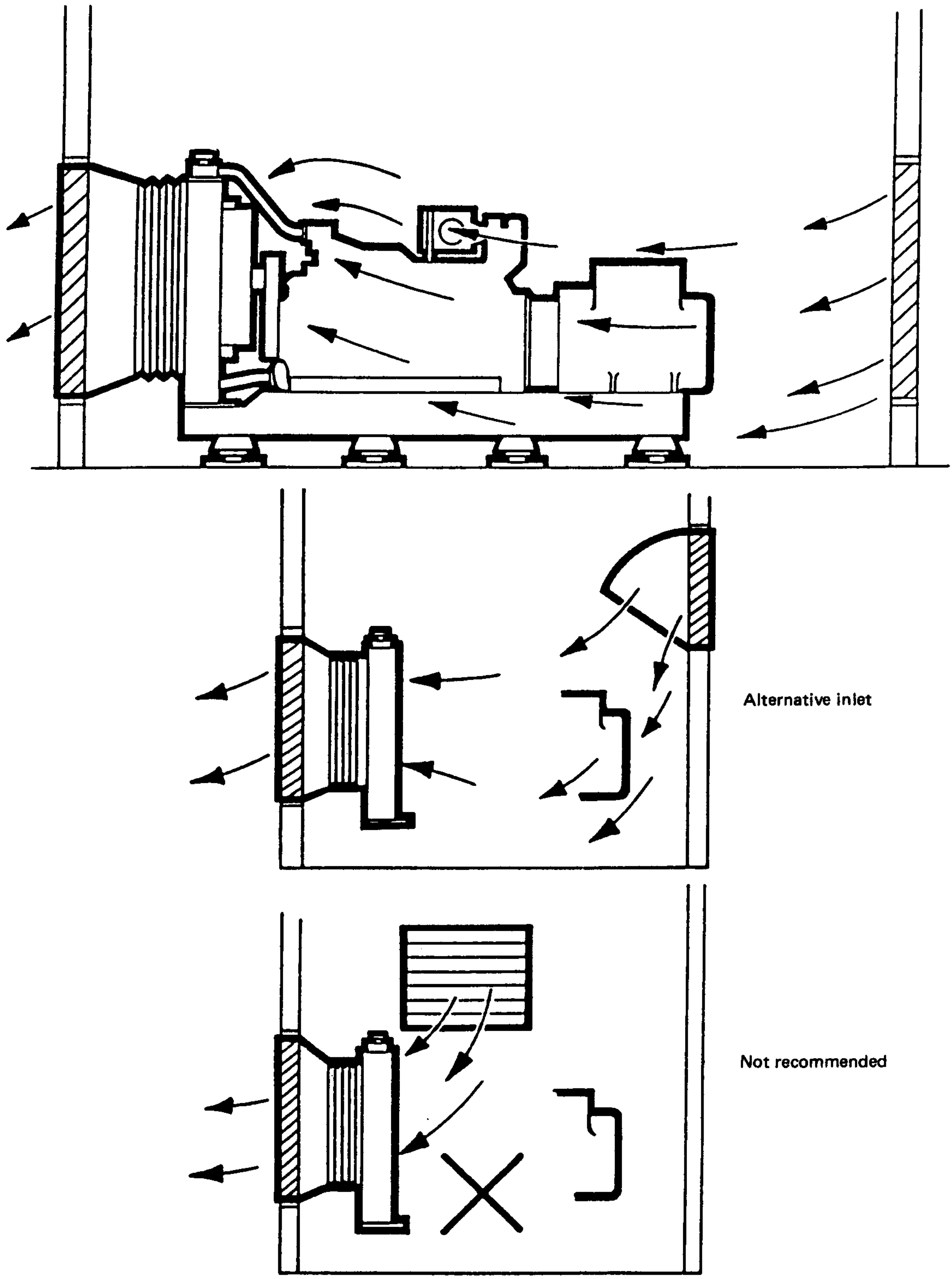



**Figure 13.9** Plant room ventilation, making effective use of the engine radiator's cooling fan (Courtesy: Dorman Diesels Ltd)

Another ventilation aspect that is often overlooked is that relating to engine crankcase breathing. All engines are fitted with breathers which prevent the build-up of pressure within the crankcase caused by blow-by from the pistons. The resulting fumes contain contaminants from the combustion process and minute globules of lubricating oil and will pollute the engine room if they are not directed to atmosphere.

Often, where engines are equipped with radiators located in the engine room, the crankcase gases are allowed to disperse into the room and reliance is placed on the radiator's 'pusher' fan to disperse them through the radiator matrix to atmosphere outside the building. This is not the best arrangement because the fumes will eventually deposit oil on the matrix. Any dust particles in the exit air would then tend to stick to the oil and impair the performance of the radiator and lead to engine overheating.

In all cases, and particularly when engines are cooled by heat exchangers associated with remote radiators (or cooling towers), it is good practice to arrange for the crankcase gases to be piped to outside the building. Pipes should be generously proportioned to minimize the back pressure, and diameters should be equal to or larger than the stems of the breathers on the crankcase. Some engines may have more than one breather. Where this applies it is usual to pipe them together to feed (via a flexible connection) into a common pipe to a separating tank which is positioned either inside or outside the engine room. A pipe is then taken from the top of this tank to discharge at a high level outside the building. A breather should be fitted to the top of this pipe.

The crankcase gases should never be piped into the engine air intake system or be allowed to exit close to engine room air intakes so that they can be ingested by the engine air filters. This avoids contaminants (including acids) being circulated round the engine and causing harmful long-term effects. In some instances the fumes may be detrimental to air filter elements.

The same precautions apply on multi-engine installations. The breathers from each engine must have their own individual runs to outside atmosphere. They should not be terminated into a common separating tank because the fumes from running engines could leak back into stationary engines.

If there is a danger of rain entering a 'terminal' pipe an oil trap should be incorporated in the pipe run. Also, if there is a likelihood of undue condensation in the pipes a drain tap should be fitted in the lowest point of the system.

## 13.4 Noise and vibration attenuation

In those installations where noise is likely to be a community problem the appropriate noise control treatments should be selected and applied in order to restrict the noise transmitted and radiated from plant rooms to a value below the levels promulgated by communal interests or local legislation.

The noise control methods that may be considered are discussed in some detail in Chapter 14. They would include the use of:

- acoustic barriers and baffles;
- partial enclosures;
- vibration damping materials;
- vibration isolation;
- inertial blocks;
- lined duct work; and
- splitter silencers in ventilation inlets and hot air discharge outlets.

Any treatment applied should not prejudice the operation, maintenance and safety of the plant.

## 13.5 Foundations

The provision of a strong foundation is critical to the satisfactory operation of any diesel generating plant. Structure and mass must be adequate, in every case, to absorb any vibration that arises through unbalanced forces. Requirements will vary with the size (power/weight ratio) of the plant and with the speed of the prime mover. The substance of the following discussion is drawn from the first-rate paper presented in 1972 by R.B. Croft [10] to the Diesel Engineers and Users Association - now the Institution of Gas Turbine and Diesel Engineers. The author of that paper was a member of the committee responsible for drafting the subsequent BSI Code of Practice for *Foundations for Reciprocating Machines* (CP 2012: Part 1: 1974).

The responsibility for the design of the foundation should be placed with a civil or structural engineer specializing in this type of work. The plant manufacturer must furnish details of:

- the static and dynamic characteristics of the plant;
- the plant's operating temperatures (since problems can arise due to the temperature difference between the machinery and its foundation; heat transfer from machines to concrete foundations will produce thermal differentials within the concrete mass and could lead to undesirable tensile stresses) ;
- the overall dimensions of the proposed foundation mass; and
- the mounting and fixing arrangements of engine and generator (or of their composite baseframe).

To prevent undue settlement of the foundations it is necessary to ensure that the total weight (foundation block and generating plant) is evenly distributed over an area sufficient to reduce the bearing pressure to well within the capacity of the subsoil [1]. Subsoils vary greatly in respect of load-bearing capacity and it is therefore essential that the site's subsoil characteristics are known. Investigations should be made where data are not already available. The information required by the civil engineering contractor is defined in CP 2012: Part 1.

Cohesive soils, such as clays and silts, will compact under steady pressure but their rate of compaction is not significantly affected by vibration. Sands and gravels, on the other hand, may compact rapidly when subjected to vibration but are less susceptible to consolidation under steady pressure. One needs to be particularly wary of made-up ground.

The following table offers a rough guide on the bearing capacities to be expected from subsoils.

| *Subsoil* | *Bearing capacity (kNi* m²) |
|---|---|
| Soft clay | 144 |
| Soft chalk | 144 |
| Hard clay | 290 |
| Soft rock | 380 |
| Coarse gravel | 530 |
| Hard compact rock | 2395 |
| Sandstone | 3640 |
| Limestone | 6227 |
| Granite | 6898 |

This compares with 958 kN/m² for a 1-2-4 mixture of concrete and about 50 kN/m² for typical made-up ground. (Note: 1-2-4 implies 1 part cement, 2 parts clean sharp sand and 4 parts 20 mm maximum washed ballast.) These values should be related to an expected static pressure of not more than 70 *kNI* m² on the underside of the foundation block for generating sets above 3 MW. The diagrams of Figure 13.10 [10] show some of the many types of foundations that have been employed for sets of this size.

Where satisfactory subsoil conditions exist foundations are usually of the rigid reinforced concrete block type, supported by the soil or by a basement concrete slab or raft (Figure 13.lO(a». The block may be piled (Figure 13.lO(b» where an adequate bearing stratum does not exist at an economical depth.

On the largest generating sets, where anti-vibration mountings may not be part of .the manufacturer's supply, a resilient mounting system may be incorporated into the foundation to support or suspend the foundation block and 'isolate' it from the main building structure. This attenuates the

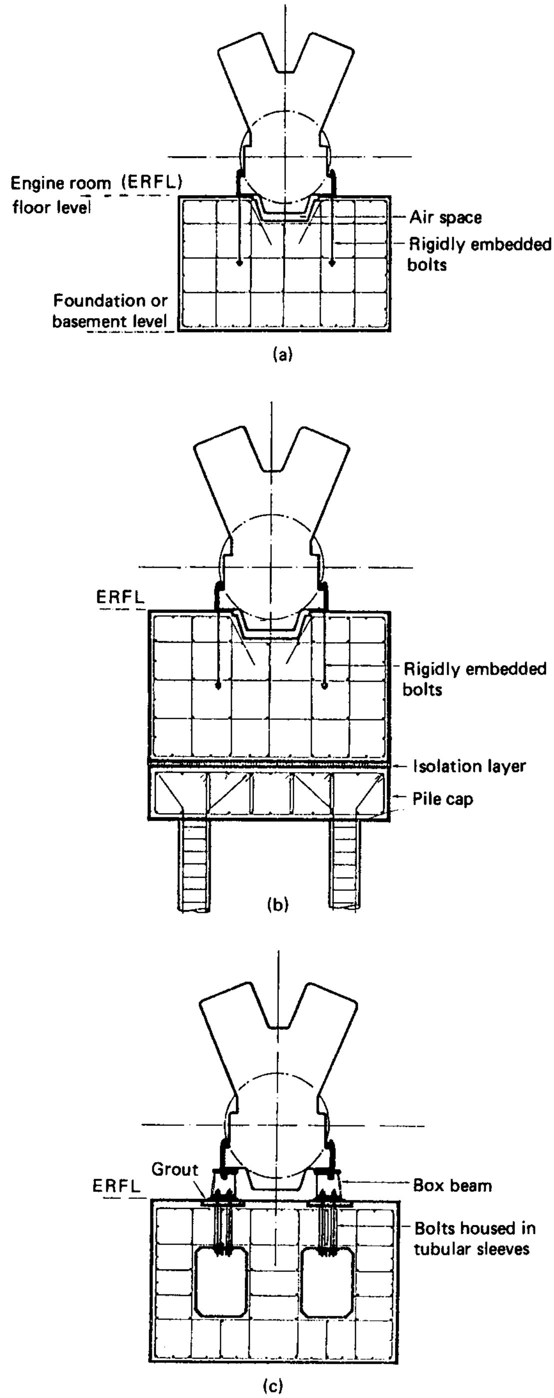



**Figure 13.10** Some types of foundation for diesel-generator plant (a) Typical rigid foundation resting on soil or basement slab (b) Typical rigid foundation resting on piles (c) Typical engine foundation using steel box beams (Courtesy: The Institution of Diesel and Gas Turbine Engineers)

transmission of vibration and noise (see Figure 14.50 of Chapter 14). The arrangement has particular merit in those stations which have auxiliary equipment located in basement areas. If the mountings are of the steel spring or leaf spring types it is possible to adjust the natural frequency period of the total system. In this context, one should be wary of the use of resilient mats or layers of cork or rubber. These may be affected by oil and water, may harden with age or stiffen under dynamic load (see the section on 'vibration control in practice' in Chapter 14).

The existence of a temperature differential between the machinery bedplate(s) and the foundation surface inevitably results in a restriction on the thermal expansion of the bedplates - where these are bolted directly to the foundation mass. This raises stresses at the interface and within the foundation mass. The use of steel reinforcement in concrete foundation blocks is therefore strongly recommended. Croft suggests that this reinforcement is most effective when '... placed horizontally and vertically near all exposed faces of the foundation block including the top, or machinery mounting faces, and at the bottom; consisting of at least 12mm diameter bars spaced at centres not exceeding 300 mm '. The use of steel or cast iron box beam girders for fixing engines and generators (or, better still, designing the girders into a complete and rigid cellular frame) reduces the temperature differential by introducing an air space between the underside of the bedplates anp the non-bearing parts of the upper surfaces of the foundation (see Figure 13.lO(c)).

At least seven days should elapse between pouring concrete and mounting the generating set on its foundation block.

The difficulties of finding suitable civil engineering contractors in developing countries has led to the wider acceptance of steel foundations (as opposed to concrete blocks) for slow- and medium-speed engines. Their cost is minimal (of the order of 1% of the generating set's price) compared with the total cost of an installation. (See Figure 13.11 [5])

Important considerations in the design of a block foundation are:

1. The natural frequency should be low (about one-third or one-fifth of the engine's exciting frequency). See 'vibration control principles' in Chapter 14.
2. Both the engine and its driven generator should be mounted on the same foundation block to prevent errors of alignment.
3. The block should be of uniform depth so that its mass is evenly distributed about the common centre of gravity of the engine-generator - this despite the fact that the generator may be lighter and better balanced than the engine.

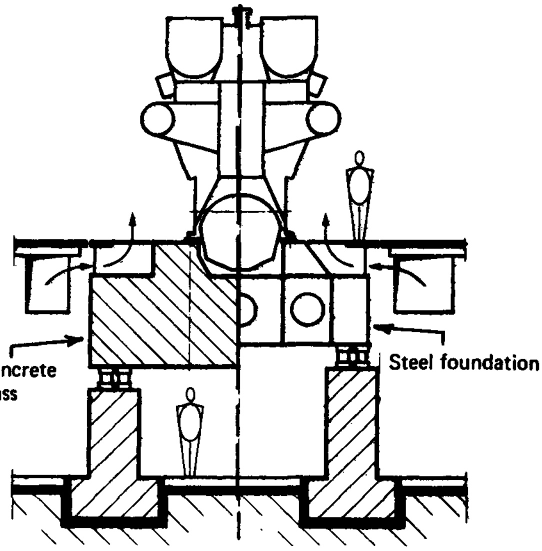



**Figure 13.11** The alternative use of a steel foundation (right) for slow- and medium-speed power plants (Courtesy: MAN B & W AG)

4. Accurately positioned pockets should be cast into the top of the foundation block, into which the plant's fixing bolts may be grouted. Cutting holes after casting may damage the concrete. A non-shrink grout or an epoxy resin should be used, care being taken to follow the procedures laid down by the suppliers of these materials.

Where transportable plant (such as skid-mounted units or those housed in ISO containers) is to be used on a temporary basis, site preparation need only be fairly basic. All that is necessary is to ensure that a compacted area about 1 m larger all round than the equipment size is provided. It should be levelled to within ±20 mm and the ground compacted to a density capable of supporting 60 kN/m$^2$. Where equipment is likely to be on a site for a year or more it is prudent to substitute a concrete raft for the compacted-soil area. This also applies to those locations where heavy rainfall occurs. Steel stools or concrete piers designed to recess into the ISO corner blocks may be used to raise containerized equipment off the ground in those locations where flash floods are likely.

## 13.6 Auxiliary systems

Mobile and containerized power plants must include all the necessary ancillaries that would be required for the same prime mover in a stationary installation. This equipment is either incorporated in the combined engine-generator set or is housed within the plant enclosure. Bulk fuel storage and associated transfer piping must be catered for separately, as illustrated in Figure 13.7.

We shall now consider plant auxiliary systems and discuss essential requirements and desirable features under the following headings:

- Fuel supply.
- Cooling of prime mover and generator.
- Engine starting.
- Engine lubrication.
- Engine exhaust gases.

### 13.6.1 Fuel supply

The purpose of the fuel-supply system is to store an adequate supply of fuel oil and deliver it to the engine(s) in the power plant. The oil must be cleaned and treated (in the case of the heavy residual fuels) before it is delivered to the fuel injection equipment. The elements in a typical distillate fuel system are shown in Figure 13.12.

#### *Bulk storage tanks*

The bulk storage tank should be sited adjacent to the power house and located to permit easy access by delivery tankers. It may be necessary to provide an electric motor driven unloading pump at the fuel delivery point. This may be housed in a lockable kiosk which should also contain a remote-reading gauge for the bulk tank's oil level and an over-filling alarm.

If the tank is some distance from the plant, or if it is located underground, an electrically driven pump should be used to transfer fuel to the service tanks within the power house. This pump may be sited by the service tank or may be adjacent to the bulk storage tank, depending on the delivery distance and the head involved. It should be controlled by a float level switch in the service tank. It is good practice to equip the pump with a relief valve to return excess oil from the discharge to the suction side [11].

Guidance on storage practice may be found in BS 799: Part 5 and in the Institute of Petroleum's Code of Practice 3002.

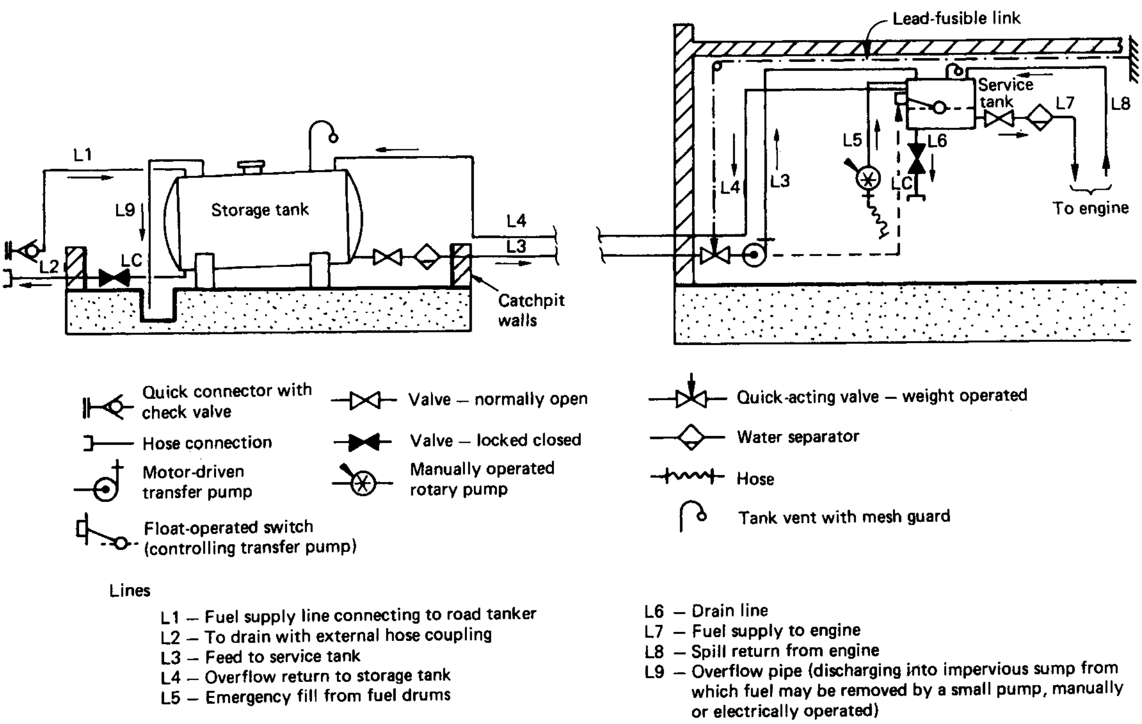



**Figure 13.12** Typical distillate fuel storage and handling system for a single engine installation

The storage tank should incorporate the following facilities:

1. provision for isolation during cleaning or repair (where multiple tanks are installed);
2. an oil level indicator;
3. a filling connection;
4. a service tank overflow connection (essential as a safeguard against pressurizing the service tank(s) in the event of failure of the float switches controlling the fuel transfer pump);
5. an inspection or manhole cover, preferably with provision for a dipstick;
6. a breather or vent pipe;
7. a drain cock at the lowest point for drawing off sludge and water;
8. a feed connection to the transfer pump as far removed from the drain cock as possible and fitted with a strainer (and possibly a foot valve). A freefall fire valve should be provided in the outlet feed to the fuel transfer pump (see Figure 13.12).

The tank piers or supports should be arranged so that the tank is tilted some 5° from the horizontal. The drain cock is fitted at the lower or 'deep' end (see Figure 13.12). Supports should be so constructed or protected as to have a standard of fire resistance of at least 4 hours. They should permit movement of the tank due to changes in temperature. That end of the tank to which the principal pipelines are connected should be secured to its supports, the other end being free to move.

A catchpit should be provided for all above-ground storage tanks. It may be defined as an enclosure having a floor and walls but no ceiling. Its purpose is to retain any oil which may leak from the tank or overflow due to overfilling. It may be a well in the ground or an enclosed space beneath the tank. Its specification should include the following requirements [12]:

1. It should have a capacity of at least 10% more than that of the storage tank and should be structurally strong enough to contain this amount of oil.
2. The floor should be laid to fall to an impervious undrained sump.
3. Walls and floor should be lined with an impervious lining.
4. Sufficient space should be provided between the tank's sides and the walls to allow easy access to all tank mountings and fittings.
5. Facilities should be provided for the removal of water from the catchpit, typically, by means of a small semi-rotary hand pump or by a manually controlled electric pump. The electric motor and its associated starter, when located within the pit itself, must be suitable for use in a Division 1 hazardous area (BS 5501 ; CP 1003 and the IP *Electrical Safety Code).* A lightweight roof may be fitted to prevent the entry of rain water.
6. The metalwork of the tank, piping and fittings should be earthed in accordance with IEE regulations (see Sub-section 13.9.2)

For underground tanks the size of excavation should be sufficient to allow for easy installation. The pit should be large enough to permit a clear gap of at least 1 m between the shell of the tank and the walls before backfilling. The tank's protective coating should not be damaged when lowering the tank on to its concrete or masonry supports. The backfill, which should be carefully consolidated, should be free from rocks and other abrasive materials. About 0.6 m of cover should be provided on the top of the tank. Where concrete- or masonry-lined pits are used adequate provision must be made to prevent migration of the backfill material [13]. Underground tanks should be fitted with an extended nozzle of sufficient length to bring the manhole cover above ground. The manhole should have an inside diameter greater than 55 mm.

### *Daily service tanks*

There should be a service tank for each engine in the installation. Interconnection of tanks is frequently arranged and is indeed desirable. This allows for uninterrupted running of all the engines while periodic cleaning of a tank is being undertaken [14]. Also, with an individual tank for each engine it is easier to measure fuel consumption. Where several tanks are supplied from the one storage facility it is usual to provide common rails to which feeds to and returns from the bulk tank are connected.

Tanks should be adjacent to the sets they serve and positioned so that their bottoms are on a level with or just above the engine's fuel inlet connection. Where this is not possible (or desirable for safety reasons) due allowance should be made for any limits set on pressure head and suction lift by the engine's fuel lift pump. Typically, these limits would be 5.5m and 1.5m, respectively, for a high speed engine fitted with a block type fuel injection pump.

The tanks fitted to mobile plant are usually carried on stillages mounted on the engine-generator's common baseplate. They should be equipped with baffle plates to prevent the fuel from being thrown around inside them. Also, they should be protected against vibration, physical damage and heat from the engine and exhaust pipes - the latter in particular.

Good practice requires that service tanks should have the following fittings.

1. A manually operated fuel transfer pump with a flexible suction hose permitting the tank to be filled from fuel drums in an emergency.
*(Note:* If item 1 is omitted a capped filling

connection should be provided. The cap should have a vent hole.)
2. A filling connection to which the feed pipe from the storage tank is connected.
3. An outlet connection; the stand pipe within the tank should be above the bottom of the tank to prevent water and sediment entering the fuel line.
   *(Note:* A suction strainer or gauze filter fitted to the end of the stand pipe may seem a commendable feature until it needs to be cleaned.)
4. An overflow connection for fuel return to the bulk storage tank. The return pipe should be at least of the same diameter as the feed pipe in item 2.
5. An excess fuel and spill return connection. The return pipe from the engine is normally connected above the operating level of the fuel in the tank in order to permit venting of air and other gases. However, some fuel injection pumps require the return to be below the operating fuel level [15].
   *(Note:* The return pipe should never be connected to the engine feed or suction line.)
6. An access cover suitably bolted and gasketed for inspection and cleaning purposes.
7. A sludge and water trap in the form of a stand pipe or dished plate fitted with a drain cock or plug.
8. A breather or vent pipe. This may be incorporated within the inspection cover of item 6 above, and should have a cross-sectional area at least equal to that of the filling connection. It is recommended that on unattended plant vent pipes should terminate outside buildings.
9. A contents indicator which may be of the float-operated type. If a sight gauge is used it should be of the 'fail-safe' pattern. Remote indication is possible using transducer-operated units.
10. A fuel oil transfer pump switch and a high level alarm switch. These may be of the float-controlled type

The free-fall fire valve arrangement shown in the outlet from the bulk oil storage tank (Figure 13.12) is best suited to single engine installations. The practical alternative on multiple engine installations is to fit a three-way weight operated valve adjacent to each service tank. This valve should be arranged to close the fuel outlet to the engine and open a jettison outlet in the service tank. Each valve should be fitted with a single pole changeover micro-switch which operates into the control circuit of the direct-on-line contactor in the bulk fuel transfer pump starter. Then, should anyone of the fire valves operate, the pump motor will be automatically stopped. The jettison outlets from each service tank should be fed back to the bulk storage tank. The system should be designed so that a service tank's maximum capacity can be drained within 5 minutes. The ancillary gear for each three-way fire valve would include operating cable, fusible link, pulleys, cable strainer, tension link, and the necessary warning notices.

Those local Public Authorities having responsibility for approval of equipment and installations should be consulted concerning applicable bye-laws and regulations governing the size of service tanks to be sited within plant rooms housing emergency generators. A typical limit is 500 litres. The rules relating to stand-alone power stations are less restrictive. In such installations it is usual to size service tanks to give about 6 hours of operation at full load. Expected fuel consumption should be ascertained from the engine maker's data but as a rough guide one may calculate tank capacity on the basis of 0.36 litres of fuel per kWh at full load.

Those installations designed to comply with American National Standards Institute (ANSI) requirements should conform with the following National Fire Protection Association (NFPA) standards:

1. NFPA 37-1984 - *The installation and use of stationary combustion engines and gas turbines;*
2. NFPA 110-1988 - *Emergency and standby power systems.*

NFPA 37 applies to stationary engines up to 7500 horsepower and also to portable engines which remain connected for use in the same location for a period of one week or more. The standard defines portable engines as those mounted on skids or on wheels (or otherwise so arranged) that can be moved from place to place as the required service indicates. Incidentally, NFPA 110 prohibits the gravity feeding of fuel to a prime mover, except from an integral tank (one which is mounted on the engine). The capacity of integral tanks is restricted to 230 litres.

The schematic diagram of a typical fuel system for a medium-speed engine is shown in Figure 13.13

## *Heavy fuel supply systems*

A different approach to that described above is applied in the storage and handling of heavy fuels. Residual fuels need to be heated prior to pumping, treatment, and use in engines. They should be handled at temperatures between 5° and 15°C above their pour points or serious pumping difficulies may arise.

Table 13.1 [16] shows suitable storage and handling temperatures for BS 2869 Class D, E, F, G and H fuels.

Guidance on storage is contained in BS 799: Part 5 and in the IP Code of Practice 3002 Part 3. Figure

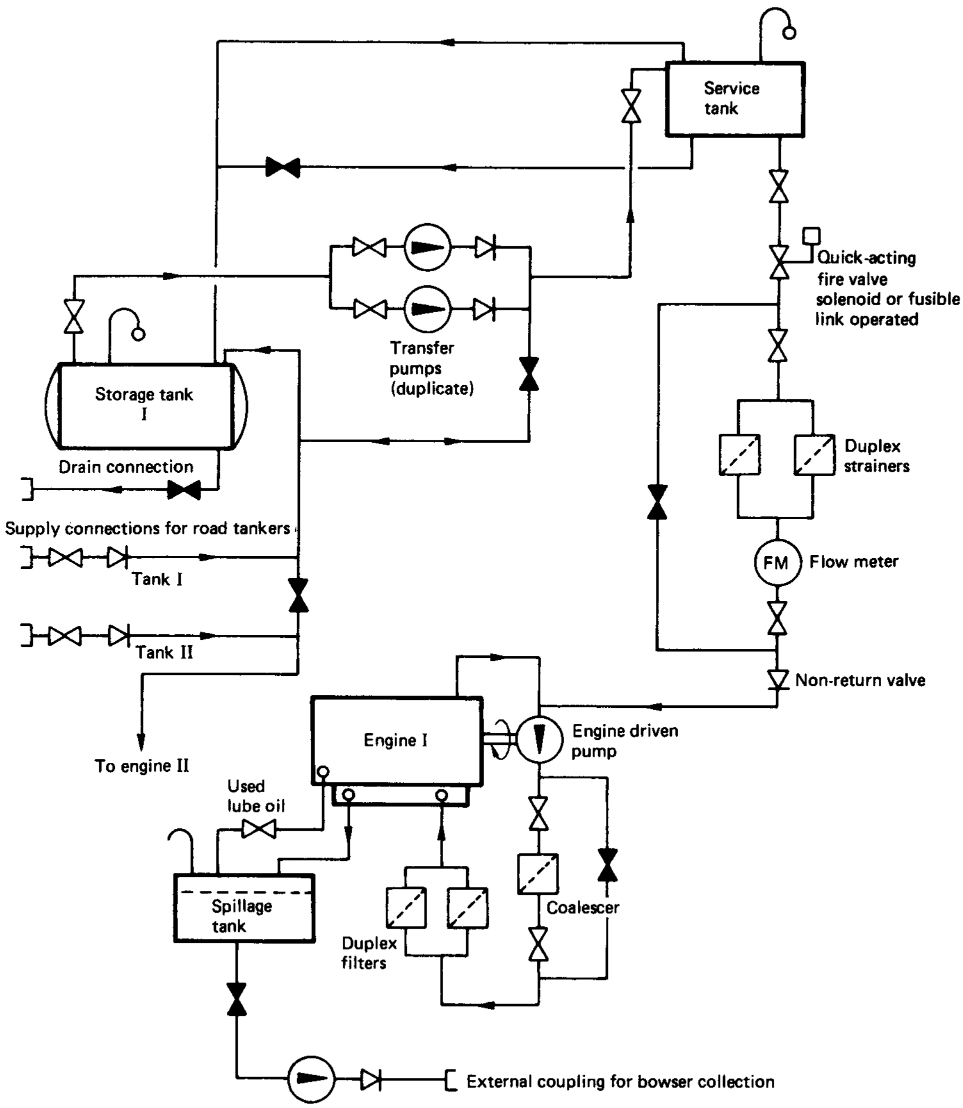



**Figure 13.13** Schematic diagram of a typical fuel system for medium-speed engines

**Table 13.1** Storage and handling temperatures for heavy fuels

| *BS* 2869 *Class* | *Storage temperature* (0C) | *Outflow temperature* CC) |
|---|---|---|
| D | No preheat normally necessary | No further heating normally required |
| E | 5 | 5 |
| F | 20 | 25 |
| G | 25 | 40 |
| H | 30 | 50 |

13.14 [17] shows a typical above-ground storage tank for residual grades of fuel.

The heavier fuels need to be purified before use. They usually contain water, sand, rust, organic matter, and some catalyst fines. Stored fuel is transferred to heated settling tanks in which the fuel is maintained at between 59° and 70°C. The main contamination of water and sludge is gravity-settled in the tank, which should be regularly drained. Before the purified fuel can be used in the engine its viscosity needs to be reduced. This is achieved by heaters in the day tank and by maintaining the temperature at about 98°C during the oil's passage to the fuel injection equipment.

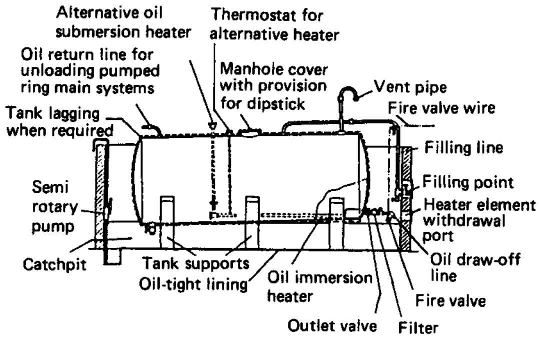



**Figure 13.14** Storage tank for residual grades of fuel

Engines using the heavier oils are started and stopped on light distillate oils and the supply systems for these light oils follow the installation principles and practices described earlier in this Sub-section.

*Tank and pipework materials*

Tanks should be manufactured from sheet steel. Copper sheeting, galvanized or hot-galvanized plate should not be used. External galvanizing or anti-corrosive painting is permissible and desirable.

Piping should be seamless steel tubing, preferably of the 'Bundy' type, with welded or compression type fittings. All lines should be connected to the engines by flexible sections of synthetic rubber construction (or of a material that is resistant to the action of fuel oil) which are sheathed with stainless steel braided covers. It is prudent to use flexible sections that are capable of withstanding a flame temperature of lOOO°C for five minutes without failure and a bursting pressure of at least four times their maximum working pressure in service. The flexible sections should be examined every day if the plant is in continual use and they should be replaced at intervals not exceeding five years. It is sound prac~ice to fit emergency shut-off valves in the fixed lines upstream of flexible hoses to prevent discharge of fuel oil in the event of a hose failure.

On the smallest engines plastic or nylon pipes specifically manufactured for use with fuel are often employed as flexible sections. Care should be taken to ensure that they are routed well away from any heat sources such as exhaust manifolds. Their use would almost certainly be prohibited in those plants which must be insured against fire.

*Gaseous fuel supply systems*

The schematic arrangement of Figure 13.15 for a gas fuelled engine shows the typical elements of a system.

Where natural gas is obtained from a utility the supply pressure mayor may not be higher than that needed by the engine. If it is higher some form of automatic pressure regulating device is required. The regulator is arranged to increase its outlet pressure as engine load increases. If the gas supply pressure is less than that needed, or if the utility's distribution mains pressure fluctuates with changing demand from the engine(s), pressure boosting equipment is required. The booster pump or compressor then feeds the pressure regulator (as shown in dotted lines in the schematic).

In those installations using natural gas (as opposed to, say, sewage disposal plants where methane gas holders are often installed) there is no on-site gas reservoir. The regulator should be of the type that automatically shuts off the supply of gas if the engine stops for any cause. If it is not then a fuel control valve or an auxiliary valve must be fitted to give positive cut-off. For automatically started or unattended engines reliance must not be placed on the regulating valve, even if it is of the zero governor type. A fuel control valve or an auxiliary valve must be installed upstream of the pressure regulator.

The presence of highly flammable air-gas mixtures in confined spaces in the vicinity of sources of ignition such as hot exhaust pipes is an explosion hazard. Badly maintained exhaust systems can result in open flames being emitted. It is good practice to use exhaust scavenging devices on gas fuelled installations. This ensures that any trapped gas is cleared away before engine start up since silencer explosions can otherwise occur (18].

Gas vent lines from regulators and relief valves must be routed to the outside of the building and at least 1.5 m away from any structure opening. A regulator that operates with gas pressure on both sides of the diaphragm does not require venting, but a relief valve should always be fitted downstream of any regulator when the gas pressure on the upstream side is more than 3.5kPa (O.035bar) (NFPA 37-1984). Positive displacement compressors should be equipped with pressure relief devices on the discharge side.

Piping must be sized to vent the required volume of gas. As in the case of liquid-fuelled engines, flexible connections should be capable of withstanding fires of short duration. Plastic pipes must not be used.

### 13.6.2 **Lubrication** systems

High-speed and medium-speed engines use high pressure, forced-feed circulating systems employing engine driven pumps, oil coolers, full flow filtration and either wet or dry sumps. With the exception of the tank required for dry sump operation, all components are built in or attached to the engines.

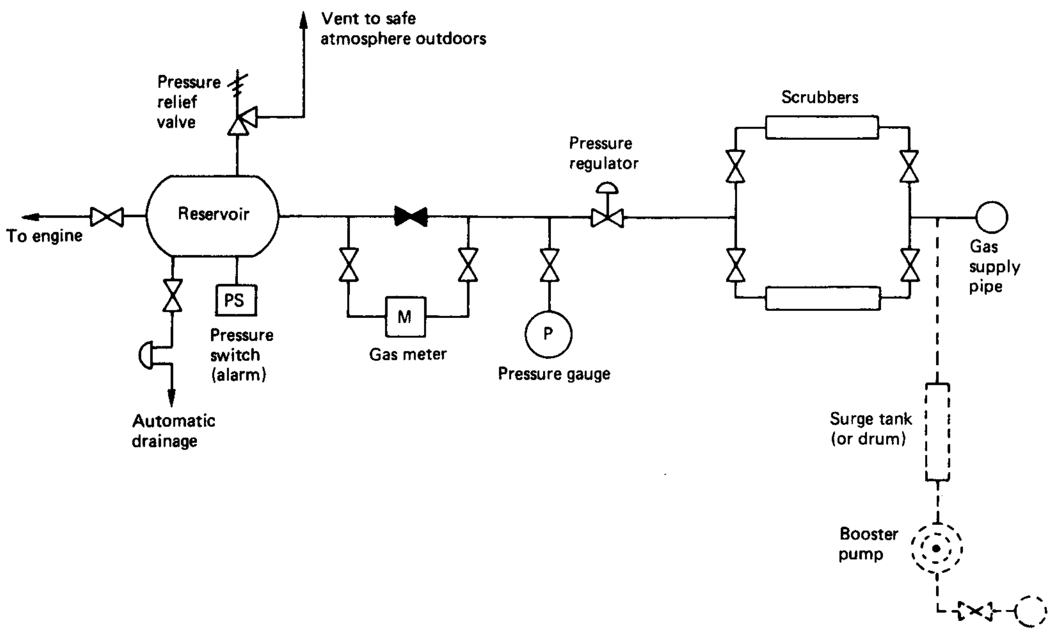



**Figure 13.15** Typical gaseous fuel system

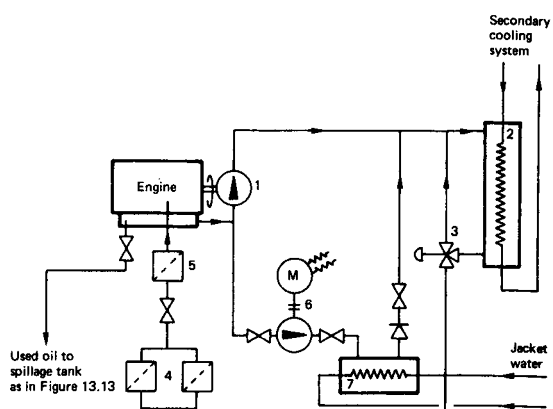
Turbochargers may incorporate their own lubrication circuits.

The schematic diagram of a typical lubricating oil system for a medium-speed engine is shown in Figure 13.16.

Some engine manufacturers offer standardized and pre-assembled auxiliary equipment modules within which those essential items closely linked in fuQction are incorporated. Because all the items are already piped together at the manufacturer's works, all that is required on site is to place the module on a pre-prepared plinth and couple up to the lubricating oil connections on the engine. Typically, the main items in such a unit would be an oil cooler, a full-flow filter, and a lubricating oil priming pump incorporating a thermostatically operated by-pass valve to ensure that the oil rapidly warms up to its operating temperature. Instrumentation might include a flow indicator and filter inlet and outlet pressure gauges.

Low-speed engines and some medium-speed engines use a separate mechanical forced-feed system to lubricate the cylinders walls. The lubricators, driven from the engine, provide a regulated quantity of oil to each cylinder. In most cases the excess oil drains into the engine crankcase, but in some arrangements it is drained to a tank for purification or laundering.

Full-flow filters are fitted with a by-pass which opens when a predetermined drop in pressure is reached across the filter. Unless another filter is automatically brought into action at this stage unfiltered oil will pass through the engine [19]. In *continuous by-pass* purification methods part (between 5 % to 15 %) of the oil in the circulating




1 – Engine-driven lubricating oil pump
2 – Lubricating oil-to-secondary coolant heat exchanger
3 – Thermostatically controlled 3-way valve
4 – Duplex changeover filters
5 – Centrifugal filter
6 – Electric motor driven priming pump
7 – Lubricating oil-to-engine jacket water heat exchanger

**Figure 13.16** Schematic diagram of a typical lubricating oil system for medium-speed engines system is withrawn from circulation and passed through very efficient filters or a centrifuge before it is returned to the system - preferably through a full-flow filter. In large power stations this arrangement offers the only practical method for continuous fine purification of quite large quantities of oil which would otherwise be discarded after engines have been replenished with fresh charges. The alternative of continuous treatment of the total oil in circulation is costly because the equipment needed is expensive and is only practicable with low rates of oil circulation.

If treatment is by filtration the by-pass filters should be of the waste-packed mechanical type (as opposed to those of the chemical type, which tend to remove the additives from oils). Because the lubricating oils have relatively high viscosities, high performance filters are very slow. The more usual method is to use a centrifuge as a clarifier.

In *batch treatment* oil drained from engines is stored in a main reservoir from which it is continuously or periodically withdrawn to be purified and stored for later replacement in the engines. Either stationary or portable pump-purifier arrangements may be employed in power stations. Before re-using the purified oil it is advisable to have it analysed to determine whether it is suitable for further use in engine circulating systems.

After purification the chemical condition of the oil will always be inferior to that of new oil. This is because of the presence of the products of oil deterioration, which are only partially removed during reclamation, and of unburned fuel, which may be unaffected by the purification treatment. The oil supplier's advice should be sought on what steps may be taken to render the oil fit for further service in the engines. It is usually necessary to adjust the viscosity by mixing fresh oil (of lighter or, more often, heavier viscosity grade) with the recovered oil [19].

Batch *settling methods* are sometimes used but the oil recovered is generally not sufficiently pure for re-use in engine lubrication. Briefly, the process involves the use of large settling tanks in which the spent oil is initially heated before being stored for weeks or months. When the heat is turned off the batch starts to cool and water, carbon, sludge and solid contaminants settle to the bottom of the tank. These are drawn off and clean oil is taken from some point higher in the tank. The settling method does not remove those impurities that are dissolved in the oil.

Where considerable quantities of oil are to be reclaimed it may be worth investigating the cost benefits of having the oil re-refined by specialist companies. Unfortunately, with additive oil types, the additives may be removed in the process.

It should be noted that brass, iron and aluminium are compatible with lubricating oils. Copper and zinc act as catalysts and should be avoided in all pipework, tanks and associated fittings.

### 13.6.3 **Cooling** systems

#### *Water-cooled engines*

The various types of cooling systems that may be used have been discussed in Sub-section 1.7.1 of Chapter 1 and illustrated in associated Figures 1.12 and 1.13. Factors affecting choice include cost of the installation, the availability of water and its purity, climatic conditions, the space available on site, and the need to regain the rejected heat. (See Section 1.8 of Chapter 1.)

Cooling towers and evaporative coolers need to be located in open spaces. Radiators, as we have seen in a preceding section (Section 13.3), can be used more freely. Where plant layout restricts the use of a set-mounted radiator, a remote unit must be employed. Installation requirements will vary from one engine type to another and the manufacturers' advice should be sought. The installations shown diagrammatically in Figure 13.17 follow one manufacturer's recommendations.

The so-called 'short remote' installation (Figure 13.17(a» uses the engine's water pump for coolant circulation through the entire cooling system. The sum of distances A and B must not exceed 4.6m (15 ft), where A is the vertical distance from the engine centre-line to the radiator top and B is the distance from the front of the engine to the radiator's centre-line. The size of pipes throughout the system should be the same as the engine inlet and outlet fittings.

In the 'long remote' installation of Figure 13.17(b) the sum of distances A and B exceeds 4.6 m (15 ft), but the vertical distance (A) alone should not exceed 4.6 m. Here a surge tank is employed. Coolant is circulated through the tank and engine cooling system by an electrically driven auxiliary pump (in conjunction with the engine coolant pump). Note that the top of the radiator or the top of the surge tank must be at the highest point in the systems of diagrams (a) and (b). Sections of plumbing above them can cause air pockets which would prevent coolant flow and result in engine overheating.

Where the top of the remote radiator is more than 4.6 m above the engine centre-line, a hot-well (or 'break') tank must be used (Figure 13.17(c». The tank, in providing coolant storage, serves to reduce the coolant head pressure on the engine to within acceptable limits. It is a two-section tank incorporating a partial baffle to separate the hot side (from engine outlet) from the cold side (to engine inlet).

The engine pump circulates coolant between the hot-well tank and the engine and the auxiliary pump circulates coolant between the tank and the remote

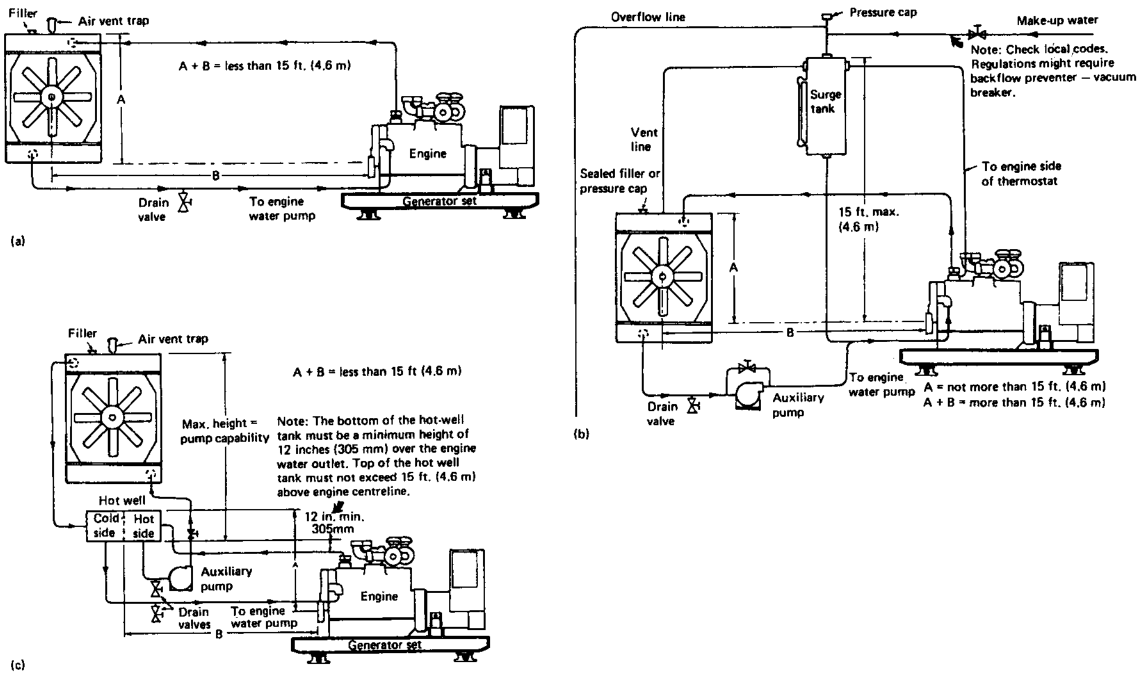



**Figure 13.17** Remote radiator systems (a) Short remote installation (b) Long remote installation using a surge tank (c) High remote installation using a water mixing break tank (hot well) (Courtesy: Onan Corporation)

radiator. Certain rules must be applied to ensure efficient operation.

1. The hot-well tank must be capable of containing the full coolant capacity of the engine, the piping, radiator, and the volume needed to keep inlets and outlets submerged, plus a further 8 % of this total for expansion.
2. Inlets to the tank must be at a higher level than the outlets and both inlets and outlets must be lower than the lowest possible operating coolant level.
3. The partial baffle in the hot-well tank must have an opening large enough to allow free water passage up to the flow rate of engine or auxiliary pump - whichever is greater; this is because the radiator drains into the hot side of the tank after engine shutdown.
4. The tank should be fitted with a vent cap.
5. The maximum coolant level in the tank must never exceed 4.6 m above the engine centre-line and the bottom of the tank must be no more than 305 mm above the engine coolant outlet.
6. The vertical distance between tank bottom and radiator is limited only by the auxiliary pump's capability.
7. The supports for the tank must be capable of carrying the weight of the coolant plus 60 % of the cooling system capacity (this condition arises when the engine is not running).
8. The auxiliary pump should be mounted at the tank's hot side outlet and below the coolant level during engine running; this prevents air from entering the pump during operation.

The choice of cooling system having been made, it is necessary to design and construct foundations for cooling towers, remote radiators, and closed circuit heat exchangers, etc. Routes for the pipework must be determined and trenches excavated where applicable. Again, flexible hoses should be incorporated in the pipe runs at the engine and radiator coolant inlets and outlets.

It should be appreciated that the size (and therefore the cost) of cooling towers and of air blast radiators is affected by climatic conditions. High air ambient temperatures diminish their capacity because the smaller temperature difference between the water and air causes less direct heat transfer. For the same temperature difference radiators take more fan power than evaporative coolers. Also, the efficiency of an evaporative type cooling tower depends on the humidity of the ambient air. Since moist air absorbs less vapour, more air must be circulated to remove the same amount of heat [11].

### *Air-cooled engines*

Special care has to be taken in the design of plant rooms housing air-cooled engines. Cooling air is drawn into an engine-driven impeller and discharged through shrouding to the finned external surfaces of cylinders and cylinder heads. It is important that the hot air is expelled from the machinery space and is not recirculated within it as this will cause both engine and generator to overheat. The use of simple ducting and deflectors is recommended for most applications. See Figure 13.18.

All wall apertures should be protected with louvres against the ingress of rainwater and snow, etc. Suitable shields should be provided for protection of the cooling air intake against dust and fine particles of sand. On remote and unattended sites in desert locations use is often made of heavy duty, self-cleaning air filters in the ventilation and cooling air intake(s) of plant installed in confined spaces (such as in ISO containers).

The air intake apertures shown in Figure 13.18 are sited to provide cool air for the following purposes:

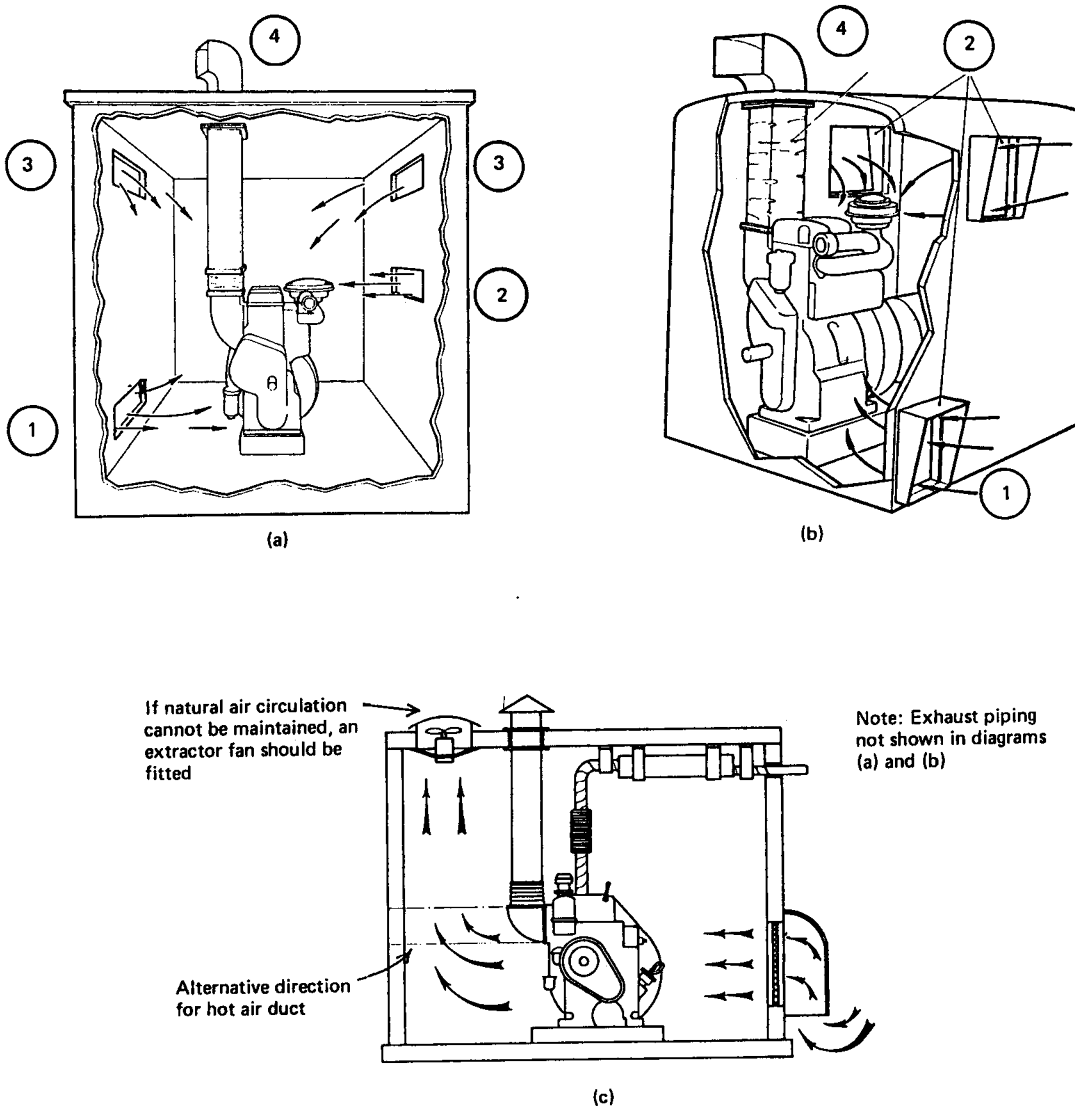



**Figure 13.18** Installation of air-cooled engines (a) Installation in a moderately sized enclosure (b) Installation in a confined space (c) Installation with forced draught ventilation (Courtesy: Hawker Siddeley Power Plant Ltd)

- those at (1) for directing air to (a) the engine sump to assist lubricating oil cooling, and (b) the generator air intake;
- those at (2) to ensure a good supply of combustion air to the engine's air intake filter;
- those at (3), near the top of the plant room, to prevent an accumulation of hot air above the engine.

Except in very high ambient air conditions (about 50°C) it is not advisable to place air intake apertures opposite the engine impellor because the rest of the plant will not be ventilated. All intake apertures should be of the same size to ensure an even spread of intake air into the machinery space.

Louvres have not been shown on the diagrams for clarity of illustration. They may be of the fixed, motorized or gravity-operated type. In emergency generator installations all ventilation louvres should be either permanently open or motorized to open on engine start (see Section 13.3).

The total of the free areas of the air intakes should be at least 50% larger than the engine outlet duct aperture. The cross-sectional area of the air outlet duct (item (4) of Figures 13.18) needs to be increased to compensate for long runs. R.A. Lister recommend, for example, the following multiplication factors for their HR series engines:

| *Trunking lengths* (m) | *Factor* |
|---|---|
| >1.5 | 1 |
| 1.5–3.0 | 1.4 |
| 3.0–7.5 | 2.25 |
| 7.5–15 | 3.5 |

### 13.6.4 Engine exhaust systems

An engine's exhaust system should be designed:

1. to convey the gases of combustion to atmosphere - at a convenient point in the installation;
2. to attenuate the noise produced by the pressure pulsations of the gases; and
3. to accomplish 2 without creating excessive back pressure on the engine. High back pressure reduces engine power, increases fuel consumption and increases exhaust gas temperature, all of which result in overheating, excessive smoke emission and a reduction in the life of valve heads and valve seats.

A key requirement is the need to comply with the noise limitations imposed on the plant by its environment. The topic of exhaust noise attentuation will be discussed in some detail in Chapter 14. We shall confine our attention here to those aspects of system design and installation which are considered to ~ 'good practice'.

An exhaust system will consist of piping from engine exhaust manifold (or turbocharger) to a muffler, or mufflers, and thence to atmosphere. Mufflers (so-called silencers) may be of the absorptive type or of the reactive type (see Figure 14.43 and the associated text of Chapter 14).

Piping is usually of steel. Where engines operate on residual fuels with high sulphur content it may be necessary to use wrought iron pipes. This is because long runs of relatively cool steel pipe may be subjected to severe corrosion caused by condensation of the by-products of combustion. See Sub-section 12.7.2 of Chapter 12. Cast iron fittings are acceptable.

All pipework has resistance to the flow of the medium it conveys. The smaller its cross-sectional area and the greater its length and the more abrupt its changes of direction, the greater is its resistance to flow. For a particular line size all the component parts of a piping system (such as bends, expansion joints, reducers, and enlargers) may be defined in terms of *equivalent lengths* of pipe having the same resistance. For example, the equivalent length of a long radius elbow fitted in a 250 mm diameter line would be about 3.5 m.

In terms of system design the information given by engine manufacturers varies considerably from one manufacturer to the next. All define the maximum back pressures allowed for their engines. Values may be expressed in several ways, the most common being in millimetres water gauge (mm WG or mm $H_2O$) or in millimetres mercury (mm Hg). (The relationships between different units are as follows: 1 mm Hg = 13.595 mm WG = 0.13332 kN/m$^2$ = 1.3595 x $10^{-3}$ kgf/cm$^2$ = 0.13595 kPa.) Also, exhaust gas flow rates (usually against the maximum permissible back pressure) and full-load temperatures at different speeds are given in engine technical data sheets. In some cases this is all the information that is offered to the installation designer.

Some manufacturers tabulate recommendations for pipe diameters against lengths of run. For example, for their range of engines these may take the following form:

| | *Pipe diameter for length* | | |
|---|---|---|---|
| | *Up to 10 m* | *10 to 20 m* | *20 to 30 m* |
| **Engine X X** | 100 mm | 125 mm | 150 mm |

Others may present their recommendations in tables listing, against each engine type, the maxi-

| *Exhaust pipe size:* *Engine type* | *lOOmm* | *125mm* | *l50mm* | *200 mm* | *250 mm* |
|---|---|---|---|---|---|
| | | *Maximum equivaltnt exhaust pipe length* (m) | | | |
| X X | – | 15 | 46 | 152 | |
| Y Y | – | | 52 | 76 | 182 |

mum 'equivalent exhaust pipe length' including one muffler. The latter is usually one which is expected to have the largest back pressure drop, e.g. one which is suitable for sensitive residential areas or hospitals. The tables may take the form shown above.

These engine manufacturers usually provide tables giving the 'equivalent lengths' of the very basic pipe fittings against line diameters. Typically, these may include standard, medium radius, and long radius elbows.

In its Installation Instructions, Volvo Penta gives a nomogram to be used for dimensioning the size of exhaust pipe lines. Before reading the nomogram the system designer must determine the back pressure expected from the muffler he intends to install. In the example illustrated in Figure 13.19 it is assumed to be 200 mm $H_2O$. The maximum system back pressure permitted on the maker's turbocharged engines is 500 mm $H_2O$. This means that the combined resistance of piping and fittings must not exceed 300mm$H_2O$.

When reading the nomogram one begins with the proposed pipe length (the scale at the bottom left of the sheet). In the example this is 54m. One then projects a series of vertical and horizontal lines to intersect individual curves in successive nests of characteristics which cover:

- the number of 90° elbows to be used (in this case nil);
- engine speed (in this case 1800rpm);
- engine type (in this case the turbocharged TD 100);
- the allowable back pressure, less muffler (300mm$H_2O$); and
- insulated or uninsulated pipes,

before finally arriving at the pipe diameter to be used (the scale at the top right of the sheet). In the example this is 124 mm for a non-insulated line and 133 mm for an insulated line.

In the absence of helpful data such as those given in Figure 13.19, the installation designer is left to calculate the resistance (or pressure loss) in each element of his proposed system. The following procedures, taken from [20], may be used to estimate total pressure drop.

The pressure loss in each element of the system (bend, straight pipe length, etc.) is dependent on the average velocity $(V)$ through it.

$$V\ (\text{m/s}) = Q/A$$

where $Q$ is the volume flow ($m^3/s$)
$A$ is the gross cross-section of the element ($m^2$)

**The velocity pressure ($p_v$) is obtained from $V$ and the air density, ρ, using the expression:**

$$p_v = ½\ \rho\ V^2$$

**where $p_v$ is in pascals (Pa)**

**ρ is in $kg/m^3$ – for our purposes it may be assumed to be 1.2 $kg/m^3$**

**The velocity pressure is then multiplied by a factor, $K$, to give the pressure drop ($P_f$) across the particular element. Thus:**

$$P_f = K \times ½\rho\ V^2$$

Typical values for $K$ have been established for the more common system elements (see the worked example which follows). Daly [20] warns that '... different authorities do not always agree on the values, but exactitude is not to be expected'. He goes on to comment that in a practical system' ... an overall accuracy of ±10% in the total pressure drop estimation would be good indeed'.

The elements of total pressure drop are then added together for the complete system. The following worked example will help illustrate the calculation method.

*Example.* We are given the following data by the engine manufacturer:

1. the exhaust flow rate is 120 $m^3$/min;
2. the maximum back pressure allowed in the system for this particular engine is 690 mm $H_2O$.

The preliminary layout is shown in Figure 13.20.

*Element D:* Assume we need to use a residential type muffler and that the data provided by the manufacturer indicate that for the unit we have selected we should expect a pressure drop of 250 mm $H_2O$ for the given bore velocity. Data provided by muffler manufacturers are in the form of velocity/resistance curves at a stated temperature. A typical example for a combined reactive and absorptive silencer is given in Figure 13.21.

Before we go on to apply our formulae to each element we first need to convert the exhaust flow rate to $m^3$/s.

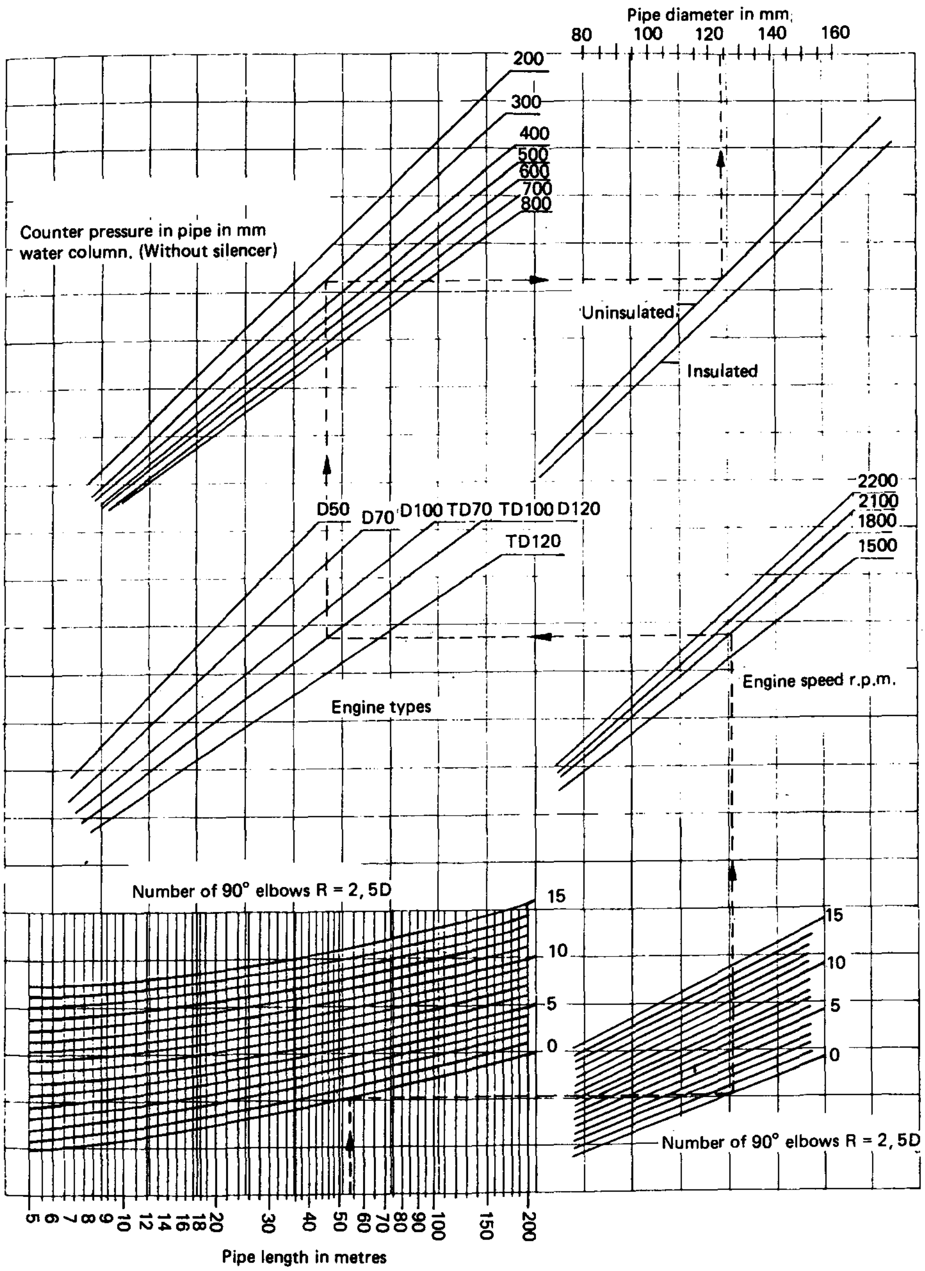



**Figure 13.19** An engine manufacturer's nomogram for calculating the pipe diameter in an exhaust line (Courtesy: Volvo Penta U.K. Ltd.)

$$Q = 120\,m^3/min = 2\,m^3/s$$

and then calculate the gross cross-section, $A$, for the 250 mm diameter elements we propose using throughout our system. Remember, $A$ is in $m^2$.

$$A = \pi D^2/4 = \pi (0.25)^2/4$$
$$= 0.1964/4$$
$$= 0.049\,m^2$$

The average velocity

$$V = Q/A = 2/0.049 = 40.8\,m/s$$

The velocity pressure

$$p_v = \tfrac{1}{2}\rho V^2$$
$$= \tfrac{1}{2} \times 1.2 \times 40.8^2$$
$$= 999\,Pa$$

Now, taking each of the system elements in turn, we determine the pressure drop across them.

*Element A*: The value of factor $K$ for a straight length of pipe is given by:

$$K = 0.02\,L/D$$

where $L$, the length, and $D$ the diameter are in metres. In this case

$$K = (0.02 \times 6)/0.25$$
$$= 0.48$$

The pressure drop across the element

$$P_f = 0.48 \times p_v$$
$$= 0.48 \times 999$$
$$= 480\,Pa$$
$$= 48\,mm\,H_2O$$

*Elements B* (2 off): These are long radius 90° bends, whose geometry is shown in the inset diagram of Figure 13.20. (*Note*: It is recommended that the minimum radius of bends in exhaust systems should be as shown, i.e. 3 times the pipe diameter. Some authorities measure radius to the centre-line of the bend. In such cases $R$ should be at least $3.5 \times D$.) The factor, $K$, for such a bend is 0.18. The pressure drop across each bend

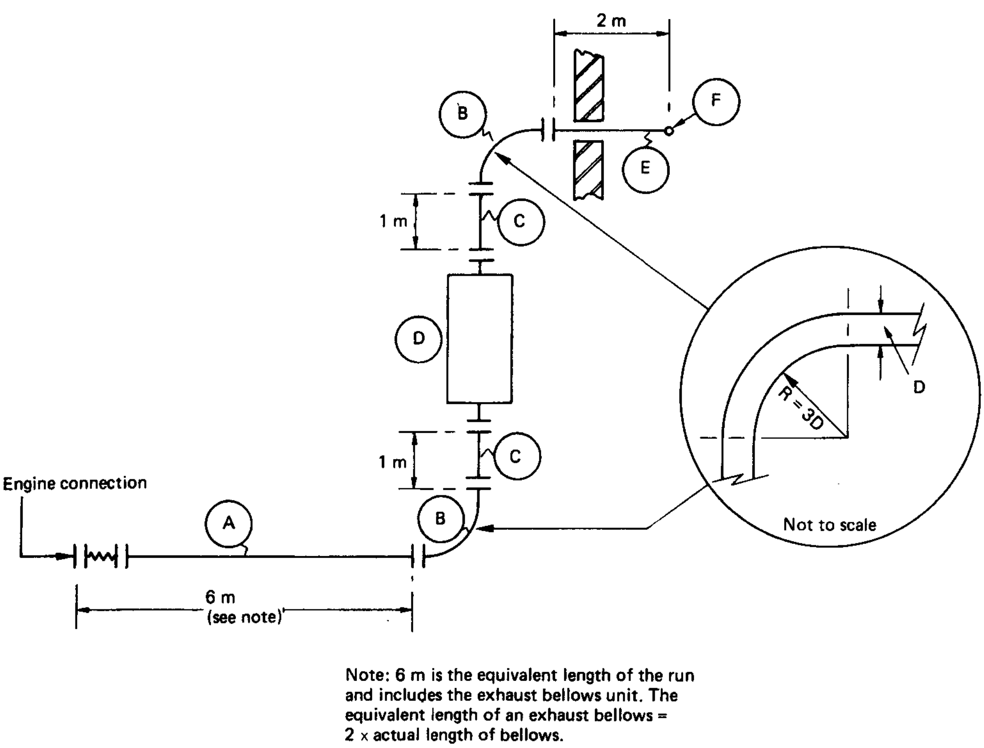
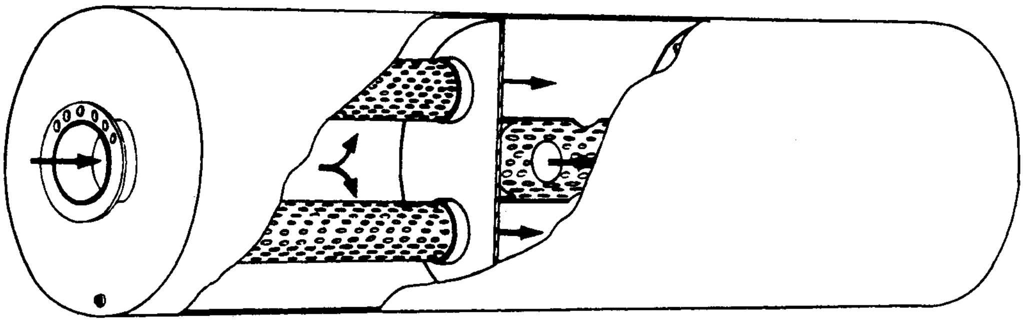
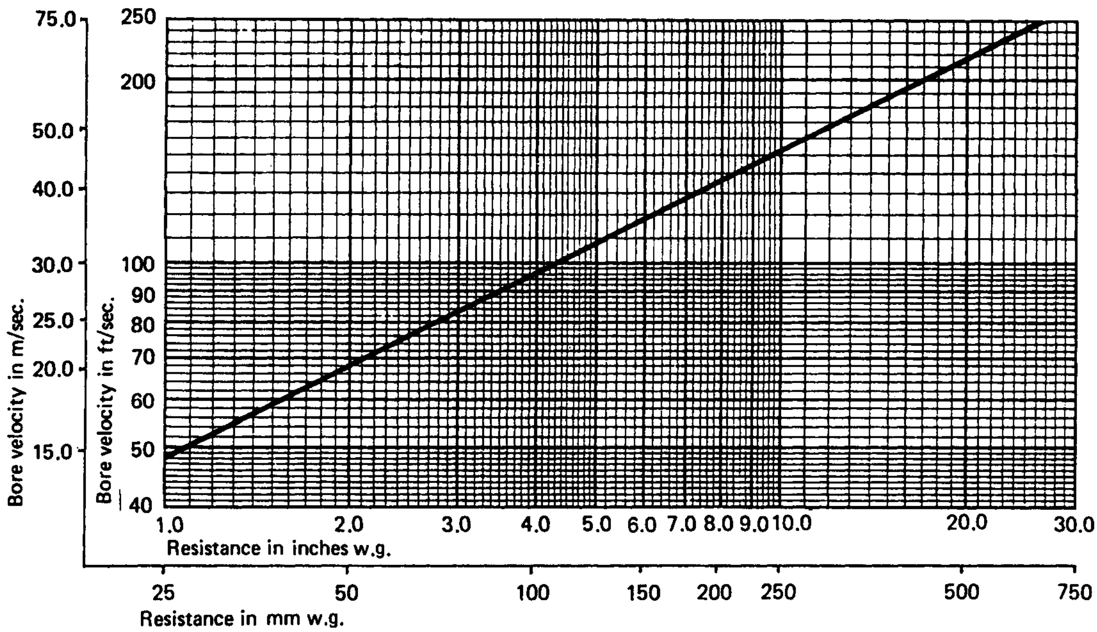



**Figure 13.20** Exhaust system layout for the worked example on pressure drop calculations (see Sub-section 13.6.4)






Resistance at temperature T deg C: $RT = R400 \times \frac{673}{T + 273}$ where R400 = resistance at 400 deg C from graph

**Figure 13.21** Exhaust muffler manufacturer's velocity/resistance curve at 400°C (Courtesy: Nelson-Burgess Ltd)

$$
\begin{aligned}
Pl &= 0.18 \times Pv \\
&= 0.18 \times 999 \\
&= 180\,\text{Pa} \\
&= 18\,\text{mm}H_2O
\end{aligned}
$$

*Elements* C (2 off): The pressure drop calculation is as for Element A. Since this element is one-sixth the length of Element A its pressure drop will be one-sixth that of the latter, i.e. 80Pa or 8mm$H_2O$.

*Element E:* The pressure drop in this case is one-third of that of Element A, i.e. 160Pa or 16mm$H_2O$.

When using the total pressure drop method of calculation it is important to remember that the loss of total pressure at the system outlet must always be included [20]. In our case, with no sudden section change or orifice in the outlet pipe, factor $K$ is 1.0.

The pressure drop at the outlet *(Element F)* is therefore given by:

$$
\begin{aligned}
Pl &= 1.0 \times 999\,\text{Pa} \\
&= 999\,\text{Pa} = 100\,\text{mm}\,H_2O
\end{aligned}
$$

The total pressure drop in our system is the sum of the pressure drops in each element, and is as follows:

| *Element(s)* | *Pressure drop* (mm HP) |
|---|---|
| A | 48.0 |
| B (2 off) | 36.0 |
| C (2 off) | 16.0 |
| D | 250.0 |
| E | 16.0 |
| F | 100.0 |
| Total | 466.0 |

This total back pressure is less than that permitted by the engine manufacturer (690 mm HzO). We may therefore proceed with the detail design of our system. Incidentally, had we proposed to use the next smaller size of pipe (200mm), we would have exceeded the permissible back pressure by about 100 mmHzO.

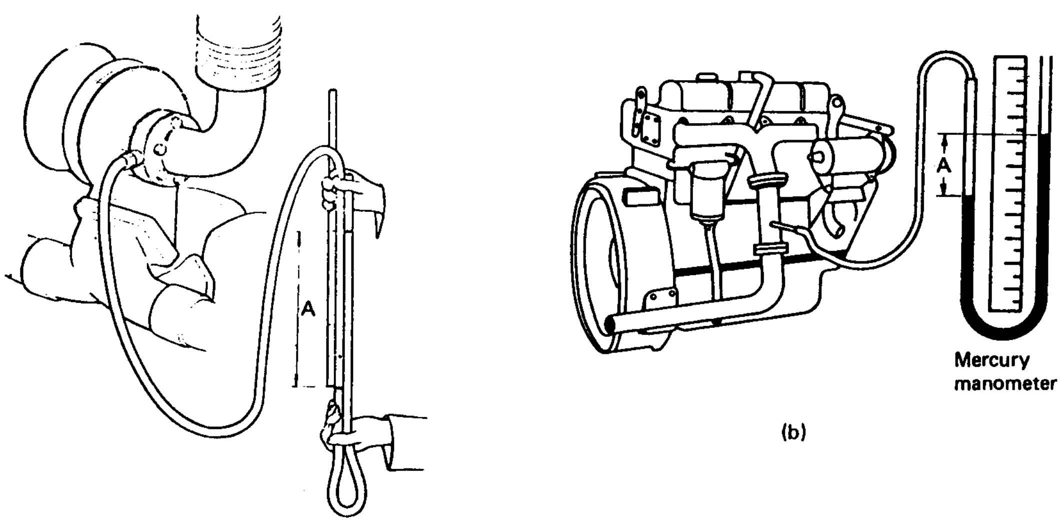
The back pressure of an installed system is checked using a manometer. The sketches in Figure 13.22 show how this is done. The connection to the manometer is made downstream of, and as near to, the engine's exhaust outlet as is possible (no more than five times the pipe diameter). Sketch (b) illustrates the use of a spool inserted into the pipe run after the exhaust manifold outlet flange. A length of Bundy tube is brazed into the spool flush with its inside. The manometer may be constructed from a length of transparent plastic hose partially filled with water (as in Sketch (a». In each case the level difference (A) of the manometer liquid gives the back pressure measurement. It is important that measurements are made only after the engine has reached its operating temperature at full load and at rated speed.

## *Conventional practices*

The following recommendations, based on conventional practice, should be observed in the design, construction and installation of exhaust systems:

1. Runs should be kept as short as possible and should include the minimum of bends. Where bends are used they should be of the long radius type as defined earlier.

2. All rigid piping and mufflers should be designed and supported in such a manner that the engine's exhaust outlet connection is not stressed. Due consideration should be given to thermal expansion and resultant movement of the piping. (Steel pipe will expand some 0.001 % for each 60°C rise in temperature. Exhaust temperatures are of the order of 550°C). Pipes should be routed so that they are supported by fixtures to the building fabric or by existing structural steelwork where such methods are acceptable. Otherwise, separate floor-standing structures must be fabricated to support pipes and mufflers. Supports (and this includes hangers) should be designed to allow for pipe expansion. Roller type supports are frequently used. It is necessary to use expansion joints on long runs.




(a)

**Figure 13.22** Measurement of exhaust back pressure (Courtesy: Volvo Penta U.K. Ltd. and Perkins Engines Ltd)

3. A stainless steel, bellows type, flexible section should be incorporated as near as possible to the exhaust manifold or a turbocharger outlet. This acts as a vibration break and as an expansion joint, and alleviates stress on the engine exhaust outlet connection. It must be installed in a straight run in all planes to permit maximum movement.

4. All flexible sections should be well sealed and not permit the release of dangerous quantities of gas into the plant room.

5. Exhaust pipes must termimate outside the building or structure. The termination point should be so selected as to ensure that exhaust gases or sparks are not directed against combustible material and structures or into hazardous atmospheres containing flammable vapours or gases or combustible dusts. Also, the outlet should be positioned to reduce the possibility of exhaust gases entering other buildings or of recirculating into the plant room through openings such as doors, windows and ventilation apertures. The outlet should also be placed downwind from the prevailing wind.

6. Where exhaust pipes pass through combustible roofs, walls or partitions they must be guarded, at their point of passage, by metal sleeves, plates or ventilated thimbles, insulated from the combustible material by not less than 200 mm of fireproof material. See Figure 13.23 and Figure 14.52. The rain cap is forced open by the exhaust gas discharge and automatically closes when the engine is stopped. It affords protection for the exhaust system from rain, snow, etc..

7. All horizontal pipe runs should be sloped downwards away from the engine. This will ensure that any condensation in the pipes does not run back into the exhaust manifold or turbocharger. It is prudent to install a condensate collector or trap, fitted with a plug or drainage valve, as near to the engine as possible. A trap must be fitted at the lowest point in any system where vertical pipe runs are employed. It also serves to collect small amounts of rainwater which may have entered the system.

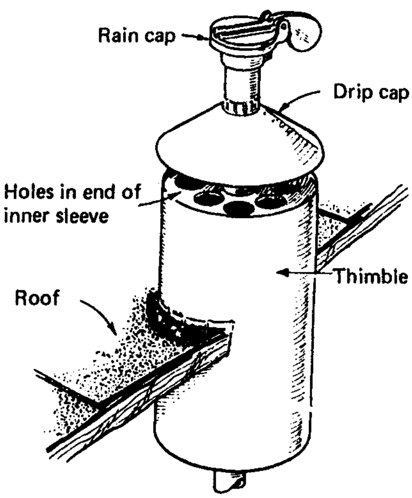



**Figure 13.23** A typical exhaust pipe thimble (Courtesy: Onan Corporation)

8. For all but the shortest runs it is advisable to lag pipes and mufflers with fireproof and insulating materials such as cellular glass, cellular silica, mineral wool or calcium silicate. The use of asbestos is prohibited. Thermal lagging not only reduces heat emission and noise radiation but it also provides personnel protection in areas where contact with exhaust system elements is possible (at heights below 2.5 m above floor level). The lagging, which should be between 50 and 65 mm thick, should be secured by means of wire ties spaced about 250 mm apart. It may then be protected with a metal cladding or jacket. If aluminium sheets are used care should be taken to ensure that they are kept dry prior to application, to prevent water stain between sheets. Joints in the jacket should be lapped and arranged to shed water. The jacket should be secured with bands installed at about 250 mm centres.

Mineral wool insulation should be used for expansion joints. The protective coverings may be constructed in the form of cylindrical shrouds made from metal net and fastened at one end only of the expansion joint. Bends should be insulated with prefabricated covers or with mitred sectional pipe insulation securely wired in place and covered with mitred sections of cladding.

It is not usual to insulate flanges. Insulation should be stopped short of uninsulated flanges a sufficient distance to allow bolt removal without damage to the insulation. The insulation at these points should be cut square. Suitable weatherproofing should be applied at junctions of insulated and uninsulated surfaces. One way of achieving this is to apply a tack coat of mastic over the insulation followed by a layer of wrinkle-free glass fibre. This is followed by a 3 mm thick coat of mastic weathercoat of the asphalt emulsion type. When this is dry a final coat of mastic should be applied to ensure that there is no porosity in the weatherproofing.

Where insulated flanges are specified, block insulation may be shaped to closely fit the contour of the flange and its bolts. The retaining metal jacket should be fabricated in two parts and assembled with clip-type fasteners.

Special care needs to be taken with insulation and jackets at pipe support points. Two methods which both ensure that the supports cater for thermal movement of the piping are shown in Figure 13.24. The first (diagram (a» uses a guided pipe support shoe, the second (diagram (b» a support saddle fitted to the pipe. The saddle is preformed to the outside diameter of the insulation and is designed to

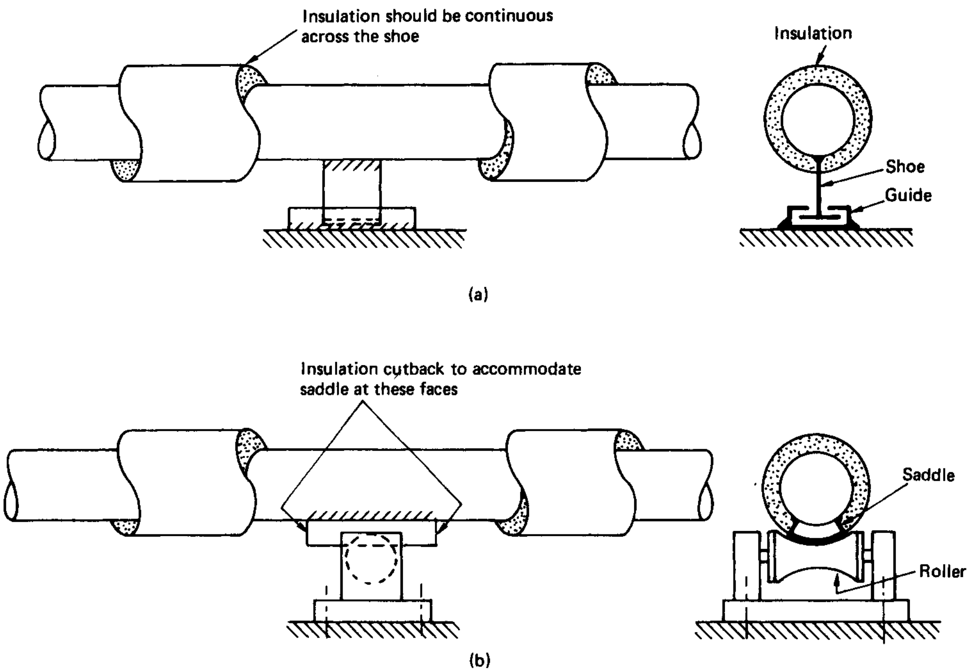



**Figure 13.24** Two methods of support allowing free movement of insulated pipe

prevent undue compression of the insulation due to the weight of the piping. Support saddles are usually used on the larger lines.

BS 5422 is the standard specified for the insulation and cladding of pipelines and ancillary fittings

9. The use of mufflers for noise attentuation is discussed in Chapter 14. In sensitive areas it is generally necessary to fit two mufflers in series. The first may be of the reactive type, fitted as near as possible to the engine's exhaust outlet connection. The second (an absorptive unit) should be fitted directly after the reactive unit. Whenever practicable mufflers should be located outside a building, in order to reduce their heating effect.

10. Each engine in a multiple-engine installation should have a separate exhaust system. When more than one engine exhaust is fed into a common line gases from engines in operation can enter those at standstill. Besides being dangerous this may also lead to serious corrosion damage.

11. The exhaust gases in standby generator applications are sometimes required to be discharged into existing, disused, boiler chimneys. The chimneys should be carefully checked-out for gas tightness before proceeding with the exhaust system installation. With a little ingenuity proprietary smoke bombs may be used for such checks. Engine exhaust gases should never be discharged directly into chimneys serving other fuel burning devices, such as boilers. The engine's exhaust gas pulsations will interfere with the chimney draught and there is the real risk of explosion from unburnt gases. NFP A 37: 1984 stipulates that, where other fuel burning appliances are vented into the same chimney, the engine exhaust pipe shall extend up into the chimney beyond any other flue connection.

12. In the context of chimneys, one should be aware of the need (in the United Kingdom) to satisfy the requirements of the Clean Air Act of 1956. The third edition of the 1956 Clean Air Act Memorandum - *Chimney Heights* (published in 1981 by the Department of the Environment [21] provides a guide for calculating the approximate chimney heights desirable in normal circumstances. The document uses the rates of emission of sulphur dioxide (S02) and other pollutants, such as nitrogen oxides ($NO_x$), produced in combustion to determine the minimum heights required. The significance of the third edition of the Memorandum is that it introduced a lower threshold of sulphur dioxide emission (commencing at 0.1 kg/hr) than those of earlier editions. In so doing, it effectively brought standby generators larger than about 30 kVA into contention. Lovett [22] observed that this means 'exhaust via a stub through a side wall to outside the generator room will no longer be allowed'.

The sulphur content of fuel varies with the type or class of fuel (see Sub-sections 12.5.8 and 12.7.2 of

Chapter 12). The distillates burned in high speed engines may contain 0.3 % by mass, while the fuels used in medium and slow speed engines may contain as much as 5 %. The installation designer should determine, from the engine manufacturer, the maximum S02 emission rate to be expected at rated speed and load. A rate of 0.26 kg/hr is typical for a 100kVA, 50Hz generating set.

The alignment Chart II of the third edition of the Clean Air Act Memorandum, reproduced in Figure 13.25, may be used to estimate the *uncorrected chimney height (U* - in metres) required for S02 emissions from 0.1 to 1.0kg/hr. A line starting from the emission rate on the left hand side and produced through the points A, B, C, D or E (representing the category of the district in which the installation is located) will indicate, on the right-hand side of the chart, the appropriate uncorrected chimney height. The district categories are defined as:

A - an undeveloped area where development is unlikely;
B - a partially developed area with scattered houses;
C - a built-up residential area;
D - an urban area of mixed industrial and residential development;
E - a large city or an urban area of mixed heavy industrial and dense residential development.

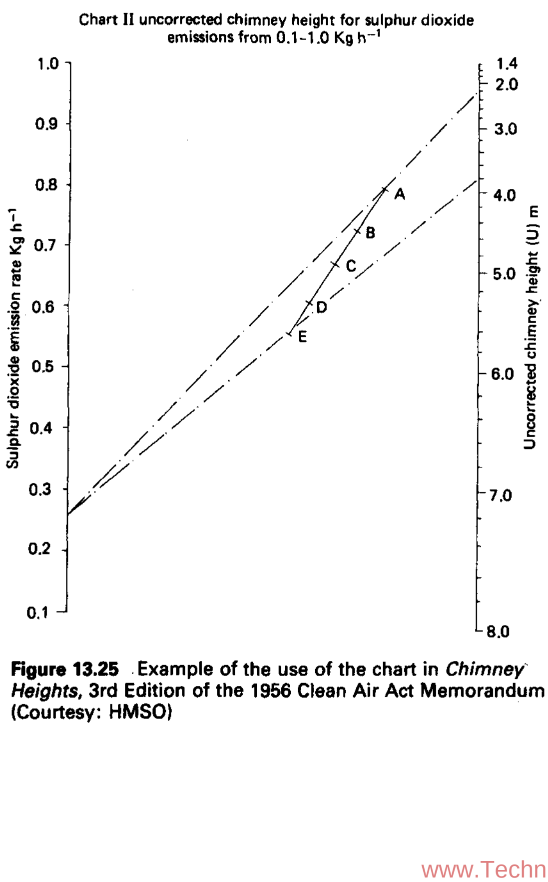



**Figure 13.25** Example of the use of the chart in *Chimney Heights,* 3rd Edition of the 1956 Clean Air Act Memorandum (Courtesy: HMSO)

An example of the use of the chart is shown by the dotted lines in Figure 13.25 - taking the typical emission rate of 0.26 kg/hr for a 100kVA generator. The values of *U* for district types at the top and bottom ends of the category scale are 2.2 and 3.8m, respectively [22].

Account must be taken of adjacent buildings or chimneys, to determine the final (corrected) height required in a particular application. If the calculated value of *U* is less than 2.5 times the height of the building (or enclosure) to which it is attached (or any other building within a distance of *5U* of the chimney), the calculations given in [21] should be made to determine the corrected chimney height C. In the common case, where there is only a single building (wider than it is high) in the area to be considered, C may be obtained from the expression:

$$C = H + 0.6U$$

where, *H* is the building height (in metres) to the ridge or highest point - ignoring plant rooms and other protrusions less than 1% of the roof area.

Clearly, if the generator in the illustrated example of Figure 13.25 is located in the basement of a building in a large city or urban area, its exhaust gases must be vented to atmosphere at a level *0.6U* (2.3 m) above the building's height. Because the building is likely to be multi-storeyed, this requirement would be difficult to achieve without greatly exceeding the exhaust back pressure limitations imposed by the engine. This effectively means that the best location for the generator is a plant room on the roof of the building. The exhaust outlet of the engine must then be at least 3 m above the building roof level (Clause 25 of [21]). This requirement should also be met if the roof-mounted generator is housed in a custom-built weatherproof steel enclosure or in a modified ISO container. In theory, an exhaust outlet in the side or end wall of an ISO container would not do, since the walls are only 2.5 m high.

## 13.6.5 Engine starting systems

Starting systems and equipment have been discussed in some detail in Sub-section 1.7.2 of Chapter 1. We shall confine our attention here to those system features that relate to installation practice.

### *Electric starting*

The significant points to be noted here are:

1. Starter batteries should be located as close as possible to their generating sets but readily accessible for servicing. It is common practice to mount batteries on wooden or metal stands which may be free-standing (on the floor) or fixed to the generating set bedplate. If the former

arrangement is used, cables to the starter motors must be as flexible as possible - especially where generators are vibro-mounted. Battery stands should have insulated and adjustable feet.

2. If the batteries are to be located in a battery room some distance from the starter motor(s), due allowance must be made for voltage drop in cables. The cable cross-sectional area may need to be sizeably increased. The breakaway current drawn by the starter motor on a 600 kW engine is of the order of 1500 A, and the steady cranking current demand is about lOOOA. Voltage drop should not exceed 4 % of battery voltage (i.e. 1 V on a 24 V system).
3. Because hydrogen and oxygen are emitted during charging, vented lead acid and nickel cadmium batteries should be located in well ventilated areas. *(Note:* this does not apply to sealed cells working on the gas-recombination principle. See Appendix B of this handbook.) An explosive atmosphere is created if the concentration of hydrogen in air exceeds 4 % by volume. It is recommended that the average hydrogen concentration within the battery location area should not exceed 1 % except in the immediate vicinity of the cell tops. Problems should not arise in those installations where the ventilation principles outlined in Section 13.3 above have been followed. Where separate battery rooms are planned it is important that they are well ventilated. The required number of air changes per hour *(A)* within a room is given by the expression [23]:

$$A = (0.045 \times N \times I)/V$$

where $N$ = the number of battery cells
$I$ = the recommended charge rate, in amperes
V = the volume of the room, in cubic metres

The ambient temperature within the room should be between lOoC and 27°C and, wherever possible, the battery should be positioned out of direct sunlight. NO SMOKING signs should be displayed on the access doors and on the walls opposite them. First aid and eye wash equipment and protective clothing (including goggles and gloves) should be readily available inside the room. Protective clothing should comply with BS 6408, and the fabrics from which they are made, with BS 3546. It should be appreciated that clothing manufactured from some synthetic fibres (e.g. nylon) may generate high static electricity within an operative's body. This could cause explosions, through static discharge when working on vented cells [23].

4. There should be compliance with the manufacturers' recommendations regarding the storage of batteries prior to installation.

The following British Standard Codes of Practice should be consulted for the health and safety aspects associated with the handling and use of stationary batteries:

BS6132: 1983 - *Code of practice for safe operation of alkaline secondary cells and batteries*
BS6133: 1982 - *Code of practice for safe operation of lead acid secondary cells and batteries*

## *Air starting systems*

Compressed air may be expanded in air motors or directly into the cylinders of engines to effect starting. The compressed air is stored in receivers charged by air compressors which may be driven from the main engines or, as is more often the case, by electric motors or by small diesel or petrol engines. Single-stage air-cooled compressors are generally used, but for higher pressures two-stage units may be installed. A schematic arrangement of equipment is shown in Figure 13.26.

Being small compressors they usually take their air supply from inside the power house. They should be located in the coolest part of the building. An air intake filter should always be included to remove the dust which is inevitably present. A differential pressure gauge measuring the pressure drop across the filter will give an indication of when the filter needs cleaning or replacing.

On large or critical installations it is usual to provide back-up for key auxiliaries. The primary compressor would, perhaps, be electric motor driven and the standby unit would be R.I.C. engine driven.

The compressor should be automatically controlled, preferably using an unloading valve. The unloading valve and by-pass circuit shown in Figure 13.26 is connected upstream of the discharge isolating valve, and downstream of the suction isolating valve. It ensures circulation through the compressor during unloading and permits the equalizing of pressure within it. *Unloading* is the removal of compression load from the compressor during startup and when the air receivers are fully charged. Damage to the compressor's driver may otherwise result from suddenly applying full compression duty.

The pressure relief valve on the discharge side of the compressor may be vented to the suction line (as shown in Figure 13.26). All relief valves in the system should be capable of discharging the full capacity of the receiver [7]. A non-return valve should be installed in the discharge line between compressor and receiver(s) to prevent leakage of air back to the compressor. Besides prolonging the working life of the compressor's delivery valves, it is an important safety feature in any installation.

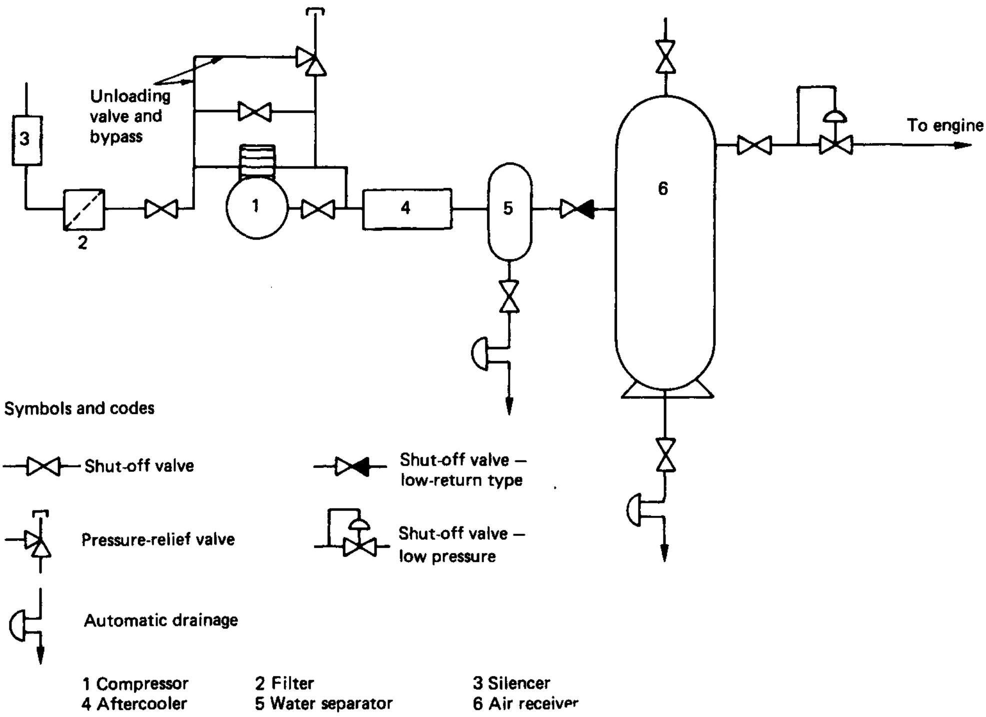



**Figure 13.26** Typical schematic arrangement of compressed air equipment

Air receivers must be sized to suit the operational needs of the installation and be located close to the compressor(s). It is good practice to provide more than one air receiver. As a rough guide, capacity should be about $0.20 m^3$ per $100 kW_m$ engine rating, i.e. a $1000 kW_m$ engine would need air receivers of $2 m^3$ capacity. The receivers should be so interconnected that anyone may be isolated from the system and held in reserve to provide an immediate source of compressed air in an emergency [24]. Each receiver should be fitted with a relief valve (set at about 10% above working pressure), an isolating valve, a pressure gauge, and a condensate trap - which is an automatic, self-emptying valve.

Air receivers are classified as pressure vessels. As such, they are required by legislation in most countries to be certificated and thoroughly examined after specified periods in use. In the United Kingdom this period is once every 26 months (the Factories Act 1961: Section 36, and supporting sets of regulations). In American practice the legal requirement is for compliance with the ASME (American Society of Mechanical Engineers) *Boiler and Pressure Vessel Code.* The current code is that published in 1989.

The *aftercooler* (which may be air- or water-cooled). serves to chill the compressed air and to remove much of the moisture from it. The *separator* acts to remove the remaining moisture from the air and also any oil present.

Discharge and distribution lines are in screwed piping and usually have malleable-iron fittings. They should be sized to 150% of calculated flow and for a maximum pressure drop at the engine inlet point of 10%. All pipework runs should be arranged to drain naturally into the air receiver(s). Where this is not possible condensate traps of the self-emptying type should be provided at the lowest points in the runs.

### 13.6.6 Identification of pipelines and services

BS 1710: 1984 specifies the colours to be used for identifying pipes conveying fluids in liquid or gaseous condition, and for conduits carrying electrical services. Three methods of identification are recognized:

1. basic identification colours only;
2. basic identification colours and code indications; and
3. basic identification colours, used in conjunction with the user's particular colour coding scheme.

The alternative methods of applying the colours to the pipes are given in Section 6 of the Standard.

The colours applicable to RIC engine power plants would be:

| *Pipe contents* | *Basic identification colour* | *BS 4800 colour reference* |
|---|---|---|
| Water | Green | 12 D 45 |
| Oils & combustible liquids | Brown | 06 C 39 |
| Gases (in gaseous or liquified form) | Yellow ochre | 08C35 |
| Air | Light blue | 20 E 51 |
| Electrical services | Orange | 06 E 51 |

It will be necessary to differentiate between those pipes which convey diesel fuel and those which convey lubricating oil. The colour guide in Appendix D of the Standard suggests the following bands are used:

Brown - White - Brown: for diesel fuel
Brown - Emerald Green - Brown: for lubricating oil

Also, it is suggested that Green - White - Green bands should be used for identifying pipes carrying primary cooling water.

There are three safety colours:

1. red for fire fighting;
2. yellow for warning; and
3. auxiliary blue (used with the basic green colour) to identify pipes carrying fresh water - potable or otherwise.

## 13.7 Switchgear and controlgear

The choice and arrangement for switching and control equipment will vary with the particular requirements of the power system. In many cases switchgear and controlgear cubicles may be mounted on the engine-generator baseplate. In others, especially in large power stations, HV and LV switchgear may be located in separate rooms annexed to the main generator hall.

Whatever the choice, it is important that adequate access and working space is provided around equipment to permit safe operation and maintenance. The American Standard ANSI/NFPA 70-1990 (*National Electrical Code* (NEC», for example, defines requirements in this regard. The well-designed installation will provide at least 1 to 1.5 m of clear working space in front of cubicles. Where withdrawable circuit breakers are used cubicle front access may need to be increased to cater for insertion, removal and replacement of such units (see Section 9.9 of Chapter 9). Do not neglect the requirement for space for cable pulling, especially where cable entry is from below or to the rear of switchboards.

Having confirmed that sufficient area is provided for the switchgear, it is necessary to ensure that the floor loading rating is adequate for the weight of the equipment to be installed. All too often this aspect is overlooked, especially where switchgear is housed in container packages. Extreme care should always be exercised in setting-down and aligning multi-cubicle switchboards in order to prevent stressing of insulators and bus structures.

Consideration must be given to the access provided for the switchgear. Designers are usually aware of the need to check door openings and the size of lifts (elevators) to get equipment into a building, but it is easy to forget that the access floor areas should also be rated to carry the weight of the equipment transiting across them [25]. Temporary structural changes to building fabric may be necessary to permit access for the larger equipment.

If equipment has to be stored on receipt, a dry location should be provided for the purpose. Where anti-condensation or conditioning heaters are fitted they should be energized throughout the period of storage, otherwise temporary heaters should be provided. Additional dehumidification may be necessary in some semi-tropical and tropical locations where the air's moisture content may well be of the order of 2 to 2.5 % by weight.

Switchgear and controlgear should be installed in clean, dry and well-ventilated areas. Air movement rates should be of the order of five air changes per hour. The heat generated by power losses from all the equipment located in the area should be considered. The range of electrical losses to be expected from apparatus is given below [26]. Values are expressed in terms of 'percentage energy loss' at full load. This is the ratio of power consumed within the equipment to the total energy passed through it. Manufacturers will furnish data on the heat losses from their equipment.

Air conditioning is usual where central control rooms are provided in power stations.

| | *Percentage energy loss* |
|---|---|
| H.V. switchgear | 0.005–0.02 |
| L.V. switchgear | 0.13–0.34 |
| Transformers | 0.40–1.90 |
| Cable | 1.00–4.00 |

## 13.8 Cabling

The cables in power generating plants vary from multicored light current control and communication types to large single core power-frequency HV types. They are installed in a variety of ways:

- in open runs directly attached to structural surfaces, such as walls, beams and columns;
- in trenches, open, enclosed or back-filled;
- on cable trays;
- in underground ducts; and
- in metallic or plastic conduits and trunking.

Figure 13.27 [27] illustrates some of the various forms of cable enclosure and supports.

The layout of cable systems is primarily influenced by the need to keep the distances between plant and associated switchgear and controlgear as short as possible - consistent with the clearances needed for and from other facilities in the installation.

The factors that influence the selection of conductor size are:

1. temperature;
2. continuous, short-term, and cyclic-loading requirements;
3. the type of protection afforded against overload current;
4. the fault level of the system, i.e. the power source's fault capacity; and
5. voltage drop considerations for the installation.

The conductor metals common to most types and classifications of cable are copper and aluminium. Cables for modern diesel generating plants use polymeric insulation and sheathing. The polymerics are divided into two broad classes: thermoplastics and elastomerics (or thermosetting).

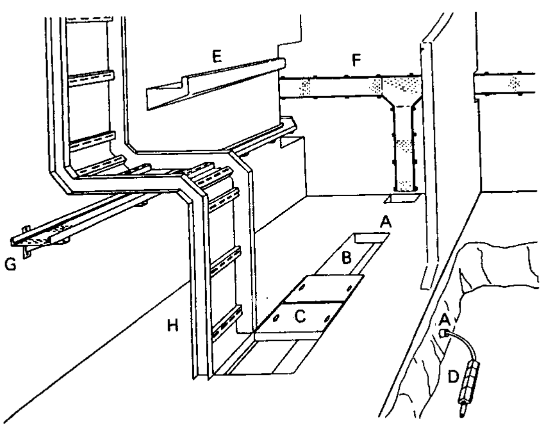



**Figure 13.27** Various forms of cable enclosure and supports (A – Duct (Enclosed cable way or pipe); B – Open cable trench; C – Enclosed cable trench; D – Cable tiles (Protection external to building); E – Cable Shelf (part of the building); F – Vertical cable tray; G – Horizontal cable tray; H – Ladder rack. (Courtesy: The Association of Superviory and Executive Engineers)

A thermoplastic material is one which which does not return to its original shape and dimensions after deformation at room temperature, whereas an elastomeric material is one which does. Polyvinyl chloride (PVC) is the thermoplastic material most widely used as an insulant, as a bedding for armour wires, and for sheathing. It tends to harden at temperatures below O°C, but quickly recovers its flexibility at normal ambient temperatures. Although basically flame retardant, PVC can transmit flame and decompose in the presence of serious fires. It emits dense smoke and toxic acidic fumes under such conditions. Cable conductor temperatures are limited to 70°C.

The elastomeric materials include:

- ethylene propylene rubber (EPR);
- cross-linked polyethylene (XLPE);
- chlorosulphonated polyethylene (CSP); and
- polychloroprene (PCP).

EPR has the flexibility and electrical properties of natural rubber but with a higher operating temperature (see Table 13.2).

XLPE is less flexible than EPR or PVc. Because its operating and short-circuit temperatures are higher than that of pvc, a reduction in conductor size is possible for the same current rating. Of course this only applies where voltage drop is not a limiting factor. The increased current rating (15 to 20 % above PVC) is of particular benefit where cables are to be used in conditions of high ambient (or ground) temperature, such as in the tropics. While XLPE will ignite and burn readily, it has low smoke and fume emission characteristics. See the later discussion on fire-performance (FP) cables in Sub-section 13.8.5.

CSP is a synthetic rubber widely used as a sheathing material on EPR-insulated LV power and control cables in marine and offshore applications. It can be formulated to give good heat-resistant, oil-resistant, and flame-retardant (HOFR) properties.

PCP is another synthetic rubber and is slightly inferior to csp in terms of heat resistance. Its oil-resistant and flame-retardant properties, and its particularly high resistance to abrasion, make it ideal as a sheathing material (on EPR-insulated cables) for the rough handling often associated with mobile and transportable generators.

The Du Pont registered trade marks of 'Hypalon' and 'Neoprene' are synonymous with CSP and PCP, respectively.

Joints in polymeric cables are fairly easily and speedily made using proprietary kits. These comprise metal jointing sleeves, simple shell-type plastic moulds, and cold poured two-pack resins. When the

**Table 13.2** Temperature properties of some polymeric materials (°C)

| *Material* | *Self-ignition* | *Minimum for installation* | *Conductor limiting temperatures* Continuous use | Short circuit (5 s) |
|---|---|---|---|---|
| PVC, general purpose | 390–450 | 0 | 70 | 140–160 |
| EPR | 400 | −40 | 90 | 250 |
| XLPE | 350 | −40 | 90 | 250 |
| CSP | 400 | −35 | 85 | 250 |
| PCP | 400 | −40 | 60 | 250 |

resin is mixed on site it is fluid and penetrates all the cavities of the mould. It then sets quickly to a hard solid mass giving reliable protection against moisture and mechanical damage. Most joints can be completed within $1^1/_2$ hours and can be energized immediately [28].

### 13.8.1 Cable construction

Before we consider some of the typical constructions used for the power, control, instrumentation, and protection cables in generating plant, we shall discuss the selection of standard cables (of appropriate voltage designation) for particular systems. The type of system and its earthing arrangements are the keys to the selection. Systems may be divided into two categories [29]:

1. *Category* 1 systems are those in which one of the following applies:
   (a) The neutral or mid-point is earthed in such a manner that, even under fault conditions, the maximum voltage that can occur between any conductor and earth does not exceed *0.8 V* (defined later).
   (b) A protective device is installed which automatically and instantly cuts out any part of the system which becomes accidentally earthed.
   (c) The neutral point is earthed through an arc suppression coil, with arrangements for isolation within an hour of the occurrence of a fault.

For systems in this category the rated voltage $V_0$ of the cable should be not less than the system voltage to neutral or mid-point, and the rated voltage $V$ of the cable should not be less than the system voltage between lines.

The rated voltage $V_0$ is the power-frequency voltage to earth for which the cable is designed, and the rated voltage $V$ is the power-frequency voltage between conductors for which the cable is designed. Cables are designated by their rated voltages expressed in the form *Vr/V;* hence 600/1oo0V, 1900/3300 V, 6400/11 000 V, etc.

2. *Category* 2 systems comprise the following:
   (a) One-wire (earth-return) systems.
   (b) Two-wire systems either completely insulated or having one pole earthed.
   (c) Insulated multi-wire and polyphase systems.
   (d) All other systems that do not fall into Category 1.

For Category 2 systems, both rated voltages of the cable *($V_0$* and U) should not be less than the system voltage between lines. It should be noted that when determining the voltage of a d.c. system derived from rectifiers consideration should be given to the peak value since it is not modified by smoothing when the rectifiers are operated on an open circuit.

Copper and aluminium conductors are mainly of the stranded and compacted type - either circular or shaped. Reference is always made to nominal cross-sectional area (and not stranding composition) when ordering cable. Wide use is also made of solid-sector shaped aluminium conductors to give a compact and economic power cable design. BS 6346 (the specification for PVC-insulated power cables) does not cater for stranded aluminium conductors. It chooses the more economic form of cable construction - the solid conductor, which is particularly suitable for PVC insulation.

A *bedding* for wire *armouring* is applied over the assembled cores. PVC tape or an extruded PVC compound may be used for this purpose. Cables with voltage designations above 1900/3300 V usually have extruded bedding. Any cables installed in hazardous locations must also have this type of bedding (BS5345: Part 3).

Cables not installed in conduit or trunking should be armoured. The armouring may be either wire or tape (strip). For multi-core cables the wire armour consists of a helically applied single layer of galvanized steel wire (GSW) and is described as steel wire armour (SWA). The armouring of single core cables for a.c. circuits should be in a non-magnetic material, e.g. either aluminium wire (AWA) or strip, or tinned phosphor-bronze wire.

Regulation 521-8 of the 15th Edition of the IEE Wiring Regulations [30] requires that single-core cables entering ferrous enclosures are so arranged that they are not separated by a ferrous material. If steel gland plates are used they should be slotted as shown in Figure 13.28. Better still, use non-ferrous plates such as brass or aluminium, hardwood or paxolin.

Regulation 522-7 of the lEE Wiring Regulations requires that the non-magnetic armour of all single-core cables in the same circuit must be cross-bonded together at one or both ends (known as *single point* and *solid* bonding, respectively). Where solid bonding is used circulating currents will be set up in the armouring and will reduce the natural cooling of the cables. The current rating tables in Appendix 9 of the Regulations allow for this extra heat. Where solid bonding is achieved by means of steel gland plates the cables will be subject to iron losses. The bonding may be broken at one end by using suitable insulation at that end, e.g. an insulating gland plate.

When single point bonding is used the following requirements must be met [27, 31]:

1. the method must have the approval of a suitably qualified electrical engineer;
2. conductors must have a minimum cross-sectional area of 50 $mm^2$;
3. the length of cable must be such that the induced e.m.f. between armour and earth (that which would drive the circulating current when solid bonding is used) is limited to 25 volts;
4. there are no corrosive effects (along their full length) when the cables are carrying their full load current; and
5. there is no danger or damage to property when the cables are carrying short-circuit current.

The use of single point bonding does permit a higher current carrying capacity than that indicated in Appendix 9 of the lEE Wiring Regulations.

It is normal practice to employ the armour on cables as a circuit protective conductor (c.p.c.) connecting the exposed conductive parts of equipment to the main earthing terminal of the installation. The cross-sectional area (c.s.a.) of the armour must be large enough to ensure that no over-heating occurs within it during the passage of the maximum prospective earth fault current. The minimum c.s.a. is determined by using the adiabatic equation of Regulation 543-2 in the lEE Wiring Regulations. As a generalization, it may be taken that the wire armour on standard PVC insulated cables to BS 6346, and on XLPE insulated cables to BS 5467, will provide a protective conductor complying with the lEE requirements. It is certainly true that if the circuit protective device is rated in accordance with lEE Regulation 433-2 and provides protection against both overload and short-circuit, the armour will comply with Regulation 543-2. Indeed, it is possible that the Regulation's requirements will be met even when the rating of a separate short-circuit protective device is a step above the cable rating. The cable manufacturer's advice should be sought in such circumstances.

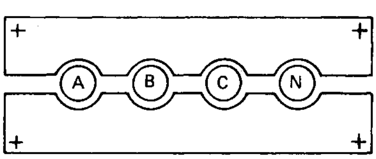



**Figure 13.28 Split gland plates in ferrous material for single-core cables**

All modern cables are fitted with protective oversheaths - usually of extruded black PVC. The *sheath* provides protection against corrosion, gives a clean finish, and makes the cable easy to handle. PVC compounds are available that can provide protection against termite attack and can reduce acid emission under fire conditions. Low smoke zero halogen (LSOH) cable constructions are usually based on XLPE or EPR insulation with an outer sheath of a flame retardant LSOH compound such as ethylene vinyl acetate (EVA), or CSP which has better resistance to oil, water and abrasion than eva.

Examples follow of typical cable constructions for power ~lant applications. Single-core cables up to 630 mm are used for heavy currents in systems operating between 415 V and 11 kV. They would be armoured with a non-magnetic material such as aluminium wire.

### *HV power cables*

In rated voltages from 6.6kV to 33kV, cables are *screened* with semi-conducting layers over the conductor and over the XLPE insulation. These layers are usually extruded simultaneously with the dielectric - XLPE or EPR. The insulation layer is followed by a layer of copper tape or of concentric copper wires. The cores are then provided with a PVC extruded bedding, galvanized steel wire armour (aluminium for single cores), and a PVC oversheath. See Figure 13.29 for typical constructions.

Cables are designed to comply with BS 6622. The related, but not equivalent, International Standard is lEC Specification 502 *(Cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 3800/6600 V up to 19000/33000 V)*

Cables rated up to 3.3 kV are designed to comply with BS5467. They are not semi-conductor screened. Insulation may be XLPE or hard etyhylene propylene rubber (HEPR). The armouring (GSW for multicore or AWA for single core) is bedded in PVC and is PVC sheathed overall. A typical ordering code might be: 400mm$^2$, single core, 1900/3300 VG, XLPE insulated, aluminium

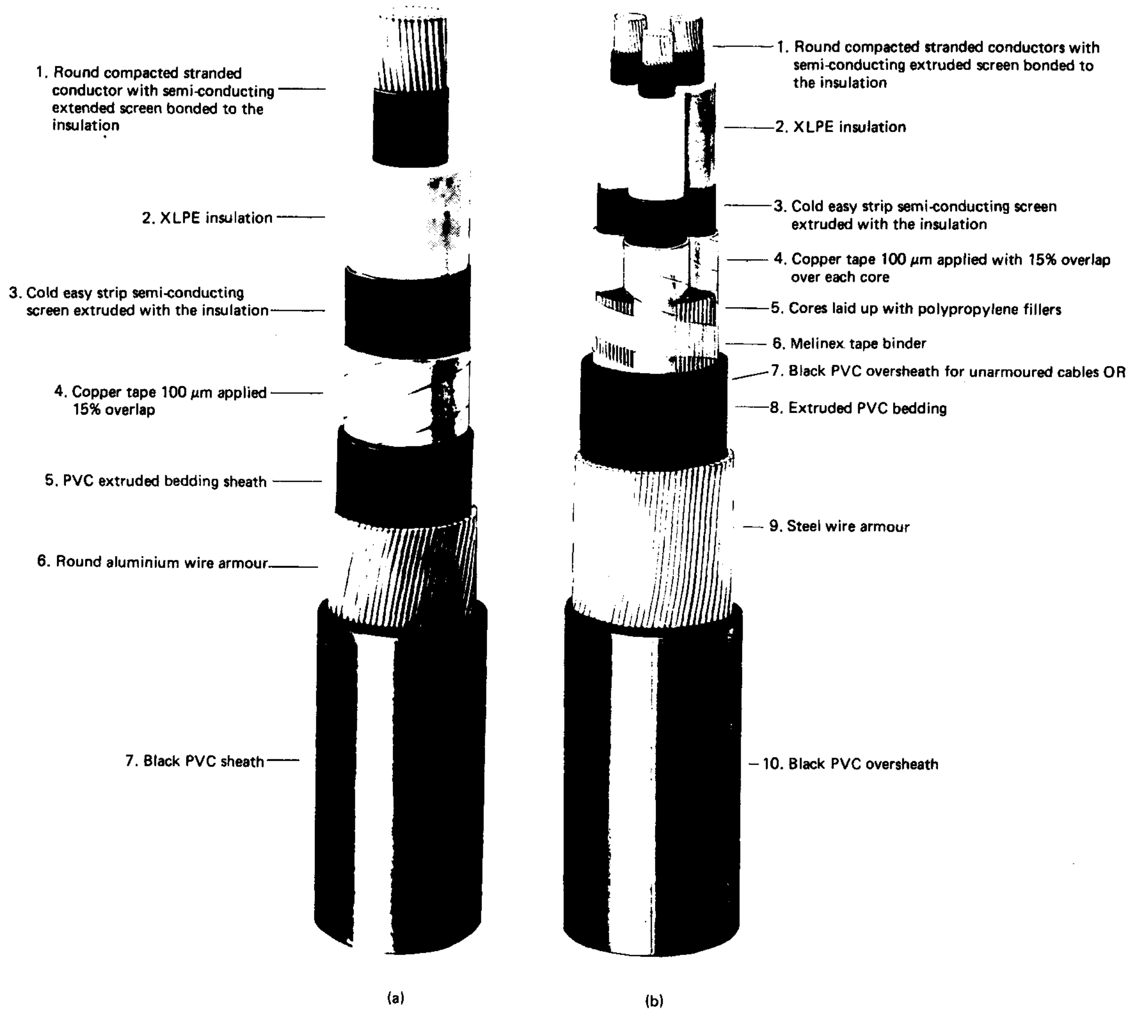



**Figure** 13.29 Typical M.V. elastomeric cable constructions (a) *6.4111* kV single core copper conductor XLPE cable (b) 12.7/22 kV three core circular copper conductor XLPE cable (Courtesy: Pirelli General Pic)

wire armoured, PYC-sheathed cable (i.e. *XLPEI* AWNPYC).

Although the rated voltage of PYC-insulated cables to BS 6346 extends up to *1900/3300* Y grades, the modern tendency is to use XPLE cables at 3.3 kY for the reasons given earlier,

## *L V power cables*

Here PYC-insulated cables have the greatest impact. Choice of specification is between the 450/750 voltage grade, non-armoured cables of BS 6004 and the *600/1* 000 grade armoured cables of BS 6346. The PYC insulated and pvc-sheathed (PYC/PYC) cables of BS 6004 are suitable for surface wiring where there is little risk of mechanical damage. More usually they are run in conduit or trunking. The armoured cables to BS 6346 are suitable for installation in the ground, in ducts or in air.

## *Control and miscellaneous cables*

Here there is a fairly wide choice. BS 6346 multicore (2- to 48-core) cables are widely used.

Where cables may be subjected to corrosive attack an alternative is the PYC-insulated, multicore, lead covered, PYC-bedded, galvanized steel wire armoured, PYC-sheathed cable manufactured to Oil Companies Materials Association (OCMA) specification ELEC 4 Type B.

Multicore and multi pair cables to the Electrical Supply Industry standard ESI *09/6* are widely used for remote control and telemetry. The 600/1000 voltage grades are of PVC/SW A/PVC construction, and may have up to 37 cores of 2.5 $mm^2$ cross-sectional area. In the 110 volt grade the cables may be armoured or unarmoured and may have up to 100 pairs of 0.5 $mm^2$ cross-section.

Multipair, multitriple, and multicore polyethylene-insulated or PVC-insulated cables to BS 5308: Parts 1 & 2 are used for instrumentation. These, and the 110 V grade cables of ESI 09/6, must not be used as power cables or for the direct connection of equipment to low impedance power sources, such as mains supplies.

### 13.8.2 Cable ratings

Cables must be chosen so that their current-carrying capacity (related to cross-sectional area) is not less than the full load current they are required to carry. The continuous current rating of a cable is dependent upon the way the heat generated in its conductor(s) is transmitted through the cable's insulation and sheathing materials and is then dissipated from its external surfaces [28]. Clearly, the temperature of the cable's surroundings plays a large part in determining the steady-state temperature. that will be attained within the cable when it is carrying its rated current. Installation conditions have, therefore, to be taken into account when determining the size of cable to be used. More often than not, the limiting factor in LV installations is cable voltage drop.

In summary, the current-carrying capacity of a cable is influenced by:

1. conductor material - copper or aluminium;
2. insulation material;
3. the nature of its protective finishes - bedding, armouring and sheathing;
4. the installation ambient temperature; and
5. the method of installation - be it, in open air, in trenches, buried, grouped with cables of other circuits, etc.

The most common reference sources for cable ratings are manufacturers' catalogues and data sheets. This is particularly true for those power generation, transmission, and distribution systems which are outside the scope of the lEE Regulations for Electrical Installations. Other sources are the British Cable Makers' Confederation (BCMe) whose data closely align with those from the Electrical Research Association's (ERA Technology Ltd) multi-part Report ERA 69-30 *(Current rating standards for distribution cables).*

Those low-voltage installations which come within the scope of the lEE Regulations (and these would include standby and emergency generators in public and commercial buildings) must comply with the requirements of Regulation 522. This means using the methods given in its Appendix 9 for determining the cross-sectional areas of cable conductors to comply with Regulation 522-1.

The data tabulated in Appendix 9 are derived from that provided by ERA and BCMC, but are based upon an ambient air temperature of 30°C (compared with the 25°C of ERA/BCMe). Even when the appropriate ambient temperature correction factor is applied the lEE ratings are still a little lower than those of ERA and BCMC. It is hoped that the 16th Edition of the lEE Regulations will remove the ambiguity.

In shipboard applications higher base ambient temperatures and lower maximum operating temperatures are specified. In the United Kingdom it is customary to work to the lEE's *Regulations and Recommendations for the Electrical and Electronic Equipment of Ships.*

On the wider scene, the International Electrotechnical Commission documents IEC 448 and IEC 287 give, respectively, the current-carrying capacities of cables and the calculation methods for determining current ratings. Values prepared by all other bodies are almost always derived by the methods specified in IEC287 [28]. In American practice, documents and standards prepared by the Insulated Power Cable Engineers' Association (IPCEA) and by Underwriters Laboratories (UL) are applicable.

Having established the standard rating for the cable one intends to use, and its particular installation conditions, one has to apply certain correction factors to obtain the on-site rating of the cable. These factors cover variations in ambient air and ground temperatures, depth of laying, soil thermal resistivity, and cable grouping. It is then possible to determine the actual rating for cables installed in free air, in ducts, in trunking and conduit, and in open, enclosed, and back-filled trenches.

Appendix 9 of the lEE Regulations and [27], in particular, will provide the reader with valuable guidance on calculation methods.

### 13.8.3 Methods of installing cables

Figure 13.27 shows some of the various forms of cable enclosure and supports that are used. We shall now deal with those installation aspects which need particular comment, in the context of *good practice* for generating plant.

#### *Conduit*

1. Screwed conduit of the welded type to BS 4568 should be used, having fittings of the same finish. Class 2 enamelled conduit and fittings normally suffice for indoor applications. Class 4 hot dipped galvanized finishes are used for external work, and for damp and corrosive conditions.

2. Surface conduits should be supported and fixed by means of distance saddles spaced as recommended in Table 11C of the lEE Wiring Regulations. Saddles should be located within 300 mm of bends or fittings. Allowance should be made for the longitudinal expansion of rigid conduits.
3. Runs must be earthed and must be mechanically and electrically continuous across all joints and fittings. This also includes connections to the metal cases of equipment.
4. The conduit system should be completely erected before cables are drawn-in.
5. A space factor of at least 40 % should be provided, i.e. the aggregate overall cross-sectional areas of the enclosed cables should not exceed 40 % of the internal cross-sectional area of the conduit. Appendix 12 of the lEE Wiring Regulations describes a 'unit system' method of determining the size of conduit (or trunking) to accommodate cables to give compliance with Regulation 529-7.
6. The inner radii of bends should never be less than 2.5 times the outer diameter of the conduit. They may need to be larger to allow for the minimum bending radii of cables - as specified in Table 52C of the lEE Wiring Regulations.
7. Draw-in boxes should be provided, and so located as to ensure that cables are not drawn round more than two right angle bends in one operation.
8. Conduit systems should be designed so that they can be sealed against the entry of dust and water. Nevertheless, ventilation outlets should be provided at the highest and lowest points in each section of the system. These will permit the free circulation of air and provide drainage outlets for any condensation that may have accumulated in the runs.
9. To maintain the integrity of walls, ceilings and floors, in respect of their ability to withstand the spread of fire, any openings made in them should be 'made good' with materials that restore the fire integrity of the particular building element. For small openings, cement or a similar fire-resisting material often suffices. In other cases, fire barriers or proprietary cable transits may have to be considered.

### *Trunking*

1. Steel trunking must comply with BS 4678.
2. Proprietary fittings must be used. This ensures that bend radii are adequate. Entries to switchboards should be made using flanged assemblies or flared adaptors. Flanges should be securely bonded to the trunking, and bolted to the switchgear enclosure.
3. As with steel conduit, steel trunking may be used as a protective conductor provided it satisfies the lEE Wiring Regulations; it must not be used as a combined protective and neutral (pen) conductor.
4. A space factor of at least 45 % should be provided (see the previous sub-section.) It is wise to plan for the accommodation of about 25 % more cables than those initially required to be installed.
5. Supports should be spaced at distances not less than those specified in Table 11D of the lEE Wiring Regulations. Ends should not overhang a fixing by more than 300mm. Where a vertical run exceeds 3 m pin racks should be used to support the cables.
6. Trunking should not be installed with covers on the underside. Covers should be solidly fixed in passage through walls, floors or ceilings.
7. On vertical runs internal heat barriers (of glass fibre or similar material) should be provided to prevent air at the topmost part of the run attaining excessively high temperatures. The material should be packed firmly round the cables and secured to the trunking. Internal fire barriers should be fitted at each floor level on vertical runs and where horizontal trunking passes from one zone of fire protection to another.

### *Segregation of circuits*

Where LV installations include telecommunications, fire alarm or emergency lighting circuits which are connected to the main supply system, special precautions are prescribed by the lEE Wiring Regulations (525-1 to 525-9). These call for the segregation of the cables of different circuits to prevent electrical and physical contact. Three circuit categories are defined in the Regulations. They are:

*Category* 1: LV circuits (other than for fire alarm or emergency lighting circuits) fed from the main supply system.
*Category* 2: Extra low voltage or telecommunication circuits fed from a safety source (e.g. telephones, address, and data transmission systems)
*Category* 3: Fire alarm or emergency lighting circuits.

The diagram of Figure 13.30 summarizes the requirements relating to the segregation of circuits in enclosures, such as conduits, trunking and ducts.

Where it is intended to install Category 1 cables in the same enclosure as cables of a telecommunication system which may be connected to lines provided by a public telecommunications system authority, the approval of that authority is necessary. Cables used to connect the battery chargers of self-contained luminaires to mains supply circuits are not deemed to be emergency lighting circuits.

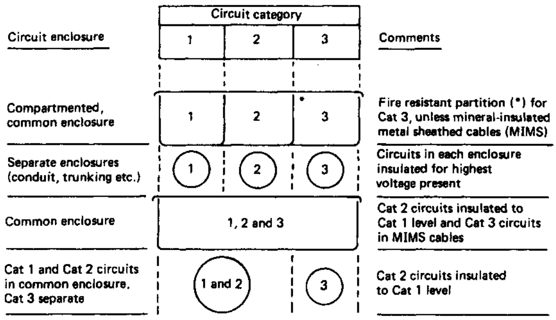



**Figure 13.30** Segregation of electrical circuits

Related British Standards are BS 5266 for emergency lighting circuits, and BS 6259 and BS 6330 for telecommunication circuits.

## *Cable trays*

The most commonly used method for installing above-ground sheathed and armoured cables is by clipping them to perforated trays in which the holes must occupy at least 30 % of the surface area. The trays should be galvanized or protected with rust-preventing finishes applied before erection. Cleats or clips should be of galvanized steel or brass. If they are brass, only good quality soft material should be used as the harder qualities are liable to fracture at sharp bends. Clips should be well radiused at their edges so that they do not bite into the cable.

Cables should, preferably, be laid in a flat formation. Allowance should made for the high repulsive forces that will be generated between phase conductors under fault conditions. We have established (in Section 9.4 of Chapter 9) that this force is directly proportional to the length of the paralleled conductors and to the square of the r.m.s. fault current, and inversely proportional to the spacing between the conductors. It is not always practicable to separate cables in flat formation. It is therefore good practice to allow for a sine wave formation of cables by using cleats which are capable of swivelling at the 90° and 270° positions [32]. The maximum spacing for clips and cleats should be 450 mm.

Tray supports should be spaced to minimize the amount of sag due to cable weight. The usual spacing is at about 1200 mm. Expansion guide supports should be employed at about 6 m intervals, and hold-down clamps and tray expansion joints every 24 m. Joints in trays should be installed at a support point wherever possible. Trays should be bonded using stranded and insulated copper wire of at least 25 $mm^2$ cross-sectional area. Bonds must be provided around expansion joints and where the tray system is discontinuous.

Steel supports and trays should be of sufficient strength and size to accommodate the future addition of approximately 25 % more cables than those initially planned.

## *Trenches*

Trenches within plant rooms and generator halls should be of the enclosed type with concrete slab or steel chequer plate covers. As far as possible, separate trenches should be provided for electrical cables and for engine and auxiliary plant pipelines. In standby generator installations the one trench may have to suffice. A typical arrangement is shown in Figure 13.31.

The diagrams in Figure 13.32 are based on those in the Association of Supervisory and Executive Engineers' Guide to the IEE Wiring Regulations [27]. They show the minimum spacings between cables and from trench walls for the three sizes of 'enclosed trench' given in Table 9A of the IEE Wiring Regulations (installation Methods 18, 19, and 20 - with current rating factors as Table 9C3).

Trench bends should be contoured to accommodate the minimum bending radius for the largest cable installed (usually not less than eight times the overall diameter of the cable). The most economical construction is obtained by using the designs illustrated in the plan view diagram of Figure 13.33. Note the geometric similarity with trunking fittings.

Trenches should be kept as straight as possible. The bottoms should be smoothly contoured and

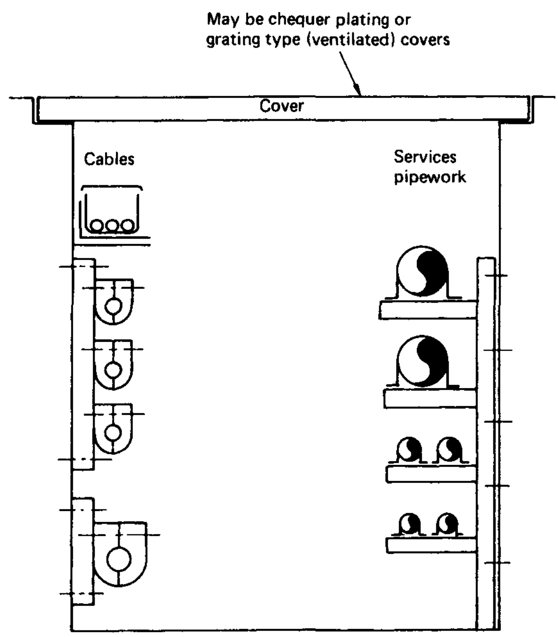



**Figure 13.31** A section through service trench showing typical arrangement of cables and pipework for a standby generator installation

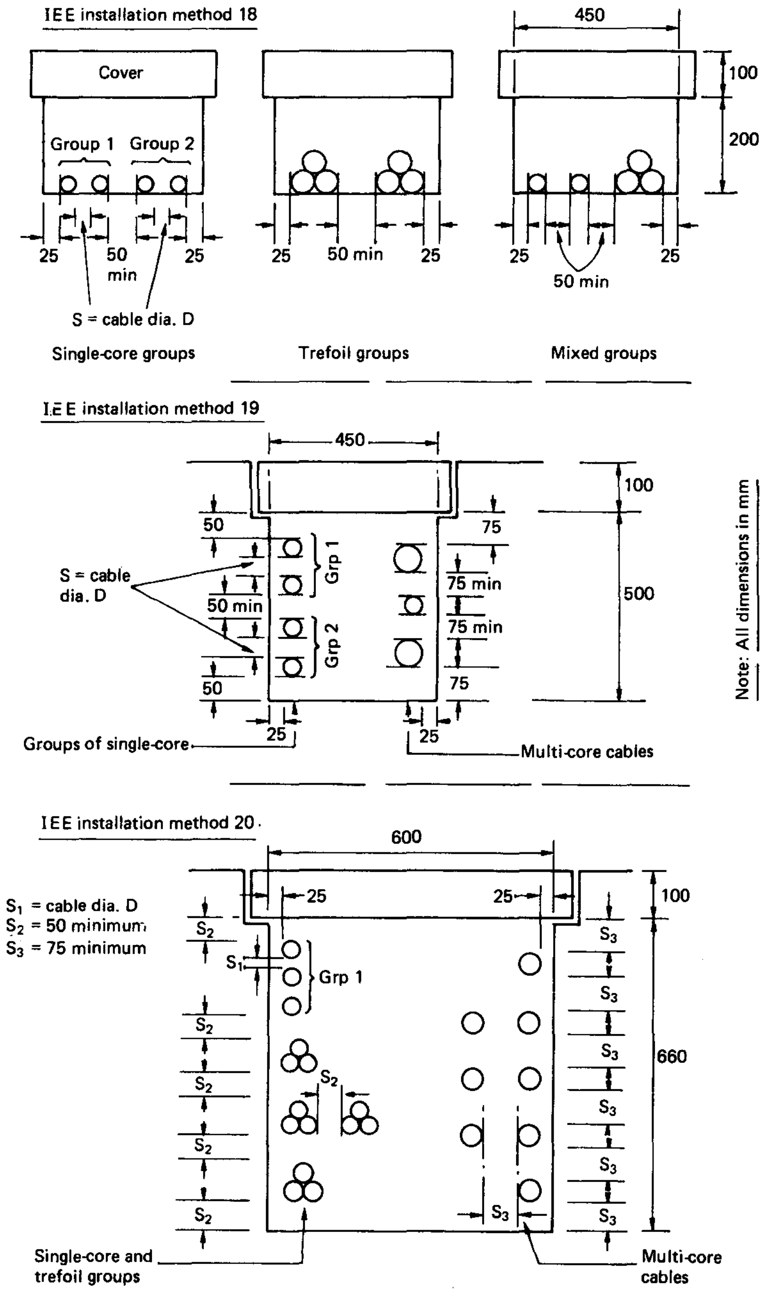



**Figure 13.32** Spacings for cables in enclosed trenches

arranged to 'fall away' from engine plinths so that water and oil spillages do not accumulate within the trenches but are drained away to a common catchment pit from which liquids may be periodically pumped.

Trenches external to buildings are often back-filled. In such cases the excavated top soil should be set aside and re-used to form the top layers when re-instatement is made. Large pieces of rock, concrete, or metal removed during excavation should not be replaced when back-filling. Where these have been removed, or where cables pass from indoor trenches through ducts into the ground (see Figure 13.34), the back filling should be consolidated

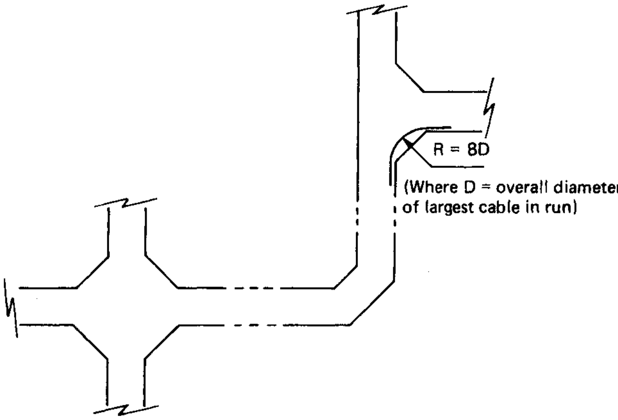



**Figure 13.33** Plan view geometry of cable trenches

before the cable is installed. This ensures that there is no further ground settlement. Back filling should be made in even layers, each layer being consolidated.

### *Laid direct in ground*

Where armoured and sheathed cables are run external to buildings and are laid direct in the ground, they should be laid on a 75 mm deep bedding medium (typically, freshwater sand). Where more than one horizontal layer of cables is to be laid the vertical spacing between the layers should be at least 75 mm. Bedding material is then placed around and over each layer to a level of 75 mm above the top of the cables.

Every cable in the uppermost layer should be protected by interlocking cable tiles (to BS 2484). The cable trench markers shown in Figure 13.34 (item D) are concrete blocks about 300mm wide, 500mm long and 150mm deep, placed at every point where the cable route changes direction, or at intervals not exceeding 15 m. Each marker should carry a stainless steel label or plate stamped or engraved with the salient details of the cable, e.g. voltage and the cable number.

Plastic marker tape, buried some 50 mm below ground level, should be used for additional indication of the direction of the cable run. Tiles and tapes should be centred above the top of the cable. Each cable should be indentified underground by stainless steel bands stamped with the cable number and secured to the cable with tie-wraps. These bands should be spaced at a maximum of 10 m apart. Note that a trefoil formation should be adopted for single-core cables forming a three-phase circuit.

The separation distances between HV and LV cables in trenches or laid direct in the ground should be between 160mm and 400mm, depending on the space available.

Cables passing under roads, pavements, or building structures should be drawn through ducts and must be of a type incorporating a sheath and/or armour which is resistant to any mechanical damage likely to be caused during drawing-in (lEE Wiring Regulation 523-24). The ducts for single core a.c. cables must be earthenware or an equivalent material. Where such cables form one three-phase circuit the ducts should be of the trefoil type. Ducts carrying multicore cables may be constructed of metallic materials. Socketed and spigotted cast iron pipes to BS 437 are often used. They should, preferably, be coated internally and externally with a bituminous based compound and be jointed with tarred yarn and lead caulked [33]. The ducts should be laid on a firm, consolidated base. The ends of the ducts should always be sealed by plugs until the cables are installed.

No more than one cable should occupy a duct-way. Again, it is good practice to provide a number of spare ways for future cables (say, 25 % more than those initially required). The internal diameter of the duct-way should be of the order of 1.5 times the overall diameter of the cable it houses. Ducts should extend at least 250 mm beyond the structure they span.

Figure 13.34 illustrates typical installation details for ducted cable entries into buildings.

lEE Wiring Regulation 521-14 requires that where a duct is cast *in-situ* in concrete (whether or not formers are left in place), the radial thickness of the concrete surrounding the completed duct must be at least 15 mm at every point (see Figure 13.35).

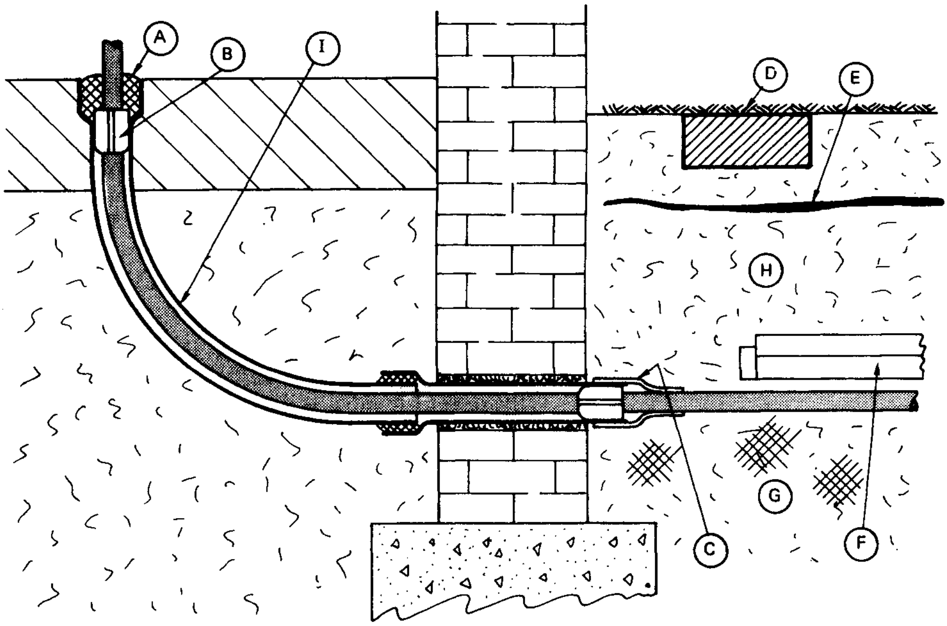
Before any cables are installed the ducts should be cleared with a mandrel followed by a pull-through to remove any dirt that may have accumulated. Ensure that the duct ends are sealed with plugs until the cables are installed.

### 13.8.4 Cable termination

The termination of any power cable should be designed to meet the following requirements [26]:

1. electrically connect the insulated cable conductor(s) to electrical equipment;
2. physically protect and support the end of the cable conductor, insulation, shielding system, and the sheath or armour of the cable; and
3. effectively control electrical stresses to give the dielectric strength required for the insulation level of the cable system.

As far as 3 is concerned it is only necessary on LV systems to apply tape from the lower portion of the terminal lug down onto the conductor's extruded insulation. The tape should be compatible with the cable insulation. An alternative method is to use heat-shrinkable sleeves and lug 'boots'. Where cables




(A) Weak mix of sand and cement — easily removed, if required (alternatively: vermiculite concrete — fine or coarse grade; and insulating concrete)

(B) Split pipe bung

(C) Bitumastic tape or heat shrink sleeve

(D) Trench marker(s) — concrete blocks

(E) Plastic marker tape

(F) Interlocking cable protection tiles

(G) Ground power punned to level of cable

(H) Infill soil hand consolidated

(I) Bend radius to suit bend radius of cable (usually 8 times overall diameter)

**Figure 13.34** Typical ducted cable entry into a building

are connected direct to busbars which are likely to be operating at higher temperatures than the cable conductors, it is advisable to remove the conductor insulation for a distance of about 150 mm from the connection and replace it with high-temperature insulation - in sleeve or tape form.

Screened MY cables need a bit more care. The shielding must be terminated at a sufficient distance back from the conductor(s) to give the creepage distance required between conductor and shield. Because maximum electrical stress is raised at this point it is necessary to reduce it by gradually increasing the total thickness of the insulation at the termination of the shield. This may be done by adding insulation (tape or pre-moulded rubber) to form a stress-relief cone. The shield is then carried up to the cone and terminated at a point some 3 mm behind the largest diameter *bf* the cone [26].

It is recommended that one of the proprietary heat-shrink termination kits is used in 11 kV XLPE cables. These incorporate stress control, non-tracking and weatherproof tubes, cable gloves (or cable crutch udders) and termination boots. Only fully experienced personnel should be employed in the making of this type of termination.

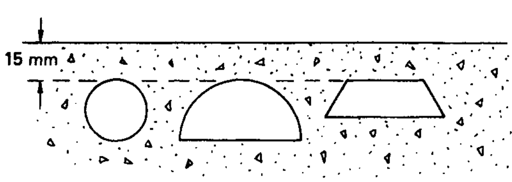
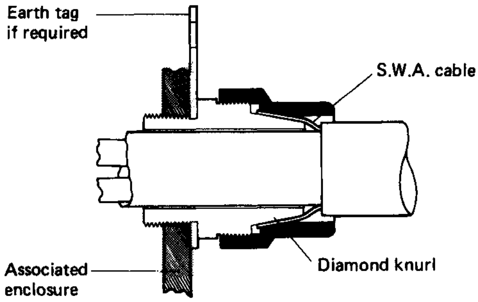


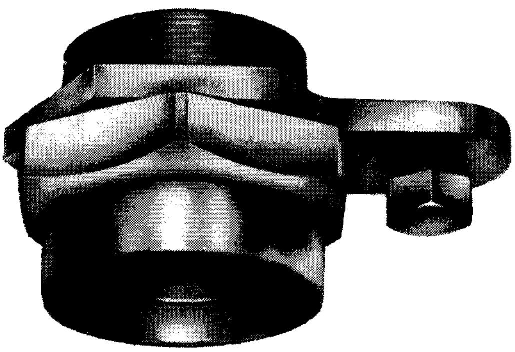

**Figure 13.35** Minimum radial thickness of concrete for ducts cast *in situ* (IEE Wiring Reg. 521.14)

## *Glands*

Polymeric cables should be terminated using mechanical type compression glands to BS 6121. The material of the gland must be compatible with the cable armour. Where the glands terminate in non-metallic gland plates they must be fitted with earth tags (see Figure 13.36). Where glands are to be screwed into




(a)



(b)

**Figure 13.36** Cable glands with slip-on and integrally cast earth tags (a) Pirelli general type BW gland suitable for XLPE insulated SWA cables in indoor application (b) CMP Glands Ltd type BW gland with integrally cast earth lug (Courtesy: The manufacturers)

aluminium or zinc base alloy plates, use cadmium plated glands.

Under phase-to-earth fault conditions the fault current on armoured cables will pass along the armour wires through the terminating gland into the earth system. It follows that the gland must be capable of withstanding the fault current during the time required for the cable protective device to operate. Where a circuit breaker is used the fault clearance time could be near 1 second. Sole reliance should not be placed on the effectiveness of current paths through gland plates and cable boxes. Gland earth tags will afford a more substantial path. Tags may be of the slip-on type or , better still, those that are cast-on to the gland body itself.

It is good practice to fit PVC or neoprene shrouds over armoured cable glands, particularly in outdoor applications. Special lubricants, smeared on the inside of the shrouds, will facilitate fitting.

*Connections to terminals*

Power cable conductors are usually terminated in compression type cable lugs using a hydraulic tool. The hexagonal joint appears to be the most popular crimp shape for conductors over 25 $mm^2$. Insulated crimped lugs are used on the stranded conductors of small power and control cables. Soldered lugs and shell type washer terminations are now seldom specified.

*Cable tails*

Cable tails from the gland to the terminals of the apparatus should be of sufficient length to prevent the development of tension within them. Due allowance should be made for the movement of cables connected to the terminal boxes of any plant mounted on vibration isolators. In these circumstances, and where connections to the main switchboard are in single core armoured cable or in multicore unarmoured cable, it is usual to terminate in a free-standing terminal box mounted as close as possible to the plant. Flexible connections, e.g. in single-core, PVC-insulated or PVC/XLPE insulated and PVC-sheathed cables, are then used between this floor-mounting box and the plant terminals. The connections should be generously looped.

### 13.8.5 Fire-performance cables

In recent years there has been an increasing demand for cables to meet a number of safety requirements in the unfortunate event of their becoming involved in fire. The performance required of the cables then varies with the nature of the particular installation. For example, in marine application and in power station basements the prime requirement might be for cables that do not propagate fire. In commercial and public buildings the priority will be for low smoke and low corrosive gas emission. On safety circuits, such as in fire-alarm and extinguishing systems, in vital equipment protection schemes, and in emergency lighting, cables will be required to retain their circuit integrity [34]. *Fire-performance* (FP) cables may be classified under four headings:

1. *Fire resistant cables:* those which satisfy the IEC331 test in which the cable is exposed to a 750°C gas flame for three hours with the rated voltage applied. Such cables will survive a fire and continue to function in the circuits they serve. In practice, cables will also be required to withstand water spray and mechanical impact under fire fighting conditions. The more realistic tests of BS 6387 provide the basis for classifying LV cables by their resistance to fire alone, to fire and water, and to fire with mechanical shock [34].

2. *Flame retardant cables:* those cables which are self-extinguishing and do not add to the fire or to the hazards associated with it. Tests are carried out on single vertical cables (BS 4066: Part 1 (IEC332-1)). Cables that pass this test should not be regarded as flame retardant when installed together on vertical ladder racks and trays. Under these conditions propagation of fire can take place due to the total volume of combustible material in the cable run.
3. *Reduced (flame) propagation cables:* those cables designed to limit flame propagation when bunched. The appropriate test is that of BS 4066: Part 3 (IEC332-3) which simulates typical installation conditions. Bunches of cable are categorized by the volume of combustible material per metre, and their classification is based on the extent of charring.
4. *Low smoke zero halogen (LSOH) cables:* those cables which incorporate halogen-free compounds and have low smoke emission characteristics. BS 6724 is the specification for arinoured power cables having elastomeric (thermosetting) insulation. Smoke evolution is assessed by burning samples of cable in a chamber and measuriI\g the attenuation of a light beam by a photoelectric cell. The halogen acid content of the gases evolved during combustion is measured by the test method of BS6425 (IEC754-1). The limit for acid gas emission is set by BS 6724, at 0.5 % by weight of the halogen-free compound. In contrast, general purpose PVC cables may emit 30 % acid gas.

## *Fire resistant cables*

The most widely used constructions for fire-resisting cables are:

*Mineral-insulated metal sheathed (MIMS):* the conductors are insulated in a highly compressed magnesium oxide (MgO) powder and sheathed in a metallic cover, which may be copper, aluminium or stainless steel. This sheath may also have a PVC oversheath to provide protection against corrosion. The oversheath limits the permissible operating temperature of the cable (to 70"C for PVC). Bare MI cables with copper sheaths can operate at sheath temperatures up to 250°C. Above this temperature significant oxidation of a copper sheath occurs but the cable can operate, for limited periods, at temperatures in the region of lO00°C [28].

Because the magnesium oxide is hygroscopic the ends of cables must be protected from moisture. This demands particular care in making terminations and requires special stripping tools, watertight glands, and sealing compounds. The conductors which emerge from the seal must be protected with sleeves suitable for operating under the full range of temperature to which the cable is subjected in service. Single or multicore cables are available in ratings up to 1000 volts.

One big advantage with MIMS cable is that the metallic sheath may be used as a combined neutral and earth conductor (cne) on *protective multiple earth* (pme) systems. The major disadvantage with MIMS cables is that they are susceptible to damage from impulse voltages.

BS 6207: Part 1 specifies the requirements for mineral-insulated copper sheathed cables which have copper conductors (MICC cable). Part 2 of the same specification (withdrawn in 1988) covered the alternative aluminium sheathed types having copper or aluminium conductors. BS 6081 specifies the test and construction requirements for MIMS cable terminations.

*Silicone rubber insulated:* widely applied in marine and offshore installations, these cables come in several constructions. In the simplest form the conductors are insulated with silicone rubber and are covered with an outer sheath of the same material. Other types may employ a glass fibre braid, a woven tape, or aluminium foil lapping around the insulation, followed by an oversheath of aluminium. Maximum operating temperature is 180°C, with an intermittent rating of 250°C.

A feature of silicone rubber insulation is that it reduces to a silicone dioxide ash ($SiO_2$) in a fire. This ash has similar volume and insulating properties to the original silicone material. The braiding! taping and the oversheath retain the ash in position and provide some protection against the ingress of moisture, besides giving good electrical screening. Unlike MIMS, this type of cable does not require any special installation tools or skills.

*Mica-glass tape insulated:* this has largely replaced the silicone rubber insulated type on offshore installations and meets the onerous test conditions of BS 6387. A typical construction consists of a mica-glass tape lapping over the conductors, covered by extruded EPR or XLPE insulation, a halogen-free bedding followed by glass fibre woven lapped tape, a galvanized steel wire braid or armouring, and an extruded oversheath of flame retardant LSOH compound. In a fire the extruded elastomeric insulation is reduced to a conducting ash but the insulation integrity of the mica-glass tape is unimpaired [34].

It should be noted that special current protection measures may be necessary when using high temperature cables since voltage drop and power loss in the cables are high.

## *Reduced flame propagation (RP) cables*

When fires occur in enclosed spaces the amount of oxygen present in the space is reduced and the proportion of carbon dioxide is increased. If cable insulation and sheathing materials continue to burn in such conditions carbon monoxide is quickly produced. This of course is highly toxic and would be lethal to any personnel in the area.

The *oxygen index* of a material (often called its limiting oxygen index (LOI» is a useful guide to its flame retardant or self-extinguishing properties, but should not be taken as an absolute measure of the ignitability of a material. It is described in BS 2782: Part 1: Method 141 as the minimum percentage volume concentration of oxygen (in a mixture of oxygen and nitrogen) that will just support combustion under equilibrium conditions of candle-like burning [32]. The oxygen content of normal air is about 22 %. This means that a material with an oxygen index (01) value of less than 22 would ignite and burn freely in air. BS 4066: Part 1 requires a minimum of 25 for a cable to be classified as flame retardant, and an 01 of 30 is necessary if RP cables are to pass the more stringent tests of Part 3. It follows that the higher the cable's 01 value the less likely it is to propagate flames.

It has been found that closely spaced cables burn more readily than touching cables. It may even be better to bunch cables to reduce the availability of oxygen. Where cables are spaced, the spacing should be as great as possible [34].

Normal flame-retardant materials such as PVC, PCP and CSP contain chlorine. One of the products of their combustion is hydrogen chloride gas. This can combine with moisture in the air to produce toxic and corrosive hydrochloric acid (HCl). PVC compounds complying with BS 6746 and meeting BS 4066 flame retardance requirements emit about 300 mg of HCl per gram of compound burnt. This is expressed as an HCl rating of 30. The HCl value of a material denotes the amount of gas evolved from it under laboratory test conditions - the lower the value the less the HCl given off. Nowadays, acid-gas emission limits of less than 5 % (HCl 5) are frequently specified and specially formulated compounds provide sheathing capable of meeting these requirements.

## 13.9 Health and safety aspects

Electrical power generating, transmission and distribution systems will be required to comply with the applicable statutory regulations and approved codes of practice of the particular country of installation.

### 13.9.1 Legislation

It is outside the scope of this handbook to give more than a brief outline of the requirements relating to power systems in Great Britain. Full details may be found in [27, 30, 35 and 46].

*Statutory regulations*

1. Electricity Supply Regulations 1988: security of the safety of the public and ensuring a proper and sufficient supply of electrical energy.
2. Electricity at Work Regulations 1989, Statutory Instrument 1989 No. 635: these came into force on the 1st April 1990 and apply to all work places - not only factories and substations.
3. Health and Safety at Work, etc. Act 1974: imposing requirements for safety (including electrical) in all employment situations; and the control of certain emissions into the atmosphere.
4. The Highly Flammable Liquids and Liquefied Petroleum Gases Regulations 1972: this and the following regulation (5) cover premises where fire risk is of an unusual character and requires special consideration.
5. The Petro[eum Consolidation Act 1928.
6. The Construction (General Provisions) Regulations 1961: apply to construction sites and contain regulations relating to precautions to be taken against contact with overhead lines and underground cables; may also apply to temporary power installations under particular local authority and insurance company requirements.

The administrative or legislative authority for (1) is the Secretary of State for Energy; in every other case it is the Health and Safety Commission.

Some regulations are sufficiently detailed as to set down just what has to be done for compliance. They mayor may not include direct reference to codes of practice. Where they do, such codes have the same legal force as the regulations themselves. Other generally accepted codes of good practice, which are not directly referenced, are not legally enforceable.

With any legislation there is always a need for guidance on the application of regulations. The following publications are recommended reading. They are obtainable from HMSO.

1. Explanatory Notes on the Electricity Supply Regulations 1988.
2. Memorandum of guidance on the Electricity at Work Regulations 1989, HSE booklet HS(R) 25.
3. In the context of the Petroleum Consolidation Act 1928, the Home Office Model Code of Principles of Construction and Licensing Conditions: Part 1. *(Note:* local authorities are empowered to grant licences for the storage of petroleum spirit on premises within their jurisdiction. The conditions for licence may vary from one authority to another.)

Where it is proposed to install a protective multiple earthing system it is mandatory, in the United Kingdom, that prior approval is obtained from the Secretary of State for Energy. Government authorization is now largely delegated to area electricity boards.

Another point to be noted is that before a generating station or transmission line is erected, prior approval of the local planning authority must be obtained. This is a requirement of the Town and Country Planning Acts in the United Kingdom [35].

### *Codes of practice*

Approved codes of practice are usually generated by the Health and Safety Commission, possibly in conjunction with industrial committees or with the British Standards Institution. Codes of practice otherwise published by BSI or professional and trade bodies are classified as non-approved codes. The BSI Codes of Practice are supplemented by detailed specifications covering application and design of equipment, and material and manufacturing standards.

Of the codes and standards prepared by professional institutions and trade associations perhaps the most important, in our context, are the lEE Regulations for Electrical Installations. Whilst they may not be legally enforceable they represent the best practice in electrical safety. Indeed, failure to comply with the fundamental safety requirements contained in Part 1 of the Regulations (Regulations 13-1 to 13-29), could lead to an Electricity Supply Authority withholding a supply of energy to an installation.

### *Overseas regulations*

It is necessary to ascertain what regulations apply when designing an overseas installation. For example, in those locations where American practice is observed, safety codes are inevitably those prepared by the National Fire Protection Association (NFPA). The BSl's *Technical Help to Exporters* (THE) service should be consulted for guidance on other territories.

## 13.9.2 Earthing

*Earth* (or *ground,* in American parlance) is the conductive mass of the Earth, whose electrical potential at any point is conventionally taken as zero [30]. An effective earth system is one that ensures at all times an immediate discharge of electrical energy without danger to the lives or health of personnel operating within the installation.

Earthing may conveniently be discussed under the following sub-headings:

1. system earthing;
2. equipment earthing;
3. lightning protection systems; and
4. connections to earth.

### *System earthing*

While the leading Classification Societies permit the use of both *isolated* (unearthed) and earthed neutral systems on ships, the choice is almost always for isolation. Earthed systems are forbidden on tankers [36].

An earthed system is one in which an intentional electrical connection is made between the electric power system's neutral and earth. The neutrals of diesel generator power systems are either solidly earthed, or earthed through a fault limiting impedance (resistance or reactance). See Sub-section 10.4 of Chapter 10.

### *Equipment earthing*

Whilst the lEE Wiring Regulations do not apply to private (or separately derived) power supply systems, it is recommended that their requirements for earthed equipotential bonding are met (Regulation 413-2). On standby and emergency generator installations, where reliance is placed on metallic paths back to the neutral point of the utility's power supply, such bonding would be obligatory. Also, compliance with Regulation 413--2 normally satisfies the relevant requirements for PME (protective multiple earthing) Approval.

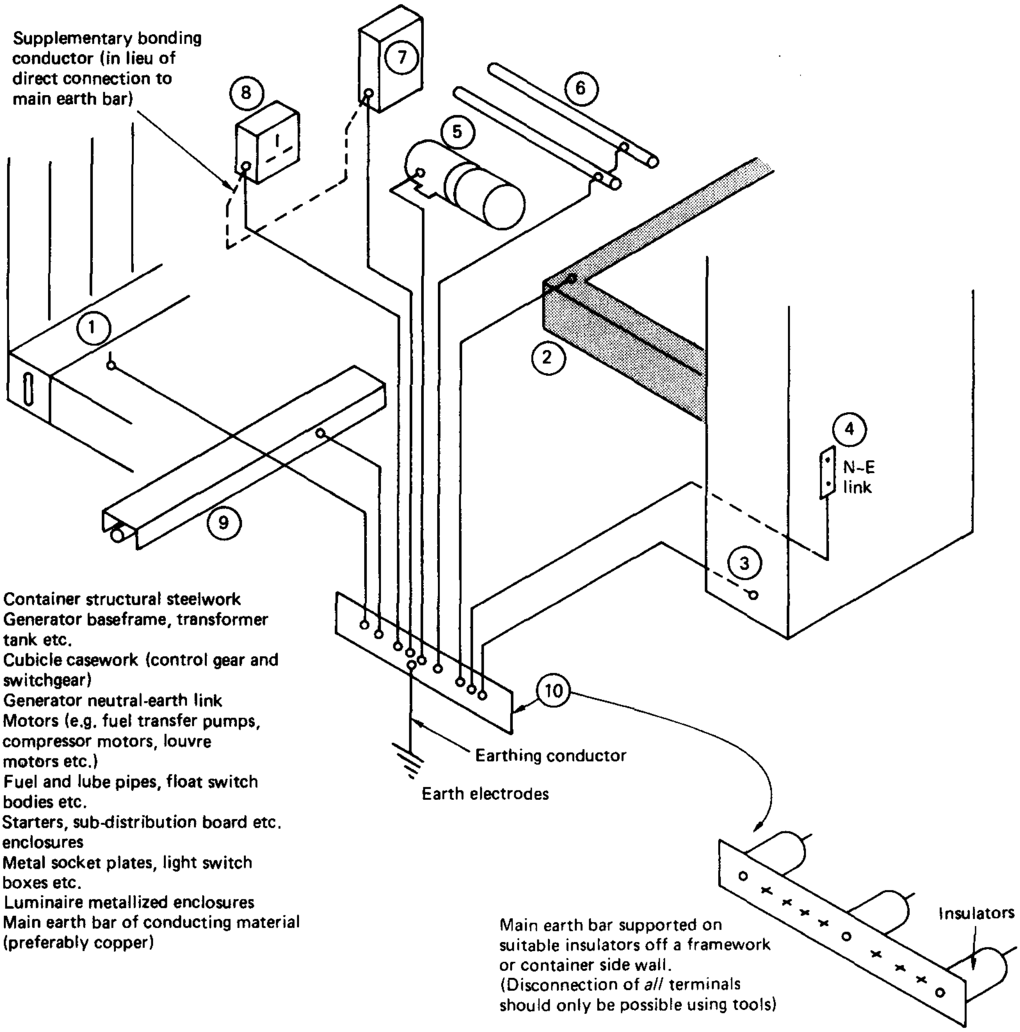
One needs to be aware of the distinction between a *protective conductor* and a *bonding conductor.*

The protective conductors in an installation are those which are used to connect together any of the following:

1. exposed conductive parts within the electrical installation - defined as those conductive parts of equipment which can be touched and which are not live parts, but which may become live under fault conditions;
2. extraneous conductive parts - those conductive parts which do not form part of the electrical installation but which are liable to introduce a potential (generally earth potential);
3. the main earthing terminal;
4. earth electrodes; and
5. the earthed point of the supply source.

The purpose of bonding conductors is to ensure that a dangerous difference of potential cannot exist between the earthed metalwork of the installation's equipment and the conductive parts of other 'services', such as water, gas, fuel, compressed air and lubricating oil metallic pipes, and air service ducts.

The exposed metal casings of all electrical apparatus should be connected to a designated earth point in the installation. This permits circuit protective devices to operate in the event of contact between live conductors and metalwork, thereby minimizing the risk of shock to personnel and the risk of fire. The diagram of Figure 13.37 shows the use of




1 = Container structural steelwork
2 = Generator baseframe, transformer tank etc.
3 = Cubicle casework (control gear and switchgear)
4 = Generator neutral-earth link
5 = Motors (e.g. fuel transfer pumps, compressor motors, louvre motors etc.)
6 = Fuel and lube pipes, float switch bodies etc.
7 = Starters, sub-distribution board etc. enclosures
8 = Metal socket plates, light switch boxes etc.
9 = Luminaire metallized enclosures
10 = Main earth bar of conducting material (preferably copper)

**Figure 13.37** Example of typical arrangement for earthing system and protective and bonding conductors in containerized plant

protective and bonding conductors in a typical earthing system on a small containerized plant. The principles illustrated would equally apply to larger-scale generating plant.

It is important to ensure that the current paths afforded by the protective and bonding conductors are of sufficient capacity to deal with the maximum fault currents. Also, conductor resistances should be low enough to prevent a dangerous voltage appearing between any points which a person could reach simultaneously.

Referring to Figure 13.37, the conductors connecting Items 4,5,7,8 and 9 to the main earth bar are, by definition, protective conductors. Their cross-sectional areas may be calculated using the adiabatic formula of IEE Wiring Regulation 543-2, or size may be selected from Table 54F in Regulation 543-3. See also Sub-section 13.8.1.

The main equipotential bonding conductor (that from the container's structural steelwork, Item 1, to the main earth bar) should have a cross-sectional area (c.s.a.) not less than half that of the installation's earthing conductor. The minimum size must be 6 $mm^2$ and it need not exceed 25 $mm^2$ if the conductor material is copper.

The supplementary bonding conductors, from Items 2,3, and 6 to the main earth bar, should have a c.s.a. of not less than 2.5 $mm^2$ if mechanical protection is provided on them, or 4 $mm^2$ if there is no mechanical protection. It is often more convenient to run a supplementary bonding conductor via an exposed conductive part (such as Item 7 of Figure 13.37) rather than direct to the main earth bar. The bonding conductor's c.s.a should then not be less than that of the protective conductor connected to the exposed conductive part. This is subject to a minimum c.s.a. of 2.5 $mm^2$ if mechanical protection is not provided.

### *Lightning protection systems*

While BS 6651 (see Section 13.11) permits earthing and lightning protection systems to be linked in what is called a *counterpoised* earthing system, most Electrical Engineers would prefer to see them separate. They should only be linked at the earth terminal by means of a removable link permitting measurement of the impedance of the lightning protection system [37].

BS 6651 confines itself to conventional lightning protection systems. In so doing it excludes those other devices or systems (such as radioactive terminals) which claim to provide enhanced protection. Research has failed to substantiate the performance that these devices claim.

The principal components of a lightning protection system are [38]:

1. air termination networks;
2. down conductors;
3. bonding to prevent side flashing; and
4. earth termination networks.

Before we discuss system design it is necessary to define the terms *zones of protection* and the *protective angle.* The zone of protection is that volume within which a lightning conductor provides protection against a direct lightning strike by attracting the strike itself. The zone falls within a protective angle considered to be 45° for buildings below 20 m in height (see Figure 13.38). For taller structures, a *rolling sphere* should be used to determine the areas where lightning conductors are advisable. Wherever the sphere touches the building structure determines the extent of the air termination network.

*Air termination networks.* The air termination network is that part of the lightning protection system which is intended to intercept lightning discharges. The use of pointed air terminations on roofs is no longer regarded as essential (BS 6651). American practice differs, in that the use of vertical finials is recommended. The network concept introduces the use of a system of horizontal conductors on roofs, supplemented by vertical conductors on all sides of tall buildings. BS 6651 requires that no part of the roof within the air termination network should be more than 5 m from a conductor. For large flat roofs this requirement may be met by a network 'mesh' of 10m x 20m.

If there is considerable variation in the height of a structure more than one roof termination network may be necessary. In such cases the lower roof network(s) should have their own down conductors. These conductors should be be connected to the down conductors of the taller portions of the structure. All metal projections on the roofs, such as ladders, handrails, cooling equipment, masts and aerials, should be correctly bonded to the air termination networks.

*Down conductors.* Down conductors are designed to provide a low impedance path from the air termination network to the earth termination network. Various types may be used. These include combinations of strip and rod conductors or the steel stanchions and concrete reinforcing bars (re-bars) of building structures. Where the metallic components of the structure are used it is essential that they are effectively bonded to the air and earth termination networks and that they give good electrical continuity. Illustrations of proprietary clamps used for bonding metalwork are given in Figure 13.39.

The following principles apply in the design of the down-conductor system:

1. The conductors should take the most direct route from the air to the earth termination networks.
2. The number of conductors to be used is determined by the following criteria:
   (a) a structure having a base not exceeding $100\,m^2$ may only have one down conductor;
   (b) in a structure with a base larger than $100 m^2$, the number of conductors should equal the smaller of the following:
   - one, plus one for every $300\,m^2$, or part thereof, in excess of the first $100 m^2$ (see the Table below), or
   - one for every 30 m of perimeter.

| *Areas between* (m') | *Number of down conductors* |
|---|---|
| 1<J0-400 | 2 |
| 400--700 | 3 |
| 700-1000 | 4 |
| 1000-1300 | 5 |
| 1300-1600 | 6 |
| 1600-1900 | 7 |

3. Conductors should be symmetrically installed around the outside walls of the building structure, starting from the comers. They should be spaced 20 m apart around the perimeter at roof or ground level, whichever is the greater. Spacing is reduced to 10 m for structures higher than 20m.
4. Conductors should be routed to avoid side-flashing. (When a protection system has been hit

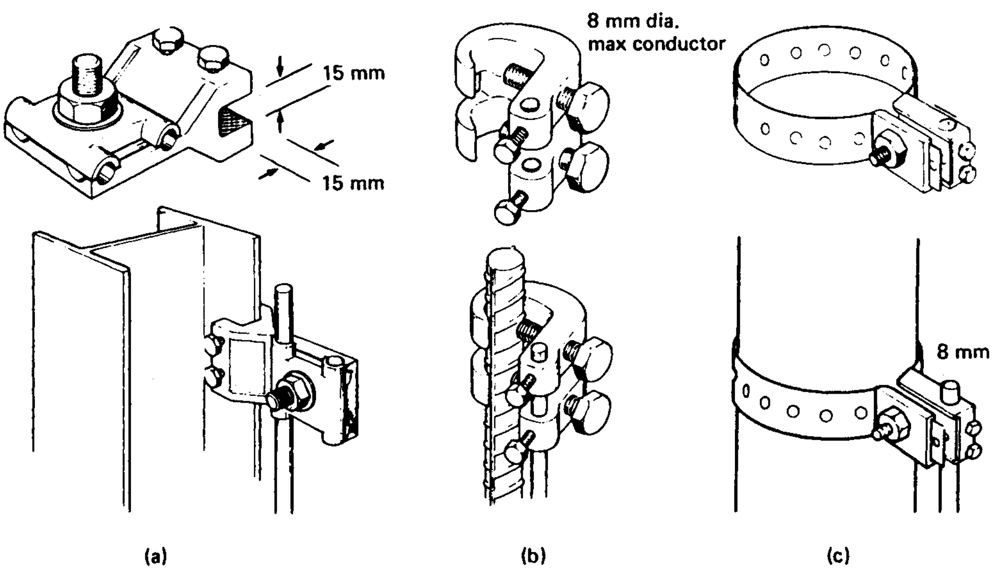



**Figure 13.39** Typical proprietary clamps used in metalwork bonding (a) metalwork bond (b) re-bar clamp (c) pipe bond (Courtesy: W.J. Furse & Co. Ltd)

by lightning its electrical potential with respect to earth is raised significantly - it could well be to the order of 1MV instantaneously. The discharge may seek alternative and lower impedance paths to earth by side-flashing to other metalwork within or on the building structure.)

5. Re-entrant loops should be avoided. Such loops may produce high inductive voltage drops leading to lightning discharges jumping across the side of the loop. BS 6651 recommends that the length of the conductor forming the loop should not exceed eight times the width of the open side of the loop (see Figure 13.40).
6. Each down conductor should have its own earth electrode.

*Bonding of exposed metal work.* There are two ways of preventing side-flashing occurring. The first is to isolate (by distance) any exposed metal fixtures from the lightning protection system, but this is not always possible. The second method is to bond the metalwork to the system. BS 6651 provides a mathematical and graphical means of determining the minimum isolation distance required for a given set of parameters. Where internal bonds need to be applied they can be of reduced cross-sectional area when compared with external bonds, e.g. 30 $mm^2$ versus 50$mm^2$ (BS6651).

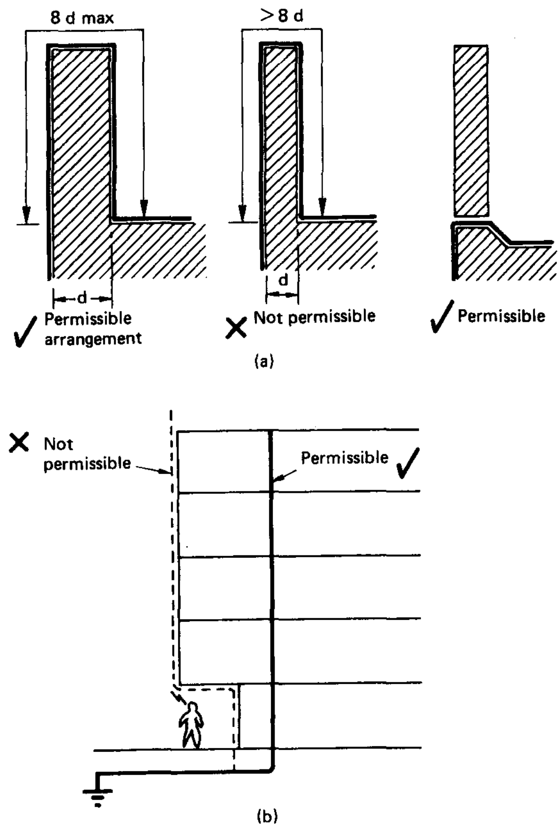



**Figure 13.40** Re-entrant loops on down conductors (a) parapet walls (b) building cantilevered from first storey upwards

## Connections to earth

A good earth connection should have [38]:

1. a low electrical resistance to the path of lightning or fault currents;
2. good corrosion resistance;
3. ability to carry high currents repeatedly; and
4. the ability to perform the above functions for the life of the plant and the building.

To obtain an effective earth one needs to have a soil of low resistivity and high moisture content and earth temperatures that are constantly above freezing.

*Soil resistivity.* Although many different formulae exist for determining the theoretical resistance of an earth electrode (each dependent upon the basic assumptions made) all have soil resistivity as the common and most important factor. The resistivity of a soil is defined as the resistance between the two opposite surfaces of a metre cube of a particular sample of the soil. It is measured in ohm-metre or, more usually, in ohm-centimetre (Ocm). 10m = 100Ocm. Soils with resistivities between 1000 and 10000Ocm are said to be of 'low' resistivity and therefore have good conductance.

The factors, affecting the resistivity of a soil are:

1. physical composition;
2. moisture content;
3. chemical composition;
4. temperature; and
5. depth.

*Physical composition:* Conductivity in a soil is made possible through an electrolytic process known as ion conduction. Conductivity varies with a soil's composition, the size of the soil particles, and the degree of soil compaction.

Table 13.3 gives 'ball-park' values of resistivity for various soils. The wide variation in values for each type is mainly due to moisture content. The table should only be used by the system designer to determine an arbitrary, pre-survey value of the soil resistivity to be expected in an area whose soil composition has been loosely categorized in tender documents. Appendix C of this handbook details the method of making soil resistivity surveys and tests.

Clearly, dry, sandy, rocky ground should be avoided. More often than not, no choice is available.

**Table** 13.3 Typical soil resistivities

| *Type of soil* | *Resistivity* [ohm-cm] |
|---|---|
| Ashes | 350 |
| Coke | 20-800 |
| Marshy ground | 200--270 |
| Loam and arable soils | 500-5000 |
| Clay (40 % moisture) | 800 |
| Clay (20 % moisture) | 3500 |
| Very dry clay | 5000-15000 |
| Clay, sand and gravel mixture | 4000-25 000 |
| Sand and gravel | 6000-10 000 |
| Mainly sand (90 % moisture) | 13000 |
| Mainly sand (normal Moisture) | 300k to 800k |
| Chalk | 5000-15 000 |
| Sandstone | 8000-50 000 |
| Consolidated sedimentary rocks | 1000--50000 |
| Crystalline rocks | 20k to lOOOk |
| Concrete | $10^7$ |
| Granite | 10" |

*Moisture content:* The moisture content of soils normally varies between 5 % and 40 %. A variation of a few per cent makes a marked difference in the effectiveness of earth connections. This is especially true for moisture contents below 30 %. Table 13.4 [38] demonstrates this point.

The moisture content of any soil will vary for different localities. It may generally be taken to be 10 % in dry seasons and about 35 % in wet ones, with an overall average of about 17 %.

Figure 13.41 shows how the resistance value of a 'driven' earth varies with rainfall patterns. The particular region has its minimum rainfall in the northern hemisphere's winter and autumn. The increase in earth resistance over these periods is very obvious.

*Chemical composition:* Pure water is not a conductor of electricity. It needs impurities, like soluble salts, to decrease its resistivity. For example, the infinite resistivity of pure water is reduced to 2500 ncm by the addition of 0.02 % common salt

**Table** 13.4 Effect of moisture on resistivity

| *Moisture content % by weight* | *Resistivity* (Oem) *Top soil* | *Sandy loam* |
|---|---|---|
| 0 | $10^9$ | $10^9$ |
| 2.5 | 250k | 150k |
| 5 | 165k | 43k |
| 10 | 53k | 18.5k |
| 15 | 31k | 1O.5k |
| 20 | 12k | 6.3k |
| 30 | 6.4k | 4.2k |

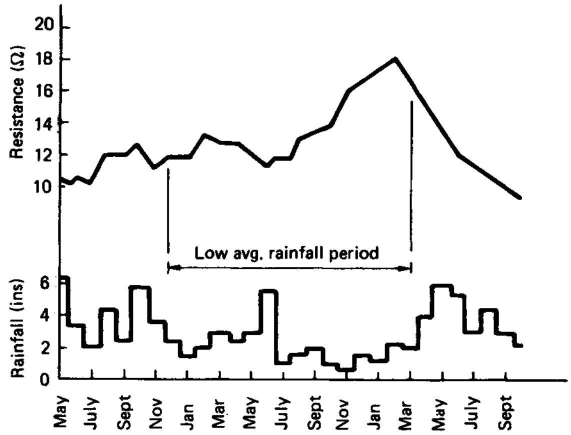



**Figure 13.41** Seasonal variation in resistance with rainfall

(NaCl), and to 300ncm by increasing the salt content to 0.2 % by weight.

Abundant rainfall in an area doesn't necessarily mean low soil resistivity. High seasonal rains may result in soluble salts being washed away or leached out - much in the same way as they are in the beds of running streams and rivers.

Having stated that the presence of salt reduces a soil's resistivity, it must be added that salt has a corrosive action on earth electrodes and for this reason both BS 6651 and CP 1013 recommend that it is not used.

One method that minimizes the corrosive effects uses treated soil not directly in contact with the electrode (see Figure 13.42). The soil may be treated with copper sulphate, sodium sulphate (gypsum), magnesium sulphate (Epsom salts), or sodium carbonate (washing soda) solutions. The disadvant-

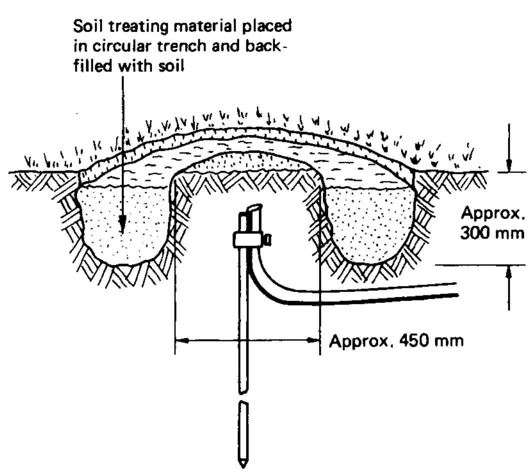



**Figure 13.42** Trench method of soil treatment

ages are that large volumes of solution are required and that they eventually leach out of the soil. The least corrosively agressive solutions are the sulphates. Of these, perhaps the cheapest, the most sparingly soluble, and one which provides adequate conductivity in solution, is gypsum. Sulphates have a deleterious effect on concrete and they should only be employed at safe distances from concrete foundations. If system layout makes this impractical, use washing soda.

The treated soil will need to be replaced after a few years, depending on the porosity of the local soil and on the rainfall. In Middle East territories rainfall is likely to be heavy over very short periods so that the chemicals will be leached out rapidly. It is, therefore, good practice to stipulate that treated materials should be replaced once every two years, coincident with the most recent rainy spell.

Table 13.5 [39] shows the resistivities of solutions of common salt, washing soda, and gypsum, in distilled water. Bear in mind that 500 to 1000ncm solutions are considered to be suitable for the treatment of electrodes.

By far the best method of reducing local soil resistivity is to use a soil-conditioning agent. There are several proprietary materials available, including *Bentonite* (Steetley Minerals Ltd) and *Marconite* (Marconi Communication Systems Ltd). Bentonite is a processed clay rock similar to 'Fuller's Earth'. It has the characteristic ability to swell to many times its dry volume when in contact with water. The result is suspensions of jelly-like consistency which, when stirred, become fluid but revert to the jelly form if allowed to stand. It is available in either powdered or granular form. The powder is mixed with water to give a 4 to 10% solution forming a gel of consistency similar to wallpaper paste. This slurry is backfilled into the excavated earth around the electrode and topped-up with local soil. In its granular form Bentonite may be used in one of two ways:

1. the granules are poured into the electrode excavation, this is followed by water and the excavation is capped-off with earth; or
2. the granules are mixed with locally cut soil and backfilled into the excavation.

Moisture is retained by the soil around the electrode for at least six months.

Marconite is an electrically conductive concrete or cement made with graded granular carbonaceous aggregate instead of conventional sand or aggregate. It has a resistivity of 10ncm.

Both Bentonite and Marconite are ideal for high resistivity soil conditions, especially where electrode rods cannot be driven deep into the ground because of the presence of hard rock or shales. In such cases holes are drilled to the required depth using a portable drill rig. The electrode is then inserted into the pre-drilled hole which is back filled with the soil conditioning agent - a grout in the case of Marconite (see Figure 13.43).

*Soil temperature:* We have established that the resistivity of soil is largely determined by its moisture content. Because water has a large negative temperature coefficient the resistivity of moisturized soil will increase as its temperature is decreased. If the temperature falls below freezing point the resistivity will rise sharply due to the high resistivity of ice. Earth electrodes should, therefore, always be installed below any predicted frost layer. Even when rod electrodes are driven below the frost line some variation in soil resistance is to be expected since the frozen upper soil has the effect of shortening the active lengths of the rods. Decreasing the soil temperature from 20°C to -5°C may result in a ten-fold increase in resistivity, as is shown in Table 13.6 for tests in a sandy loam soil with a 15.2% moisture content [38].

*Depth of soil:* Soil is seldom of uniform resistivity throughout its depth. Figure 13.44 shows the relationship between *calculated* resistance and depth for a soil of uniform moisture content at all depths. The greatest reduction in resistance is to be found in the first two metres of depth. This accounts for the fact that the most popular length of driven rod is 2.4m (8ft). Longer rods may sometimes be necessary but in most locations this depth is sufficient to reach permanent moisture.

The topmost layer, up to a depth of 1 metre, tends to have high resistance because it is subjected to alternate wetting and drying-out due to variations in rainfall. The soil at lower depths is more stable since it is unaffected by seasonal changes. In field

**Table** 13.5 Resistivity of solutions at 20°C

| | | *Resistivity* (Ocm) | | |
|---|---|---|---|---|
| % *solution* | *NaCI* | *Washing soda* | 95% *gypsum* | 99% *gypsum* |
| 0.24 | 250 | 667 | 715 | 590 |
| 0.12 | 500 | 1180 | 1250 | 1000 |
| 0.06 | 1000 | 2270 | 2220 | 1790 |

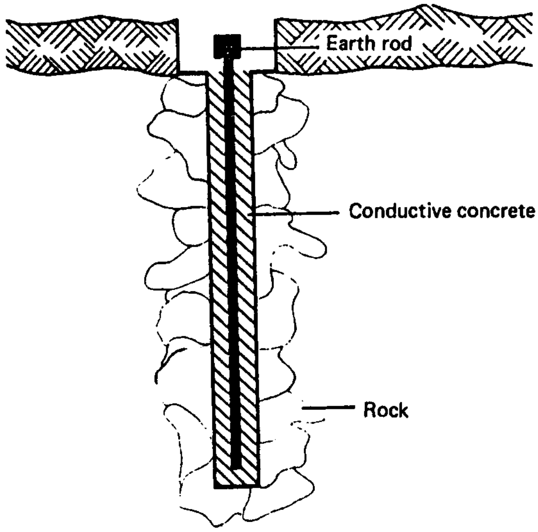



**Figure 13.43** *Marconite* used with conventional earth rod to provide increased loss-resistance contact area (Courtesy: Marconi Communication Systems Ltd)

**Table** 13.6 Effect of temperature on resistivity

| *Temperature* (''q | *Resistivity* (!lcm) |
|---|---|
| 20 | 7200 |
| 10 | 9900 |
| 0 (water) | 13800 |
| 0 (ice) | 30 000 |
| -5 | 79 000 |
| -15 | 330 000 |

conditions the advantage of depth becomes more pronounced because moisture content tends to increase with depth.

*Types of earth terminal network.* Various methods of earthing may be employed. The main ones are:

- deep driven earth rods;
- parallel driven earth rods;
- buried conductors (tape/strip or wire);
- buried plates or mats;
- cast iron earthpipe electrodes; and
- the networks of steel reinforcing rods and tie wires in concrete foundations.

The method to be used at a given site must be governed by the physical nature of the ground and the resistance of the soil. The nature of the ground and the site available for the termination influence the decision as to which type of electrode is to be used. Soil resistivity will control the extent of the electrode system necessary to achieve the required

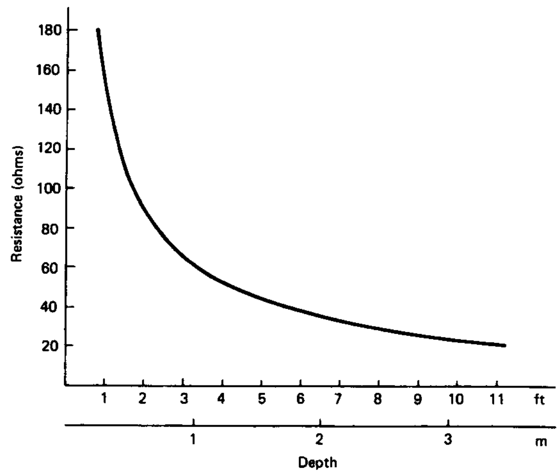



**Figure 13.44** Relationship between depth and resistance of driven earth rod for a soil with uniform moisture content at all levels (Courtesy: W.J. Furse & Co. Ltd)

earth resistance value - between 1 and 2 0 for large prime power systems; less than 50 for smaller prime power plants, and 100 for lightning protection networks. On standby and emergency generator installations much depends upon the supply system adopted by the utility or electricity board. Because there can be significant variations in this respect it is recommended that an additional electrical earth should be provided by the user of a generator [40]. The resistance to earth should not exceed 200 (UK) or 25 0 (American National Electrical Code).

*Driven earth rods:* metallic rods are the most widely used type of electrode for earthing power installations and lightning protection systems. Proprietary rods are available in modular lengths from 1.2 to 3.0 metres. Extensible deep-driven rod electrodes offer the most economical means of reaching permanent moisture and frost-free soil levels. They may be driven into the ground by hand or by rig-mounted hammers powered electrically, pneumatically or by i.c. engines.

Where a single rod does not provide a low enough resistance path to earth several electrodes may be driven at suitable distances apart and linked together to obtain the value of resistance required.

Because a rod occupies such a small space the voltage gradient (or *step potential)* caused by substantial earth fault or lightning discharge currents is confined to a small surface area of the ground. The risk of lethal shock is therefore reduced. (The step potential is the potential difference, measured in volts, that exists between the feet of a person standing near the electrode whilst the fault or discharge current is being dissipated in the soil.)

Earthing rods may be divided into two types: those made from base metals such as steel, cast iron and nickel; and those made entirely of copper, or which have a copper bond on a base metal core.

Zinc-galvanized steel rods suffer from the disadvantage that a poor-quality plating can be damaged by driving. Although plain steel driving rods are some 45 % cheaper than copper rods, they are not popular because of rusting and their poor general appearance. They are often used to earth steel tanks. Austenitic stainless steel rods offer high resistance to galvanic action but are expensive compared with copper-based rods. Perhaps the most popular form of base metal rod is that made from a cast iron-nickel alloy. The one snag is that blow holes in the cast iron may lead to troubles with broken rods. One proprietary rod electrode uses extensible steel tubes to the bottom of which a copper tape or stranded wire conductor is jointed. The steel tube remains in the ground after driving. One problem with this arrangement is that, because of the rather bulky copper connection at the base of the tube, hardening of the tape/wire conductor can occur when the tube is being driven, especially in hard grounds. If this happens the copper conductors tend to pull out [41].

Copper rods are available in three general categories:

1. solid copper;
2. steel-cored rods with an unbonded copper sheath or tube; and
3. steel-cored rods with a thick weld-bonded copper coating.

Solid copper rods are expensive compared with the other types. They are not generally suitable for driving into hard grounds because they tend to deform at their dowel-screwed joints. The driving heads are also prone to push into the rods (see Figure 13.45(a».

Copper sheathed rods (2) have a tendency to strip-back their sheaths when driven into hard ground. For this reason they are not as reliable as rods in the third category, which are the most commonly used because of their good all-round performance in terms of conductivity, ease of driving, and stability in the soil. Figure 13.45(b) illustrates one of the many proprietary designs available.

It should be noted that the effect of rod diameter on electrical characteristics is negligible. For example, doubling the diameter of a rod reduces its resistance by just under 10%. Weighed against this is the increased mass and cost of the rod (four times). The soil surrounding the electrode, and not the rod's diameter, is the major factor in determining the electrode's resistance. In the light of the resistance variations likely to occur over a period of time (due to changes in weather and soil conditions), the contribution from a larger diameter rod is relatively insignificant. Always select the thinnest rod that soil conditions will allow to be driven.

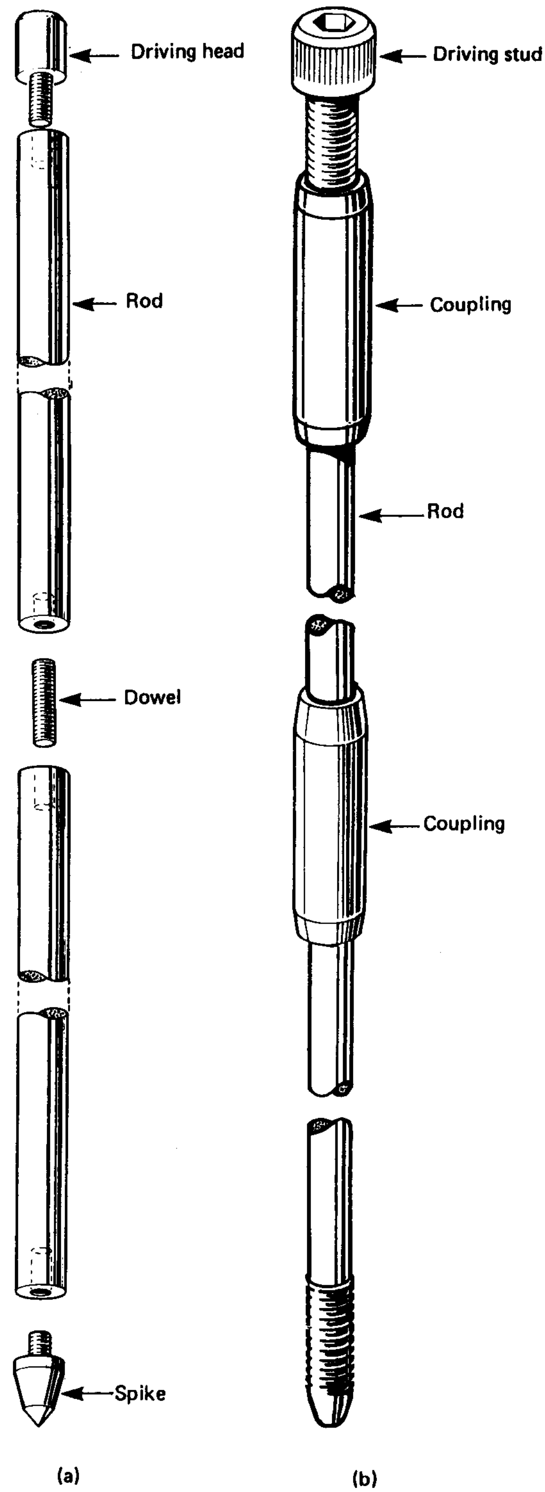



**Figure 13.45** Examples of copper earth rods (a) Solid copper (b) 'Copperbond' (Courtesy: W.J. Furse & Co Ltd)

*Installation aspects:* Earthing conductor connections to electrodes must be protected against mechanical damage and corrosion. Accidental removal of these connections should be avoided, by using a durable label reading SAFETY ELECTRICAL CONNECTION - DO NOT REMOVE. See Figure 13.46 which illustrates typical connections and proprietary inspection pits.

*Resistance values*

Rod electrodes: As mentioned earlier, many different formulae are in existence for calculating the resistance of rods in homogeneous soils. A typical one giving approximate resistance values for

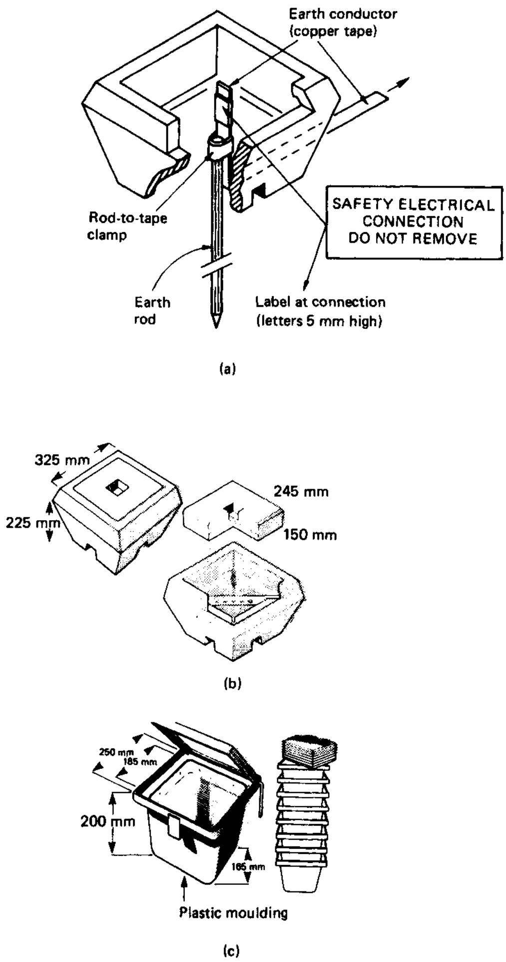



**Figure 13.46** Earthing conductor connection; and proprietary inspection pits (a) Connection of earthing conductor to earthing electrode (b) Concrete inspection pit (c) Galvanized lid inspection pit (Light duty) (Courtesy: W.J. Furse & Co. Ltd)

cylindrical rods driven into untreated soil of uniform resistivity [38, 39] is:

$$Re = (p/275L) \times 10glO(400Lld)$$

Where $Re$ = apparent earth electrode resistance, in ohms
p = soil resistivity, in ohm-cm
$L$ = length of electrode, in metres
$d$ = diameter of rod, in centimetres

In practice, it is extremely unlikely that a single rod will give a sufficiently low resistance value for a power system earth. More than one rod is usually necessary. These are linked together by conducting tapes or strips to form a grid or matrix arrangement. The distance between rods needs to be at least equal to 1.5 times their driven depth. No significant decrease in resistance is achieved by using a spacing in excess of twice driven depth. Because of the mutual influence of the overlapping electrode fields in the earth the usual law of parallel resistance cannot be applied. The graph of Figure 13.47 may be used to determine the earth resistance for multiple-rod installations (spaced 1.5 $L$ apart), and is based upon the use of a reducing factor *'K'* defined as:

$$K = RT/R$$

Where $R_T$ is the total resistance of the paralleled rods, and
$R_E$ is the mean value of the earthing resistance of the individual electrodes

In areas of low soil resistivity the required number of paralleled rods may be small. If, additionally, space prohibits large inter-rod distances, it may be possible to use one of the configurations shown in Figure 13.48. The accompanying graph enables res-

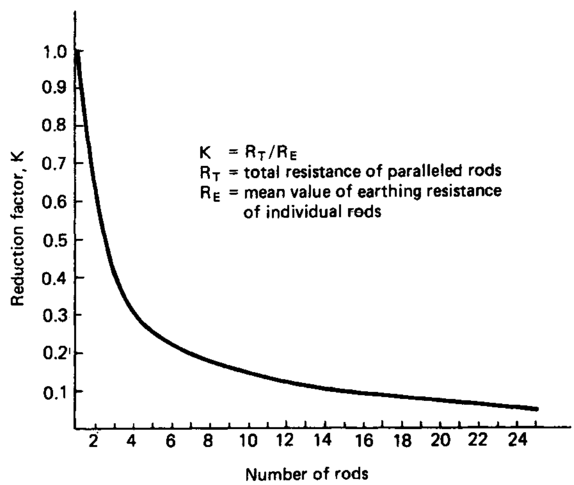



**Figure 13.47** Resistance reduction factor for numbers of electrodes in parallel

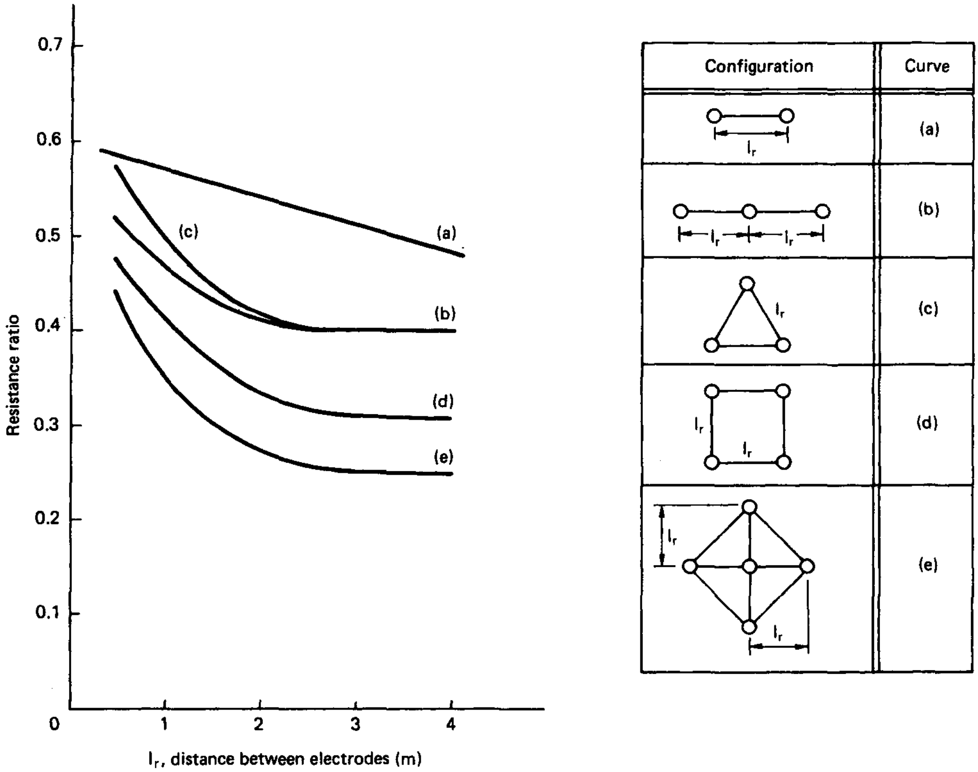



**Figure 13.48** Resistance ratio for various earth electrode configurations

istance computations to be made for each configuration [42]. The term 'resistance ratio' is defined as:

(the earth resistance of an array of electrodes) -:- (the earth resistance of a single electrode)

The assumption made is that all the electrodes in an array are of similar size and shape.

Calculations for more complex arrays using combinations of rods and horizontal tapes can be very complicated, especially when it is necessary to use two values for p - one for the rods and the second for the horizontal conductors. In such cases the approximate total resistance of the array may be taken to be 15% less than the value obtained from the graph in Figure 13.47 when using bare horizontal conductors.

*Buried or horizontal strip conductors:* Buried radial electrodes are best suited to those sites where there is only 1 to 1.5 metres of soil depth above bedrock. Values of earth electrode resistance may be calculated using the following formulae.

1. for rectangular-section strips:

$$R_e = (\rho/275L) \times \log_{10}(200L^2/wD)$$

2. **for circular-section strips:**

$$R_e = (\rho/275L) \times \log_{10}(100L^2/dD)$$

Where $Re$ = apparent earth electrode resistance (O)
p = soil resistivity (Ocm)
$L$ = length of electrode (m)
$w$ = width of electrode (cm)
$D$ = depth of electrode (m)
$d$ = diameter of electrode (cm)

For the same cross-sectional area, circular strips or wires are not as efficient as rectangular tapes - in terms of resistance.

High conductivity conductors in annealed copper tape are available in widths of 1.25 up to 5.0 cm. The common thickness for all widths is 3 mm but the four largest widths are also available at 6 mm.

In order to minimize the effects of seasonal variations in soil moisture, strip conductors should be laid at least 1.5 m below surface. Installation can be expensive since it necessitates the excavation of trenches. The cost is reduced if the strips can be back filled into trenches that are otherwise provided for cables or piped services.

Where horizontal conductors are used to connect multiple driven rods, they need only be laid 0.5 m below the surface. Aluminium or copper-clad aluminium conductors should not be employed as final connections to earth electrodes (lEE Wiring Regulation 542-17).

The table in Figure 13.49 [52] gives the correction factors to be applied for systems using L, Y and X tape formations.

*Buried plates or mats:* The resistance formula for a horizontally laid plate r521 is:

$$R_e = (\rho/420) \times [(1/WL) + (0.16/D)]$$

Where $R_e$ = apparent earth electrode resistance (Ω)
p = soil resistivity (!km)
$W$ = width of electrode (m)
$L$ = length of electrode (m)
D = depth of electrode below surface (m)

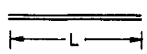
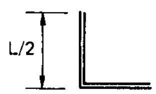
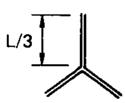
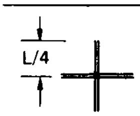
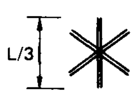
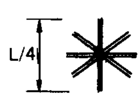
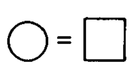
| Configuration | Total resistance (related to $R_E$ for straight L) |
|---|---|
|  | $R_E$ |
|  | $1.03R_E$ |
|  | $1.06R_E$ |
|  | $1.12R_E$ |
|  | $1.42R_E$ |
|  | $1.65R_E$ |
|  Perimeter = L | $1.10R_E$ |

**Figure 13.49** The earth resistance values for tapes connecting symmetrically-disposed multiple earth electrodes

Solid copper earth plates are available in standard sizes 600 mm x 600 mm and 900 mm x 900 mm in both 1.5 and 3 mm thicknesses. Latticed plates made from copper tape are also available in similar overall sizes and cost half as much as solid plates. Their effective resistances are 30 % higher.

Earth plates have been superseded to a large extent by driven rods and horizontal conductors because, for the same effective resistance, they are uneconomical in terms of material and on-site excavation costs. For example, the material cost of a solid plate is 10 times that of rod electrodes, and 50 % more than tape conductors.

*Cast iron earthpipe electrodes:* The metalwork of buried pipes in public gas and water services should not be used as an earth electrode. This is because of the risk of discontinuity due to the increasing use of plastic pipe sections and joints/gaskets in such services. The metalwork must, however, always be bonded to the main earth terminal in the installation (see Sub-section 13.9.2).

Soil conditions permitting, effective use can be made of cast iron pipe electrodes. When this type of electrode system is used it should not be located within 5 m of other metalwork unless the latter has been especially protected against corrosion.

*Metallic reinforcement of concrete foundations:* In areas of high soil resistivity the most economic earthing method is perhaps the use of the mass of concrete-encased metal within a building's foundations and footings. Not only is the concrete a better electrical medium than most earth materials, but it also protects the steel reinforcing bars, stirrups, and mesh reinforcement from corrosive disintegration. Metal reinforcement provides a unified and extensive electrode. lEE Regulations, British Standard Codes of Practice CP 1013 and BS 6651, the American National Electrical Code (NFPA 70-1987) and ANSI/IEEE 142-1982 (see Bibliography) all recognize the use of concrete foundations for electrical earthing.

Wright [43] cites a raft foundation measuring 80 m x 29 m founded 3.5 m below ground level as having a resistance to earth of 0.1 O; and that even buildings founded on basalt lava flows have measured resistances to earth between 0.5 and 3.00.

ANSI/IEEE Std 141-1986 [26] suggests that the reinforcing bars (re-bars) of foundation piers have been shown to have half the resistance of a rod electrode driven to the same depth in earth. Earthing conductors may either be fusion welded to a vertical trimmer bar, or a J-clamp of the type shown in Figure 13.39 may be used to make a connection to that bar or to the column base plate.

Avoid welding to those bars which are required to provide structural strength and are therefore under appreciable tension; and do not weld to any prestressing cables within the reinforced concrete.

[26] also offers the following rule of thumb for determining the effective overall resistance afforded by footings: divide the resistance of one typical footing by half the number of footings around the perimeter of the building. (Inner footings contribute little to reduction of the overall resistance because they are not directly exposed to the moisture of the soil surrounding the building.)

Scuka [44] offers the following formula for approximating the value of earthing resistance for an installation using the grid metalwork of reinforced concrete foundations:

$$R_e = \rho/[1.57\ \pi(V)^{1/3}]$$

Where $V$ is the volume of earth within the construction area ($m^3$). ρ is in Ωm.

On those sites where bore holes have been drilled for soil investigation purposes or where holes have been excavated for foundation piling, these could be used to locate conventional plate or rod electrodes before being back filled.

### *Thermal capacity of earth electrodes*

The high current densities ($j$) caused by high fault currents not only create high voltage gradients in the soil ($\rho/j$ volts/metre), but they may also cause plasma channels (*streamers*) to build up in the soil. The critical current density, $j_c$, at which these streamers first develop may be calculated using the following expression [44]:

$$j_c \simeq 5 \times 10^5/\rho\ [A/m^2], \text{ where } \rho \text{ is in } \Omega m.$$

The streamer phenomenon can be of great practical value where large prospective fault currents are likely to occur in deep-driven earthing systems, especially where soil resistivity is high. Its effect is to reduce the value of electrode resistance. The graphs in Figure 13.50 [44] show the typical relationship between ratio $R_{eff}/R_e$ and fault current in measurements taken on earthing installations in various types of soil.

$R_{eff}$ is the effective resistance of the earthing installation at high current density and $R_e$ is the resistance at low current density.

Curve A is for stone, clay where $R_e$ is 50–180 Ω, curve B is for gravel, stone, clay where $R_e$ is 70–120 Ω, and curve C is for sand where $R_e$ is 70–120 Ω. The depth of driven-earth was 2.4 m in each case.

The hysteresis characteristic of a typical current/voltage curve at high current density is illustrated in Figure 13.51 [44]. This shows that $R_{eff}$ only returns to its high level ($R_e$) when the current density falls to a level below $j_i$. In other words, the reduced resistivity of the soil does not return to its high initial value until the current falls considerably below the critical current level which started the streamer formation.

Whatever the earth system type, it is essential that electrodes are adequately rated to safely carry the prospective fault current (more so if one is to benefit from the streamer phenomenon). Faults should be cleared by protective devices before electrode temperature reaches 100°C because at that temperature any moisture in the immediate soil around the electrode is driven off as steam, which is a good insulator. The result is complete failure of the electrode.

The heat produced by the passage of fault current in an electrode is absorbed by the metal of the electrode. The temperature rise of the electrode is regulated by the specific heat and the resistivity of the metal, and by the cross-sectional area of the conductor. The following expressions give

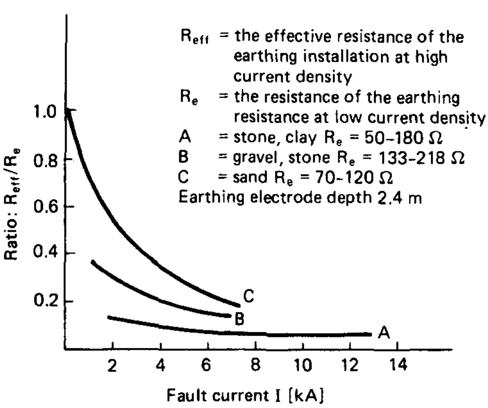



**Figure 13.50** Relationship of ratio $R_{eff}/R_e$ to current density in various soils (Courtesy: AB E. Skoglunds Tryckeri)

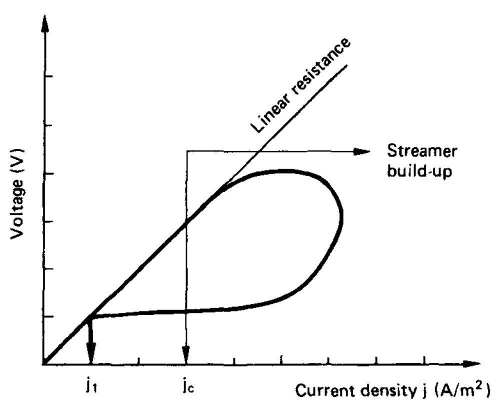



**Figure 13.51** The hysteresis characteristic of the current/voltage curve, at high current density (Courtesy: AB E. Skoglunds Tryckeri)

approximate values of the permissible current densities of solid copper and steel-cored copper bonded electrodes, assuming a temperature rise 50°C above ambient.

$$\text{for solid copper} \quad j = 90/\sqrt{t} \quad [\text{A/mm}^2]$$
$$\text{for copper bonded} \quad j = 65/\sqrt{t} \quad [\text{A/mm}^2]$$

Where $t$ is the duration of the earth fault (in seconds).

Because of the extremely short duration of lightning discharges thermal factors are of little consequence and the current-carrying capacity of electrodes is not as important as it is in power system earthing installations (BS 6651).

In summarizing these discussions we may liken the earthing system to a chain. We know that any chain is only as strong as its weakest link. It is important, therefore, that system design ensures there are no weak links in the *earthing chain* between the fault and the point(s) at which the fault current is dissipated into the ground. The following requirements must be met [45]:

### *Earthing conductors*

- must not fuse or melt during the fault
- must be mechanically strong to prevent physical damage
- must have low resistance to prevent dangerous potentials

### *Connections*

- must have a current rating no less than the earth conductor( s)
- must not deteriorate with age
- must be capable of withstanding repeated faults

### *Earth electrodes*

- must be of adequate size, quantity, and material to carry the prospective fault currents
- must be at sufficient spacing and depth
- must be corrosion resistant

### *Soil*

- must have as Iowa resistance value as possible, and
- seasonal changes in resistivity must be catered for.

## 13.9.3 Fire protection

Every country has its own codes, standards, laws and regulations governing the design of buildings for fire prevention, and codes of practice for the provision of fire detection and alarm systems and for fire extinguishing equipment. Insurance companies underwriting the installation's insurance are usually valuable sources of information on the requirements to be met in various countries. Also, advice may be sought from the British Standards Institution's *Technical Help to Exporters* service (see Sub-section 13.9.1) ..

A common-sense approach should be used beyond meeting legal and insurance requirements. The primary objectives must be to avoid conflagrations, to restrict damage to localized areas, in the event of a fire occurring, and, above all, to protect life.

### *Legislation*

The main acts and regulations in the United Kingdom which affect the design of premises for fire protection are [46]:

1. The Factories Act, 1961 (Sections 40-52). It requires certification by the local fire authority of the adequacy of the means of escape, provision of apparatus for giving alarms and calling the fire brigade, and the provision of fire fighting equipment. Section 148 empowers local fire authority personnel to enter premises to inspect fire risks and the precautions taken to control them.
2. The Fire Precautions Act, 1971 - Designating Order S.l 1972 No. 238.
3. The Highly Flammable Liquids and Liquefied Petroleum Gases Regulations, 1972.
4. The Health and Safety at Work, etc. Act, 1974.

*Standards and codes.* In the United Kingdom fire protection installations would be required to comply with the standards and codes of practice prepared by such bodies as the British Standards Institution, the Fire Officers' Committee, the Home Office Scientific Advisory Board, the Insurance Technical Bureau, the Fire Insurance Research and Technical Organisation (FIRTO), and individual insurance companies.

### *General requirements for building design*

The degree of fire resistance required for the structure will vary with local requirements. It is only possible to briefly mention those design features that are considered to be 'good practice' in the context of buildings housing power plant [46].

1. Structural steelwork should be encased in concrete, brickwork or thermal insulating material.
2. External walls should be non-combustible and have a fire resistance of at least two hours.
3. The walls and floors of switchrooms, control rooms, workshops and offices, etc. should be of one hour fire-resisting construction and finishing materials should be fireproofed. Doors should be no less fire resistant than the walls themselves.

Where ducts and cables penetrate walls and floors the openings should be sealed with non-combustible material.

4. Roof coverings should be of non-combustible material.
5. Because of the real risk of fuel and lubricating oil spillage the floors of plant rooms and generator halls should be finished with a screed which is non-oil-absorbent.
6. Lubricating and fuel oil storage/treatment areas require a fire resistance of at least four hours. Storage areas should be at least 6 m from the main power plant building.
7. Provision should be made for releasing smoke and heat from generator halls and basements housing auxiliary plant as an aid to fire fighting personnel. This is usually achieved by providing special fire vents in the roof of the hall and smoke extractor fans in the basements.
8. Great emphasis is rightly placed on the provision and design of personnel escape routes. The following principles should be observed :
   (a) All escape routes should be as short as possible «30 m) and provide safe egress to open air at ground level, either direct or via well ventilated, fire-resisting stairways, corridors or enclosures. The aim should be to permit all personnel using a particular route to reach a safe area in less than two minutes. The minimum width needs to be 750 mm.
   (b) At least two escape routes should be available to everyone in the building. This allows for the possibility of one route being made unusable because of penetration by smoke or fire.
   (c) Stairways, corridors or lobbies forming part of an escape route should be enclosed and 30-minute fire rated. Self-closing doors should be provided at the entrance and exit to lobbies and at intermediate points on long corridors.
   (d) Fire escape routes and exits should be clearly identified as such. Doors must be designed to be easily opened from the inside, and should open outwards. A clear distinction should be made between escape doors and those which must not be opened in the event of a fire. King and Magid [46] suggest that escape doors are painted green to distinguish them from the conventional red colour of those which are to be kept permanently closed. Personnel must be trained to recognize the difference.

### *Fire-protection systems*

Four classes of fire are recognized by BS4547. The purpose behind the classification is to rationalize the choice of extinguishant and fire-fighting apparatus and the precautions to be taken in fire protection and fire fighting. The classes likely to occur in generator installations are:

- Class B: Flammable liquids. The most common causes are leaks of fuel and lubricating oil onto ignition sources, such as hot exhaust manifolds, unlagged turbochargers and exhaust piping.
- Class C: Gases. This applies to gas fuelled and dual-fuel engines. Causes usually stem from leaking or fractured gas supply piping.
- Electrical fires caused by the overheating of apparatus (overloaded cables and poor connections, etc.) leading to the ignition of insulation, or of vapours, dust, fluff and other combustible materials. The British Standard does not recognize an electrical fire. An 'unofficial' Class E is used to cover fires involving live electrical equipment.

### *Fire-extinguishing media*

Water should not be used on live electrical fires. It is best suited to fires on solid materials which are liable to re-ignite if not sufficiently cooled. Fuel and lubricating oils are lighter than water and do not mix with it but float on it. Water will not extinguish fires involving these liquids. It will merely cause them to spread into surrounding low lying areas - basements, drains, etc.

High expansion and medium expansion foams act to smother and blanket a fire. They are very effective against Class B fires but because the foams conduct electricity they should not be used on Class E fires. The one big difficulty with their use in fixed fire-protection systems is that of conducting the foam to the seat of a fire. Large ducts are required between the foam generators and the extinguish ant distribution points.

Dry chemicals or powders such as sodium or potassium bicarbonate are effective against both Class B and Electrical fires (because they are non-conductive). The powder is driven by pressurized gas (usually $CO_2$) through a system of piping to nozzles sited in areas of known risk within the machinery spaces. There are certain disadvantages in the use of powders [46]:

- if there is delay in starting the system and the distribution pipes get hot, there is a danger of the dry chemicals 'fusing' in the pipes and causing blockage;
- the chemicals may have a deleterious effect on some machinery;
- once the powder has settled there is virtually no extinguishing effect and there is a risk of re-flashing occurring.

Gas extinguishers act either to reduce the oxygen content of the atmosphere or to interrupt the chemical reaction in a flame. They are excellent for dealing with both Class B and Class E fires and are innocuous to the types of machinery and equipment used in generating plant. Typical agents are carbon dioxide and halogenated hydrocarbons such as Halon 1211 (BCF) and Halon 1301 (BTM).

The major disadvantage with $CO_2$ is that because it lowers the oxygen content of the air it has an asphyxiating action on people who may be present during its discharge. The decomposition products of the Halons on exposure to flame or hot surfaces can be hazardous - those from Halon 1211 being slightly more so than than those from Halon 1301. It follows that all personnel must be evacuated from an area before any gas discharge begins.

The gases are stored in cylinders of various capacities. These may be manifolded together to give the quantity of gas required for the hazard area. Where protection is to be provided for large fire-risk areas bulk storage should be considered. $CO_2$ gas is stored in refrigerated tanks at low pressure (18 bar) at a temperature of -18°C. Although the discharge can give a 'cold shock' to warm engines and generators, the method has several advantages over the alternative multi-cylinder approach:

- reduced capital outlay;
- less space required;
- delivery of gas by road tanker reduces recharging time and costs;
- additional reserVe capacity can be economically designed-in.

In bulk storage Halon systems the liquified gas is stored in an unpressurized tank sealed with a bursting disc. Banks of nitrogen cylinders discharge, when activated, into the tank and raise its pressure sufficiently to rupture the bursting disc and provide a controlled discharge to the protected area.

In every case, gas is discharged through 'balanced' pipe runs to horns or nozzles located within the protected area. Gas containers may be actuated by hand, electrically or pneumatically.

Unfortunately, not sufficient attention is given to reserves and, all too often, installed quantities are only sufficient for one extended discharge. This means that once the charge is expended the fire-risk areas are deprived of further extinguishing capability. Too much reliance can be placed on the speedy provision of recharged $CO_2$ cylinders. Incidentally, besides being less expensive than the Halon gases, the big advantage of $CO_2$ is its wide availability throughout the world. This is not the case with Halon gases.

There are two basic methods of treating hazard areas in machinery spaces:

1. by total flooding; and
2. by local application.

The total-flooding system is best suited to small plant rooms or to ISO containers housing standby generators. As its description implies the system protects an area by rapidly flooding it with agent gas. Flames are normally extinguished within 15 seconds. Openings such as doors and windows should be closed, but it is possible to have screening nozzles installed to discharge the gas across these openings. The curtain of gas gives the equivalent effect of closing them. Controls may be arranged to shutdown mechanical ventilation systems during gas discharge.

The local-application technique (mainly confined to Halon gases) may be used to protect generators located in large areas which are uneconomical to flood entirely. Discharge horns may then be placed over individual generating sets and at those points (such as fuel service tanks) to which the fire may be expected to spread. A British firm (Critchley Ltd.) markets an automatic fire extinguishing system designed for use in switchgear and controlgear cabinets, engine compartments, and other confined areas. The extinguish ant (Halon liquified gas) is contained in a pressurized canister. A trace tube made of specially formulated plastic, connected directly to the cannister and secured by cable ties above the likely source of fire, acts as a local heat sensor. Its surface softens in the presence of heat and the pressure of the gas forces the tube wall to rupture. The extinguishant gas sprays through this hole directly onto the heat source.

Control systems are designed to comply with B55306 (Part 4 for $CO_2$; and Parts 5.1 and 5.2 for Halon 1301 and 1211, respectively). Safety features include:

- Adjustable time delay for release of the agent, to allow personnel to evacuate the area
- So-called 'double knock detection' - in which the protected area is split into two zones. The discharge system cannot be actuated until incipient combustion has been detected in both zones. The first zone raises an initial alarm (and closes down any ventilation systems). The second zone initiates a separate alarm, and starts the gas discharge procedure.
- An 'automatic control isolation' facility, whereby the automatic gas release control may be inhibited whilst the area is occupied by personnel.
- An emergency manual control of the system.
- The automatic monitoring of all critical circuits for open and short circuits, e.g. detection, release, alarm and remote manual release circuits.

A variety of fire detectors are available (BS 5445 and BS 5446). These include optical and ionization smoke detectors, fixed temperature and rate-of-rise heat detectors, infra-red and ultraviolet radiation detectors, combustible gas detectors, and fusible links. Choice is governed by the need to discriminate between a fire and the normal environment that exists within the building or machinery space. It is important to know the limitations of the detectors in order to plan their location and the numbers to be employed. BS 5839 should be the starting point in any design planning exercise.

Discussions have intentionally been confined to plant rooms and machinery spaces. On the larger power stations it will be necessary to consider the special needs of other areas such as offices, control rooms, switchgear rooms, workshops, and stores. Guidance on specifications for fire alarm, control and indicating equipment is contained in BS5445: Part 5 and in BS 5839: Part 4. It is advisable on the larger installations to consider a central panel which brings together the key information from all the protected zones in the complex. The precise location of a fire having been established, decisions may then be made to evacuate the areas immediately threatened. In this context it is advisable to include flashing visual alarms in addition to the conventional audible alarm devices (bells, sirens or electronic sounders) in those machinery spaces where high ambient noise levels exist.

It is necessary to be able to deal quickly and efficiently with very small and localized fires before they develop into major incidents. This is best done by providing portable fire extinguishers at stategic points in the installation and made available for immediate use by well-trained plant personnel. Perhaps the two most versatile types for power plants are carbon dioxide (colour code: black) and Halon BCF (colour code: green). Dry powder extinguishers (colour code: french blue) have excellent 'knock-down' properties for fires involving flammable liquids and are safe for use on electrical fires. They are rather messy and can damage delicate electrical equipment by injecting powder into moving parts and circuits [47]. Caution should always be exercised in extinguishing gas fires. James [47] suggests that it may be better to let a gas leakage burn until the escape can be stopped by closing a valve rather than extinguish the flame and allow flammable gas to build-up in an enclosed space where it may cause a serious explosion. See also Sub-section 13.6.1.

BS 5423 and BS 5045 are the British Standards applicable to portable fire extinguishers. Reference should be made to code of practice BS 5306 when considering where to site extinguishers.

A useful method of smothering small fires is by the use of a fire blanket made from a glass-fibre material. Blankets are available in small cylindrical containers or in flat-packed satchels. Heavy duty industrial types to BS 6575 should be specified.

### 13.9.4 Lighting

The primary factor in the design of interior lighting is that there should be sufficient light, whether natural or artificial, in every part of the premises to allow work tasks to be undertaken effectively and safely at all times. Satisfactory illumination depends very much upon the proportions of the area being lit and on the nature of internal finishes.

The mandatory regulations in the United Kingdom (Section 5 of the Factories Act 1961 and the Factories (Standards of Lighting) Regulations, Statutory Rules and Orders No. 94: 1941) require the lighting levels to be 'sufficient and suitable for the nature of the work', without a precise indication of what is *sufficient.* It is customary to regard the Illumination Engineering Society (IES) *Code for Interior Lighting* and the Chartered Institution of Building Services *Interior Lighting Code* as being representative of present requirements. The installation designer should consult either code before planning his lighting schemes.

The BSI code of practice BS 8206: Part 1 describes the processes concerned with artificial lighting design, considers the particular lighting requirements of various types of buildings and recommends methods of meeting them, and deals with some aspects of installation. BSDD73: 1982 deals with design of daylighting in buildings and artificial lighting systems to supplement available daylight.

In the context of artificial lighting, metal vapour discharge lamps create a stroboscopic effect on rotating and reciprocating objects causing them to appear to be running slowly, to be stationary, or even to be running backwards. This could be a safety hazard in areas such as workshops and plant rooms. The effect is overcome by ensuring that adjacent lighting fixtures are fed from different phases of a three-phase supply.

#### *Emergency lighting*

One important aspect of interior illumination is that relating to emergency lighting. Both the Fire Precautions Act of 1971 and the Health and Safety at Work, etc. Act of 1974 empower a local authority to insist on the installation of emergency (escape or evacuation) lighting. Code of practice BS 5266 forms the basis for local Fire Regulations requirements in the United Kingdom. The more important of its recommendations are:

#### *Positioning of luminaires*

1. Luminaires should be located to indicate clearly and unambiguously the designated escape routes, and provide illumination along such routes to allow safe movement towards and through all exits. They should be located to avoid glare and positioned not lower than 2 m above floor level.
2. A luminaire should be sited near each exit and emergency exit door and at those points where it

is necessary to emphasize potential hazards along the escape route. For example:
(a) at intersections of corridors and at changes of direction en route (other than on a staircase);
(b) at each staircase so that each flight receives direct illumination, and at any change of floor level which may constitute a hazard;
(c) outside, and close to, each final exit point.

3. All fire alarm points and fire-fighting equipment along the escape routes should be adequately illuminated.

*Directional signs*

4. Signs are required to ensure that escape routes may be easily recognized and followed from any position within the premises, during an emergency.
5. All exits and emergency exits should be indicated by illuminated signs bearing the legend EXIT or EMERGENCY EXIT as appropriate.
6. Where direct sight of an exit is not possible an illuminated directional sign or signs should be provided and should be so placed that personnel moving towards each sign are progressed towards an exit by a suitable legend and arrow. Painted signs may be used provided they are illuminated at all material times and on failure of the mains supply are illuminated by emergency lighting.

*Level of luminance*

7. The minimum level of luminance at floor level along the centre line of an escape route must be 0.2lux (lux = lumen/$m^2$) - the equivalent of bright moonlight. One must bear in mind that this level may not be sufficient in plant areas because of the possibility of obstructions on some passage-ways in the near vicinity of escape routes during the first few critical moments of normal lighting failure.
*(Note:* Lighting equipment manufacturers publish data in chart form giving the maximum spacings permissible between luminaires to achieve the minimum 0.2lux. One must ensure that the data are based on end of rated discharge voltage i.e. after either 1 or 3 hour durations)
8. The maximum diversity ratio (or the uniformity ratio) between the luminance directly below a luminaire and that mid-way between two should not exceed 40:1.

Before commencing detailed design work on an emergency lighting installation, the local Fire Prevention Officer should be consulted in order to obtain overall approval of proposals.

## *Choice of system*

The installation designer has two power options for an emergency lighting system. Choice lies between:

1. a self-contained (or single-point) system; and
2. a central battery system.

*Self-contained system:* In this system use is made of self-contained luminaires comprising lamp, battery, automatic charger/inverter, and supply changeover device - all in the one housing. Installation costs are low because the battery which provides power to the lamp on mains failure is contained within the luminaire. If the luminaires are wired into the normal lighting circuits they operate not only in the event of total mains failure but also when a local circuit failure occurs. See the comments on circuits at the end of this sub-section.

Other advantages of the system include:

- ease of extension, when required;
- each unit operates independently of the others;
- no maintenance required, apart from periodic functional checks and routine cleaning;
- fail safe operation of wiring;
- a battery room is not required; and
- protected wiring is not required.

The disadvantages are:

- the restricted battery life (5-8 years for sealed nickel cadmium and 4-5 years for sealed 'maintenance-free' batteries);
- the luminaire ambient temperature range is normally restricted to between O°C and 25°C because of battery characteristics. Raising the ambient temperature to 50°C will, for example, reduce the charge acceptance by some 25 %, which affects not only the battery life but reduces the duration period (defined later);
- *standard* units cannot be switched automatically or manually to prevent unnecessary discharge of the batteries during a period of mains failure during daylight hours or when the premises are unoccupied.

Emergency luminaires may be operated in one of three modes (see Figure 13.52).

1. *Non-maintained (NM):* in which the lamp (or lamps) are illuminated only when the mains power source fails.
2. *Maintained (M):* in which lamps are illuminated at all material times and automatically switch to battery supply when mains power fails. The same lamps are used on both battery and mains power.
3. *Sustained (S):* these are the same as non-maintained units but for the addition of separate and independent lamp(s) powered direct from the mains. Operation is as follows:
   - mains powered lampes) extinguish when the mains power fails;
   - the remaining lamp(s), which are battery powered, illuminate automatically on mains power failure.

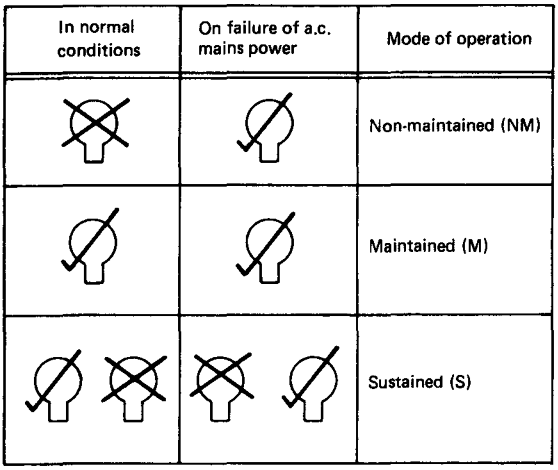



**Figure 13.52** Modes of operation for emergency lighting luminaires

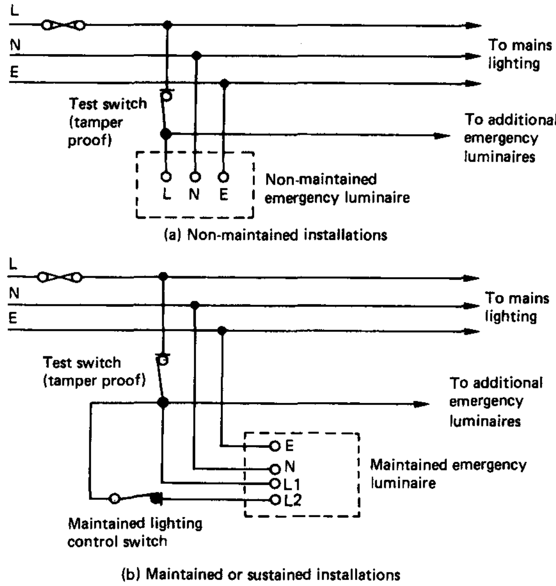



**Figure 13.53** Wiring installation details for emergency lighting installations

Illumination is thus 'sustained' at all material times.

All three operational modes are possible with both self-contained and centralized battery systems. For most generator plants either maintained or non-maintained systems will prove to be equally satisfactory.

Systems may be rated for 'duration periods' of 1 hour or 3 hours. In statutory terms, 1 hour rated luminaires need only be installed in power plants, since they are non-residential premises. In practice, it is usual to fit 3 hour units as the cost difference between 1 hour and 3 hour self-contained luminaires is not significant. Recommendations are contained in BS 5226 and the Industry Committee for Emergency Lighting (ICEL) Code 1003.

The following points need to be considered when installing self-contained luminaires:

1. The supply to them should be taken from an unswitched local lighting power source.
2. The source of supply should be from the same local fuse as the normal lighting so that in the event of fuse failure the emergency lighting is brought into operation in the same locality.
3. It must be possible to disconnect emergency luminaires from the mains supply for servicing and testing purposes. This can be done by connecting groups of emergency luminaires in parallel, fed from appropriately protected distribution boards. These boards may then be isolated by a key switch (or a retractive, tamper proof test switch) to prevent unauthorized disconnection (see Figure 13.53).
4. Facilities should be incorporated within maintained and sustained luminaires which permit their mains-operated lamps to be switched without affecting emergency mode operation (see Figure 13.53(b».
5. Cabling should be of the same type as that used for the normal lighting in the installation. For example, were FP cables to be used on the emergency luminaires and not on the normal lighting circuits, it is possible that in the event of a fire the normal lighting would fail and the emergency lighting would remain inoperative.

*Central battery system.* A central battery system is one in which the batteries for a number of luminaires are housed in one location - usually for all the luminaires in one lighting sub-circuit (a so-called mini-central system) but sometimes for all the emergency luminaires in the building.

The central battery installation has its own battery charger, battery control systems, and mains failure contactor. Luminaires are wired to the battery in fire-resistant cable (e.g. MICe). The advantages of the system are as follows:

- the battery may be chosen for long, medium or short life - see Table 13.7;
- there is no basic restriction on lamp wattage and hence light output;
- the comparatively low cost of the luminaires-simple housings are required for incandescent (tungsten filament) lamps, those for fluorescent lamps must be equipped with individual in-built inverters providing high frequency a.c. for the miniature tubes;

Table 13.7 Battery comparison chart

| *Battery type* | *Life expectancy (years)* | *Maintenance intervals (months)* | *Resistance to abuse* | *Capital cost •* | *Weight •* | *Volume •* |
|---|---|---|---|---|---|---|
| Lead acid flat-plate | 10-12 | 6 | poor | 100 | 100 | 100 |
| Lead acid tubular | 10 | 6 | poor | 106 | 85 | 100 |
| Lead acid sealed recomb. | 8-10 | none | poor | 117 | 70 | 56 |
| Lead acid sealed gel | 4-5 | none | poor | 45 | 58 | 52 |
| Lead acid Plante | 20-25 | 9 | poor | 130 | 147 | 160 |
| Nickel cadmium vented | 20-25 | 12 | good | 196 | 93 | 95 |

.•.= 'index' numbers related to base 100 for the flat-plate lead acid type

- testing is easier than with self-contained luminaires; and
- luminaires may be sited in very hot or very cold environments.

The disadvantages of the system are as follows;

- it is not easily extended unless allowed for at the design stage;
- the maintenance of batteries and charging plant requires skilled operatives - this should be no real problem on generator installations;
- a separate battery room may be required on the larger installations;
- failure of the battery disables the system;
- distribution cables must either be protected in conduit or segregated in trunking (see Subsection 13.8.3), or they must be of the mineral insulated metal sheathed type;
- sub-circuit monitoring is necessary - the relays required to sense faults introduce potential failure points;
- cable sizes must be carefully selected to minimize voltage drops; and
- the high initial cost of the equipment and the distribution wiring - where more than about 25 fittings are required the central system becomes the more cost-effective method.

Also included under the generic description of central battery systems are those which use bulk static inverters to produce a.c. at normal mains frequency. The above comments generally apply to them because they derive their base power from a central battery.

Should it be decided that a central battery system is the more suitable choice for a particular installation, the system designer must determine which type of battery is to be used. Table 13.7 [48] compares the six major types that may be considered. Appendix B of this handbook describes some of them in the context of engine starting duty.

## 13.10 Commissioning

The wide variety of applications makes it impracticable to give a definitive programme for commissioning diesel generating plant. Installations will vary in complexity from the base load power station supplying townships in developing territories to the single-generator plant providing standby power to commercial and industrial premises.

In every case it is essential that a well-planned commissioning programme is executed. The fundamental principle to be observed in the preparation of any programme is that it should consist of a series of logical steps progressing from checks to confirm that the installation work is satisfactory, through first runs and acceptance guarantee performance tests, to the final handover of the plant in efficient working order. It is necessary to establish in the early stages of a contract - if not at the pre-contract stage - exactly what the testing programme is to be.

It should include tests at individual equipment manufacturers' works, combined tests at the main contractor's premises, and the acceptance tests required on site.

The need for careful planning of the commissioning programme cannot be overstated. This ensures not only that supporting equipment is available on time but also that plant outages, permits to work, staff allocation, etc. are arranged in an ordered manner. Commissioning exercises will, more often than not, reveal several defects that need correcting. Reasonable rectification time should therefore be included in the planned overall time.

Guidance on the content of test programmes will be given in ISO 8528: Part 6 (see Sub-section 2.2.3 of Chapter 2). That document cannot be explicit since the extent of any acceptance programme must depend upon the type of plant. However, certain basic requirements apply in every case.

The starting point in the preparation of any check-lists must be the preparatory procedures given in the equipment manufacturers' instruction manuals. The example lists which follow are by no means exhaustive. They contain some of the more usual checks and tests, with comments where appropriate. They are arranged in a reasonably logical sequence, and cover those mechanical and electrical aspects which need to be considered in most installations. Tests should be sequenced to ensure that nothing already tested is disturbed during subsequent tests.

### 13.10.1 General checks

The following checks relate to the installation as a whole, and should be made before the plant is first run-up.

*Mechanical aspects*

1. Completeness of the plant to contract schedules.
2. Safety guards are fitted and are satisfactory.
3. Service pipework is correctly installed and colour coded, and is clean. It may be prudent to conduct pressure tests on selected runs. The pressure applied is usually 1.5 times relief valve pressure for compressed air pipes, and twice the maximum gauge working pressure for all other pipes. Pressures should be maintained for 30 minutes.
4. Checks for plant alignment:
   - confirmation that composite bedplates (or individual engine bedplate and generator frame) are level in all directions;
   - all anti-vibration mounts are properly installed and located;
   - tightness of all fixing nuts and bolts, and dowels are fitted, if called for;
   - proper alignment of engine and generator shafts, and a check on the main drive coupling;
   - generator rotor air gap checks.

   (Engine crankshaft deflections may be measured and later compared with those taken after final performance tests.)
5. Check that all temporary inhibitors and transit protections have been removed.
6. Checks on the engine coolant systems:
   - that they are filled with coolant and entrapped air has been released. (Engines should be left overnight and checked the following day for signs of leakage);
   - that radiator and engine block/frame water drain points are free from sludge and other blockages;
   - that water jacket and radiator heaters (if fitted) are in working order;
   - that the water level in any separate water make-up tank is adequate and that its ball valve and overflow work.
7. Checks on the lubricating oil system:
   - that the sump has been cleaned prior to filling with a lubricating oil charge of the correct type and grade;
   - that all pipes supplied loose with the engine have been fitted;
   - that all filters contain elements (it is preferable to use slave elements, which are replaced after the performance acceptance tests);
   - that the lubricating oil priming pump (if one is fitted) works satisfactorily;
   - that governor and turbocharger are filled with the correct type and grade of oil and to the correct level.
8. Checks on the fuel system:
   - that the service tanks are clean and that level indicator float arms are free of obstructions;
   - that the service tanks are filled with sufficient fuel for the performance tests;
   - that the system pipework to the engine is free of obstruction and does not leak (the pipes may be flushed by disconnecting the run at the lowest point on the engine and running-off fuel into a container);
   - that the system up to the injector pump( s) is bled so that it is free of air inclusions;
   - that governor control linkages and solenoid linkages (if any) are clean, have freedom of movement, and are correctly adjusted.
9. Checks on the air starting system (if applicable):
   - that the air receivers are clean and clear of debris and moisture (this may be done by blowing air, from a charged receiver, through the drain cock);
   - that the pipework to the engine connection is clean and clear of obstruction and moisture. (Again, this may be done by disconnecting

the inlet pipe at the engine end and blowing-through with air from a charged bottle);

SAFETY NOTE: compressed air is a hazard, especially in a dusty environment. Safety goggles should be worn during these operations.

*Electrical aspects*

10. Check that all interconnecting cables to equipment conform to drawings.
11. Check that all earth bonding is satisfactory.
12. Check the cables and connections on those power circuits in which faults could have serious consequences. (In theory, the cores of all external power cables should be checked for continuity and insulation level. In practice, only those power, control, and protection circuits directly associated with generators, auxiliary motors, governor controls - particularly on those of the electronic type, automatic voltage regulators, and generator circuit breakers need be checked out initially. Final terminations should be secure and clearances adequate.)
13. The insulation of generator, and auxiliary motor, windings should be measured and recorded - especially if equipment has been stored in damp conditions prior to installation. (If the insulation levels are lower than permissible, the windings should be heated. Follow the manufacturer's recomendations in instruction manuals.) Polarization index tests should be made on the stators of HV machines - at the voltage recommended by the machine manufacturer. (This is based on the fact that on first energization of a winding, an initial capacitance charging current and a rapidly decaying absorption current component flow within the winding. The steady-state level after this decay is the leakage current. A 'Megger' is used for the test [49].)
14. Check that all the batteries in the installation have been correctly installed and commission-charged to the instructions given in the manufacturer's handbooks. Check that battery, load, charger, and any distribution equipment are connected together in accordance with the requirements of each particular system (e.g. engine starting, switchgear, controlgear and emergency lighting). Also ensure that all connections are tight and that the cell pillars and intercell connections are well coated with petroleum jelly or a no-oxide grease. Check the electrolytic levels and the specific gravity on vented cells, and the voltage readings.
15. Check cubicle and panel access doors for proper opening and closing and the functioning of any door interlocks.
16. Ensure that any blocks or plates fitted for transit have been removed from power-switching devices, such as fixed and withdrawable circuit breakers, bar-type contactors, etc. Follow the manufacturer's recommended preparatory procedures, before checking any opening and closing operations - particularly on those breakers which can be racked-out and removed from cubicles.
17. Check the protective relay system. The more complex schemes are usually commissioned by the relay manufacturer. In any event, the following checks and tests should be made:
    - a general visual inspection of the equipment checking all small wiring interconnections, terminations for tightness, and labels on termination boards, etc;
    - measurement of insulation resistance on all circuits;
    - ratio and polarity tests on all current transformers;
    - ratio, polarity, and phasing tests on voltage transformers;
    - inspect and test relays (either with the relays disconnected from the power and trip circuits or, more usually, by secondary injection, i.e. with the primary of the current transformers de-energized) ;
    - check calibration of all relays by secondary injection;
    - tests on the complete system by primary injection. This simultaneously checks transformer ratios, secondary wiring, polarity, relay operation and phase identity;
    - check the tripping and intertripping circuits of all breakers in the scheme; and the alarms also.

    (There should be a patterned approach to inspection and test. For example, the a.c. circuits may be considered as feeding *into* the protective gear and the d.c. circuits as feeding *out from* the protective gear to tripping relays and circuit breakers. The inspection and commissioning tasks may then be conveniently split into manageable sections, each of which is cleared before the complete scheme is tackled [50]).

## 13.10.2 Prior to first run-up

1. Check that the governor is able to fully close the fuel rack(s) and that the overspeed trip functions.
2. Check the operation (by 'manual' control) of any electric motor driven auxiliaries directly associated with the engine, e.g. lubricating oil priming pump, fuel pressurizing pump, water circulating pump, etc. Common problems are direction of rotation, cabling errors between the switch-

gear and external interlock contacts, and pump seizure caused by corrosion while in storage [51].

### 13.10.3 First runs

1. Start the engine in manual control. If it is started by direct air injection into its cylinders the initial turn-over is usually made with the indicator cocks open.
2. Initially run for a period of up to 5 minutes. Check for any excessive vibration and unusual running noises. Check integrity of flexible connections on mechanical and electrical services.
3. Check hand control of generator voltage.
4. Check instruments and gauges for normal operation and response, making due allowance for no-load conditions.
5. Check bearings and liners in accordance with manufacturers' running-in instructions.
6. Before proceeding with load tests check that the engine-generator and auxiliary plant control systems function satisfactorily. Checks would include:
   - start/stop sequences, in manual and automatic modes;
   - alarms; and
   - trips.

### 13.10.4 Performance or running checks

1. Run the generators at various loads (preferably at rated power factor) for predetermined periods - typically:
   - 1 hour at 75% continuous site rating;
   - 4 hours at continuous site rating;
   - 1 hour at 10% overload rating.

   (More often than not, there is insufficient 'consumer' load available at site. On standby generator applications it is often not convenient or possible to use the essential loads that must be supplied by the generator. In such cases it is necessary to use portable load banks. These are available for hire, in various power ratings up to about 6 MVA. They consist of modularized resistive and reactive load elements switched by contactors. The units are self-cooled by ventilation fans and may be chassis-mounted on road wheels or even housed within ISO containers. Local and remote controls may include programmable timing permitting repeatable test sequences without operator input. Sophistication now extends to complete systems measuring governor and a.V.L responses, engine efficiency, and specific fuel consumption. Former methods, using water rheostats (or brine tanks) are no longer acceptable in the light of the new and revised international standards for prime movers and generators. The old methods gave a poor level of control and could be very hazardous - in terms of electrical safety.)
2. Readings should be taken at agreed intervals (usually at half-hourly periods) of all electrical and physical parameters. This also includes measurements on all essential dependent auxiliaries, i.e. those necessary for the continued use of the plant. See Sub-section 2.2.4 of Chapter 2. Power plant instruments may be used for such tests if they are sufficiently accurate; if not, calibrated, temporary instrumentation of the requisite accuracy should be provided by the contractor. During the tests each gauge/indicator/recorder on the switchboard, controlgear and engine panels should be observed to assure satisfactory functioning.
3. Frequency and voltage regulation tests.
4. Vibration measurements at no-load and full-load operation.
5. Torsional oscillations of the crankshaft-generator assembly during run-up, at rated speed, and at 110% rated speed - if these have not already been recorded during tests at the contractor's premises.
6. Acoustic noise measurements during load tests at selected points (both within and external to the installation) to confirm compliance with the specified noise limits.
7. Upon completion of the tests, the following checks/inspections should be made:
   - generator winding(s) final temperatures;
   - a general inspection for leaks on engines, piping systems, tanks, etc.;
   - checks for blow-by;
   - crankcase contamination;
   - crankshaft-generator alignment.
8. If generators are to run in parallel with others or with a utility supply, the following procedures should apply:
   - first, check the quadrature current compensation circuits (QCC) and ensure that they all give a voltage droop with increasing reactive load (see Chapter 8);
   - with one generator on full load, synchronize a second unit and operate both in parallel (at 50% load on each if the sets are of equal rating) for about 15 minutes. Increase the load in increments until both sets are fully loaded. Observe load sharing at each load increment. Adjust the load until each unit is again at half-load and transfer load from the first generator to the second (incoming) unit. Check, at every stage, for load sharing stability, for any periodic pulsations or evidence of frequency hunting, and for load surging. Similar test procedures should apply when a set, or sets, are required to run in parallel with a utility supply.

### 13.10.5 The commissioning log book

It is a good idea to make up a lever arch folder with sections, separated by coloured subject dividers, containing:

1. the agreed programme of tests;
2. a set of check-lists;
3. a diary of daily progress;
4. working copies of test sheets;
5. a 'running' list of outstanding items;
6. copies of electrical circuit and service pipework schematic diagrams, each filed in reinforced clear plastic pockets.

On multi-generator installations it may be convenient to initially set up log books for each generator. Selected extracts from them may then be collated into a master log book to provide a final record of the whole installation. Log books are extremely valuable for any future fault investigations.

## 13.11 Referenced standards

Listed below, under subject headings, are the British Standards to which reference has been made in this chapter. Where there are corresponding international standards these are shown in brackets. The extent of their agreement with the British Standards varies. Some are completely identical and have dual-numbering. Others have substantial technical equivalence, with differences perhaps in wording and presentation.

*Foundations*

CP 2012: Part 1 - *Foundations for reciprocating machines*

*Fuel supplies*

BS 799 - *Specification for oil burning equipment*
  Part 5 - *Oil storage tanks*

CP 1003 - *Electrical apparatus and associated equipment for use in explosive atmospheres of gas or vapour other than mining applications*

(*Note:* This has been replaced by BS 5345 (Parts 1 to 8) but is retained temporarily by BSI as a reference guide for existing plants. See Cabling below. )

BS 5501 - *Electrical apparatus for potentially explosive atmospheres*

*Exhaust systems*

BS 5422 - *Specification for the use of thermal insulating materials*

*Starting systems*

BS 3546 - *Coated fabrics for water resistant clothing* (in 3 Parts)

BS 6132 - *Code of practice for safe operation of alkaline secondary cells and batteries*

BS 6133 - *Code of practice for safe operation of lead-acid stationary cells and batteries*

BS 6408 - *Specification for clothing made from coated fabrics for protection against wet weather*

*Pipelines*

BS 1710 (ISO/R508) - *Specification for identification of pipelines and services*

BS 4800 - *Specification for paint colours for building purposes*

*Cabling*

BS 5308 - *Instrumentation cables*
  Part 1 - *Specification for polyethylene insulated cables*
  Part 2 - *Specification for PVC insulated cables*

BS 5345 - *Code of practice for selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosive processing and manufacture*
  Part 3 - *Installation and maintenance requirements for electrical apparatus with type of protection 'd'. Flameproof enclosure.*

(*Note:* This replaces CP 1003. See Note in fuel supplies above.)

BS5467 (IEC502, IEC504) - *Specification for armoured cables with thermosetting insulation for electricity supply*

BS 6004 (IEC 227) - *Specification for PVC-insulated cables (non-armoured) for electric power and lighting*

BS 6346 - *Specification for PVC-insulated cables for electricity supply*

BS 6622 (IEC 502) - *Specification for cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 3800/6600 up to 19000/33000 V*

BS6746 (IEC227, IEC540) - *Specification for PVC insulation and sheath of electric cables*

*Cable installation*

BS 437 - *Specification for cast iron spigot and socket drain pipes and fittings*

BS 2484 - *Specification for straight concrete and clayware cable covers*

BS 4568 - *Specification for steel conduit and fittings with metric threads of ISO form for electrical installations*
  Part 1 (CEE 23) - *Steel conduit, bends and couplers*
  Part 2 (CEE 23) - *Fittings and components*

BS 4678 - *Cable trunking*
  Part 1 - *Steel surface trunking*

BS 6259 - *Code of practice for planning and installation of sound systems*

BS 6330 - *Code of practice for reception of sound and television broadcasting*

*Cable termination*

BS 6081 - *Specifications for terminations for mineral insulated cables*

BS 6121 - *Specification for mechanical cable glands for elastomer and plastics insulated cables*

*Fire-performance cables*

BS 2782 - *Methods of testing plastics*

Part 1: Method 141 (ISO 4589) - *Determination of flammability by oxygen index*

BS4066 - *Tests on electric cables under fire conditions*

Part 1 (IEC 332-1) - *Method of test on a single vertical insulated wire or cable*

Part 3 (IEC 332-3) - *Method of classification of flame propagation characteristics of bunched cables*

BS 6207 - *Specification for mineral-insulated cables*

Part 1 (IEC 702) - *Copper-sheathed cables with copper conductors*

BS 6387 - *Specification for performance requirements for cables required to maintain circuit integrity under fire conditions*

BS 6425 - *Methods of tests for gases evolved during combustion of electric cables*

BS 6724 - *Specification for armoured cables for electricity supply having thermosetting insulation with low emission of smoke and corrosive gases when affected by fire*

*Earthing*

CP 1013 - *Earthing*

BS 6651 - *Code of practice for protection of structures against lightning*

*Fire-protection systems*

BS 3116 - *Specification for automatic fire alarm systems in buildings*

Part 1 - *Control and indicating equipment*

BS4547 (EN 2, ISO 3941) - *Classification offires*

BS 5045 - *Transportable gas containers* (in 5 Parts)

BS 5306 - *Fire extinguishing installations and equipment on premises*

Part 4 - *Specification for carbon dioxide systems*

Part 5.1 - *Halon 1301 total flooding systems*

Part 5.2 - *Halon* 1211 *total flooding systems*

BS 5423 (EN 3 Parts 1,2,4 and 5) - *Specification for portable fire extinguishers*

BS 5445 (EN 54) - *Components of automatic fire detection systems* (in 5 Parts)

BS 5446 - *Specification for components of automatic fire alarm systems for residential premises*

BS 5839 - *Fire detection and alarm systems for buildings*

Part 1 - *Code of practice for system design, installation and servicing*

Part 4 - *Specification for control and indicating equipment*

BS 6575 - *Specification for fire blankets*

*Lighting*

BS 5266 - *Emergency lighting*

Part 1 ~ *Code of practice for the emergency lighting of premises other than cinemas and certain other specified premises used for entertainment*

*[Author's Note:* the latest revision to BS5266: Part 1 (in 1988) has introduced additional qualifications on illuminance levels. These include a widening of the limits on uniformity of illuminance by allowing a 40:1 variation between average and minimum levels (as opposed to the 40:1 between maximum and minimum stated in the text of Sub-section 13.9.4. of this chapter), and, in addition to the 0.21ux minimum illuminance along the centre line of the escape route, requires a minimum of 0.1 lux over at least 50 % of each route.]

BS 8206 - *Lighting for buildings*

Part 1 - *Code of practice for artificial lighting*

BS DD 73: 1982 - *Basic data for the design of buildings: daylight*

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The text-books listed in the references have been used by the author in the preparation of this chapter.

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*Batteries*
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*Cables*
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*Earthing*
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    (ii) G 12/2 - *National Code of Practice on the application of protective multiple earthing to L V networks*

*Fire-protection*
11. *The Manual of Firemanship* by the Home Office (Fire Department). This consists of 18 books. In our context, the books of particular interest are:
    (i) Book 1 (1974) - *Elements of combustion and extinction equipment*
    (ii) Book 3 (2nd edition, 1988) - *Hand pumps, extinguishers and foam*
    (iii) Book 8 (1975) - *Building construction and structural fire protection*
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# 14 Plant noise reduction

**Contents**

## 14.1 Introduction

As a minimum requirement, the noise emitted from diesel-generator plant needs to be controlled to levels that meet the standards set by National Regulations applying to in-plant and off-site locations. This chapter examines the problems associated with plant noise control and deals with the principles, procedures, and codes of practice that are invoked in overcoming them. It first describes the physical nature of noise and the units and definitions used.

The subjective nature of noise is emphasized by its definition as 'sound that is undesired by the recipient'. Noise evaluation criteria are discussed in the light of the need to define target limits for various environments. This is followed by an explanation of how acoustical parameters are measured and the measurement methods applicable to generating plant.

The final sections of the chapter are devoted to noise attenuation techniques, outlining the general principles upon which control measures are based, and how these principles are applied in diesel-generator noise control schemes.

## 14.2 The physics of sound

A basic knowledge of the fundamental physics of sound and the way it behaves is essential for any understanding of how to control noise. The most important characteristics and properties of sound, and certain fundamental concepts must be understood before noise reduction methods can be considered. These concepts and the special expressions and terms which occur most often are described here.

### 14.2.1 Basic mechanisms of sound

Sound is a vibration travelling in waves in elastic media - liquids, gases, and most solids. The simplest examples of sound sources are the tuning-fork and the harp string whose vibrations, initially at least, may even be seen by the naked eye.

To emit a sound a body must be in motion as a whole. The prong of the tuning-fork vibrates to disturb the air next to it. This disturbance propagates from particle to pa~ticle, causing alternate layers of compression and rarefaction to move away from the vibrating prong in the direction of the wave's travel. This movement produces pressure variations about the mean atmospheric pressure. When these travelling waves reach the ear of the listener they excite the eardrum. The bones of the middle ear amplify and convert the pressure waves (through a complex system of hair cells and auditary nerves) into nerve signals to the brain, resulting in the sensation of *hearing.*

The compressibility (or the modulus of elasticity) of the medium or material in which the sound is travelling determines the speed of the sound wave. The velocity of sound in any medium is given by:

$$K \sqrt{E/\rho}$$

where $E$ is the modulus of elasticity of the material
p is the density of the material
$K$ is a constant

Sound, therefore, travels faster in materials with higher elasticity and lower density. Common building materials such as brick (9), wood (10), concrete (10), steel (15) and glass (12), all transmit sound waves well. The figures in parentheses represent the speed of sound in that material referred to the speed of sound in air (unity). It is this ability of these building materials to transmit sound waves that presents problems in the design of plant rooms and enclosures.

The relative slowness of the speed of sound in air accounts for the echoes and long reverberation times experienced in plant rooms. Reverberation results from successive reflections of sound in a room. A delay of more than 0.06 seconds in any sound, related to directly received sound, gives rise to an echo.

#### *Wavelength and frequency*

The pressure wave transmitted by the prong of a tuning-fork, vibrating in a simple harmonic motion (i.e. sinusoidally) will be at the same frequency, and have the same characteristic vibration, as the prong itself. Figure 14.1 shows that successive high pressure points are regularly spaced apart, as also are the successive low pressure points. The wave length (A) of a sound wave is defined as the distance the wave travels during one cycle, i.e. the distance between successive pressure points of the *same sense* on the travelling wave.

The wave's frequency (f) expresses the number of vibrations per second (Hz) or, stated another way, the number of like-pressure points which pass a fixed observation point per second.

The frequency, wavelength, and velocity of propagation of sound waves through a medium are related by the expression:

$$\lambda = c/f = cT$$

where $\lambda$ is the wavelength (m or ft)
$f$ is the frequency of the disturbance (Hz)
$c$ is the speed of sound in the medium (m/s or ft/s)
$T$ is the time between successive compressions or rarefactions in the sound wave (s)

It is important to understand this relationship. Different noise control techniques apply for long-wavelength, low-frequency, sound waves to those

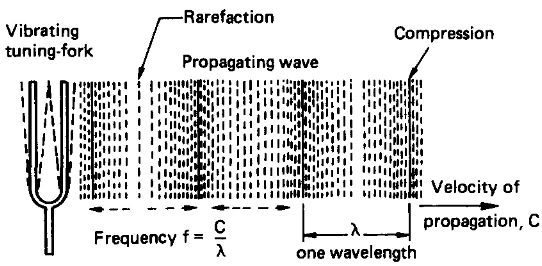



**Figure 14.1** The transformation of tuning-fork vibrations into waves

required for the attenuation of shorter-wavelength, higher-frequency ones. In the range of frequencies that are audible to humans (20 Hz to 20000 Hz) the wavelength range extends from about 17mm to 17m.

In general, long-wavelength sounds are only affected by large obstructions. They diffuse around edges and through any holes without losing intensity, and then re-radiate from such edges or holes just as if they were new sources of low-frequency sound. For this reason, partially-open or louvred covers for cooling air intakes (a high-level source of low-frequency sound) are of little value as noise attenuators on diesel plant.

On the other hand, high-frequency sound waves are affected by those small obstructions which are comparable in scale to their wavelength. Such sound waves behave like beams of light. They have directional qualities and create noise-free shadow zones behind the obstacles.

### *Travelling and standing waves*

Sound waves travelling from a source to a receiver are known as *forward-travelling waves* and those travelling in the opposite direction, as *backward-travelling waves.* The latter may originate from a second vibrating source or from a reflecting surface in the path of the original forward-travelling wave.

The simplest way of explaining the 'progressive wave' is to consider an open tube or cylinder, at one end of which a piston moves cyclically backwards and forwards in simple harmonic motion. The sound wave started by the piston progresses down the tube. Assuming that the length and cross-section of the tube are infinite, the resulting travelling wave is called a *plane* (or *free progressive) wave.* It is one-dimensional, in that all the parameters of the wave relate to one distance.

Because the tube is open-ended and echo-free, it is said to have an *anechoic termination.* If we were to place a wall at the end of the tube, the forward-travelling wave would be reflected back on itself. The resultant wave - a combination of the backward-travelling and the forward-travelling waves – is no longer a travelling wave. It is said to be a *standing wave*, and its presence, in practical situations, may cause large errors in sound measurements.

The closed tube closely resembles the acoustic condition that exists in large plant enclosures. The interaction of forward- and backward-travelling waves in these enclosures is rather complex. Suffice it to say that it is possible for six discrete sets of standing waves to exist within them.

### 14.2.2 Sound intensity and power

Sound pressure waves transmit energy by reason of their movement. The pressure they transmit equates to a force. Because this force is moving, there is a net flow of energy. Energy implies an ability to do work and this work is the product of force (in our case, pressure) and distance.

Energy propagation is described in terms of intensity ($I$) which, in turn, is defined as the amount of energy that passes through a unit area in a unit of time. It is usually expressed in watts per square metre (W/m$^2$) or in watts per square centimetre (W/cm$^2$). There is a direct relationship between acoustic intensity and pressure. $I$ is directly proportional to the square of the pressure: $I \propto p^2$.

The sound power of a source is defined as the total sound energy radiated by that source in a unit of time. If a sound source radiates power uniformly in all directions, all the energy generated must break through a surface enclosing the source. As the radius of the enclosing or control surface increases, the power per unit area decreases. In other words, the further from the source, the lower the sound intensity.

It can be shown that the acoustic intensity at any point of the control surface is given by:

$$I = p^2/\rho c \text{ watts/m}^2$$

where $p$ is the effective, or r.m.s., sound pressure (N/m$^2$)
$\rho$ is the density of the transmitting medium (kg/m$^3$)
$c$ is the velocity of sound in the medium (m/sec)

The product $\rho c$ is the *specific acoustic impedance* or *characteristic impedance* of the medium.

The analogy with electrical theory should be noted.

$$\text{Power} = (\text{voltage})^2/\text{impedance}$$
$$\text{Sound intensity} = (\text{sound pressure})^2/\text{acoustic impedance}$$

By definition, the intensity at an elemental area $\delta A$ on the control surface would be given by:

$$I = \delta W/\delta A$$
$$\text{or } p^2/\rho c = \delta W/\delta A$$

and, therefore

$$\delta W = p^2 \delta A/\rho c$$

To obtain the total power generated by a sound source, one would have to integrate the power passing through each of the elemental areas ($\delta A$) over the whole spherical surface. The expression for total power would then become:

$$\text{Total power} = p^2.4\pi r^2/\rho c$$

We can simplify this by expressing it as:

$$W = IA$$

where $W$ is the total sound power generated by the source (watts)
$I$ is the intensity, and
$A$ is the total surface area

The intensity is the power of the source divided by the area of the control surface, i.e.

$$I = W/(4\pi r^2)$$

and is, therefore, inversely proportional to the square of the distance between source and receiver.

Where a source is assumed to radiate sound equally in all directions, sound pressure *(P)* is constant at all elemental areas on the control surface. In practice, many noise sources exhibit strong directional effects but the same principles apply for calculating total power. The major difference is that the variation of *p2* in the expression &W= *p2&Alpc* must be determined *before* any integration is made over the whole spherical surface.

This brings us to the definition of a *point source of sound* which is one whose dimensions are small in relation to its distance from the receiver. Individual diesel generators, aircraft and road vehicles are normally treated in this way.

If, in our earlier model of the piston source in the tube (Sub-section 14.2.1), we had constrained all radiated power within a hard-walled cylinder and had assumed that there were no other losses, the acoustic energy flowing through unit area (in unit time) anywhere along the tube would be independent of the distance from the piston source and numerically equal to its sound power. The total power would be given by:

In practical terms, plane waves and plane sources (such as our piston-in-tube model) are only encountered in duct systems.

Sound power and sound intensity cannot be read directly on instruments. Since the human ear responds to sound pressure, it is logical that most acoustic instruments are designed to measure *the effective sound pressure level.* However, one often needs to start noise reduction calculations with the more fundamental quantity of sound power. It is a useful way of defining the nature of a sound source since it is not affected by the source's environment. Webb [1] offers a simple analogy to emphasize its value as a definitive property:

> If we buy an electric fire, we buy it on a basis of power - say, one kilowatt. This power is the fundamental property of the fire and is not materially affected by the surroundings. The temperature that the fire produces in given surroundings is a function not only of the fire but also of these surroundings. The fire will raise the temperature of a small, well-insulated room higher than that of a large, poorly-insulated one. The power rating of the electric fire is analogous to the sound power of a sound source, while the temperature of the surroundings is analogous to the sound pressure. In both cases it is the power that is the fundamental property of the source although it is temperature (or sound pressure) that is easily measured; the power can only be deduced indirectly from a knowledge of the temperature and the surroundings.

If sound measurements are to be made on a diesel generator before it is installed at another location, it would be useful to estimate its sound power output. Measurements should, ideally, be made in a *reverberation chamber* or in an *anechoic chamber.* The former is one which has hard reflecting surfaces which give only small pressure variances throughout the chamber; the latter is one whose walls are covered with sound absorbing materials, and in which there is a minimum of reflected sound. Specialized chambers of this type (even if large enough for the purpose) are not readily available, and their hire is costly. In most cases, measurements are made in a large yard or open space. The generator is usually mounted on a hard reflecting surface such as concrete and is regarded as a point source of sound. Pressure level measurements are taken on the surface of an imaginary hemisphere (or a parallelepiped) centred at the diesel generator mass. See Sub-section 14.4.2.

The acoustic power is then given by:

$$W = p_m^2.2\pi r^2/\rho c \text{ (watts)}$$

where $r$ is the radius of the hemisphere (metres)
$\rho c$ is the characteristic impedance of air (rayls or $kgm^{-2}.s^{-1}$)
$p_m$ is the mean of several sound pressure level readings on the measurement hemisphere ($N/m^2$)

Radius $r$ is chosen so that the receiver microphone does not pick up sounds reflected from nearby walls or other hard surfaces. The microphone should be placed in the *far field* of the sound source - as opposed to the *near field,* i.e. at a distance greater than one wavelength from the source. Since the major frequencies on diesel generator plant are above 200 Hz, $r$ should be $\geqslant 2$ m.

*Characteristic impedance* is the term we used in the expression for sound intensity, $I$. It is the product of the density of the sound transmitting medium and the velocity of sound within the medium, and is defined as the ratio of the sound pressure to particle velocity in a plane wave travelling in an unconfined medium.

The characteristic impedance for air varies as a function of temperature and pressure [2], based on the formula:

$$\rho c = 42.86\,(273/T)^{1/2} \times H/760 \text{ rayls}$$

where $T$ is the absolute temperature (Kelvin)
$H$ is the barometric pressure (in mm of mercury)

## *Scales for sound – the decibel*

Because of the very wide range of sound power encountered in noise problems, absolute values (in watts) can only be expressed in long and cumbersome numbers. The range of sound power, from a whisper ($10^{-9}$ watt) to a space rocket at lift-off (50 million watts), gives power ratios in the order of $10^{17}$:1. Clearly, calculations in conventional linear notation would be too unwieldy. The use of a logarithmic scale makes it easier to express sound levels in manageable terms. The unit of measurement is the *bel* (named after Alexander Graham Bell). For greater convenience, values in bels are divided by ten and sound levels are expressed in *decibels* (dB). The term *level* specifically indicates that the scale used is logarithmic, and not linear.

By definition, a decibel is 10 times the logarithm (to the base 10) of a ratio of two powers. It is a term that is not unique to acoustics and is commonly used in electronic engineering. For example, in amplification, the *gain* of an amplifier is expressed as:

$$10 \log_{10}(W_0/W_1) \quad \text{decibels}$$

where $W_1$ is the input power
$W_0$ is the output power

A power ratio of 10:1 corresponds to a gain (or level difference) of 10 dB; a ratio of 100:1 corresponds to a gain of 20 dB, and a gain of 30 dB relates to a power ratio of 1000: 1.

## *Sound power level*

Because the decibel must be based on a ratio, it is essential that a *reference* power value is stated when a decibel scale is assigned to a sound power level. Sound power level (SWL) is then defined as 10 times the logarithm (to the base 10) of the ratio of source power to the reference power (BS 3045).

$$\text{SWL} = 10 \log_{10}(W/W_r) \quad \text{decibels (dB)}$$

where $W$ is the power emitted by the sound source
$W_r$ is the reference power

The reference power is standardized at $10^{-12}$ watt, but some American literature uses $10^{-13}$ watt as the reference level. It is important to know the reference power, as the following equations show.

At a reference level of $10^{-12}$ watt, a sound power level for an emitted power of $W$ watts would be:

$$\text{SWL} = 10 \log_{10}(W/10^{-12}) \quad \text{dB}$$
$$= 10 \log_{10} W + 120 \quad \text{dB}$$

With a reference of $10^{-13}$ watt the power level for the same ($W$) watts emitted would be:

$$\text{SWL} = 10 \log_{10} W + 130 \quad \text{dB}$$

i.e 10 dB more than that for the $10^{-12}$ watt reference level.

A convenient form for expressing sound power level is:

$$\text{SWL} = 10 \log W + 120 \quad \text{dB (re } 10^{-12} \text{ watt)}$$

Note that sound power level is abbreviated as SWL and the subscript 10 is usually omitted from the logarithm 'base'. Other abbreviations for sound power level include: PWL and SL. We shall use SWL.

## *Sound pressure level*

The range of sound pressures generated by common noise sources is also very large and, as in the case of sound power levels, pressure level calculations are expressed in logarithmic form. This happens to be expedient because the ear responds to stimulus logarithmically and not linearly. Also, it responds to intensity of sound (which is proportional to $p^2$) rather than pressure alone.

The lowest sound intensity detectable by the normal ear is about $10^{-12}$ watt/m$^2$. This equates to a pressure of $2 \times 10^{-5}$ N/m$^2$ (0.0002 μbar; 20 μPa or 0.0002 dynes/cm$^2$). This value has been standardized, as the reference pressure for sound level calculations (BS 3045 and ISO 131).

Sound pressure level (SPL) is defined as:

$$\text{SPL} = 20 \log (p/p_r) \quad \text{dB}$$

where $p$ is the measured pressure
$p_r$ is the reference pressure ($2 \times 10^{-5}$ N/m$^2$)

The reason for the multiplier 20 is explained as follows. Sound power and sound pressure are analogous to electrical power and voltage, and their relationships are similar.

Electrical power ($W$) = (voltage)$^2$/resistance
Acoustic power (SWL) = (pressure)$^2$/characteristic impedance

So that, when the impedance is constant, the ratio of two sound powers, $W_1$ and $W_2$, may be expressed as:

$$W_2/W_1 = (p_2/p_1)^2$$

From our previous definition of sound power level:

$$\text{SWL} = 10 \log (W_2/W_1) \quad \text{dB}$$

Therefore, in defining a decibel scale for effective sound pressure, a ratio of quantities proportional to sound power must be used – namely the ratio 'pressure squared'.
Hence,

$$\begin{aligned} \text{SPL} &= 10 \log (p/p_r)^2 \quad \text{dB} \\ &= 20 \log (p/p_r) \quad \text{dB (referred to } p_r) \end{aligned}$$

This may be written as:

$$\text{SPL} = 20 \log p + 94 \quad \text{dB (re to } 2 \times 10^{-5}\ \text{N/m}^2)$$

In summary, the distinction between sound power and sound pressure levels, both of which are expressed in decibels, is:

- SWL defines the total acoustic power emitted by a source and is independent of its (environmental) location;
- SPL depends upon the distance from the sound source and upon the environment, e.g. losses in the transmitting medium, room effects, etc., and it is always specified at a given point.

## *Dealing with decibel scales*

The decibel scales commonly used in sound measurement are listed in the table below. The appropriate abbreviations and reference quantities are also included. Sound Test Reports should always state the applicable reference quantity when a decibel scale first appears in the text.

It is important to realize that because decibel scales are logarithmic, SPL and SWL values cannot be treated in normal arithmetic terms using simple addition or subtraction of decibel quantities. When two or more sound sources are operating together, the level of the combined sound is not the arithmetic sum of the individual levels. Rather, it is that level which corresponds to the arithmetic addition of the individual *intensities.* The following examples will serve to illustrate the methods of calculation.

*Example 14.1*

*The problem*

What is the change in sound pressure level when the sound pressure is doubled?

*The solution·*

If the sound pressure was initially $p$, and the corresponding pressure level was SPLJ, we have:

$$\text{SPL}_t = 20 \log (P/p_r)$$

Doubling $p$ to $2p$, the new sound pressure level (SPLz) is:

$$\text{SPLz} = 20 \log (2p/p_r)$$

or

$$\text{SPLz} = 20 \log (P/p_r) + 20 \log 2$$

so that,

$$\begin{aligned} \text{SPLz} &= \text{SPL}_t + 20 \log 2 \\ &= \text{SPL}_1 + 6\text{dB} \end{aligned}$$

Hence, doubling the sound pressure increases the (original) sound pressure level by 6dB. It is important to note that the source remains unchang@d. Its sound is either a pure tone (i.e. of single frequency) or a more complex combination of pure tone components - these are the same before and after the pressure change.

*Example 14.2*

*The problem*

What happens to the sound power level, if the power of a source is doubled?

*The solution*

Let $\text{SWL}_t$ be the initial sound power level corresponding to a sound power of $W$ watts.
Then

$$\text{SWL}_1 = 10 \log (W/W_r)$$

Doubling the power to $2W$, the new sound power level (SWLz) is:

$$\text{SWLz} = 10 \log (2W/W_r)$$

which is the same as:

$$\begin{aligned} \text{SWLz} &= \text{SWL}_t + 10 \log 2 \\ &= \text{SWL}_1 + 3\text{dB} \end{aligned}$$

Hence, doubling the sound power increases the (original) sound power level by 3 dB.

From the above examples it will be apparent that when one speaks of 'doubling the sound', one needs to be more explicit and define whether the sound pressure or the sound power of the source is to be doubled.

| *Decibel scale* | *Abbreviation* | *Definition* | *Reference quantity* |
|---|---|---|---|
| Sound power level | SWL | $10 \log (W/W_r)$ | $W_r = 10^{-12}$ watt |
| Sound pressure level | SPL | $20 \log (P/p_r)$ | $p_r = 2 \times 10^{-5}$ N/m² <br> $= 0.0002\mu$bar <br> $= 0.0002$ dyne/cm² |

It is also necessary to distinguish between sound power radiated by a source, the sound pressure level impinging on the receiver, and the effect on the observer (loudness) (see also Sub-section 14.3.1). The following table, in summarizing the discussions above, shows the relationship between these three factors.

| *Change in sound* | *Change in dB* |
|---|---|
| Double the sound power | Add 3 dB |
| Double the sound pressure | Add 6 dB |
| Double the loudness | Add 10dB |

The table below [1] shows that a doubling in sound pressure, 2 times (or +6dB), leads to a quadrupling, 4 times (or +6dB), in sound power level. This is analogous in electrical terms to the relationship between voltage and power.

| *Power* (dB) | *Ratio* | *Pressure* (dB) |
|---|---|---|
| 0 | 1 | 0 |
| 1 | 1.25 | 2 |
| 2 | 1.6 | 4 |
| 3 | 2 ...................... | 6 |
| 4 | 2.5 | 8 |
| 5 | 3 | 10 |
| 6......................... | 4 | 12 |
| 7 | 5 | 14 |
| 8 | 6 | 16 |
| 9 | 8 | 18 |
| 10 | 10 | 20 |
| 20 | 100 | 40 |

Thus:

15dB =lOx3 = 30
23dB =lOOx2=200
lOx2= 20 = 26dB

### 14.2.3 Addition of sound source levels

It is often necessary in noise tests to obtain the combined results for different machines running together, or even for octave-band data measured on one machine alone. (Complex sound patterns are discussed later in this chapter and octave frequency bands will be examined in that context.)

*Sources of unequal frequency*

In most cases, when dealing with independent noise sources, one can assume that their sound waves have different frequencies and that significant interference of one wavefront by another does not occur. If we have two such sources at the same distance from a receiver, each producing (numerically) the same sound pressure level, they combine to produce a *mean square* sound pressure ratio given by:

$$(p_t/p_r)^2 = (p/p_r)^2 + (p/p_r)^2$$

or

$$\text{the total pressure, } p_t = p \times \sqrt{2}$$

The expression for the combined sound pressure level, for the sources, then becomes:

$$\begin{aligned} SPL_t &= 20\log[(p \times \sqrt{2})/p_r] \\ &= 20\log(p/p_r) + 20\log\sqrt{2} \\ &= (\text{SPL of each source}) + 3\,\text{dB} \end{aligned}$$

Doubling the number of sources, therefore, raises the observed sound pressure level by 3 dB. Further doubling of the sources (that is to four times the original number) raises the combined sound pressure level to 6 dB above that for the individual source; and so on. Thus, at each doubling of the number of (like) sources, the overall sound pressure level is raised by a further 3 dB, in the following patterns:

| *Number of sources, each SPL,* | *Total sound pressure level SPL/* |
|---|---|
| 1 + 1 | = SPL, + 3dB |
| 2 + 2 | = SPL, + 6dB |
| 4+4 | = SPL, + 9dB |

This is shown graphically in Figure 14.2. It will be seen that lO sources of equal intensity will give a resultant intensity and sound pressure level lOdB higher than that for any of the individual sources. Likewise, if the second of two sources is contributing twice as much sound intensity as the first source, their combination gives three times the intensity of the first source and the corresponding increase in SPL would be about 4.8 dB over that of the first, operating on its own.

The addition of sound pressures of different levels and from many different sources may be made as follows. The measured values are first reduced to absolute pressures. They are then summed to obtain the *effective mean pressure square.* Finally, the logarithm of the sum is taken, to give the total sound pressure level. The method is illustrated by the following examples.

*Example 14.3*

*The problem*

Calculate the sound pressure level for two sound sources of different frequencies, both operating together and, individually, giving sound pressure levels of 70dB and 74dB.

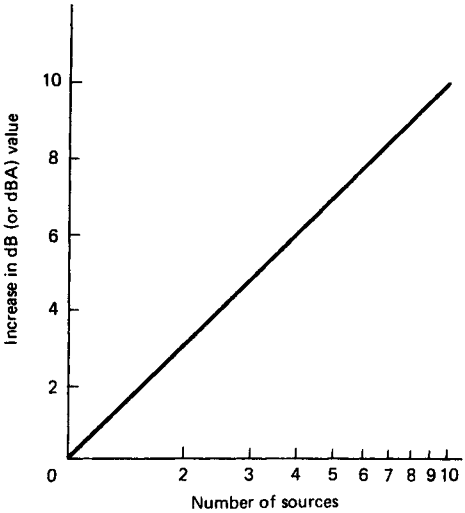



**Figure 14.2** Addition of equal sound levels

*The solution*

1. Mean square sound pressure ratio of 70 dB source

   = Antilog 70/10 = 1 x $10^7$

2. Mean square sound pressure ratio of 74 dB source

   = Antilog74/1O = 2.51 x $10^7$

3. Total mean square sound pressure ratio

   = (1 x 107) + (2.51 x 107)
   = 3.51 x $10^7$

4. Total sound pressure level

   = 10 log 3.51 x $10^7$
   = 75•4 dB

*Example 14.4*
*The problem*
Assume that a third sound source of unequal frequency and having a sound pressure level of 85 dB is to operate with the two sources of Example 14.3. Find the total sound pressure level of this combination.
*The solution:*

1. Mean square sound pressure ratio of the 70 dB source

   = 1 x $10^7$ (from example 14.3)

2. Mean square sound pressure ratio of the 74dB source

   = 2.51 x $10^7$ (from example 14.3)

3. Mean square sound pressure ratio of the 85 dB source

   = Antilog 85/10 = 3.16 x $10^8$ = 31.6 x $10^7$

4. Total mean square sound pressure ratio

   = 35.11 x $10^7$

5. Total sound pressure level

   = lOlog35.11 x $10^7$
   = 85.4dB

*(Note:* It was not necessary to find the absolute pressures for these calculations, but only their ratios to the reference pressure.)

Fortunately, there is a simpler graphical solution for the addition of sound pressure levels (or sound powerlevels) without having recourse to the type of calculation shown in examples 14.3. and 14.4 (see the chart in Figure 14.3). The use of the chart is best illustrated by solving examples 14.3 and 14.4.

In the first case, where the 70dB and 74dB sources are combined, the 4dB difference in levels indicates that 1.4 dB should be added to the higher level (74dB) giving 75.4dB. The procedure for estimating the combined effect of more than two sources is illustrated by solving example 14.4. The addition of the 70 dB and 74 dB sources gives a level of 75.4dB, as we have just seen. When this is combined with the 85 dB source the difference is 9.6dB. The graph shows that O.4dB should be added to the higher level (85 dB) to give a total level of 85.4dB. This agrees with our calculated value.

Any number of sound levels may be added together using this graph. The most accurate result is obtained by starting with the two lowest-level values and adding further levels in ascending order of numerical value.

Noise from diesel generator sets may be defined as *continuous spectrum* sound, containing components of all frequencies within a specified frequency range (see Section 14.3 below). Each frequency band in the spectrum is subdivided into a number of increments - no two having the same frequency. When sounds from two continuous-spectrum sound sources are combined, the incremental frequencies combine as pure tones of different frequencies.

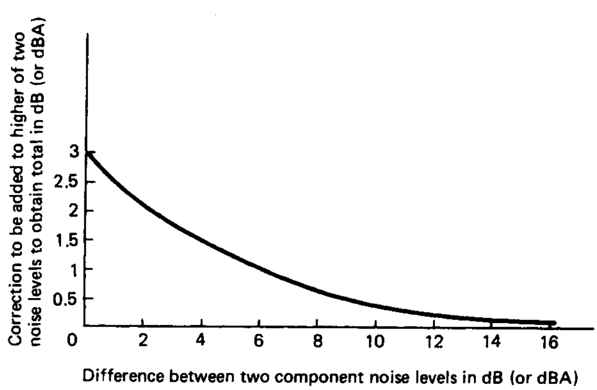



**Figure 14.3** Chart for the addition of unequal sound levels

*Example 14.5*

*The problem*

Two diesel generators with the following power spectra are to be installed in the same plant room. Determine the total sound power from the two machines operating together.

| Frequency band No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
|---|---|---|---|---|---|---|---|---|---|
| Diesel generator A | 78 | 81 | 82 | 79 | 79 | 77 | 75 | 69 | dB |
| Diesel generator B | 69 | 73 | 75 | 79 | 82 | 83 | 84 | 81 | dB |

*The solution*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Spectra difference in dB | 9 | 8 | 7 | 0 | 3 | 6 | 9 | 12 |
| Correction (dB) to be added to the higher of the two levels (read off Figure 14.13) | 0.5 | 0.6 | 0.8 | 3 | 1.8 | 1 | 0.5 | 0.3 |
| Total power level (dB re $10^{-12}$ watt) | 78 | 82 | 83 | 82 | 84 | 84 | 84 | 81 |

(*Note:* In all practical cases, there is no need to consider fractions of decibels. One can only measure sound pressure to ±1 dB, at best.)

Often, one requires to know the overall sound pressure level for the entire frequency range of a source (i.e. as though for a single band that covers all the frequency range of the source). Figure 14.4 illustrates the alternative step-by-step methods used to obtain an overall sound pressure level for the noise spectrum of diesel generator B in example 14.5. In method (a) the two lowest levels are first combined and the resultant total added to the next highest level, and so on. The alternative method (b) arrives at the same answer, but uses different combinations of frequency bands. It is evident that the overall level is very much influenced by the levels in the last four frequency bands. This is worth noting because, while the overall level may appear to be a good representation for a noise spectrum, it will not always convey the whole picture. In the spectrum of our example, the SPL's in bands 1 to 4 (which have little influence on the overall level) may seriously interfere with speech levels. Their reduction, therefore, could be of more importance than the higher levels of bands 5 to 8. A better *characterization* (or signature) of the sound source might well be a profile of sound levels in a number of frequency bands in the spectrum.

## 14.3 Noise evaluation

The British Standard BS 3383 (ISO 226) defines noise as 'sound which is undesired by the recipient'. It therefore has two aspects: the physical one, which can be measured; and the subjective one, which classifies it as undesirable sound, which is broadly divisible into the three categories acceptable, unpleasant, and damaging.

There are many factors which make noise unpleasant, including interference with speech communication, and the effects on work concentration. Prolonged exposure to noise can result in permanent loss of hearing. Intermittent exposure to high noise levels can result in temporary reduction of hearing, leading to damage if such exposure is frequently repeated.

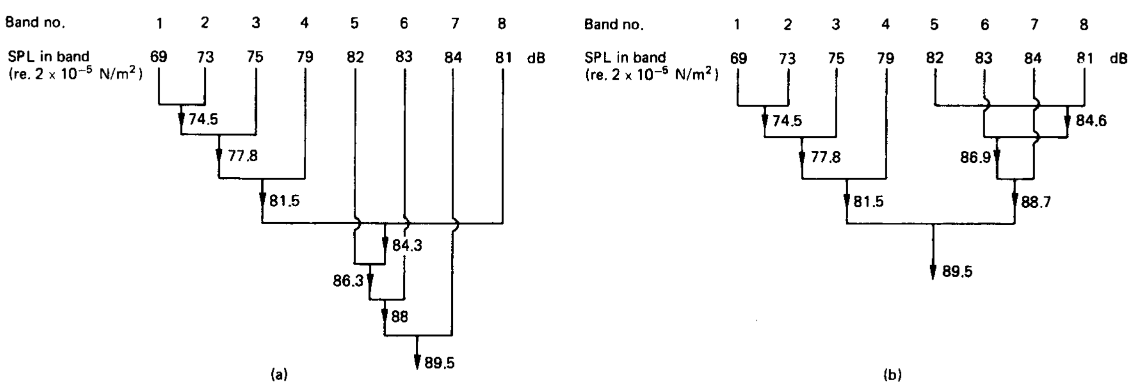



**Figure 14.4** Computation of overall sound pressure level from levels in frequency bands (a) Overall SPL for eight frequency bands = 89 dB (re 2 × $10^{-5}$ N/m$^2$) (b) Overall SPL for eight frequency bands = 89 dB (re 2 × $10^{-5}$ N/m$^2$)

Mental attitudes can override physical relationships. It is therefore important to have objective measurements for subjective effects. The levels at which noise becomes annoying or harmful have been measured, and levels of 'acceptable' noise are defined in international standards.

### 14.3.1 The attributes of noise

The three attributes of noise which should be considered in any noise reduction study are:

- intensity;
- frequency; and
- time-pattern.

#### *Noise intensity*

The range of intensities that the ear can detect, and tolerate, varies between the *threshold of hearing* (the lower limit) and the *threshold of feeling* (the upper limit). A series of curves (Figure 14.5) representing equal *loudness* can be drawn between these two limits.

Work by Robinson and Dadson, of the National Physical Laboratory in England, published in 1956 [2], has been accepted both by the British Standards Institution and the International Organization for Standardization (BS 3383 and ISO 226). The series of curves resulting from this work is reproduced in Figure 14.5. They show the noise pressure levels at various frequencies which the ear (subjectively) considers to be equally loud. There is a very marked decrease in hearing sensitivity at low frequencies.

The unit of loudness (the phon) is defined as being equal to the sound pressure level of a 1000 Hz pure tone. The curves of Figure 14.5 have the same numerical value as the SPL at 1000 Hz. The phon is only of academic interest in our context - that of plant noise reduction. It is important to know of its existence and to appreciate where it is used. There are also other scales for *loudness*, such as the *noy* which was devised for the assessment of jet aircraft noise.

The *sone* scale, also adopted by the British Standards Institution (BS 3045) and the International Organization for Standardization (ISO 131), uses a

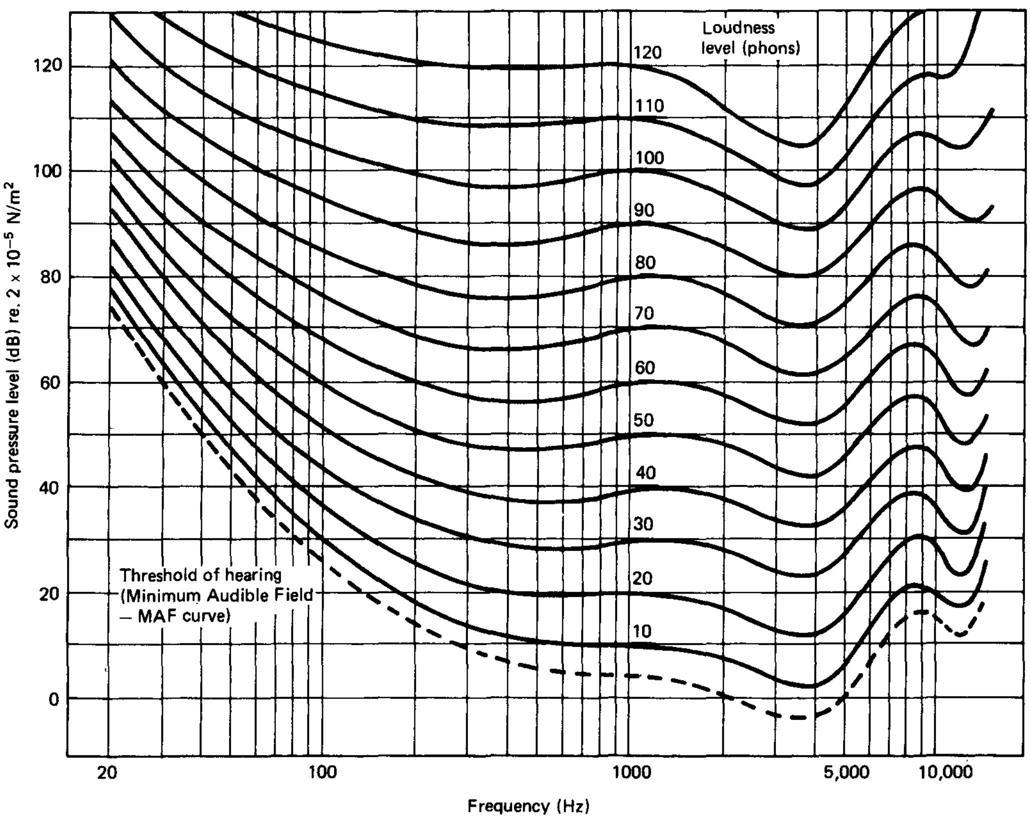



**Figure 14.5** Equal loudness sound contours for pure tones [7]

level of 40 phons as one unit of loudness - the *sone*. The mathematical relationship is given by:

$$S = 2^{(P-40)/10}$$

where $P$ is the loudness level in phons
$S$ is the loudness in sones.

The phon scale indicates the *loudness level* of a sound, but gives no indication of its absolute loudness. It does not distinguish that a level of 80 phons is twice as loud as one of 40 phons. The sone scale, which is linear, was devised to enable this distinction to be made.

One important principle, illustrated by the phon! sone relationship, is that the loudness of a noise is doubled for every 10 dB increase in sound pressure level. Conversely, a reduction of 10 dB halves the loudness.

It is possible, using Figure 14.5 and the Sop relationship, to determine the loudness level and the loudness of any *pure tone* noise of known frequency, by taking a measurement of SPL - in dB. Assessment of the loudness and loudness level of more complex sounds may be possible by direct (albeit subjective) comparison with a pure tone of 1000Hz. This is not always practicable or acceptable.

## *Noise frequency*

Figure 14.5 shows that the ear does not respond equally to every sound it receives. For example, a very low frequency noise of given pressure level will not sound as loud as a middle frequency noise of the same intensity. The maximum response will occur in the frequency range 1000-5000 Hz.

A typical noise signal is shown in Figure 14.6 (d). It consists of an irregular combination of tones, at all frequencies. It cannot be described by the three simple quantities of amplitude, frequency and phase because it is composed of more than one frequency. It may, however, be considered as the combination of a number of superimposed sinusoidal waves.

In contrast, a pure sine wave (Figure 14.6 (a» can be represented, in the frequency domain, as a single line. The addition of two sinusoids (one being three times the frequency of the other) gives the distorted wave shape of Figure 14.6 (b), represented in the frequency domain by two lines. The square wave of Figure 14.6 (c) is a complex function made up of an infinite number of lines in the frequency domain, all at the odd harmonics of the fundamental frequency *(fo).* The frequency spectra of the functions (a), (b) and (c) are harmonically related discrete lines, and are, therefore, classified as *periodic,* i.e. they repeat themselves exactly at regular and predictable intervals. Their frequency spectra are called *line spectra.*

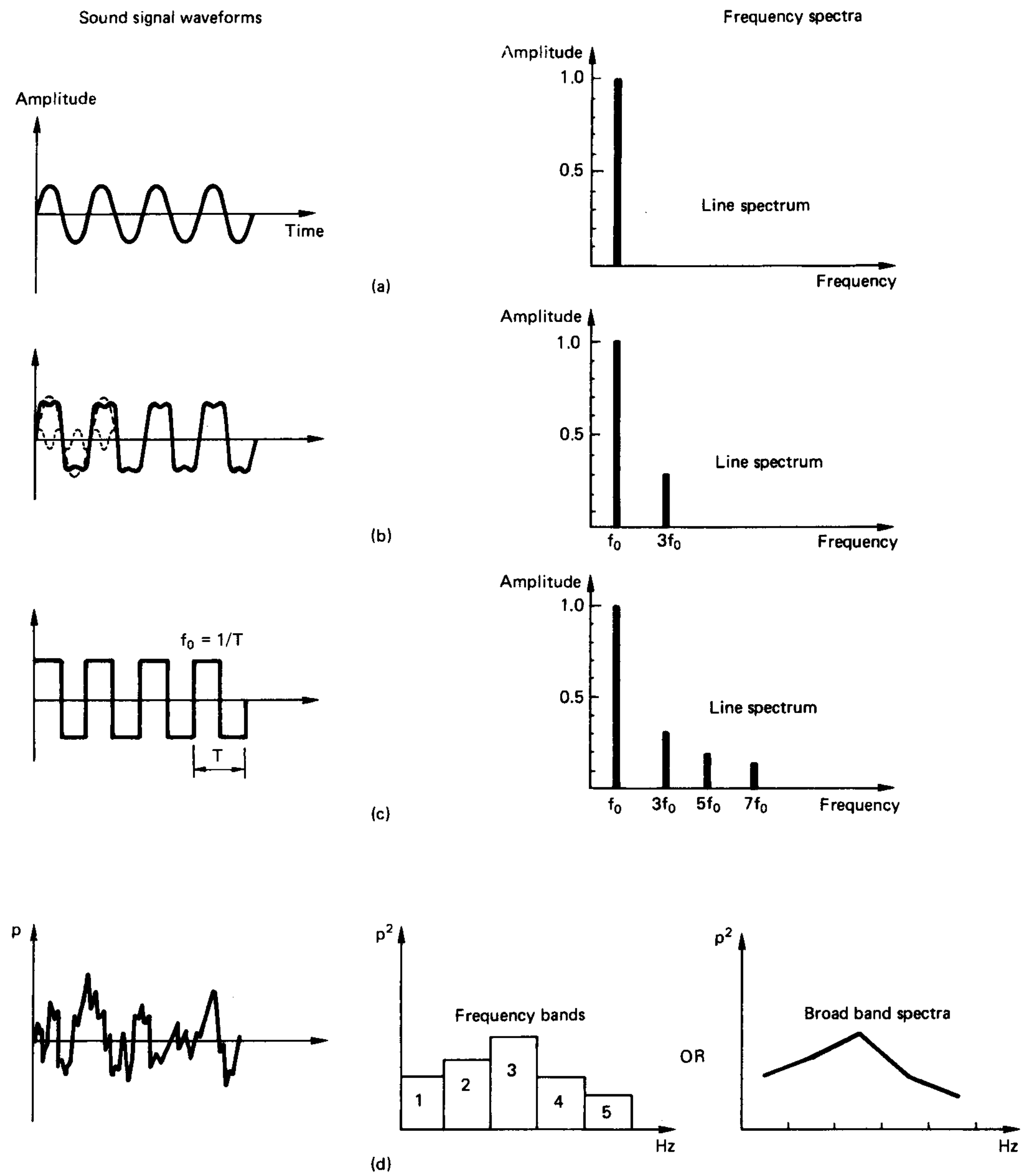
The internal combustion engine produces periodic noise containing many harmonics of its rotational speed, and its frequency spectrum is *continuous*. The (broadband) spectrum of Figure 14.6 (d) contains a large number of frequency components which are not harmonically related, giving a random, non-periodic, and continuous pattern.
(*Note*: a special case of the non-periodic signal is *white noise*, which is defined as a sound wave whose frequency spectrum is continuous, and uniform. It need not be random.)

A number of instruments are available which enable one to measure the amount of energy ($p^2$) contained within a chosen frequency band. It is then possible to plot the total intensity within each band of frequency and produce a frequency spectrum for a noise source – as in Figure 14.6 (d). It would, of course, be logical to select frequency bands that are universally *preferred* so that sound comparisons, measurements, noise analyses, and reaction assessments are simplified.

The band most commonly used in International Standard practice is the *octave band*, in which each frequency band is one octave wide. The audible frequency range is divided into ten octave bands whose centre frequencies and bandwidths are defined by International Standards (ISO 1996/2, and BS 4142). One octave is a doubling of frequency. Therefore, the centre frequencies of each consecutive octave band are twice the centre frequency of the previous one. The upper frequency in each band is twice the lower frequency limit. The centre frequency, which is used to describe the band, is the geometric average of these upper and lower frequency limits. For example, the 1000 Hz octave band stretches from 707 Hz to 1414 Hz (i.e. $1000\,\text{Hz} = \sqrt{707 \times 1414}$). Conversely, the centre frequency ($f_c$) of each band is $\sqrt{2}$ times the lower cut-off frequency, and $1/\sqrt{2}$ times the upper frequency limit.

An octave analysis is usually adequate for most diesel generator noise investigations. If more detailed information is required on the 'structure' of any noise, narrower bands may be selected. For example, half-octave, third-octave, or even 1/24 th-octave bands. Third-octave bands have a frequency bandwidth that is one-third of the width of an octave band. In practice, octave and third-octave analyses are found to be more than adequate for the examination of the frequency structure of noise transmitted from diesel generators and their ancillary plant. It is possible to obtain even more accurate information on intensity levels by using very narrow-band analysis – as little as ±1 Hz either side of a centre frequency. But, as the bandwidth decreases, the analysis time increases and the results are more difficult to interpret. The technique is therefore largely confined to use by specialists.

The (internationally) preferred octave and third-octave bands are shown in the table of Figure 14.7 [3].




**14.6** Examples of sound signals and their frequency spectra (a) Sine wave (b) Combination of two sine waves (c) Periodic square wave (d) Complex and non-periodic, random noise

It should be noted when comparing octave and third-octave analyses of the same noise source that the third-octave sound levels are always less than the octave levels. For example, the 'total' value of the third-octave sound levels at centre frequencies of 400 Hz, 500 Hz, and 630 Hz would be equal to that at 500 Hz in an octave analysis.

The diagrams in Figure 14.8 show alternative methods of presenting noise spectra in octave band form, the more conventional being that shown in diagram (b).

| Octave band centre (nominal) frequency Hz | Band limits Hz | One-third octave centre frequency Hz | Band limits Hz |
|---|---|---|---|
| 31.5 | 22–44 | 25 | 22–28 |
| | | 31.5 | 28–35 |
| | | 40 | 35–44 |
| 63 | 44–88 | 50 | 44–57 |
| | | 63 | 57–71 |
| | | 80 | 71–88 |
| 125 | 88–176 | 100 | 88–113 |
| | | 125 | 113–141 |
| | | 160 | 141–176 |
| 250 | 176–353 | 200 | 176–225 |
| | | 250 | 225–283 |
| | | 315 | 283–353 |
| 500 | 353–707 | 400 | 353–440 |
| | | 500 | 440–565 |
| | | 630 | 565–707 |
| 1000 | 707–1414 | 800 | 707–880 |
| | | 1000 | 880–1130 |
| | | 1250 | 1130–1414 |
| 2000 | 1414–2825 | 1600 | 1414–1760 |
| | | 2000 | 1760–2250 |
| | | 2500 | 2250–2825 |
| 4000 | 2825–5650 | 3150 | 2825–3530 |
| | | 4000 | 3530–4400 |
| | | 5000 | 4400–5650 |
| 8000 | 5650–11300 | 6300 | 5650–7070 |
| | | 8000 | 7070–8800 |
| | | 10 000 | 8800–11 300 |
| 16000 | 11300–22500 | 12500 | 11 300–14 140 |
| | | 16 000 | 14 140–17 600 |
| | | 20 000 | 17 600–22 500 |

**Figure 14.7** The preferred International standard octave and third-octave frequency bands [1].

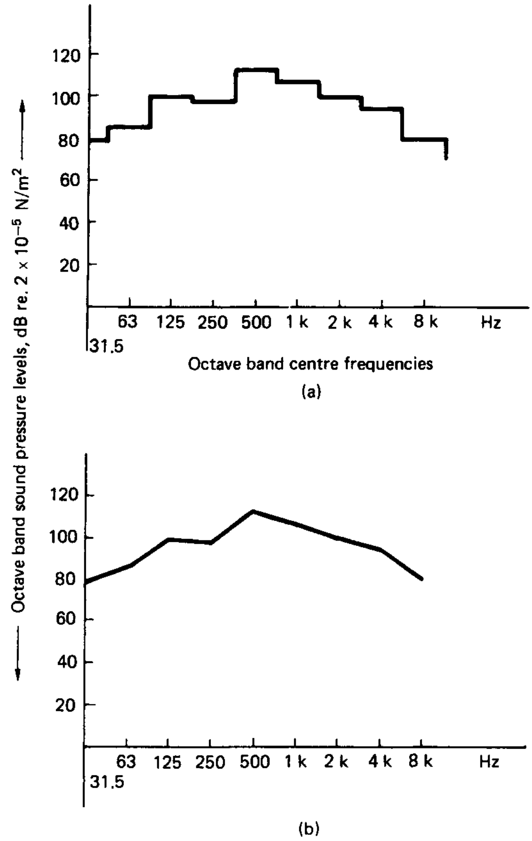



**Figure 14.8** Alternative methods of presenting noise spectra in octave band form (a) Octave band noise spectrum in histogram form (b) The spectrum of (a) in the more conventional frequency polygon form

## *Noise time-pattern*

The time-pattern of a noise governs its relative acceptability. Such criteria as how rapidly the noise occurs, when it occurs (day, night, summer or winter), and whether it is continuous or intermittent, are all pertinent. Noise characteristics may be classified according to their variation with time. Constant, continuous noise is one which remains fairly level (within 5 dB) for a long time. Examples are the noise from pumps, electric motors and gear boxes. A constant, intermittent noise is one which starts and stops at regular intervals. A typical example would be automatic machinery during a work cycle. Fluctuating noises are those which have fairly high variations in level. They may be periodic (e.g. automatic surface-grinding) or non-periodic (e.g. welding, manual component assembly, etc.). Impulse noises are normally classified as those of less than 1 second duration. Again, they may be periodic in pattern (e.g. automatic presses and automatic riveting) or they may be irregularly spaced - as in hammer blows or material handling activities.

Community noise investigations usually call for noise-annoyance evaluations within specified periods of time during which noise levels may vary quite unpredictably. The higher the noise level, the shorter the exposure time allowed. *Damage risk criteria* (DRC) curves show the sound pressure levels at which hearing conservation measures should be introduced if damage to the hearing mechanism is to be avoided through daily exposure to noise over a five-day week. Levels above 135 dB cannot be tolerated at any frequency without ear protection. Typical criteria are contained in the Department of Employment's Booklet No.25 [4], which calls for noise abatement and hearing conservation measures when factory noise levels exceed stated values for given exposure durations. Other reference sources for criteria on occupational noise exposure are:

1. In North America: *Occupational Safety & Health Act (OSHA),* subsequent to the Weber-Healey Act.
2. In Western Europe: ISO Recommendation 1999 *The Assessment of Occupational Noise Exposure for Hearing Conservation Purposes.*

Shipowners and shipbuilders are particularly concerned regarding the exposure of ships' crews to noise - not only that generated in machinery spaces, but also that transmitted to off-duty accommodation areas. These are important considerations on vessels such as tankers, which undertake long voyages and usually have continuously-manned machinery spaces.

The 'Noise at Work Regulations 1989' came into force in the United Kingdom in January 1990. Action required by employers depends upon the level of noise exposure, which is measured (in dBA) according to the perceived risk of hearing damage. 'Action levels' are set at environmental exposures of 85 and 90 dBA, with a peak action level corresponding to a sound pressure of 200 Pascals (140dB)

Factory and community noise levels fluctuate, or vary randomly, with time. Integrating sound level meters are designed to take account of the duration of noise and give a *weighting* to all noise occurring throughout the measurement period. Direct-reading instruments should be to IEC651 Type 1 accuracy. A typical meter is the hand-held Type 2221 unit marketed by Bruel and Kjaer. It offers measurement of the *equivalent continuous sound level (Leq)* and the *sound exposure level* (SEL) for continuous, erratic, and fluctuating noises. A level recorder may be used to give a time history of the noise level. A typical example of a recording for the A-weighted *Leq* of a fluctuating noise is illustrated in Figure 14.9.

### *Equivalent continuous sound level (Leq)*

The *Leq* level is a measure of the energy content of the noise over the measurement period. It is the

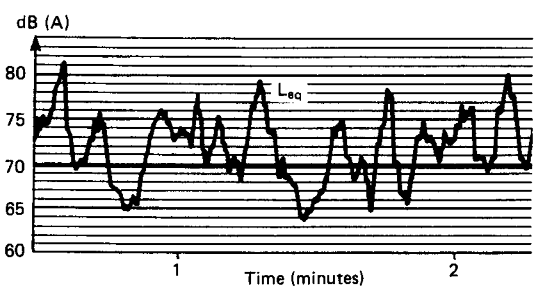



**Figure 14.9** Example of a time history recording for a fluctuating noise (Courtesy: Bruel and Kjær (UK) Ltd)

weighted energy mean of the noise level, averaged over this period. It may be regarded as a notional level which would, in the course of a predetermined period, cause the same A-weighted sound energy to be received as that due to the actual sound, over the same period. *(Note:* frequency weightings are described in Sub-section 14.3.2.) *Leq* may also be calculated, for certain environmental conditions. Typical methods are described in Appendix 3 of [5].

### *Sound exposure level (SEL)*

The SEL is the *Leq* referred to one second, and is useful for companng individual noise events of different duration - for example, the pass-by noise of goods trains, compared with commuter passenger trains and high speed trains, etc.

## 14.3.2. Subjective units for noise assessment

We established earlier in this section that the ear responds not only to the absolute sound pressure level of a sound, but also to its frequency. Subjectively-developed, equal-loudness contours were introduced to define the unit of loudness (the phon), and to demonstrate the response characteristics of the human ear.

### *Weighting networks*

If a sound level meter is to register sound exactly as it is perceived by the listener it would need to incorporate *weighting* networks which give the inverse of the equal-loudness curve (Figure 14.5) at the sound pressure being indicated. However, to incorporate such a feature would make for a very expensive instrument indeed.

Instead, the simple sound level meter (SLM), which indicates r.m.s. sound pressure level (referred to $2 \times 10^{-5}$ N/m$^2$) and normally responds equally well to all frequencies in a linear fashion, is equipped with electrical filtering networks. These are inserted between the instrument's microphone and its indicating meter. They give different *weights* to different frequency ranges (See the shapes of the weighting curves in Figure 14.10), and attempt to match, as nearly as possible, the variable sensitivity of the human ear.

It will be seen that the weighting curves mirror, approximately, the equal-loudness contours of Figure 14.5. The A-curve reflects that of the equal-loudness curve of 40 phons, and the B- and C-weighting curves, more or less, those of the 70 and 100 phon contours, respectively. The A-network was intended to be used, originally, for sounds below 55 dB; the B-network for sounds between 55 and 85 dB, and the C-network for levels above 85 dB. This approach was used for some time, until

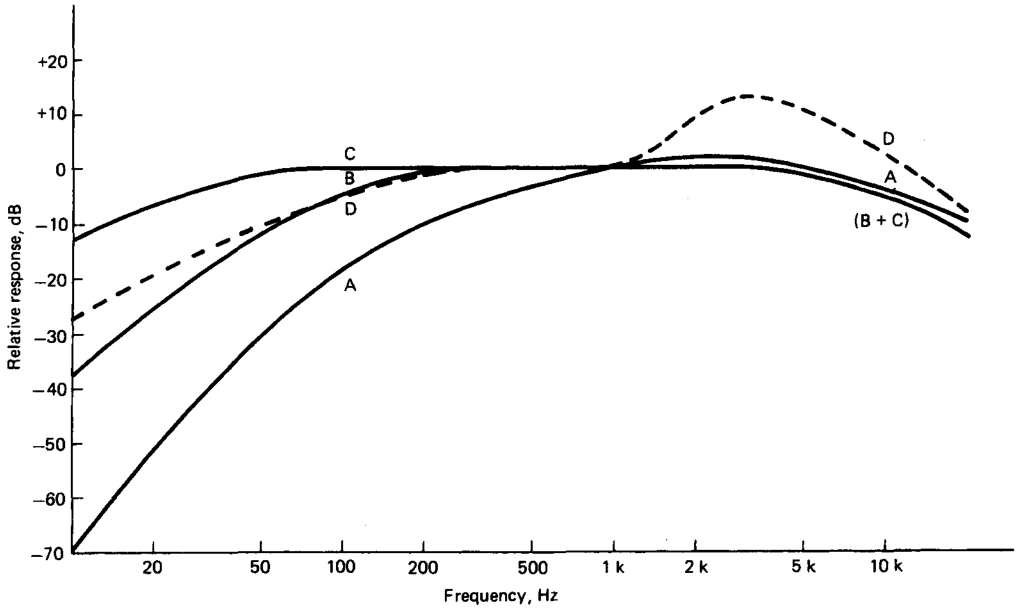



**Figure 14.10** International standard weighting networks for the sound level meter

studies showed that it was not giving any better results than using the A-network alone.

The A-weighting gives a very good indication of the loudness of sound regardless of its level. It is now commonly used for industrial steady-noise level measurements. The sound levels so obtained are indicated in A-weighted decibels, or *dBA*. The A-weighted sound level of a fluctuating signal may also be sampled to yield statistical information, such as the $L_{eq}$. Attention is directed to Appendix 5 of [5] for <;letails.

The B-network is seldom used nowadays. The C-network, as the weighting curves show, is essentially flat and sounds measured with it are called *sound pressure levels.* All frequency analyses must be made on the C-scale. Where the C-weighting network is incorporated in a sound level meter, a useful, but approximate, indication of the frequency of a measured sound may be obtained from the difference between the C- and A-weighted decibels, i.e. dBC - dBA. This difference is known as the *harmonic index.* If it is large, the implication is that a significant part of the measured noise lies in the low-frequency range (20 - 100Hz). The D-weighting is only used for single-event, aircraft noise measurements.

It is worth noting that loudness and weighted sound pressure levels are related as follows:

1. loudness (in phon) corresponds to the sound pressure level, *LA* (in dBA), for all numerical values between 30 and 60;
2. for numerical values above 60, loudness corresponds to the sound pressure level in dBB ($L_B$).

Obviously, the simplest way to determine dBA sound levels is to measure them with a sound level meter. Very often the only design data available are octave band frequency analyses. This is logical since the acoustic properties of materials and sound attenuation with distance are both frequency-dependent - as we shall see later. It is more convenient to use octave band data because they help identify the dominant frequencies of noise sources in plant rooms.

The noise limits for plant are normally specified in a single dBA figure which is related to a stated distance from the noise source. This overall dBA limit can be converted to an octave band spectrum before work starts on attenuation design. The method is described later in this section. Conversely, it is also possible to derive an overall dBA sound level from an octave band spectrum. The two methods for making the conversion are described in the examples below.

*Example 14.6*
*The problem*
A typical noise spectrum for a diesel generator, measured at 1 metre distance from it, is given by:

| Octave band centre frequency (Hz) | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
|---|---|---|---|---|---|---|---|---|
| Band SPL (dB) | 85 | 99 | 98 | 112 | 107 | 99 | 94 | 80 |

Find the overall dBA level $(L_A)$.

*The first solution - by calculation*

Step 1: Apply the A-weighting corrections, given in the following table to each octave band sound pressure level - by mathematical addition or subtraction.

| Octave band centre frequency (Hz) | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
|---|---|---|---|---|---|---|---|---|
| A-weighting correction (dB) | -26 | -16 | -9 | -3 | 0 | +1 | +1 | -1 |

*Step* 2: Add the eight, octave band, A-corrected SPL's, either by using the graph of Figure 14.3 or by using the following formula:

$$L_A = 10\log_{10} [\text{Antilog} (L_{1A}/10) + \ldots + \text{Antilog} (L_{8A}/10)]$$

where $L_A$ is the overall sound level, in dBA;
$L_{1A}$ to $L_{8A}$ are the A-weighted sound levels in the individual octave bands.

Using the formula method of calculation, we would arrive at our solution as shown in the table below.

*The second solution - by graphical treatment*

The octave band pressure levels (column 2 in the table) are plotted on a chart of equivalent A-weighted sound level contours - a family of curves based on the Walsh-Healey Act regulations, as used in American practice (see Figure 14.11).

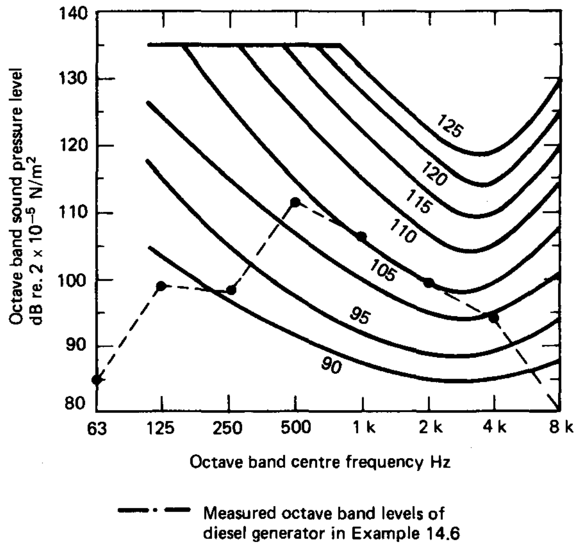



**Figure 14.11** Overall A-weighted sound level of noise obtained from equivalent sound level contours

The point of highest penetration into the sound level contours determines the A-weighted sound level. In this case there is no need to interpolate a sound level contour as the highest point touches the 105 dBA curve. The overall sound level is, therefore, 105 dBA. This graphical method is accurate enough for most practical purposes and any divergence from a result obtained by the calculation method (solution 1) is unlikely to be more than 3 dBA.

## *Some applicable noise criteria*

A great deal of work has been done to establish acceptable levels of noise for various commercial,

| *Octave band centre frequency* (Hz) | *Octave band measured SPL* (dB) | *Band correction (see table above)* (dB) | *A-corrected octave band SPL* (dB) | *dB/10* | *Antilog dB/10* |
|---|---|---|---|---|---|
| 63 | 85 | -26 | 59 | 5.9 | 0.008 $\times 10^8$ |
| 125 | 99 | -16 | 83 | 8.3 | 1.995 $\times 10^8$ |
| 250 | 98 | -9 | 89 | 8.9 | 7.943 $\times 10^8$ |
| 500 | 112 | -3 | 109 | 10.9 | 123.03 $\times 10^8$ |
| 1k | 107 | 0 | 107 | 10.7 | 117.49 $\times 10^8$ |
| 2k | 99 | +1 | 100 | 10.0 | 100.000 $\times 10^8$ |
| 4k | 94 | +1 | 95 | 9.5 | 31.623 $\times 10^8$ |
| 8k | 80 | -1 | 79 | 7.9 | 0.794 $\times 10^8$ |
| | | | | | Total= 382.883 $\times 10^8$ |

$10 \log 382.9 \times 10^8 = 10(10.58) = 106$ dBA residential, and industrial environments. Data usually take the form of curves of noise, expressed as SPL (referred to 2 x $10^{-5}$ N/$m^2$) on an octave band basis, to give national or international standards for emission.

The most commonly applied target criteria are *noise criterion* (NC) and *noise rating* (NR) curves, which are families of octave band spectra, each with its own rating number (see Figure 14.12). The NC curves were developed by Bolt, Beranek and Newman in the United States, where they are widely adopted. NR curves, developed by Kosten and Van Os, were introduced at a later date in Europe, and partially adopted by the International Organization for Standards.

It will be seen that both sets of curves progress in steps of five 'rating' numbers. However, intermediate levels may be quoted, e.g. NR 52. The NR curves extend to higher levels than the NC curves and have their foundation in mathematical formulae, whereas the NC curves are purely empirical. Another difference lies in the fact that the numbers of the NC curves correspond with the SPL at the 2kHz octave band centre frequency, whereas those for the NR curves are numerically equal to the pressure level at the 1 kHz centre frequency. Note that both sets of curves are broadly similar in shape to the equal loudness contours of Figure 14.5 and, like them, are not parallel at the lower frequencies.

### *Use of criteria curves*

The octave band spectrum of the noise to be investigated is plotted on the same grid as the family of noise criteria curves - either NC or NR. The lowest of the contour curves which is *not* crossed by the spectrum is the NC (or NR) number of that noise. (See the graphical example in Figure 14.13.) Since the sound pressure from a noise source is dependent upon location and distance from the source it is important to give this information when quoting NC and NR ratings.

These criteria curves may be used to specify acceptable noise levels in machinery spaces, in accommodation areas, and in residential locations. The total noise level from all noise sources in the stated area must then be attenuated so that it does not exceed the stipulated NC or NR level in any octave band. For example, the criterion of NR 85 represents the desirable level of noise in manned machinery spaces on board ship, where crews are continuously exposed to noise for 40 hours a week or more. In those spaces which are not continuously manned, higher levels would be acceptable. Berry [6] suggests that if no member of the crew is exposed to the noise for more than 10 hours a week, NR 90 levels may be applied, and if exposure is restricted to less than 2.5 hours a week, NR 95 levels could, reasonably, be allowed. In general, NR95, for con-

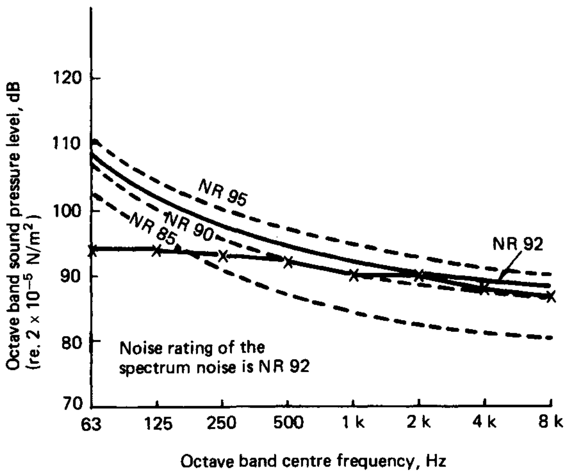



**Figure 14.13** An octave band noise spectrum plotted on the NR family of curves

tinuously manned spaces, and NR 105 for intermittently manned spaces, he argues, would appear to represent a reasonable compromise between desirability and practicability. In both instances some form of ear defender should be worn by crew members when they are actually working within the machinery spaces and are therefore exposed to local acoustic effects.

Some recommended NR values for various environments are given in the following table. The relationship between NR number and dBA level is given by: NR = dBA - 5.

| *Type of space* | *Recommended NR level* | *Equivalent dBA level* |
|---|---|---|
| Workshops | NR65 | 70 |
| Mechanized offices | NR55 | 60 |
| Restaurants | NR45 | 50 |
| Private offices and libraries | NR40 | 45 |
| Hospitals | NR35 | 40 |
| Classrooms and studies | NR30 | 35 |
| Theatres and concert halls | NR25 | 30 |

While the NR curves were designed to be applied to both internal and external environments, the NC curves, which had their origins in research on interior spaces, are usually applied to offices, conference rooms, residences, and the like, where speech communication is important. This introduces the term *speech interference level* (SIL), which gives a measure of the suitability of an environment for speech. It is defined as the arithmetic average of the three band levels centred on frequencies of 500, 1k, and 2kHz. (Occasionally, one comes across the abbreviation PSIL for the same term - the P stands for *preferred.)* The SIL (stated in decibels) is a good indicator of the ability of a noise to mask speech and has the practical advantage of being readily measured using a sound level meter with octave band facilities. The NC number shown beside each curve in the family of noise criteria curves equals the SIL, in dB. The loudness, in phons, is numerically equal to (SIL + 22).

The methods of rating industrial noise, affecting mixed residential and industrial areas, are covered in BS4142 and ISO 1996/2. Both give recommendations in terms of dBA. Essentially, a background noise level is prefered as a criterion. The planned new noise is then weighted for different characteristics such as tone, impulse, and intermittency. If the new noise exceeds the background noise by 10dBA, complaints may be expected. If the increase is less than 5dBA, the situation is deemed to be *marginal.* Sometimes a problem already exists and it is not possible to measure background level with the offending noise absent. BS4142 recommends that, in such cases, a base criterion of 50dBA is adopted and is then 'weighted' by corrections related to various environmental factors such as the type of installation causing the noise, the type of area, and the time of day, or season.

The NR curves, however, give one a far better assessment of community reaction to noise. All the environmental factors are applied to the basic (or selected) criterion only and the measured octave band is compared with the corrected criterion. If the latter exceeds the former (in any octave band) by less than 5dB, the noise is rated as 'marginal'. If the difference is 5 to lOdB, the noise is rated as 'difficult to accept'. Anything over 10dB is rated as 'unacceptable'. Note that the 'corrected' NR criterion is that which is to be met *inside* the residence. The table at the top of page 554 [3] is based on work by Kosten and Van Os, and summarizes the environmental corrections to be applied to selected NR criteria when assessing community reaction.

Having covered the topic of NR curves, it is now appropriate to consider the conversion of a targeted, overall dBA level to a more meaningful octave band spectrum. This is done by selecting that NR curve which is five less than the specified dBA limit. For example, the NR 50 spectrum for a set limit of 55dBA. The table at the bottom of page 554 shows the NR numbers equating to dBA levels. It should be realized that the octave band values given in the table are not the precise equivalents of any particular noise. They are merely the lowest values which may be expected to give the corresponding overall dBA shown in the table. This method (of using the NR equivalent to define a noise limit) has particular merit since ISO 1966/2 specifies NR curves. Although BS 4142 uses equal-loudness curves, these are, as we

*Corrections to be added to the basic (or selected) criterion NR number*

Typical base criteria:

Inside sleeping rooms NR25
Inside living rooms NR30

| | |
|---|---|
| A pure tonal or other tonal characteristic easily distinguishable | -5 |
| Impulsive andlor intermittent noise | -5 |
| Noise only during working hours | +5 |
| Noise only occurring 25% of time | +5 |
| Noise only occurring 6% of time | +10 |
| Noise only occurring 1.5% of time | +15 |
| Noise only occurring 0.5% of time | +20 |
| Noise only occurring 0.1% of time | +25 |
| Noise only occurring 0.02% of time | +30 |
| Type of area: Very quiet suburban | -5 |
| Suburban | 0 |
| Residential urban | +5 |
| Urban near some industry | +10 |
| Area of heavy industry | +15 |

have established, very close to the NR form for all practical purposes.

## *Combination of sounds on an octave band basis*

The method of determining the combined noise level for two sources whose levels are expressed in octave band spectra is best illustrated by a practical example.

*Example* 14.7

*The problem*

The octave band SPL of noise from an acoustically-treated standby generator plant measured at the site boundary of a computer complex was as follows:

| Centre frequency | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k (Hz) |
|---|---|---|---|---|---|---|---|---|
| Standby generator noise level | 26 | 29 | 33 | 27 | 19 | 8 | 11 | 9 (dB) |

Total noise levels at the boundary for four externally-mounted condenser units (associated with the computer mainframe's air conditioning plant) were assessed to be as follows:

| Centre frequency | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k (Hz) |
|---|---|---|---|---|---|---|---|---|
| SPL at boundary | 42 | 41 | 35 | 31 | 27 | 22 | 16 | 15 (dB) |

What would be the resultant sound level at the site boundary when the standby generator and the four condenser units are all operating together?

*The solution*

| Centre frequency | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k (Hz) |
|---|---|---|---|---|---|---|---|---|
| (a) Standby generator SPL | 26 | 29 | 33 | 27 | 19 | 8 | 11 | 9 (dB) |
| (b) Condenser units SPL | 42 | 41 | 35 | 31 | 27 | 22 | 16 | 15 (dB) |

Using the chart of Figure 14.3 for the addition of sound levels, we arrive at a total SPL as follows:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (c) Arithmetic difference (b) - (a) | 16 | 12 | 2 | 4 | 8 | 14 | 5 | 6 (dB) |
| (d) Addition to be made to the larger sound level of (a) and (b) - (from Figure 14.3) | 0.1 | 0.3 | 2 | 1.5 | 0.7 | 0.2 | 1.2 | 1.0(dB) |
| (e) Total SPL, to nearest decibel | 42 | 41 | 37 | 33 | 28 | 22 | 17 | 16 (dB) |

*Example 14.8*

*The problem*

If the building in which the computer complex is housed were situated in an area which can be classified as 'urban near some industry', what would be the subjective noise assessment of local residents whose houses adjoin the installation's boundary?

| *Overall target limit dBA* | *Equivalent· NR level* | 63 | 125 | *250* | *500* | *1k* | *2k* | *4k* | *8k (Hz)* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Octave band (dB)* | | | | | | | |
| 65 | 60 | 83 | 74 | 68 | 63 | 60 | 57 | 55 | 54 |
| 60 | 55 | 79 | 70 | 63 | 58 | 55 | 52 | 50 | 49 |
| 55 | 50 | 75 | 66 | 59 | 54 | 50 | 47 | 45 | 44 |
| 50 | 45 | 71 | 61 | 54 | 49 | 45 | 42 | 40 | 38 |
| 45 | 40 | 67 | 57 | 50 | 44 | 40 | 37 | 35 | 33 |
| 40 | 35 | 63 | 52 | 45 | 39 | 35 | 32 | 30 | 28 |

*The solution*
In previous discussions we established that the basic criterion for the inside of living rooms is NR30. This rating must be corrected to take account of the character ofthe noise and the (ambient) background noise level.
Correction for:

| | |
|---|---|
| Noise only during working hours | +5 |
| Urban near some industry, type of area | +10 |

so that the correct~d criterion is N~45 (i.~. 30 + 5 +: 10) Companng the tot.al SPL of lme (e) m the solutIOn to l?-xample 14.7 With the octave band SPL correspondmg to NR45 we get:

| Centre frequency | 63 | 125 | 250 | 500 | lk | 2k | 4k | 8k (Hz) |
|---|---|---|---|---|---|---|---|---|
| (i) Total SPL | 42 | 41 | 37 | 33 | 28 | 22 | 17 | 16 (dB) |
| (ii) SPL for NR45 | 71 | 61 | 54 | 48 | 45 | 42 | 40 | 38 (dB) |

This puts the anticipated total SPL well below the NR45 (corrected) criterion curve in every octave band. The conclusion is that the generated noise level would be quite acceptable to residents living on the boundary of the premises.

## 14.4 Instrumentation and noise measurement techniques

Noise measurements are an essential starting point when planning noise control measures or when establishing the basis on which to assess the noise from proposed generator plant. In the absence of existing data objective decisions for noise control cannot be made; nor can the effectiveness of any proposed measures be predicted.

Other reasons for making noise measurements would be:

1. the need to compare the noise levels obtained with those declared, or guaranteed, for a particular plant;
2. the need to ensure that noise levels are not disturbing to third parties, e.g. those in nearby residential areas.

Before undertaking any noise measurement programme the objectives must be clearly defined, the data to achieve these objectives must be selected, and a programme must be organized to achieve the objectives. The data analysis required will also influence the choice of instrumentation and the measurement procedures. The noise research programme on a prototype product (within a manufacturer's premises) would require very detailed and high-quality data which must, subsequently, be closely analysed. On the other hand, the noise control investigation (on site) of a proven production unit might require less detailed information. An important consideration in the latter case would be that the instrumentation is truly portable and, therefore, easy to set-up and calibrate on site. Preferably, it should be independent of external power supplies.

### 14.4.1 Basic noise measuring systems

Though details may differ, every noise measuring system essentially consists of a transducer, an analysis section, and a read-out section. The transducer is usually a microphone, but accelerometers or strain gauges may be substituted in certain investigations to help identify the mechanisms of noise emissions from complex vibrating sources.

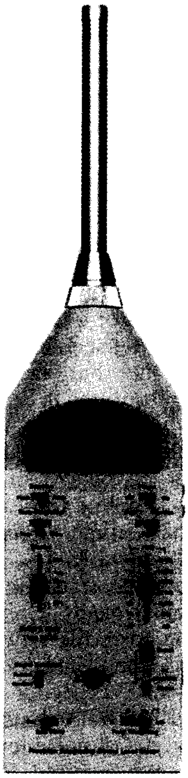
The analysis section of the system is usually the most intricate. In its simplest form it weights the frequency spectrum of the input signal according to one of the standard networks (A, B, C or D). Alternatively, it filters the signal in octave, one-third octave, or narrower bands. Units such as Leg, derived by integration from the A-weighted level, may also be obtained using time, rather than frequency, as the variable. This section of the system may also be designed to give a complete and continuous statistical analysis of noise level variations, with time - such as that required for community noise annoyance investigations. In modern instruments the display in the read-out section is usually digital. There mayor may not be additional quasi-analogue displays of lower resolution.

#### *Sound level meters and recorders*

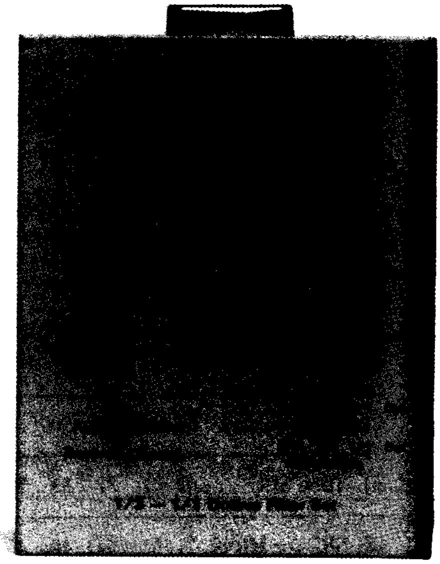
The most convenient form in which all the elements of the noise measurement system are brought together is the portable sound level meter. Instruments range in complexity from those simply giving A-weighted measurements, to more comprehensive models such as the Bruel & Kjrer Type 2230 precision integrating sound level meter illustrated in Figure 14.14(a).

The simpler instruments are intended for use by less experienced personnel undertaking preliminary surveys to identify likely problem areas. The Bruel & Kjrer Type 2230 is a comprehensive and versatile instrument which may be used for all kinds of sound level measurements - including octave and 1/3 octave frequency analysis - using snap-on filter sets of the type shown in Figure 14.14(b) and (c). For example, as configured in its basic form, it is capable of making five different measurements in parallel - by sampling the detector output, followed by analogue to digital conversion and processing by microprocessor. It may be used for:

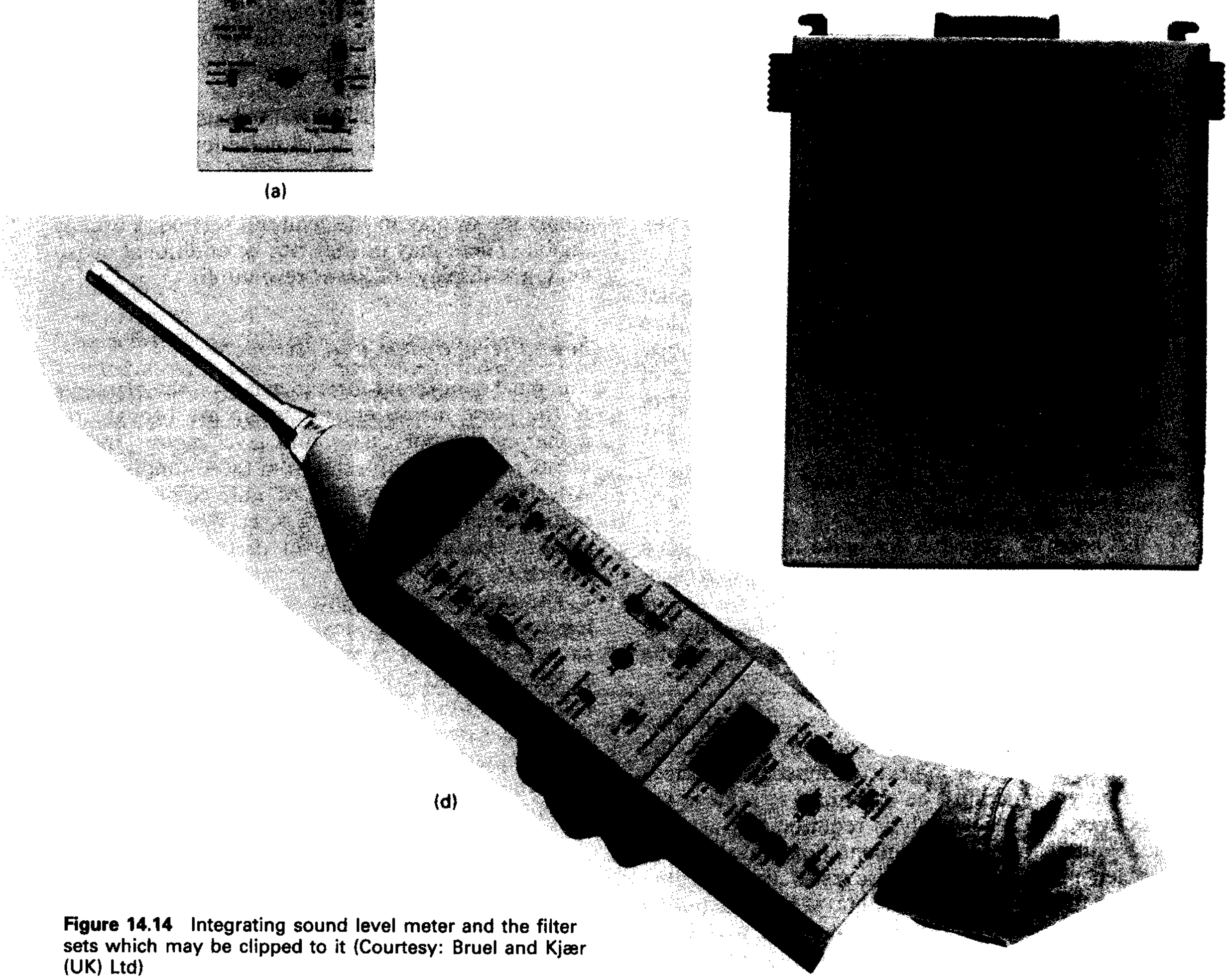
- sound pressure level (SPL) measurement;



(a)



(b)



(d)

**Figure 14.14** Integrating sound level meter and the filter sets which may be clipped to it (Courtesy: Bruel and Kjær (UK) Ltd)

- determination of the equivalent continuous sound level (Leq);
- determination of sound exposure level (SEL);
- measurement of maximum and minimum noise levels - it displays the max or min SPL held since the last time the instrument was reset.

Features include r.m.s and peak detector modes, 'impulse', 'slow' or 'fast' time weightings. Built-in frequency filters give A and C weightings in accordance with IEC651, and 'linear' (20Hz to 20kHz) and 'all-pass' (10Hz to 50kHz). The instrument is also provided with mini-jack a.c. and d.c. sockets enabling connection to:

1. a portable level recorder (see Figure 14.15(a» to give a permanent record of the noise level-either versus frequency or versus time; or
2. a multi-channel tape recorder (see Figure 14.15(b» which enables a recording to be made on site, and the tape examined and analysed later using laboratory equipment.

Recordings are of most value when they supplement, rather than replace, directly-measured data.

An alternative, more modern approach is to use a graphics printer (of the type shown in Figure 14.15(c» which communicates with a sound level meter through a digital interface and interrogates it to print out levels in numerical form, or produces a bar graph of a frequency analysis.

BS5969 (IEC651) - *Specification for sound level meters* - designates four classes of accuracy. Type O sets the highest accuracy and tolerance limits and covers laboratory, reference-class, instruments which are mainly used for product evaluation and rating, quality assurance testing, and environmental certification. Type 1 corresponds to the earlier (IEC 179) precision class, and Types 2 and 3 to the general purpose (IEC 123) and survey classes. The American standard for sound level meters (ANSI - S1.4) also uses four classifications, the first three of which, while all having the same performance goal, permit different tolerance levels. The classifications are:

- Type 1 - precision;
- Type 2 - general purpose;
- Type 3 - survey; and
- Type S - special purpose.

Most national standards are identical with, or closely related to, one of these two standards. In some countries, only measurements taken with precision grade instruments are acknowledged.

## *Microphones*

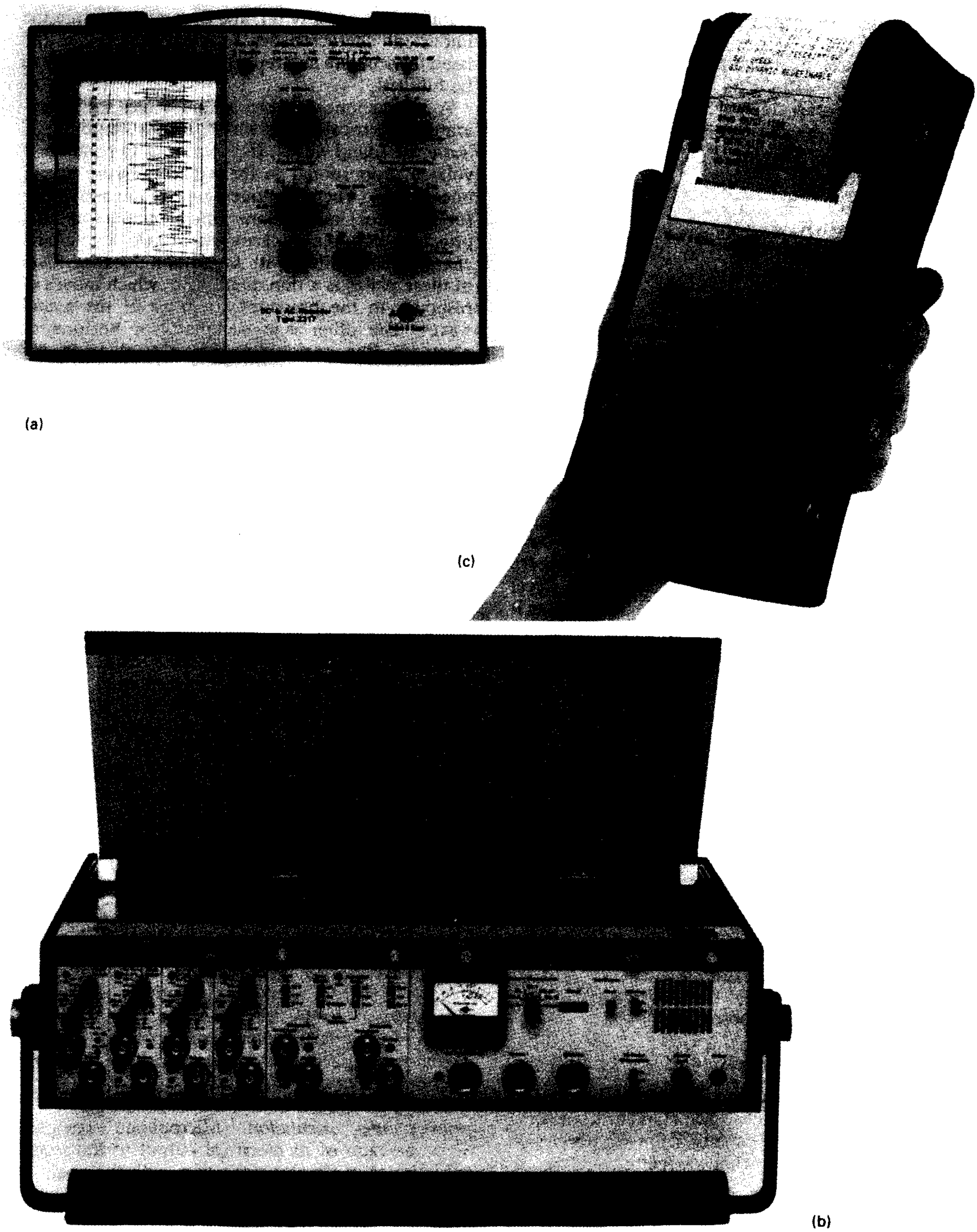
The accuracy of any sound measuring instrumentation is largely determined by the accuracy of the microphone used. Frequency response, directivity, stability (and sensitivity), and dynamic range are the important characteristics to be considered if the need for accurate and repeatable measurements is to be fulfilled.

A microphone converts sound waves into (generated) electrical waves which, ideally, should replicate the sound waves. Itsfunction is to generate a voltage proportional to the sound pressure at the microphone. The commonest type is the condenser (or capacitor) microphone which operates on the principle that the capacitance of two electrically charged plates alters with separation distance. One of these plates is a thin diaphragm, which moves in response to the pressure variations of the sound waves. The other is a backplate, or perforated, electrode (the perforations serve to dampen the principle resonant mode of the diaphragm). A polarizing d.c. voltage is applied across the capacitor through a very high resistance, and the change in capacitance produces an electrical signal proportional to sound pressure. This signal is fed to the noise level meter circuitry. Figure 14.16 shows a simplified cross-sectional view of a typical condenser microphone. The advantage of the condenser microphone is that its stability and frequency response are better than that of any other microphone type. Disadvantages of the externally polarized type include the need for a stable polarizing voltage (typically, 28 volts and usually provided from an additional preamplifier), its relative expense compared with other forms of microphone, and its limited humidity range. The latter calls for special precautions to be taken (such as back-venting and the use of dehumidifiers) to avoid self-induced background noise or complete failure in high humidity conditions due to internal electrical leakage over the surfaces of its insulators.

A more convenient form of condenser microphone (preferred for hand-held applications, such as sound level meters) is the prepolarized unit, in which the charge on the perforated backplate is fixed by a thin layer of charge-holding polymer film *electret* material. Because no free electrostatic charge exists at the surface of the diaphragm, this type of microphone gives relatively noise-free operation in humid environments. For measurements that require several microphones, the externally polarized microphone provides the more economic solution.

*Microphone orientation.* Microphone response (i.e. the ratio of its electrical output to the sound pressure at its diaphragm) varies with the angle at which the sound wave impinges upon its diaphragm. It is influenced at high frequencies by the reflections and diffraction caused by the microphone's presence in the sound field - be it *diffused* or *free.*

In a diffuse (or reverberant) field, the sound is likely to arrive at the microphone diaphragm from



(a)

(c)

(b)

**Figure 14.15** Portable sound level recorders (Courtesy: Bruel and Kjær (UK) Ltd)

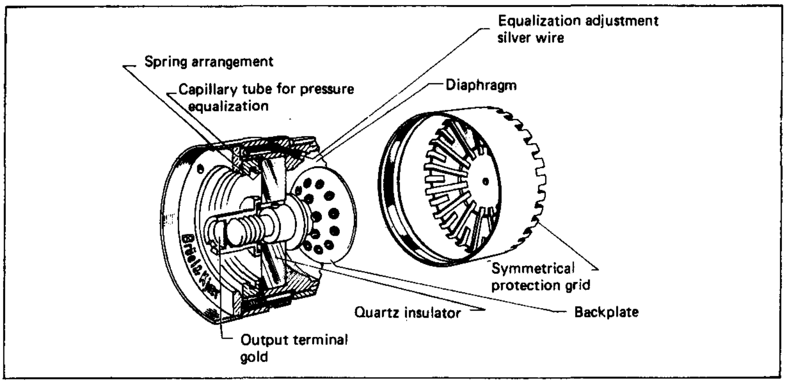



**Figure 14.16** Sectional view of a condenser microphone cartridge (Courtesy: Bruel and Kjær (UK) Ltd)

any direction. In a free field (the conditions which occur in most outdoor and in many indoor locations), sound arrives from one direction only. The sound field, or environment, is usually completely 'free' of reflecting surfaces and boundaries. If it is not, the effects of such boundaries are negligible over the frequency range of interest.

Most small microphones are omni-directional for frequencies below 1000 Hz because their physical diameter is less than one-tenth of the wavelength (335 mm) at that frequency. Above this frequency, as the microphone size becomes comparable with the wavelength of the sound impinging upon it, sensitivity increasingly depends upon the angle of incidence of the sound waves on the diaphragm.

Polar diagrams plotting variation of response with the angle of incidence are available from microphone manufacturers. The directivity patterns in them reveal both a marked symmetry about the axis perpendicular to the diaphragm, and a distinctive variation with frequency. This is illustrated in Figure 14.17.

The microphone, in this instance, is mounted on the sound level meter so that the body of the instrument itself causes sounds to be obstructed from certain directions. Response is more directional than it would have been had the microphone been remotely mounted on a camera-type tripod, and its signal brought out by cable to the sound level meter. Careful design of body shape is therefore necessary to minimize these effects on portable instruments.

Microphone characteristics are usually expressed in one of three ways:

- in free-field;
- pressure response; or
- random incidence response.

It is most important to ensure that the characteristics and the orientation of the chosen microphone are suitable for the type of sound field being investigated. Otherwise, high frequency response is likely to be impaired.

A free-field microphone will compensate for any disturbance caused by its own presence in the sound field, provided the angle of sound wave incidence is perpendicular to its diaphragm. The response characteristic is known as the *perpendicular-incidence* (or 0°) response. The direction of sound wave propagation is along the axis of cylindrical symmetry of the microphone and therefore at 0° to that axis.

A pressure microphone has a uniform frequency response to the sound field when the direction of sound waves is parallel to the diaphragm. The response is said to be the *grazing-incidence* (or 90°) response since the direction of the sound waves is at 90° to the axis of cylindrical symmetry of the microphone.

The random incidence (or truly omni-directional) microphone responds uniformly to sound waves arriving simultaneously at the diaphragm from any direction. This type of microphone should, preferably, be used when investigating diffuse or highly-reverberant sound fields. *Random incidence correctors* are available to convert 1/2 inch and 1 inch free-field microphones to omni-directional use.

*Windscreens.* Air currents blowing across a microphone will produce turbulence because of the irregular shape of the microphone. This causes the diaphragm to deflect and generate a spurious signal which, when superimposed on the acoustic signal to be measured, gives reading errors. Frequency bands in the lower ranges usually contribute little to the total intensity of wind noise, and A-weighted measurements are, therefore, less likely to be affected by wind noise.

When outdoor measurements are being taken, the microphone should be fitted with a windscreen which, when properly designed, can significantly reduce the wind noise without impairing the frequency response or sensitivity of the instrument.

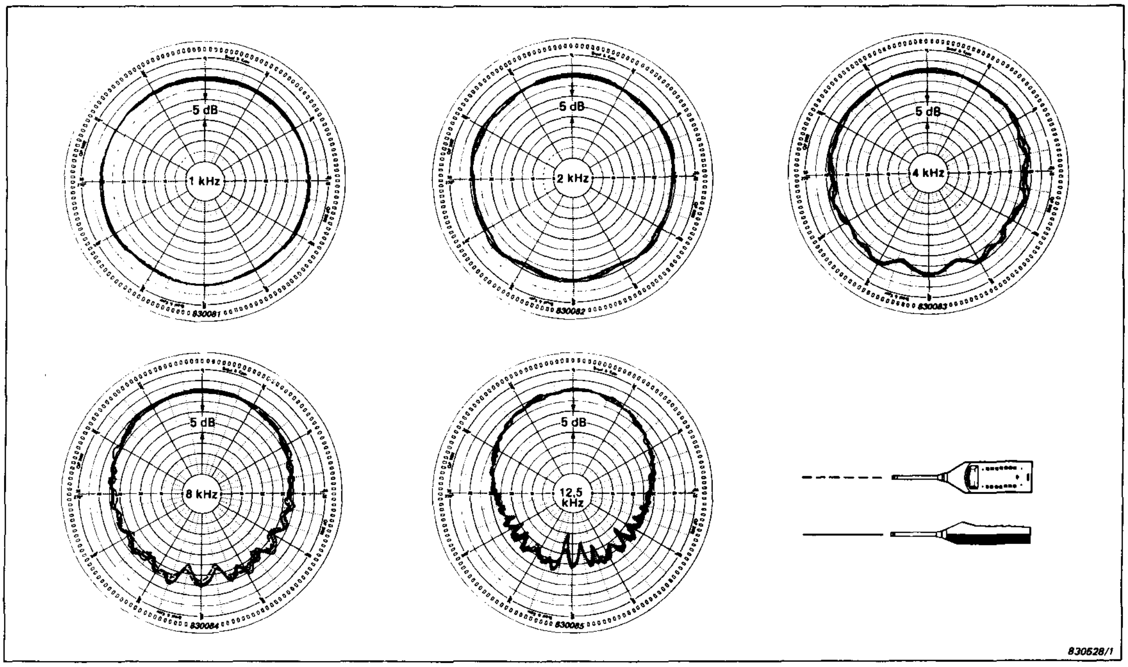



**Figure 14.17** Directional characteristics of complete sound level meter in a free field (Courtesy: Bruel and Kjær (UK) Ltd)

Common forms of windscreen are fairly large, spherical balls of porous foam plastic, or wire-frames with thin silk or nylon cloth coverings fitted over the microphone.

In conditions where airflows are at high velocities and in well-defined directions (such as at plant room inlet and outlet air apertures), nose cones should be fitted. They provide far less resistance to airflow than the windscreen forms described above. Especially designed, so-called, *turbulence screens* should be employed for noise measurements in ducts. They give good rejection of the airflow noise while allowing the acoustic signal to be measured to pass to the microphone.

The attenuation of any windscreen may be determined by reading the same noise with and without the screen, in a location where there is no wind. Manufacturers produce graphs which give details of the wind induced noise levels of screens as a function of wind speed, and their frequency response characteristics.

*Microphone calibration.* Microphones are individually calibrated in the factory and a calibration chart usually accompanies each instrument. A *reciprocity calibrator* is used to perform absolute calibration of laboratory-standard microphones over their entire frequency range. While the sensitivity of all microphones should be checked at regular intervals by an accredited Laboratory using this type of equipment, the procedure is neither justified nor practical for calibrations in field conditions.

During the course of measurements, field calibration of a complete measuring system at one frequency and at one signal level is all that is usually necessary. Battery driven, portable acoustic calibrators are available for this purpose. One of these is the *pistonphone.* The particular type illustrated in Figure 14.18(a) provides a stable 124 dB (re $2 \times 10^{-5}$ N/m$^2$) sound pressure level accurate to ±0.2 dB at 250 Hz. It employs a pair of independent pistons, driven by a battery powered electric motor to produce a sinusoidal sound pressure variation in the (microphone) coupler cavity. Different sizes and types of microphone may be calibrated. The one requirement is that the microphone should be well sealed in the coupler opening. The barometer provided is used to apply corrections (in dB) to the calibration level for any changes in ambient pressure.

The second calibrator illustrated in Figure 14.18 is a pocket-size sound source operating at 1000 Hz. Calibrations are therefore independent of weighting networks, which all have zero attenuation at this frequency (see Figure 14.10). The calibrator gives a


(a)

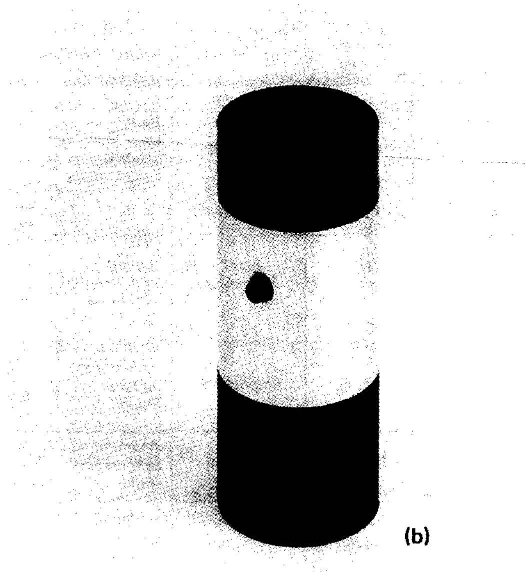

(b)

**Figure 14.18** Battery powered pistonphone (a) and sound level calibrator (b) (Courtesy: Bruel and Kjær (UK) Ltd)

signal of 94 dB (re 2 x $10^{-5}$ N/m$^2$) with an accuracy of ±0.5 dB.

A calibrator should be used when data are being recorded on magnetic tape or on sound level charts. This gives a reference sound level of fixed frequency, from which instruments used in subsequent analysis may be calibrated.

### 14.4.2 Sound power measurement methods

Sound pressure level, dependent as it is upon the environment in which measurements are made and upon the distance between noise source and observer, does not best describe the emission characteristics of a noise source. The better criteria are sound power levels which, essentially, are independent of the environment in which the data are obtained. They are best employed:

1. to calculate the sound level at a given distance from the noise source when it is operating in a specified environment;
2. to compare the noise radiated by machinery of the same or different types and sizes;
3. to determine whether plant complies with the upper limit of a noise specification;
4. when planning, to determine the amount of transmission loss or noise control required;
5. in engineering work, to assist in developing quiet machinery and equipment.

The International Organization for Standards has published seven documents (ISO 3741 to 3747, inclusive) describing methods for sound power level measurement for all types of machines and equipment. The identical British Standard is BS4196, Parts 1 to 7. The first three parts deal with measurements in a diffuse field, and the next three are for free field environments. The table of Figure 14.19, adapted from BS4196: Part 0 (IS03740) gives guidelines for the use of Parts 1 to 6 of BS 4196. Selection of the appropriate method is governed by:

1. the size of the noise source;
2. the character of the noises produced by the source and the frequency range of interest;
3. the data required, and the application of that data;
4. the highest grade of accuracy required; and
5. the type of test environment available.

Power levels in octave or third-octave bands, and at precision grade accuracy, are usually required for noise control 'development' work. An overall weighted sound power level is usually sufficient for production equipment testing, but the value of the data is considerably enhanced if power level distribution is available in octave frequency bands - to at least an engineering grade accuracy. For comparison of machines of differing size and type, power frequency spectra - to engineering grade accuracy - are required. Machines of like size and

| International Standard no. (ISO) | Equivalent B.S. 4196 Part no. | Classification of method | Test environment | Volume of source | Character of noise | Sound power levels obtainable | Optional information available |
|---|---|---|---|---|---|---|---|
| 3741 | Part 1 | Precision | Reverberation room meeting specified requirements | Preferably less than 1% of test room volume | Steady, broad-band | In one-third octave or octave bands | A-weighted sound power level |
| 3742 | Part 2 | | | | Steady, discrete-frequency or narrow-band | | |
| 3743 | Part 3 | Engineering | Special reverberation test room | | Steady, broad-band, narrow-band, discrete-frequency | A-weighted and in octave bands | Other weighted sound power levels |
| 3744 | Part 4 | Engineering | Outdoors or in large room | Greatest dimension less than 15 m | Any | A-weighted and in one-third octave or octave bands | Directivity information and sound pressure levels as a function of time; other weighted sound power levels |
| 3745 | Part 5 | Precision | Anechoic or semi-anechoic room | Preferably less than 0.5% of test room volume | Any | | |
| 3746 | Part 6 | Survey | No special test environment | No restrictions; limited only by available test environment | Any | A-weighted | Sound pressure levels as a function of time; other weighted sound power levels |

**Figure 14.19** Various methods for determining sound power levels (adapted from BS 4196: Part 0)

specification may be satisfactorily compared using only overall weighted levels. Since most generating plants are comparatively large noise sources and are not readily movable, the most appropriate noise measurement methods are those described in BS4196 Parts 4 and 6 (IS03744 and ISO 3746, respectively). The methods of BS 4196: Parts 1, 2, 3 and 5 should only be selected for the smallest generators; those which can be easily moved, and where test environments of sufficient volume are available.

Sound power levels for type testing, for noise control work, or for comparison studies can be determined, with engineering accuracy, using BS4196 Part 4, in a flat outdoor area, or in normal indoor environments, i.e. machinery spaces or plant rooms which have sufficient sound-absorptive materials in their walls and ceilings to provide a free field over a reflecting plane. The survey method, described in BS4196 Part 6, is useful for comparing machines similar in size and kind, and for rating generators in terms of their overall weighted sound power output. The method requires background noise to be lower than the noise produced by the source to be measured.

## 14.5 The principles of noise control

All noise control problems involve three parts:

- the noise source;
- the receiver; and
- the path between the two.

One has the choice of two options when trying to reduce the level of any objectionable noise. The first is to reduce the strength of the noise energy from the source. The second is to impede the transmission of this energy along its path to the receiver.

Consider the first of these options. There is a commercial limit to the amount of direct sound level reduction that can be achieved by internal and structural design changes on diesel engines and generators. There is little scope for reducing the overall sound level generated by a proprietary engine - except, perhaps, by selecting a quieter unit of similar output but at lower speed or with a smaller bore. But this introduces penalties in cost, bulk, and weight (see Section 14.8). It is far more practicable to concentrate on impeding the transmission of the noise energy along its path to the receiver.

The noise from a diesel generator is transmitted, through pressure waves, to the ear of the listener. These pressure waves may be induced by *primary vibrations* or by *secondary air vibrations.* Primary vibrations are those which are communicated directly from the plant to the surrounding area (e.g. by engine combustion and mechanical noise - amplified by the outer walls of the engine construction, by engine and generator cooling fans, and by engine exhaust and inlet air). Secondary air vibrations originating from the machines and their services' pipework and ductwork are transmitted through the floors and walls of buildings and enclosures. They sometimes have the same frequency as primary air vibrations (and therefore the same tones) and are often confused with them.

### 14.5.1 Noise attenuation by distance

Controlling noise by siting machinery to increase the distance between source and receiver is one obvious solution. But this is not always possible.

A diesel generator may be considered as a *plane* source of noise. Reduction in sound pressure level with distance is smaller than that to be expected from a *point* source of noise. The *inverse square law* only begins to apply at a distance where the source size becomes small compared with that distance. (The inverse square law applies to a hypothetical *point source* which radiates sound energy equally in all directions. It accounts for a 6 dB decrease in sound pressure level for each doubling of distance from source to receiver.)

Table 14.1 (reproduced from [1]) allows estimates to be made for sound pressure levels at distances from plane sources - such as plant room inlet or outlet air louvres, behind which there is a generator of known and constant sound power level. The use of Table 14.1 is best illustrated by an example.

*Example 14.9*
*The problem*
Assume an observer is 20 m from an air outlet louvre (2 m x 3.5 m) fitted in the external wall of a plant room housing a standby diesel generator. The sound pressure level measured in a particular octave band at 1 m from the louvre was 90 db and we want to estimate the SPL at the 20m position.
*The solution*
Using the nearest appropriate column in the plane source portion of Table 14.1, for the source size (3 x 3), the attenuation value at 1 m (11 dB) is subtracted from the value at the required distance of 20m (37 dB). This gives the attenuation between the two points (i.e. 26dB). This is then subtracted from the measured SPL at 1 m (90 dB) to give the estimated SPL 20m from the louvre: 64 dB (i.e. 90 - 26).

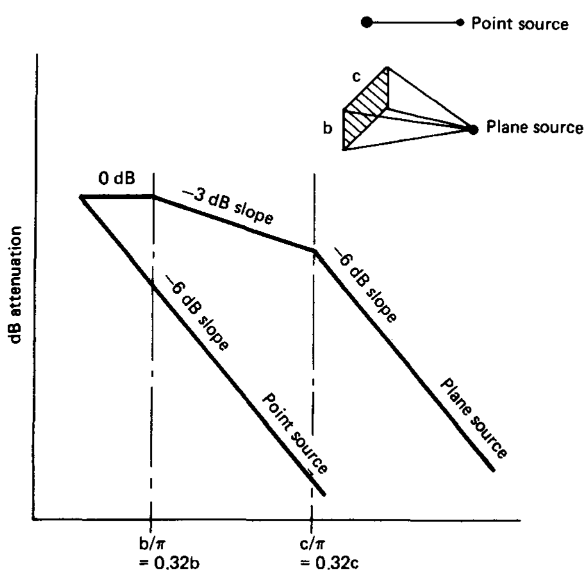



**Figure 14.20** Attenuation with distance from plane and point sources [1]

### *Directivity effects*

The sensible effects of directivity have been ignored in Table 14.1. In practice, for small horizontal and vertical bearing angles off the normal axis of the plane source, the effects of both source size and directivity must be added together. Corrections in accordance with the tables of Figure 14.21 [1] should be applied to give the increased SPL at the plane source due to directivity. Table A gives the dB values at each octave band frequency that have to be added to the SPL, at a distance out along the normal axis of an atmospheric louvre or grill. Values for both the width and height of the louvre must be added together to give the increased SPL due to directivity. If the receiver is not on the normal axis (the worst case), a reduced correction is applied for bearing angle - see Table B. The following examples illustrate the use of the tables.
*Example 14.10*
*The problem*
Assuming the observer in example 14.9 was not on the normal axis of the 2 m x 3.5 m air outlet louvre but was positioned 25° in a horizontal direction and 60° in a vertical direction, from the centre axis of the louvre, what would be the observed SPL 20 m from the noise source at the 500 Hz mid-frequency octave band?
*The solution*
The directivity correction for the normal axis of the louvre (Table A of Figure 14.21) is +4.5 dB for the height of 305m, and +4.5dB for the width 2m (giving a total of +9dB on the normal axis) at a frequency of 500 Hz. Because the observer is 25° off-axis in the horizontal plane (angle $6_h$), the directivity correction must be adjusted. This is done as follows. Read across from +4.5 dB in the 0° column of Table B to the 20° column (for 25°) to give an adjusted result of +4 dB. Similarly, for the 600offset in the vertical plane ($6_v$), read across from +4.5 dB in the 0° column to the 60° column to give a corrected result of 0 dB. Adding the corrected results together we have 4 dB (i.e. 4 + 0), which is the

**Table 14.1** Estimation of SPL at a distance from a line or plane source assuming constant SWL

| Distance in metres | *Line source* (m) | | | | *Rectangular plane source* (m × m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *3* | 10 | 30 | 100 | 1 × 3 | 1 × 10 | 3 × 3 | 3 × 10 | 3 × 30 | 10 × 10 | 10 × 30 | 30 × 30 |
| 50 | −45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| | −44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 |
| | −43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| | −42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 |
| | −41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 |
| 30 | −40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | −39 | 39 | 39 | | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| | −38 | 38 | 38 | 39 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| 20 | −37 | 37 | 37 | | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 |
| | −36 | 36 | 36 | 38 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| | −35 | 35 | 35 | | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| | −34 | 34 | 34 | 37 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 |
| | −33 | 33 | 33 | | 33 | 33 | 33 | 33 | 33 | 33 | 33 | 33 |
| | −32 | 32 | 32 | 36 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 |
| 10 | −31 | 31 | 31 | | 31 | 31 | 31 | 31 | 31 | 31 | 31 | 31 |
| | −30 | 30 | 30 | 35 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | −29 | 29 | | | 29 | 29 | 29 | 29 | | 29 | | |
| | −28 | 28 | 29 | 34 | 28 | 28 | 28 | 28 | 29 | 28 | 29 | 30 |
| | −27 | 27 | | | 27 | 27 | 27 | 27 | | 27 | | |
| | −26 | 26 | 28 | 33 | 26 | 26 | 26 | 26 | 28 | 26 | 28 | 30 |
| 5 | −25 | 25 | | | 25 | 25 | 25 | 25 | | 25 | | |
| | −24 | 24 | 27 | 32 | 24 | 24 | 24 | 24 | 27 | 24 | 27 | 30 |
| | −23 | 23 | | | 23 | 23 | 23 | 23 | | 23 | | |
| | −22 | 22 | 26 | 31 | 22 | 22 | 22 | 22 | 26 | 22 | 26 | 30 |
| | −21 | 21 | | | 21 | 21 | 21 | 21 | | 21 | | |
| 3 | −20 | 20 | 25 | 30 | 20 | 20 | 20 | 20 | 25 | 20 | 25 | 30 |
| | −19 | | | | 19 | | 19 | | | | | |
| | −18 | 19 | 24 | 29 | 18 | 19 | 18 | 19 | 24 | 20 | 25 | 30 |
| 2 | −17 | | | | 17 | | 17 | | | | | |
| | −16 | 18 | 23 | 28 | 16 | 18 | 16 | 18 | 23 | 20 | 25 | 30 |
| | −15 | | | | 15 | | 15 | | | | | |
| | −14 | 17 | 22 | 27 | 14 | 17 | 14 | 17 | 22 | 20 | 25 | 30 |
| | −13 | | | | 13 | | 13 | | | | | |
| | −12 | 16 | 21 | 26 | 12 | 16 | 12 | 16 | 21 | 20 | 25 | 30 |
| 1 | −11 | | | | 11 | | 11 | | | | | |
| | −10 | 15 | 20 | 25 | 10 | 15 | 10 | 15 | 20 | 20 | 25 | 30 |

directivity correction due to the observer's position. At a distance of 20 m on the stated bearings the estimated SPL would be:

(90 + 4 -26) dB = 68dB

obtained by adding +4 dB to the SPL measured at 1 m - for directivity, and by subtracting the 26 dB attenuation for distance (as in example 14.9).

Incidentally, had the observer been on the norma1 or centre axis of the louvre, the estimated SPL at his observation point would have been 73 dB (i.e. 90 + 9 - 26).

## *Atmospheric propagation*

When calculating sound pressure levels outdoors, one uses the methods prescribed for ideal conditions and then applies corrections for differing weather conditions. The influence of atmospheric conditions on sound propagation is a highly complex subject - one that is outside the scope of this chapter. (The reader's attention is directed to [7] (Chapter 9), and [8] (Chapter 3) for detailed treatments of atmospheric acoustics, and sound absorption by natural features.) Suffice it to say that accurate prediction is extremely difficult. Effects are only significant at

| Frequency Hz | Width or height of louvre | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.5 | 1 | 1.5 | 2 | 2.5 | 3.5 | 4.5 | 5.5 | 6 | 7.5 | 9 | 10.5 | 12 | 15 | m |
| | 1.5 | 3 | 5 | 7 | 9 | 12 | 15 | 18 | 20 | 25 | 30 | 35 | 40 | 50 | ft |
| 63 | 2 | 2.5 | 3 | 3 | 3.5 | 3.5 | 4 | 4 | 4 | 4 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 125 | 2.5 | 3 | 3.5 | 3.5 | 4 | 4 | 4 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 250 | 3 | 3.5 | 4 | 4 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 500 | 3.5 | 4 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 1 k | 4 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 2 k | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 4 k | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |
| 8 k | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | |

Table A – Correction in dB for directivity along the normal axis of a louvre

| D.I. key θ° | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 |
| 2 | 2 | 1.5 | 1.5 | 1 | 1 | 0.5 | 0 |
| 2.5 | 2.5 | 2 | 1.5 | 1 | 0.5 | 0 | −1 |
| 3 | 3 | 2 | 1.5 | 0.5 | −0.5 | −1.5 | −3 |
| 3.5 | 3 | 2.5 | 1 | −0.5 | −2 | −4.5 | −7.5 |
| 4 | 3.5 | 2.5 | 1 | −2 | −6.5 | −25 | −30 |
| 4.5 | 4 | 3 | 0 | −25 | −30 | −25 | −25 |

Table B – Correction in dB for a bearing angle away from the normal axis of a louvre

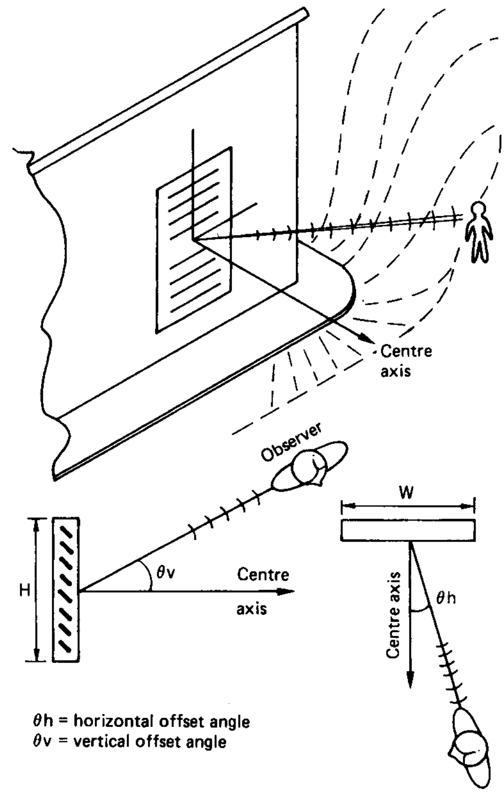



**Figure 14.21** Directivity correction for noise radiation from atmospheric louvres and grills [1]

distances over 500 m and at frequencies near 500 Hz. Variations due to wind and temperature gradients typically cover a range from:

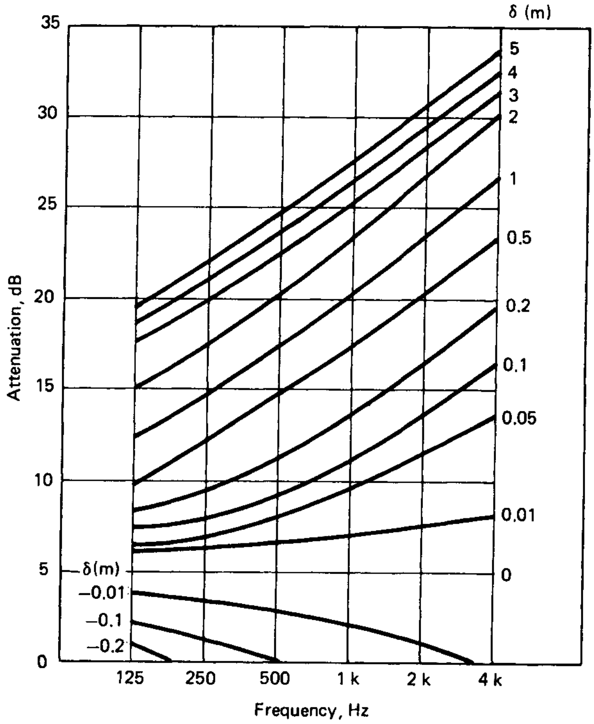
- 5 dB less attenuation than that predicted by the inverse square law when wind and temperature help propagation; to
- 20 dB more attenuation when they inhibit propagation.

Another factor affecting the reduction of noise level with distance from source is the molecular absorption of sound in air. It is only significant at high frequencies (above 1000 Hz), and varies with temperature and humidity. An indication of the order of (additional) attenuation to be expected is given by the following data:

In the 1000 Hz mid-frequency octave band the attenuation at 21°C and 60 % relative humidity is 3 dB/1000 m. It is 6 dB/1000 m at 2°C and 60 % relative humidity. In the 8000 Hz octave band equivalent values are 82 dB/1000 m and 130 dB/1000 m, respectively.

### 14.5.2 Attenuation due to screens and barriers

The transmission of noise between source and receiver can be controlled by placing acoustic screens (or barriers) in line-of-sight between them. Outdoors, screens may take the form of an earth bank, a wall, or a building. We established earlier in the chapter (Section 14.2) that sound waves meeting such an obstacle are partially reflected. Those which are not reflected continue past the edge of the obstacle. Any sound attenuation so obtained is due to the diffraction of the sound waves around the barrier. The effect is greater at higher frequencies than at lower frequencies. The degree of attenuation is related to how much further the sound waves have to travel in going around the obstacle. The critical factor is the extra distance δ (= A + B − d) that the waves have to travel (see Figure 14.22).



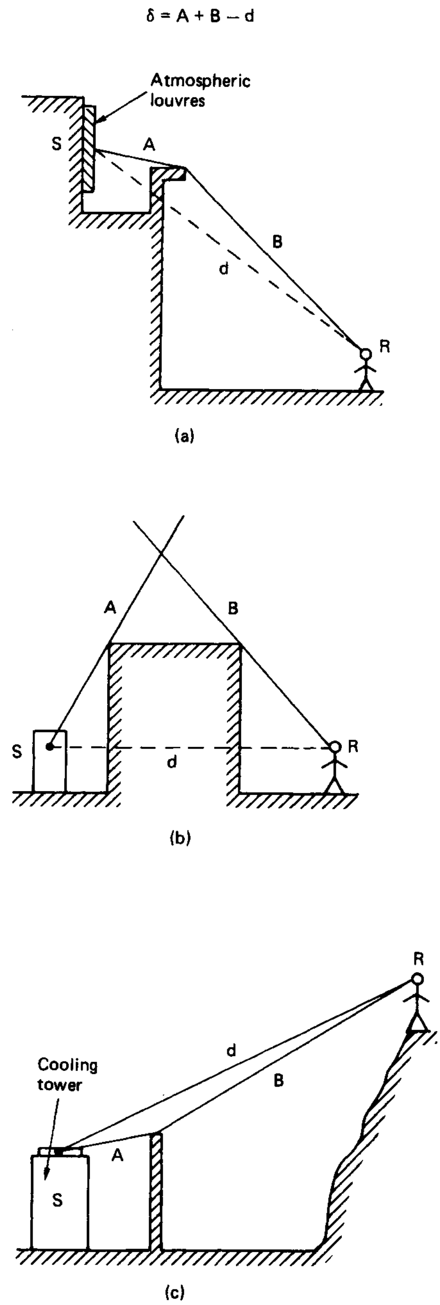




**Figure 14.22** Attenuation of noise by screens (a) No direct line of sight – S is positive (b) Low building as an obstacle – no direct line of sight – S is positive (c) Direct line of sight – S is negative

The family of curves in the figure enables the attenuation due to very long (or *infinite)* barriers to be determined for the computed distance 8. (Infinite barriers are defined as being long enough for any sound passing around their ends to make a negligible contribution at the receiving point.) Some attenuation even obtains - particularly at low frequencies - when a barrier does not appear to screen the noise source. The negative value characteristics for 8 (in Figure 14.22) should be used in these cases.

Where a small wall or screen is used to shield a listener from directly radiated sound, some of the sound will flank the three sides of the obstacle. The noise received is the sum of the total energy along the three paths. The following example shows how approximate estimates of total attenuation are then made.

*Example 14.11*

*The problem*

Calculate the attenuation at SOOHz at the listening position (R), due to the small screen defined in Figure 14.23.

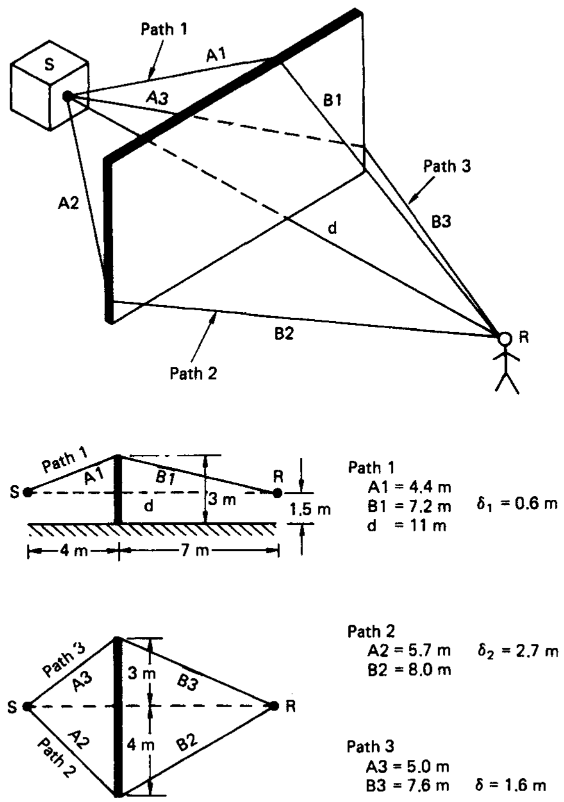



**Figure 14.23** Example of screening by a small wall

*The solution*

From the curves of Figure 14.22 the attenuation at SOOHz for the various paths $8_1 > 8_2$, and $8_3$ is:

16dB - for path 1, where $8_1$ is 0.6m
22 dB - for path 2, where $8_2$ is 2.7 m
19 dB - for path 3, where $8_3$ is 1.6 m

Using the procedure in reverse for the combination of sound levels (the chart of Figure 14.3) we get:

by combining -22 dB and -19dB: -17dB
by combining -17dB and -16dB: -14dB

so that the total screening effect is approximately -14dB. Note that, had the screen been of the same height but very long, the attenuation value would have been that of path 1 (i.e. 16dB). Similarly, if the screen had been very high, attenuation would have been determined by a combination of paths 2 and 3 (i.e. 17 dB). Approximately half of the sound energy, therefore, passes over the top of the wall and half around the sides.

A screen of relatively lightweight construction often suffices because the limiting factor is the attenuation produced by diffraction around and over the barrier. The screen itself does not need to have high attenuation properties. In summary, when estimating the attenuation by screens, the following calculation steps are necessary:

1. Determine the noise reduction based on the shortest direct path using the principles for attenuation by distance.
2. Add any effects due to directivity.
3. Compute 8 (from (A + B - d) for the screen.
4. Determine the additional attenuation due to the screen from the curves of Figure 14.22.

This needs to be done for each of the frequencies of interest.

### 14.5.3 Sound transmision between rooms

We shall now consider sound transmission between adjacent rooms. The *source room* of the diagrammatic representation in Figure 14.24 could be a generator plant room, and the *receiving room* could be a permanently-manned control room or workshop area. The figure shows some of the possible paths for sound transmission between the two rooms.

Airborne sound waves may impinge upon the common wall between the two rooms either directly (path 1) or after reflection (path lA), and may radiate into the control room. Path 2 is a *flanking path* along which the airborne sound energy travels, as vibration, through the ceiling and side walls (not shown). The transmission of sound from one room to another, other than through the common wall, is known as *flanking transmission.* The vibration of the generator(s) may also induce *bending waves* in the floor (or walls). These may travel through the floor

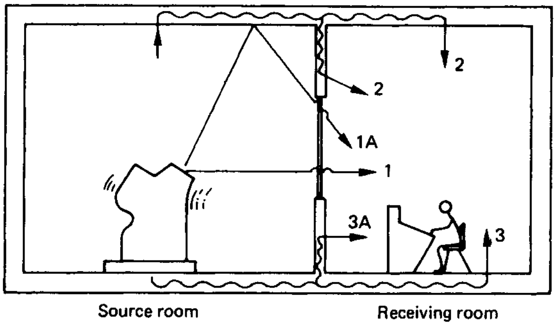



**Figure 14.24** Sound transmission paths between adjoining rooms

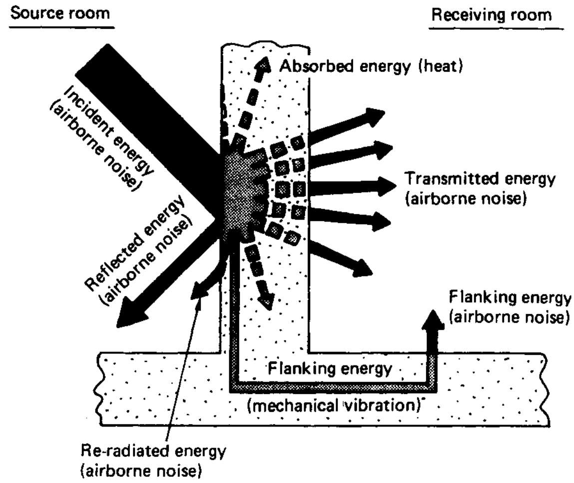



**Figure 14.25** Energy distribution from airborne sound impinging upon a partition

and common wall (paths 3 and 3A) to produce airborne waves in the receiving room.

The *sound insulation* of a room is a property of its structure as a whole. Flanking transmissions set the limit (usually between 50 and 55 dB) beyond which it is impracticable and worthless to increase the insulation of the direct path. The intensity of the *structure-borne noise* along those paths that pass through solid material is governed by the frequency, intensity, and angle of incidence of the sound waves impinging upon them, and on the dimensions and materials of the structures themselves.

We shall now examine the principles governing the control of noise transmitted between rooms.

## *Sound insulation and sound absorption*

It is very important to recognize the difference between *insulation* and *absorption,* and to understand the differences in the materials used for each purpose.

When sound impinges on a wall or a partition, some of the incident energy passes into the wall. The rest is reflected back or is re-radiated. A part of the energy which passes into the wall is transformed into heat, i.e. it is absorbed. Some of the energy goes through the wall to the other side, i.e. it is transmitted through the wall. The energy flow pattern is illustrated in Figure 14.25.

## *Sound reduction index*

The ratio of the sound energy incident upon the surface to that transmitted through, and radiated beyond, the partition is called the *sound transmission coefficient* (T). It determines the resistance of the partition to the movement of sound energy through it and is a measure of its acoustic insulation. The conversion of this ratio into decibel form gives the *sound reduction index* (SRI). It is expressed as:

$$\text{SRI} = 10 \log 1/T \quad \text{dB}$$

and is a measure of a partition's sound insulating ability. It is equal to the number of decibels by which sound energy is reduced, in transmission through the partition (or material). An equivalent term is the *sound transmission loss* (TL).

It is important to appreciate that the SRI is the difference in sound power (SWL) on either side of the partition. This is not the same as saying that it is the difference between the sound pressure levels (SPLs) on either side. The sound pressure level in a receiving room will depend, almost entirely, upon the acoustic characteristics of the room (e.g. upon its reverberation characteristics, which are determined by the *average absorption coefficient* of the room), and the size, or area, of the room's partition. Therefore, when specifying performance one must clearly indicate whether one means the SRI (the property of the partition construction) or the SPL difference between the rooms.

The insulating performance of a partition is usually given in the form of a graph or a table based upon measurements made at sixteen third-octave intervals from 100Hz to 3150Hz - the range of frequencies normally important in buildings. When dealing with well-known constructions and with noise of a broad-band character (such as that from diesel generators) an *average sound reduction index* is often acceptable. This average SRI is the arithmetic mean of the dB values between 100 Hz and 3150Hz and roughly corresponds to the insulation value at 600 Hz. For all practical purposes, the airborne sound insulation property of a partition is controlled by:

- its mass;
- its discontinuity;

- its stiffness; and
- its uniformity.

### The mass law

In engineering terms, the sound insulation of non-porous, homogeneous partitions is governed almost entirely by their surface weight (i.e. weight per unit area) and by the sound frequency. Insulation increases by about 5 dB for each doubling of the partition's weight and for each doubling of the sound frequency (i.e. per octave). However, there are practical limits to useful improvement by increasing weight. For example, a wall of single brick thickness (115 mm) has a superficial weight of 220 kglm$^2$ and an average SRI of 45 dB. Doubling the thickness of the wall to 230mm (and, therefore, doubling its weight also) gives an average SRI of 50 dB - an increase of 5 dB. One neeeds to add another 230mm (and not 115mm) to gain an additional 5 dB attenuation - giving a total wall thickness of 460 mm. This is fairly impracticable. More so, since the flanking transmission of structure-borne noise inevitably sets a limit of 50 - 55 dB on the insulation level of any building structure.

The fact that the average SRI of any partition roughly coincides with its insulation value at 600 Hz may be used to extrapolate values in the audio frequency range. For example, the SRI for a single brick (115mm) wall would be 50dB (Le. 45 + 5) at 1200Hz and 40dB (i.e. 45 - 5) at 300Hz. See Figure 14.26 which gives the relationship between weight per unit area and the average SRI of a solid partition.

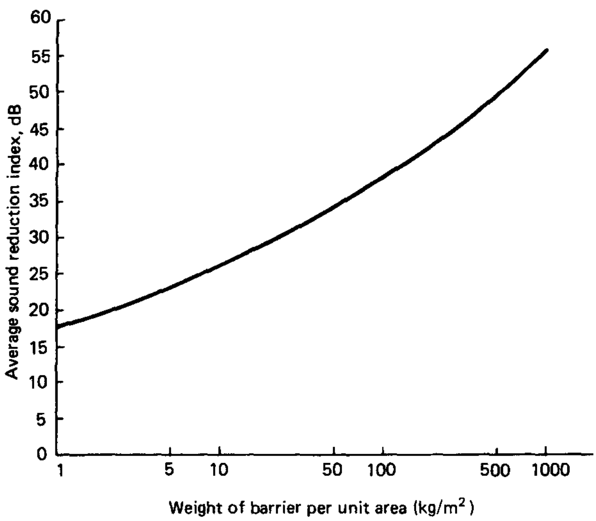



**Figure 14.26** Sound insulation values of partitions due to weight: mass law

### Discontinuity in constructions

There are simple and well-tried forms of construction in which discontinuity in partitions is used to give an increase in acoustic insulation. A typical example is a cavity wall. While floating floors are primarily intended for vibration isolation (see Subsection 14.6.3), the element of discontinuity in their construction also gives (airborne) sound insulation.

A double wall separated by an air space, or by a sound absorbing material (such as fibreglass mat, clinker blocks, or wood wool slabs) will have a sound reduction index greater than that predicted by the mass law. This is illustrated by the curves of Figure 14.27 [7] for field measurements made by the British Building Research Station on typical single and double wall constructions.

The following points are worth noting:

1. The effect of any cavity depends upon its dimensional relationship to the wavelengths of sound. Narrow cavities only improve insulation at the higher frequencies. Wider cavities (:;e: 150mm) give worthwhile improvements at all frequencies (see Figure 14.28 [1]). The minimum useful width is 40mm.
2. The leaves of the partition should be completely separate, and there should be no bridging connection. Strip metal ties nullify the effects of the cavity and may reduce the partition's insulation below that of an equally-heavy single wall. If ties are unavoidable, *butterfly wire* ties are, perhaps, the best.
3. It is better to bond both leaves solidly to the structure at the edges rather than attempt discontinuation. On lightweight partitions one of the leaves may be supported by a stud frame, and the other may be supported off it by resilient mounts such as spring clips, etc.

### Stiffness of partitions

Subjectively speaking, the middle of the audio-frequency range (in which partition materials follow the mass law) is the most important in buildings acoustics. At low frequencies the stiffness of a partition determines the amount of sound transmitted through it - the stiffer the partition, the less the sound transmitted. As the sound frequency increases, the stiffness and the mass of the partition may combine to give a series of resonant frequencies. These occur where the natural frequencies of the vibrating partition and the impinging sound frequencies coincide. The lowest natural frequency of the partition is called its *fundamental*. The amplitude of the partition's forced vibration is greatest at this frequency. The other natural frequencies are usually very close to the fundamental, but the

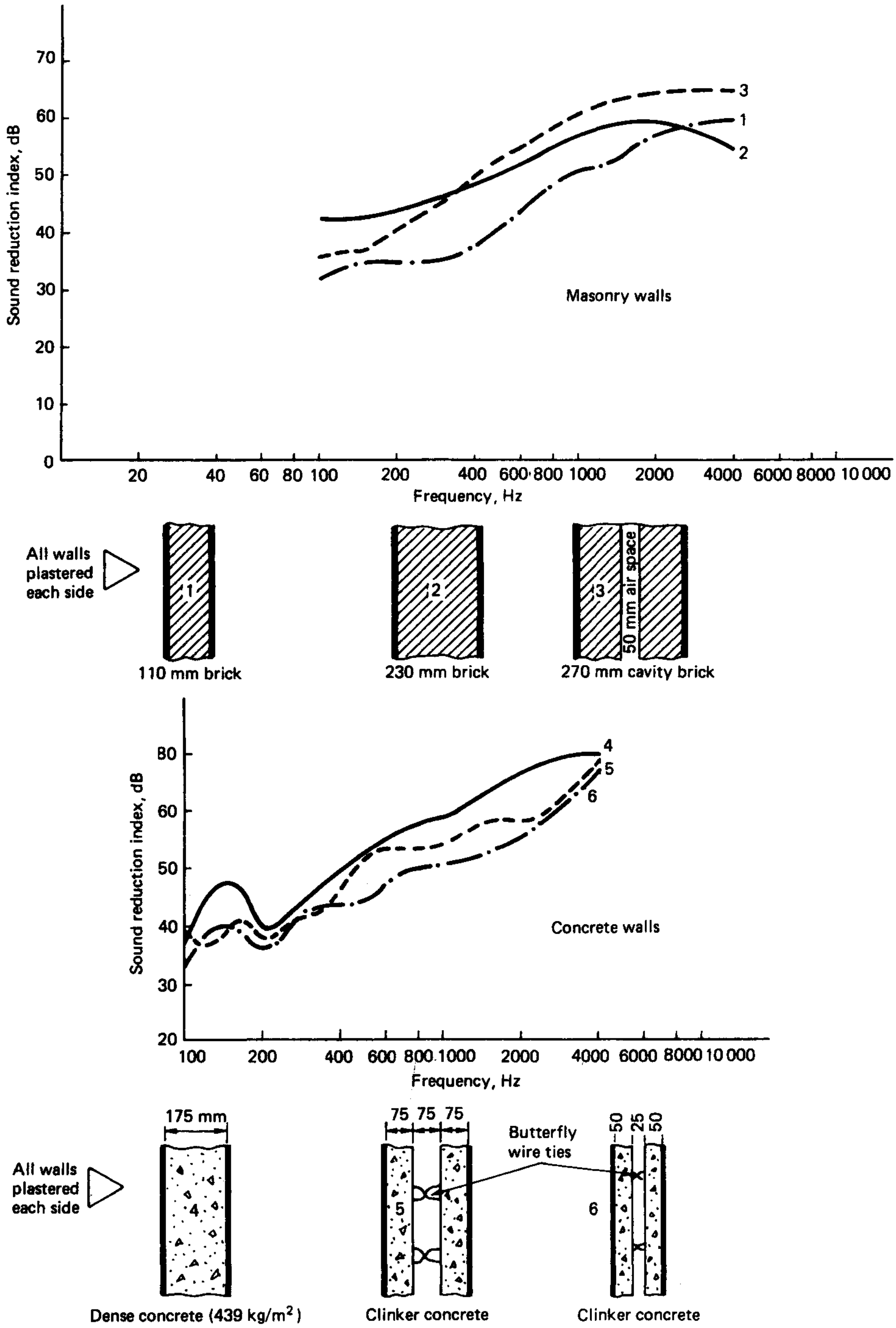



**Figure 14.27** Sound reduction indices of typical single and double construction walls [7]

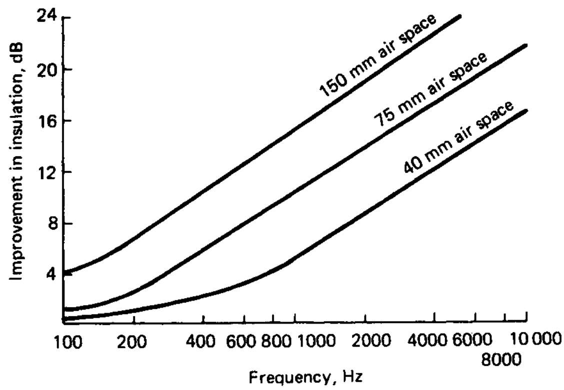



**Figure 14.28** Improvement in sound insulation due to air space [1]

vibrations caused by them have progressively decreasing amplitude. Below the fundamental frequency the stiffness of the partition controls its movement. Above the first few resonant frequencies the partition mass becomes more important. This is illustrated in the first region of Figure 14.29 which represents the idealized form of frequency response for any partition.

Between the first and third regions of the characteristic, partitions may be treated as though they were *mass* controlled. The second region covers a frequency span between 2.5 times the fundamental frequency, and the *critical frequency.* There is a pronounced dip in the insulation curve in region 3, caused by the *coincidence effect.* This is due to the wavelength of the bending waves in the partition coinciding with the wavelength of the sound wave (at a *critical frequency, fe)'* This condition is called *wave coincidence.* It should be noted that the bending wave is a travelling wave - as opposed to the more usual stationary type - and, therefore, fixed modes are not present in the partition. Also, wave coincidence can only occur when the wavelength of the sound in air is less than the wavelength of sound in the partition.

The *coincidence dip* in the performance characteristic cannot be entirely eliminated, but a partition can be designed so that the critical frequency at which the dip occurs is raised, and falls outside the frequency range of importance. This is done by increasing the ratio of the partition's weight to its stiffness - either by reducing the stiffness for a given weight, or by adding weight without stiffness. Just two of the several possibilities are:

- choose a limper or flabbier material consisting of heavy particles rather loosely held together; or
- bond-on damping panels - particularly on lightweight constructions (see later this section).

The critical frequency for a 13 mm plate of steel or aluminium is about 1000Hz. Wave coincidence may therefore occur at all frequencies above this level. Reducing the plate thickness to 2.5 mm raises the critical frequency to 5000 Hz. This fact is of

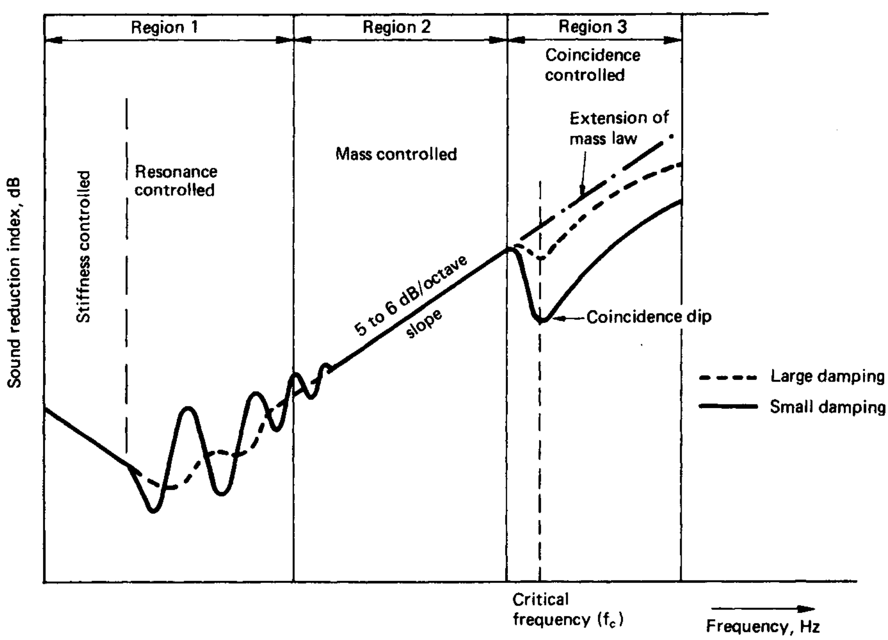



**Figure 14.29** The sound transmission characteristics of a partition

cance in the design of generator plant enclosures (see Sub-section 14.5.4).

## *Uniformity in partitions*

If the wall between two rooms is not uniform throughout its structure its overall insulation level is affected. Areas of lower insulation, such as doors, windows, and access holes for services, will reduce the net insulation of the wall as a whole. Figure 14.30 provides a ready means of computing the reduction for a partition composed of two areas of different insulation. Its use is best explained by a worked example.

*Example 14.12*
*The problem*
The partition between a generator plant hall and the control room consists of a wall having an area of 27m$^2$, with an observation window 7.2m$^2$. For a given frequency band, the sound reduction indices of wall and window are 45 dB and 30 dB, respectively. What is the effective sound reduction index of the control room partition?

*The solution*
The ratio of areas, window to wall, is 1:3.75. A horizontal line drawn from this area ratio on the ordinate of Figure 14.30 intercepts the 15 dB difference curve (representing the insulation difference between wall and window) at a point which coincides with 8 dB on the abscissa (the insulation loss scale). The net, and effective, SRI of the composite partition is therefore 37 dB (i.e. (45 - 8) dB).

There will be a flanking transmission of sound energy, from generator hall to control room if the window frame is not adequately sealed into its wall aperture. Assume that there is a 1 mm wide crack in the seal along the entire width of the window (4m). This gives a perforation area of 4000 mm$^2$, and an area ratio of 1 : 8550 - compared with the total (wall and window) area of 34.2m$^2$. The SRI of the leakage path is OdB. Referring to Figure 14.30, it will be seen that this area ratio of 1 : 8.5k intercepts the 37 dB (i.e. 37 - 0) insulation differential curve at a point that equates with a 3 dB loss of insulation on the abscissa. Thus, the overall performance of the partition falls to 34 dB due to the presence of the perforation.

The following table shows the relationship of partition SRI to the fraction of incident sound energy passing through the partition. It is derived from the expression:

SRI = 10log (I/T) dB

Where, by definition, T (the sound transmission coefficient) is the ratio of incident sound energy to that passing through the partition (discussed earlier in this section).

| *Sound reduction index (dB)* | *Fraction of sound energy passing through the partition* |
|---|---|
| 10 | 1/10 |
| 20 | 1/100 |
| 30 | 1/1000 |
| 40 | 1/10 000 |
| 50 | 1/100 000 |

If a leakage opening is 1/1000th of the total surface area of the partition (or of an enclosure), it will not be possible to get better than 30 dB noise reduction, regardless of the sound reduction index of the partition or enclosure.

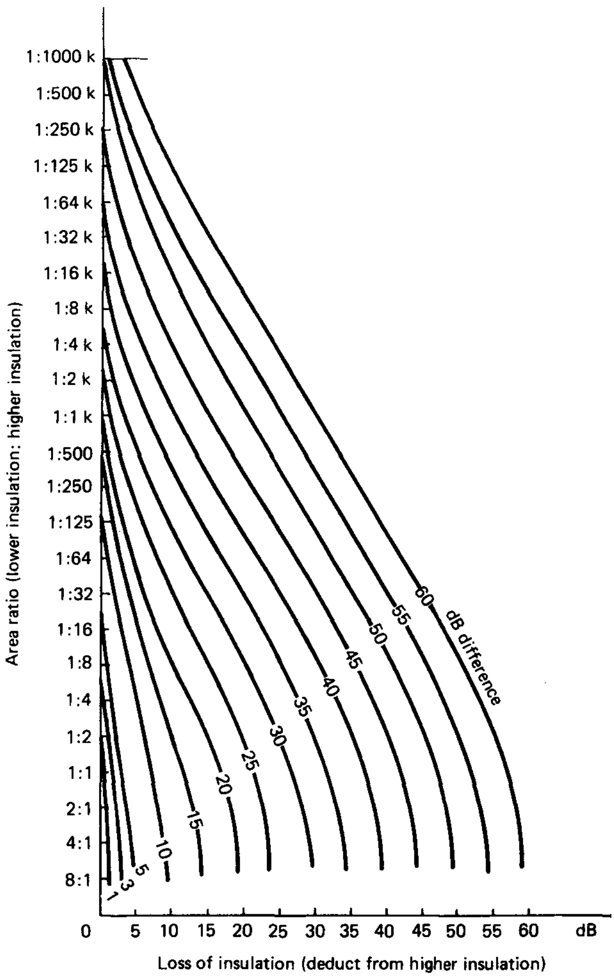



**Figure 14.30** Chart for computing octave-band SRI of composite partitions [7]

## *Damping of partitions*

We have seen that high partition-stiffness narrows the frequency range in which the mass law has its optimum effect (Region 2 of Figure 14.29). Reducing the stiffness of an existing structure is not always possible. The equivalent effect can be obtained by increasing the damping in the partition (see Regions 1 and 3 of Figure 14.29). Damping serves to increase the partition's resistance to free vibration, and dissipates the mechanical energy of this vibration by converting it into heat. It is only effective in the frequency ranges where resonance (Region 1) and coincidence (Region 3) occur. It has virtually no effect in the audio-frequency range where the mass law applies. It is, therefore, futile to add damping to an inherently well-damped structure such as a brick or concrete partition. Conversely, the performance of steel or aluminium partitions is greatly enhanced by such treatment.

Damping treatments using *viscoelastic* materials (such as rubbers and plastics) have the ability not only to store strain energy when deformed, but also to dissipate this energy - acting much like a very viscous liquid. Choice of damping material is influenced by factors such as type of structure, temperature, and the frequency of vibration. It is important that the damping material has a *stiffness* comparable to that of the material being damped. This ensures that the maximum amount of vibration energy is removed. In other words, the damping material absorbs a large proportion of the structure's energy. Figure 14.31 [7] illustrates four types of damped structure.

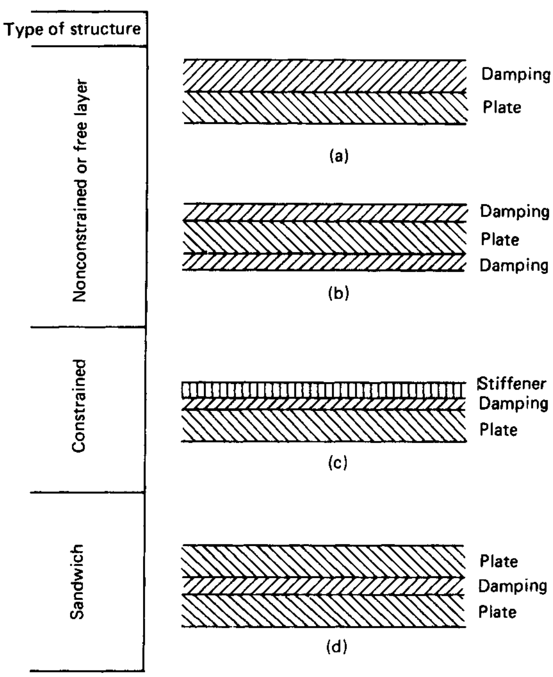



**Figure 14.31** Four types of damped plate [7](a) Single plate with single layer of damping (b) Single plate with equal damping layers on both sides (c) Single plate with thin damping layer and thin constraining sheet (d) Two plates with single damping layer between

The *constrained* form in Figure 14.31(c) uses a layer of viscoelastic material bonded to the structural plate, with a second layer of constraining material (such as stiff foil) bonded on top of that. Whatever the type of damping, it is most important that the viscoelastic material is well, and continuously, bonded to the structural plate and to any constraining layer.

For effective free-layer damping (Figure 14.31(a) and (b» the damping material should be at least as thick as, and preferably two to four times the thickness of, the metal section to which it is applied. It should have good damping properties and reasonable stiffness in the frequency and temperature ranges of interest. Beranek [7] suggests that the constrained and free-layer types of damping give equal values of damping, for weights between 10 and 20 % of the baseplate weight. Below 10 % the constrained layer damping is likely to be more effective, and above 20 % the free-layer technique is better.

## *Sound absorption*

We have established (Figure 14.25) that part of the sound striking a partition is reflected, part is absorbed within the material of the partition, and part is transmitted to the other side.

Materials which have a high superficial density and low stiffness are good insulators. On the other hand, good sound-absorbing materials usually have soft, porous or fibrous surfaces. The energy in the sound waves which strike them is dissipated by frictional and viscous losses as the sound travels through the pores of the material. Most sound absorbing materials are, therefore, very inefficient sound insulators. They are porous, and not airtight, lightweight, and not dense.

The sound absorbing quality of a material is expressed in terms of an *absorption coefficient,* a. It is defined as the ratio of the sound energy absorbed by the surface, to the energy incident upon the surface. A hard, solid surface (such as marble slate) may absorb only 1 % of the incident energy (a = 0.01), whereas some very soft proprietary materials may absorb more than 90 % of incident energy (a = 0.90). There is no rigid demarcation between 'absorbent' and 'reflecting' materials. Usually, those having coefficients (in the middle and high frequencies ranges) below 0.25 are regarded as non-absorbent; those between 0.25 and 0.40, as moderately absorbent; those between 0.40 and 0.70, as absorbent; and those above 0.70, as highly absorbent. Figure 14.32 illustrates the energy distribution at a particular frequency in a highly absorbent

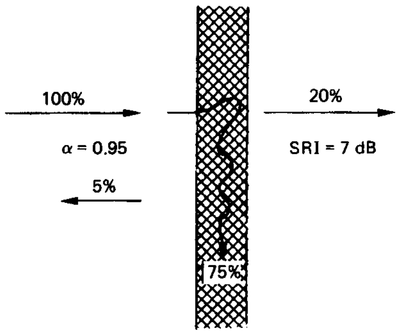



**Figure 14.32** Example of incident sound energy distribution in an absorbent material (absorption versus insulation)

material, and demonstrates what a poor sound insulator it is.

Seventy-five per cent of the incident energy is converted (by absorption) into heat within the material; 5 % is reflected, and 20 % is allowed to pass through. Viewed from the *source side,* 95 % of the sound has been absorbed (ll = 0.95), and the energy *transmitted* has only been reduced to 1/5th - in decibel terms, a reduction of 7 dB. The material is therefore a poor sound insulator. An open window would be an excellent sound absorber from the point of view of the room in which it is located (ll approaches 1.0), but it offers very little, if any, sound insulation against noise breakout from the room.

The absorption effect of a material largely depends upon how it is used and how it is mounted. Its coefficent of absorption will certainly differ with different frequencies. Material manufacturers declare absorption coefficients at 125, 250, 500, 1000, 2000 and 4000 Hz. Data are presented either in the form of a curve of ıı as a function of frequency, or in tabular form. The user should satisfy himself that the coefficients were obtained by the measurment methods specified in BS3638 (180354). A single-value absorption coefficient (known as the *noise reduction coefficient,* N.R.C.) is sometimes quoted. It may be for the value at 500 Hz, or the average of the values at 250, 500, 1000, and 2000 Hz. Care should be exercised in selecting materials on the strength of these single-value coefficients alone because generating plant noise usually has significant components above 2000 Hz. When choosing absorbent materials, small differences in their coefficients may be ignored because no significant improvement in performance results from differences less than 1.5 times the smaller coefficient value.

Increasingly higher standards of acoustic and thermal treatment are now required for new buildings. This gives opportunities for combining acoustic and thermal properties in building elements. The sound insulation of cavity walls is significantly improved, as we have seen, if a layer of sound absorbing material is fitted within the cavity. It acts to damp-out the sound waves that are reflected between the leaves on each side of the cavity.

The requirement for sound-absorbing material within a cavity often coincides with the need for a thermal insulator - to increase the thermal resistance of an airspace. Many thermal insulating materials have useful acoustic properties. These may be exploited on installations, such as enclosed or containerized generating plants, in tropical climates. Thermal insulation is usually incorporated within such plant enclosures to militate against the effects of solar radiation on their outer skins. It should not be assumed that all thermal materials are suitable for acoustic treatments. The material chosen should have an open-cell, porous structure. This allows the sound energy to be dissipated in the linked air paths provided by the pores of the material. Closed-cell, expanded polystyrene foam, while it has good thermal insulation properties, is a very poor sound absorber. On the other hand, mineral and glass fibre wools of moderate density are excellent sound absorbers; so also is open-cell polyurethane foam. Thermal insulation materials are usually covered with an impervious skin. Only porous, or very thin, film facings are acceptable for sound absorbing applications. These facings may take the form of perforated PVC. film coatings or perforated, thin steel and aluminium sheetings.

### 14.5.4 Applications for sound absorbent materials

Sound absorption principles are applied in a number of noise control techniques, to reduce machinery noise. The more important of these, in the context of generating plant, are:

1. partial or complete enclosures around the machines;
2. lined ducts;
3. sound attenuators;
4. plenum chambers; and
5. acoustic louvres.

*Partial enclosures*

The simplest form of partial enclosure is the single barrier (see Sub-section 14.5.2). Noise reduction achieved is a function of:

- the machinery noise spectrum;
- the size of the barrier, and its distance from the noise source; and
- the reflective and absorptive properties of all other surfaces near to the noise source.

For maximum effect, the surfaces (of ceilings, walls, and barrier) facing the noise source should have sound absorptive treatments. The barrier should have a sound reduction index at least 10 dB greater, in all frequency bands of interest, than the attenuation it is expected to provide. It should also extend 1 - 2 m beyond the direct sound path between noise source and receiving area in both vertical and horizontal directions.

Figure 14.33 shows some examples of partial enclosures that may be applied to generating plant. It is necessary in every case to provide for adequate ventilation and for operator access. Where engines have integral radiators it may be advantageous to provide cut-outs (shown dotted) in the end wall of a multiple enclosure (see Figure 14.33(c)).

The characteristic of Figure 14.33(d) [8] assumes an idealized point source of sound radiating uniformly through a solid angle of 360". However, it does indicate that partial enclosures can be effective in providing noise reduction (of the order 6dB) for generating plant. The curve shows that if the enclosure surrounds and completely absorbs one-half of the total radiated sound, there is a 3 dB reduction in sound level. There is a 6 dB reduction if the enclosure absorbs three-quarters of the total radiated

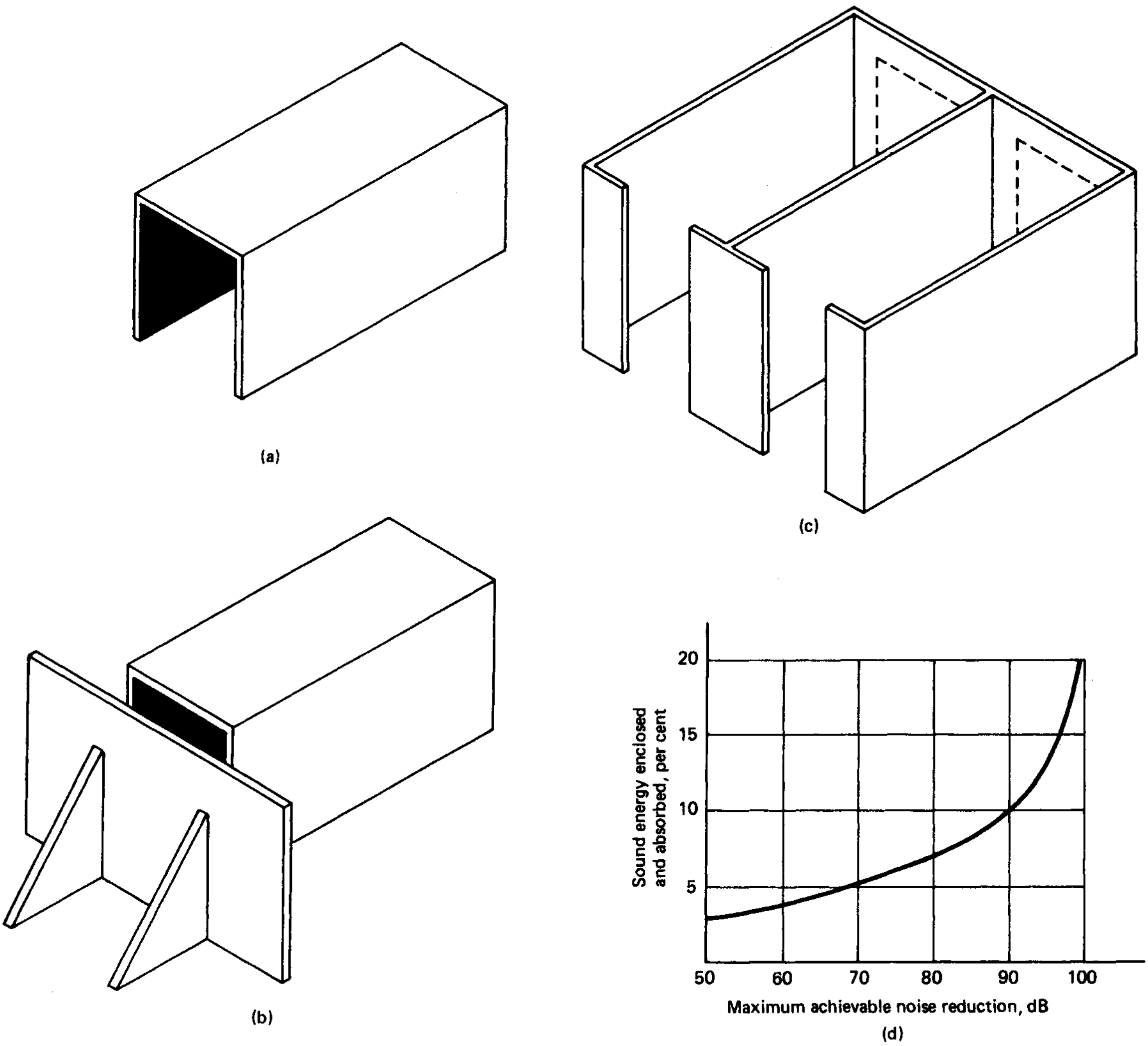



**Figure 14.33** Examples of partial enclosures used in generating plant noise control (a) Enclosure with open ends (b) Enclosure as at (a) but with movable screen at one end (c) Enclosure with one end partially open, for multiple generator installations (d) Effectiveness of a partial enclosure

sound. It is important, therefore, that the internal surfaces of partial enclosures have highly absorptive linings, and that rigid mechanical coupling with any part of the machinery is avoided. Acoustic linings for diesel generator plant (in which mechanical noise is predominantly of high frequency) should be about 50 mm thick.

In practice, noise reduction values fall short of those indicated in Figure 14.33(d). This is because it is not possible to absorb all the enclosed sound energy. It would be necessary to have a complete enclosure if reduction performances better than 15 dB are required.

### Complete enclosures

To be effective, complete enclosures must have:

1. adequate sound insulating properties;
2. as much sound absorption properties as possible in order to reduce the build up of reverberant sound. (One needs to double the amount of absorption already present in an enclosure to obtain a 3 dB reduction in reverberant sound level);
3. acoustically treated openings for access, services entries, etc.

Many proprietary constructions are available. Most are based on modular, sheet steel panels, with an infill of resin-bonded mineral fibre (or equal) faced with a thin perforated steel sheet. Because of the variety of plant configurations, care must be exercised when adopting these modular constructions for a particular application. It is often more economical to design and fabricate a purpose-built structure. Then, the two controllable variables (the absorption inside the enclosure and the insulation of walls, floor, and ceiling) can be specifically matched to the noise control requirements of the installation.

Design prediction of the noise levels inside enclosures is a complex matter and must be outside the scope of this chapter. (See Chapters 10 and 11 of [7] and Appendix D of [9] for detailed treatment of the subject.) Miller [8] suggests that the sound level inside a machine enclosure may be as much as 10 to 20 dB higher than the original sound level (at the same distance) from an unenclosed machine because of reduced absorption within the enclosure. He offers the following rule-of-thumb methods for estimating the required insulation of the enclosure wall to compensate for this increase in sound level. DNR is the *desired noise reduction* required to meet the receiver's specified criteria.

1. If the enclosure has no internal absorption:

   the SRI required = DNR + 20dB

2. If the enclosure has partial internal absorption:

   the SRI required = DNR + 15 dB

3. If the enclosure has complete internal absorption:

   the SRI required = DNR + 10dB

Openings must be provided in side walls for access, for viewing, and for services such as fuel lines and cables. The performance of 'weak' areas, such as doors and windows, must match that of the enclosure walls. Pipes, ducts or conduits passing through enclosure walls must have flexible connectors to give vibration breaks between walls and the machinery. The machinery itself should be isolated from the floor of the enclosure to avoid vibrating the structure walls (see Sub-section 14.6.3). Acoustically-treated air inlet and outlet apertures will also be required. Selection will be influenced by the degree of attenuation required. Choice (restricted in some cases by the physical space available within and immediately outside the enclosure) may be made from:

- acoustic louvres;
- baffles or plenum chambers; and
- splitter attenuators.

### Lined ducts

The terms: insertion loss, transmission loss, noise reduction, end differences, and attenuation are all used to describe the effectiveness of noise control measures.

*insertion loss* is defined as the difference between sound pressure levels (and power levels or intensity levels) measured in decibels at the same specified point in a system, before and after a muffler is inserted between the noise source and the measurement point. The *dynamic insertion loss* of a muffler is the insertion loss measured with rated air flowing through it under normal operating conditions.

*Transmission loss* (TL) is the ratio of *sound power* incident on the muffler to the sound power transmitted by the muffler. Since sound power cannot be measured directly it is only a useful analytical concept.

*Noise reduction* (NR) and *end differences* are both used to mean the same thing. They refer to the difference between the sound pressure levels measured at the input (source end) of a muffler and its output (receiving end).

*Attenuation* is the decrease of *sound power,* in decibels, between two points in an acoustic system.

Perhaps the most useful measure of a muffler's effectiveness is its *insertion loss* or, more precisely, its *dynamic insertion loss.* In practice, when engineering for noise control, one measures or calculates the SPL at some point of a system which has no acoustic treatment. This is compared with the specified (or criterion) SPL to determine the insertion loss required for the muffler.

Mufflers are generally classified as *dissipative* (sometimes called *absorptive)* or *reactive.* The former work on the principle of absorbing acoustic energy by means of sound absorptive and flow-resistive linings or baffles inside the muffler. A lined duct is the simplest form of dissipative muffler. It is, in effect, an air passage with one or more interior surfaces covered with a porous absorptive material. Reactive mufflers are those which employ chambers, which may be interconnected with pipes, slots, or perforated plates, to reflect sound back towards the source or contain it within the muffler. They do not, usually, incorporate sound absorptive material. There is no such thing as a purely dissipative or a purely reactive muffler. This is because all practical mufflers achieve noise reduction by both the dissipation and reflection of sound energy.

For all practical purposes, and certainly where inlet and outlet cooling air and aspiration air to generator enclosures is concerned, the insertion loss for dissipative mufflers can be assumed to be equal to transmission loss and to be about 3 dB less than the 'noise reduction' (NR) value:

(NR - 3) = TL = Insertion loss

The attenuation of a lined duct depends, primarily, upon:

- the duct length;
- the thickness and the flow-resistance of the lining;
- the width of the air passage;
- and the wavelength of the sound.

Doelling [7] summarizes previous work by others in calculating the predicted performance of lined ducts, and gives methods for estimating the attenuation of a lined duct for routine noise control problems. Figure 14.34 [7] shows the attenuation characteristics of ducts that have flow-resistive linings mounted directly on their walls - with no facing, or with perforated facings having open areas of 25 to 35%.

The attenuation per length of duct (ordinate Aly) is related to duct width. The ordinate must be

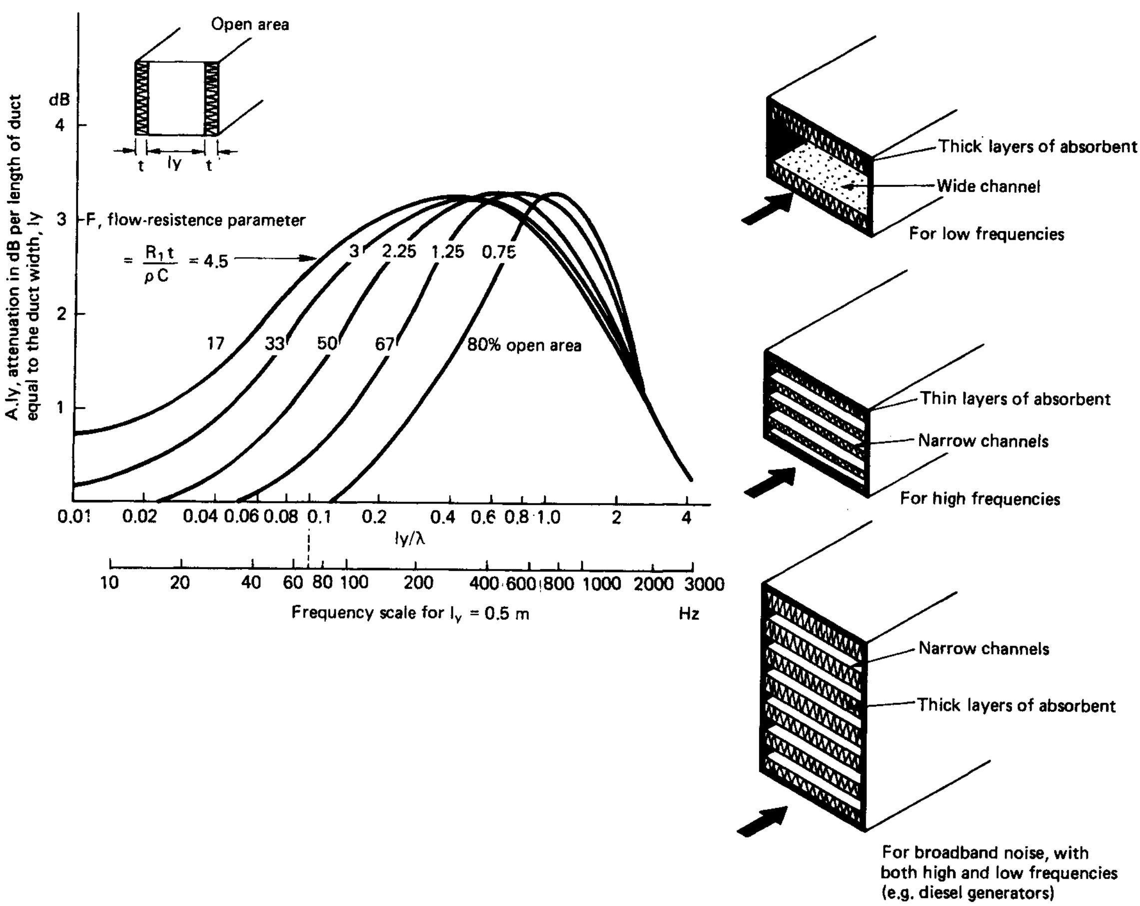



**Figure 14.34** Attenuation for lined ducts [7]

multiplied by *l,j/y,* in order to determine the attenuation of a duct of length *Ie.* The abscissa is the frequency parameter Iy/'A - the ratio of the width between the linings to the wavelength of sound in air at the frequency of interest. The scale for a 0.5 m wide duct at an ambient temperature of 20°C is included as a useful aid. It needs to be halved if the graphs are used for 1 m wide ducts. Temperature-related changes in scale may be neglected for estimation purposes on generating plant air systems.

The flow-resistance parameter *(F)* for which these data are applicable is non-dimensional. Rb the flow resistance per unit length), *t*, the thickness of the lining, and pc, the characteristic impedance of air, must be in consistent units. In SI form, therefore, *Rt* would be expressed in kg-s/$m^3$ (== rayls/9.81), *t* in metres, p in *kglm*$^3$, and c in mls.

Each of the five characteristics in Figure 14.34 relates to attenuation performance for an open area percentage of duct. The thicker the lining and the smaller the open area percentage, the better the performance at lower frequencies. For the higher frequencies, thinner absorbent linings are effective, but the resulting larger open areas allow more low frequency noise to pass directly along the duct. Thin multi-layers of absorbent material, with narrow passages, are therefore more effective at high frequencies. For the best performance over the widest frequency range thick absorbent layers and narrow passages are ideal. The diagrams in the right hand margin of Figure 14.34 summarize these conclusions.

It should be noted that attenuation is not very sensitive to changes in the flow-resistance parameter. The data of the graphs are not seriously affected if the parameter varies between one-half and twice the nominal values given. Manufacturers of porous acoustic materials will provide data on the flow-resistance characteristics of their products. The data are usually presented in the form of log x log charts which plot unit-thickness flow resistance against volume density of the material.

The -::hart of Figure 14.34 may also be used to determine the attenuation for lining configurations other than that shown. If a rectangular duct is lined on all four sides, its performance is determined by an arithmetic addition of the attenuations due to the 'sides' and the 'top and bottom' of the duct. A square duct, lined on all four sides, will have about twice the attenuation of a duct lined only on two opposite sides. A duct lined only on one side will give the same attenuation as a duct which is lined on two sides, but which is twice as wide.

Attenuation in ductwork bends is largely achieved by reflection of sound waves back towards the source. Peak attenuation occurs in unlined 90° bends at a 'resonant' frequency whose wavelength is twice the duct width. This is shown in attenuation characteristic No.1 of Figure 14.35. This should be compared with characteristic No.2 of the same figure, which shows the benefit of lining the same approximate size of bend. The lengths of the legs into the bends are twice the width (600mm) of the duct in each case.

Doelling [7] also offers a method for rapid estimation of the insertion loss of lined and unlined bends, using the chart of Figure 14.36. The total insertion loss for a lined bend is determined by adding the insertion loss obtained from Figure 14.36 to the insertion loss of the length of lined duct beyond the

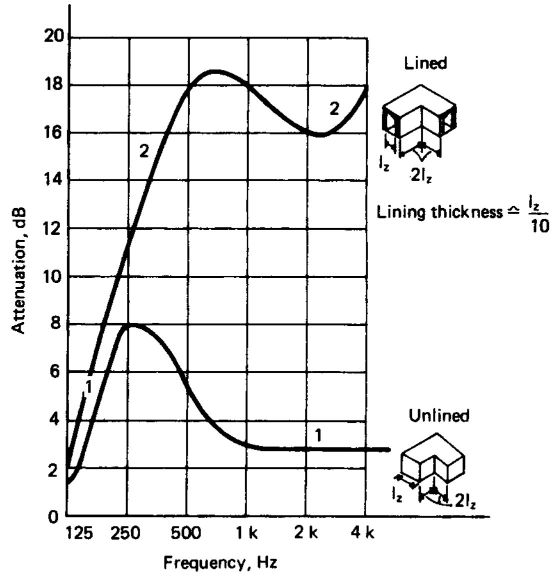



**Figure 14.35** Comparison of attenuation of lined and unlined bends in ductwork

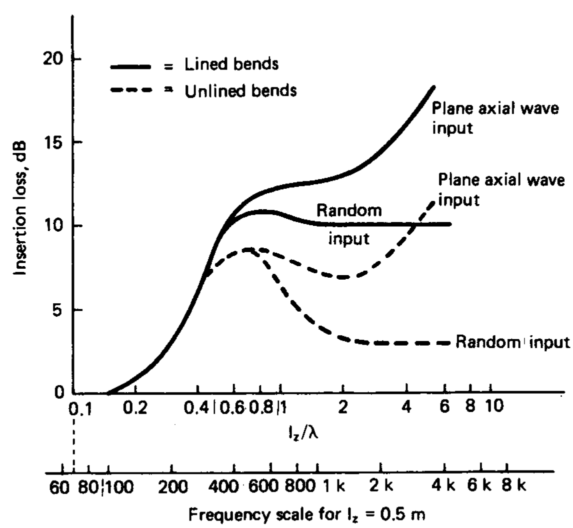



**Figure 14.36** Insertion loss for lined and unlined bends

bend (from Figure 14.34). This length shouk be between two and four times the duct width.

Note the different characteristics for plane axial wave and random wave inputs. Plane waves are those that travel along the axis of a duct. Random-in-space waves, as the term implies, impinge on the duct input at all angles of incidence. Random waves are attenuated rapidly whereas the plane (axial) wave component persists much longer. When estimating the attenuation of straight ducts, it is therefore usual to consider their performance in terms of plane wave attenuation (see Figure 14.34). Because the attenuation at bends is less at the higher frequencies for random waves than for plane waves, it is wise to use the random wave performance when making noise reduction assessments for bends in duct work.

Doelling [7] also suggests that for a rough approximation, one may assume that insertion loss is proportional to the angle of the bend - for angles less than 90°. The insertion loss of a 30° bend would therefore be one-third that of a 90° bend, and that of a 45° bend would be one-half that of a 90° bend. Insufficient data are available for bends with angles greater than 90°, but Doelling estimates that the insertion loss for a 180° bend (i.e. a return bend which changes the airflow direction through 180°) would be approximately 1.5 times that of a 90° bend.

Radiused bends and mitre bends fitted with long turning vanes (i.e. those with lower aerodynamic resistance) will give less attenuation than the 2-piece 90° mitred bends without turning vanes, whose characteristics are shown in Figure 14.35. The following table [1] shows typical attenuations of radiused bends, and of mitre bends with large turning vanes.

| *Radius (mm)* | *Octave band centre frequency* 125 | 250 | 500 | 1k | 2k | 4k (Hz) |
|---|---|---|---|---|---|---|
| 275–500 | | | 1 | 2 | 3 | 3 (dB) |
| 525–1000 | | 1 | 2 | 3 | 3 | 3 (dB) |
| 1025–2000 | 1 | 2 | 3 | 3 | 3 | 3 (dB) |

## *Sound attenuators*

The term is generally used to describe factory-made rectangular or cylindrical packaged attenuators providing sound reduction at air intake and exhaust apertures in and out of plant rooms or enclosures. Use of the cylindrical type is largely confined to conventional air ventilating systems, especially for 'on-fan' and 'in-duct' arrangements. The rectangular type (variously referred to as *splitter attenuators, splitter silencers,* and *acoustic splitters)* is widely used on generator installations.

Proprietary units employ the principle of splitting the air passage into airway sections whose width is very much smaller than their height. A minimum absorbent lining thickness of 100mm is usually applied to the sides of these airways. Typical modular designs have 200 mm wide splitters, with airway widths varying between 50mm and 200mm. The overall height (H) and width (W) of the attenuator are dimensioned to give a total free area approaching 50 % of the attenuators's face area *(W* x H). Widths and heights of proprietary units normally start at 300 mm and increase in 300 mm steps to give comprehensive ranges of square and rectangular attenuators. For example:

| | | | | |
|---|---|---|---|---|
| **Width:** | 900 | 900 | 900 | 900 |
| **Height** | 900 | 1200 | 1500 | 1800 |

Modular lengths may start at 900 mm and go through to 2400 mm - also in 300 mm increments.

For a given cross-section and length, an attenuator has three major characteristics, all of which are a function of the air velocity at its input face:

1. insertion loss;
2. pressure drop; and
3. *self-noise* - the noise generated by the passage of air through the attenuator.

In general, low insertion loss (or moderate acoustic performance) is coupled with low pressure drop, and high acoustic performance with higher pressure drops. It is important to co-relate acoustic performance with the airflow rate through the attenuator because high-velocity flow results in high pressure drops. Attenuator manufacturers should always be given accurate information regarding flow velocity and the permissible pressure drop as unit selection is best made by them. The general rule is that airway width and length determine acoustic performance, whereas attenuator height and width determine pressure loss. In other words

for better acoustic performance - reduce airway width
- increase length

for lower pressure loss - increase height
- increase attenuator width (Le. increase the number of airway/splitter modules. See Figure 14.37)

Figure 14.37 shows typical attenuation characteristics for packaged modules which employ a 200 mm thick splitter. A module comprises one splitter and one airway (thickness *d).*

The self-noise generated by an attenuator is essentially in the direction of the airflow, i.e. worse

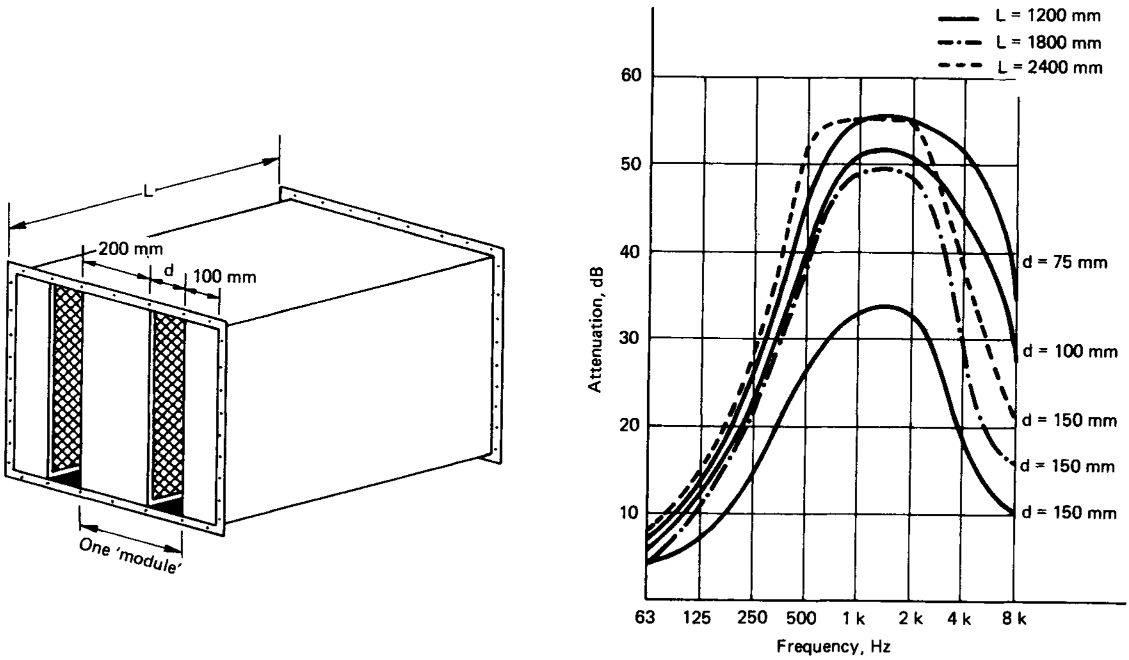



Figure 14.37 Typical attenuation by packaged acoustic splitters [3J

at its end. The possibility exists of a high-velocity air stream generating sufficient noise for it to act as a noise source flanking the attenuator's airborne-noise treatment. A check should, therefore, always be made to ensure that the noise generated by any chosen attenuator does not infringe on the noise criteria required for the installation. Manufacturers usually offer a *regeneration* guide (in NC levels) for their standard attenuators. If the installation's design criteria falls below the level of the self-noise generated by the attenuator, the latter becomes the limiting factor and problems can be expected. Regeneration levels for proprietary splitter units vary, typically, between:

- NC 25 - for attenuators of moderate acoustic performance, and a pressure loss of 2.5 mm $H_2O$;
- NC 35 - for those with a pressure loss of the order of 8.5 mm $H_2O$;
- NC45 - for higher performance attenuators with a pressure loss between 11.5 and 14.5mm $H_2O$.

(See Figure 14.12 for the family of NC curves.)

In most generator applications the lowest design criteria selected for areas immediately downstream of the plant's outlet air attenuator(s) is unlikely to be below the NC 50 level. The self-generated noise from attenuators with pressure losses between 8.5 and 14.5 mm $H_2O$ should not, therefore, be a limiting factor in noise-reduction treatments.

A major problem associated with high-velocity air streams is deterioration of the absorbent material in attenuators. The problem may be tackled in several ways: these include spraying the porous material with P.Y.C., and providing protective facings. The latter usually take the form of perforated metal with at least a 20 % open area. Glassfibre cloth or polyester membranes may also be used, under the perforated metal, to protect the absorbent materials from grease or oil-laden atmospheres, or to provide a deterrent against bacteriological growth. Care should always be exercised in applying such coverings, to ensure that they are securely clamped at all edges of the splitters. In practice, manufacturers usually encase the acoustic materials in a sewn bag of the protective cloth. Splitter panels constructed in this way easily cope with air stream velocities up to 25 mls. (The airflow from a radiator-cooled generator would be of the order of 11 mls.)

## *Plenum chambers*

Earlier discussion has shown that an absorbent room or enclosure is a simple, but effective, sound attenuator. In some installations, particularly those located in building basements, it may be possible to employ an otherwise unused space adjacent to a plant room to duct airflows into and out of the plant room. If this space is lined with sound absorbent materials, it will behave as an attenuator to reduce the level of noise escaping from the plant room. To minimize the direct transmission of sound through such a *plenum chamber*, its inlet and outlet openings should not be located directly opposite each other. The chamber should be so dimensioned that, at the higher frequencies, almost all of the sound energy is reflected several times off the lined sides in its passage from the inlet to the outlet of the chamber (see Figure 14.38(a»). The larger the volume of the chamber and the thicker the absorbent lining, the lower the frequencies which can be absorbed.

Wells has developed the following formula for determining the approximate transmission loss of a single chamber plenum [1, 3]. The geometry for the calculation is given in Figure 14.38(b).

$$TL = 10 \log \left[ S \frac{\cos \phi}{2\pi d^2} + \frac{1}{R} \right]$$

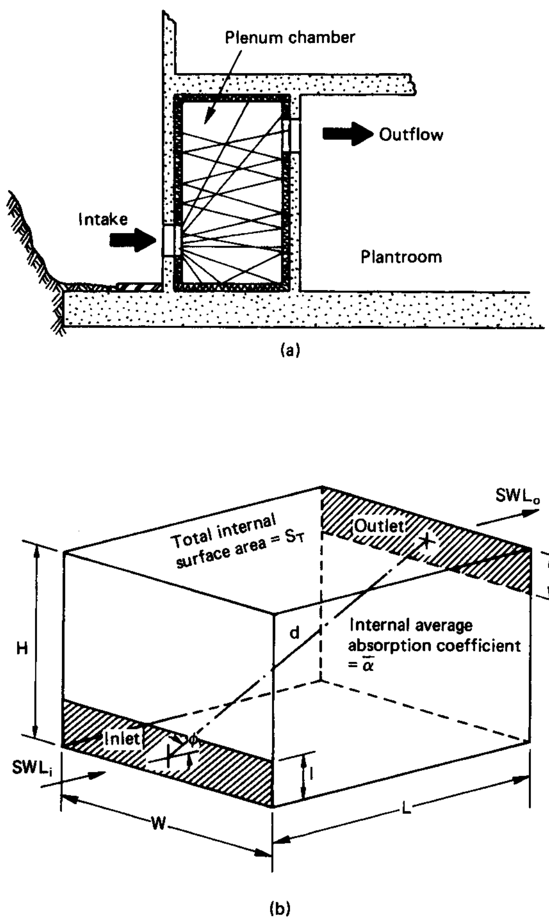



**Figure 14.38** Principle of performance and geometry of a plenum chamber (a) Principle of plenum chamber attenuation (b) Geometry of single chamber plenum

TL = transmission loss ($SWL_i - SWL_o$) (dB)
$S$ = $lW$ = area of inlet or outlet opening ($m^2$)
$d^2$ = $(H\text{-}l)^2 + L^2$
$d$ = the slant distance from the centre of the inlet to the centre of the outlet (m)
$\phi$ = the angle that $d$ makes with the inlet axis, so that $\cos \phi = L/d$
$R$ = the *room constant* of the plenum, in $m^2$ units = $S_T.\alpha/(1-\alpha)$
$S_T$ = the total internal surface area of the plenum, including inlet and outlet areas ($m^2$)
$\alpha$ = the average absorption coefficient of the internal surfaces of the plenum, given by:

$$\alpha = (S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 + \ldots \text{ etc.})/S_T$$

where Sl is the area of absorbent material having an absorption coefficient ell; S2 is an area with absorption coefficient el2, and so on. When calculating el, assume that both the inlet and outlet areas have a coefficient of 1.0.

This formula is accurate to within a few decibels for the higher frequencies whose wavelengths are less than any dimension of the chamber. At lower frequencies, where wavelengths are likely to be longer than anyone dimension of the plenum, the calculated values of TL will be some 5-10 dB lower than measured values. Transmission loss can be increased by incorporating a partial, lined baffle across the chamber to prevent direct line-of-sight between the inlet and outlet openings. Any improvement in acoustic performance is at the expense of an increased pressure drop across the chamber.

## *Acoustic louvres*

Where space is a limiting factor and precludes the use of splitter attenuators or plenum chambers, a third option is the packaged *acoustic louvre.* It has the same aerodynamic characteristic, but uses hollow, blade elements (often of semi-aerofoil construction), instead of flat sheet vanes. Each blade has an absorbent material infill, which is retained behind perforated metal sheet. Figure 14.39 shows some typical constructions and their related acoustic performances - these are presented as sound reduction indices in the octave band mid-frequencies. The constructions shown are marketed by Sound Attenuators of Colchester, England. They are available in square and rectangular modular frame sizes - ranging from 600 mm x 600 mm to maximum overall dimensions of 2400 mm x 2400 mm. Where larger face areas are required, these may be obtained by stacking or abutting standard modules using structural steel linking frames designed for the purpose.

As with splitter attenuators, acoustic performance is set-off against pressure loss - the better the per-

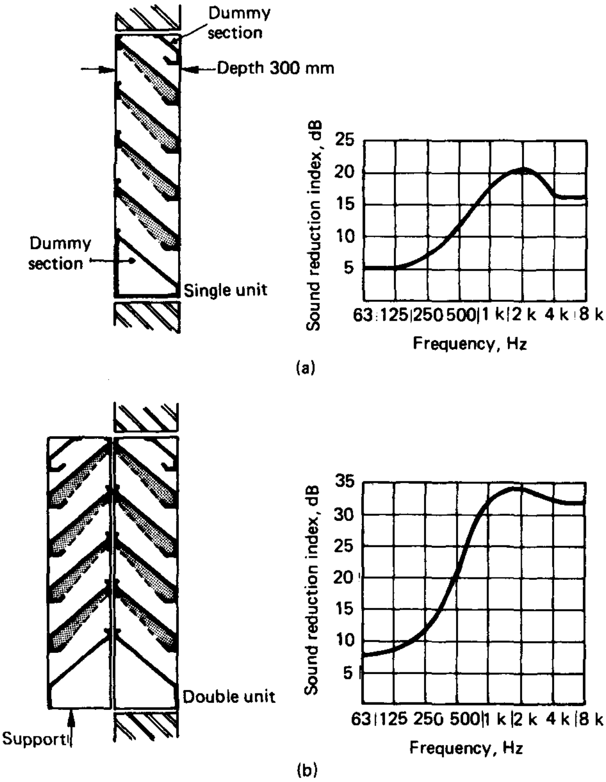



**Figure 14.39** Typical acoustic louvre structures and performances

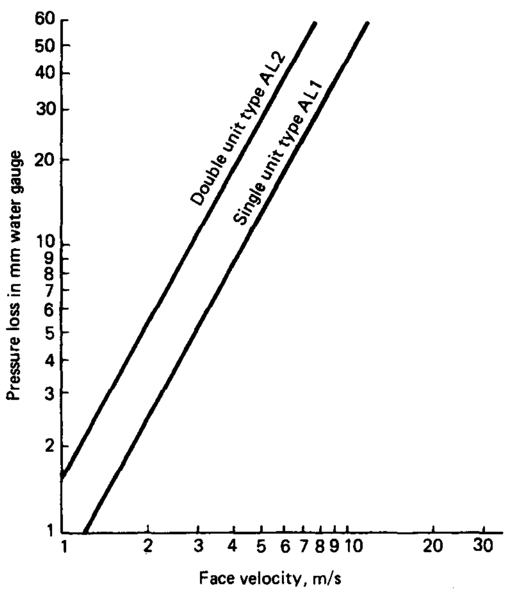



**Figure 14.40** Pressure loss characteristics of 2400 mm high S.A.L. acoustic louvres (Courtesy: Sound Attenuators Ltd)

formance, the higher the pressure loss. See the characteristics of Figure 14.40, for 2400mm single and double units, in which face velocity is directly related to pressure loss.

Assume that the airflow from the radiator of a 500kW diesel generator is *16m³/s*, and that this airis to be discharged to atmosphere through an opening in the plant room wall which can accommodate a 2400mm high acoustic louvre. Assume also that acoustic calculations confirm that a double unit (as Figure 14.39(b)) is required. Because of the danger of operating too close to the stall condition of the radiator fan, we are limited, say, to a pressure loss of no more than 20 mm $H_2O$ across the louvre. The louvre face area and face velocity are determined as follows. The width ofthe radiator matrix (1550mm) requires the use of a 2400 mm (H) x 1650 mm (W) type acoustic louvre. The face area of the louvre is therefore $3.96m^2$, which gives a face (air) velocity of *4.04m/s* (= *16/3.96).* The louvre's characteristic, in Figure 14.40, shows that the pressure loss for 4.04 *mls* is about 19 mm water gauge - which is only just acceptable. Increasing the louvre width to the next larger size (1800 mm) would give a face velocity of *3.7 mis*, which corresponds to a pressure loss of 16 mm water gauge. This gives a bit more leeway on the permissible limit of 20 mm water gauge.

Acoustic louvres may be combined to form attenuating screens or enclosures around, for example, cooling towers or generating plants. Screens and enclosures of this type may be used as positive architectural features, offering the minimum visual disturbance to the external fabric of buildings. In this regard, it is important that any need for acoustic louvres is identified as early as possible in the building's design stages.

## *Engine exhaust mufflers*

The major source of low frequency noise in diesel engine plant is the engine's exhaust gases. This noise is caused by the intermittent ejection of high pressure gas, following the opening of exhaust valves or ports in the engine cylinders. Pressure pulsations resulting from high amplitude waves being reflected back and forth in the exhaust pipelines give rise to the familiar exhaust *roar* of reciprocating internal combustion engines. The purpose of a well-designed exhaust system is to reduce these pulsations and, in so doing, achieve not only efficient noise attenuation but also decrease the power losses that are directly attributable to any exhaust system. The primary objective is to reduce the acceleration of the pulsating gas flow through the system without introducing undue back pressure. This is where the muffler makes its contribution to exhaust noise control.

Cost apart, an exhaust system design must take account of the following factors:

1. the degree of noise attenuation required;
2. the frequency spectrum (or the predominant frequencies) of the exhaust noise; and
3. the permissible back pressure.

If the 'treated' exhaust noise level is not to be significant, its contribution should be at least 10dBA lower than the targeted overall noise level from the plant.

The octave-band sound levels for a typical diesel engine are shown in the frequency analysis of Figure 14.41 [9]. The exhaust and mechanical noise components are those which contribute most to the total noise level. For clarity of presentation, the noise contributions from engine casing and engine air intake have been excluded from the analysis.

Franken and Beranek [7] have devised a chart for determining the octave band power levels of exhaust noise from an i.c. engine. This is reproduced in Figure 14.42. The mid-frequency of the octave band for the spectrum charted is determined by the engine's *average cylinder firing frequency* (fa). The number of firing impulses per second per cylinder for 2-stroke and 4-stroke engines operating at fixed speeds on generator application would be given by:

$f_a = n/60$ Hz, for a 2-stroke cycle
$f_a = n/120$ Hz, for a 4-stroke cycle

where $n$ is the engine's rotational speed, in r.p.m.

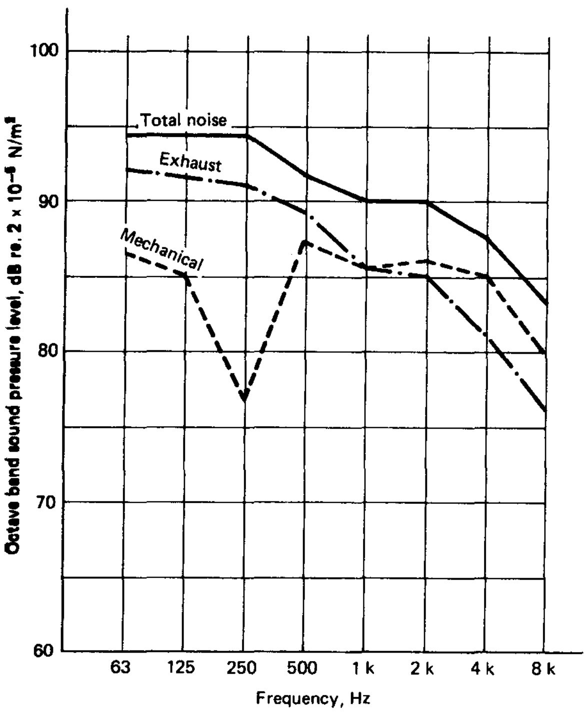



**Figure 14.41** Total noise and two major constituents for an i.c. engine [9]

The chart data are based on the assumption that the exhaust port of each cylinder is connected to atmosphere through cylindrical pipes, each equal in length to about 1/10th the wavelength at frequency *fa,* and that all these pipes are joined together in one common exhaust manifold. The power levels on the ordinate are referred to the overall sound power level (SWL) of the engine exhaust. Fraken and Beranek [7] have also derived the following formula, from experimental data, for determining the overall sound power level of an engine's exhaust noise:

$$SWL = 125 + 10 \log hp \quad dB$$

where *hp* is the total horsepower delivered by the engine shaft to the generator and any ancillary equipment.

The sound pressure level (SPL) at a point distant *l* from the engine exhaust outlet may be obtained from the relationship:

SPL = SWL - 10log (4'71-[2) dB

assuming spherical divergence of the sound.

A frequency scale has been added to Figure 14.42 for a 4-stroke engine operating at a synchronous speed of 1500rpm.

The most commonly used types of exhaust mufflers (or silencers, the more optimistic term applied to these attenuators) are:

- absorptive or dissipative type;
- reactive type; and
- expansion chamber type.

Examples are illustrated in Figure 14.43. The distinction between them is arbitrary since most combine the absorptive and reactive effects to a certain degree.

The *absorptive* muffler is usually of the straight-through type, employing a perforated tube passing through a chamber packed with an absorptive material, such as fibreglass. It usually has a fairly low back pressure and is effective in suppressing high frequency noise. It is therefore particularly suited to turbocharged engines, in which the turbocharger effectively suppresses the low frequency exhaust gas pulsations. It suffers from the major disadvantage that the absorbent material can be blocked with residues and carbon deposits, reducing its efficiency over time. Also, the absorption of such combustible matter introduces a fire hazard.

*Reactive* mufflers operate on the principle of reflecting the exhaust gas flow or subjecting it to several reversals of direction before it is discharged - thus containing the sound within the chamber. The more complex forms use baffle plates to split the chamber into sections, each of which is tuned to attenuate a specific frequency, so that the muffler's total acoustic performance covers an ~xtended range of frequencies. A multi-step

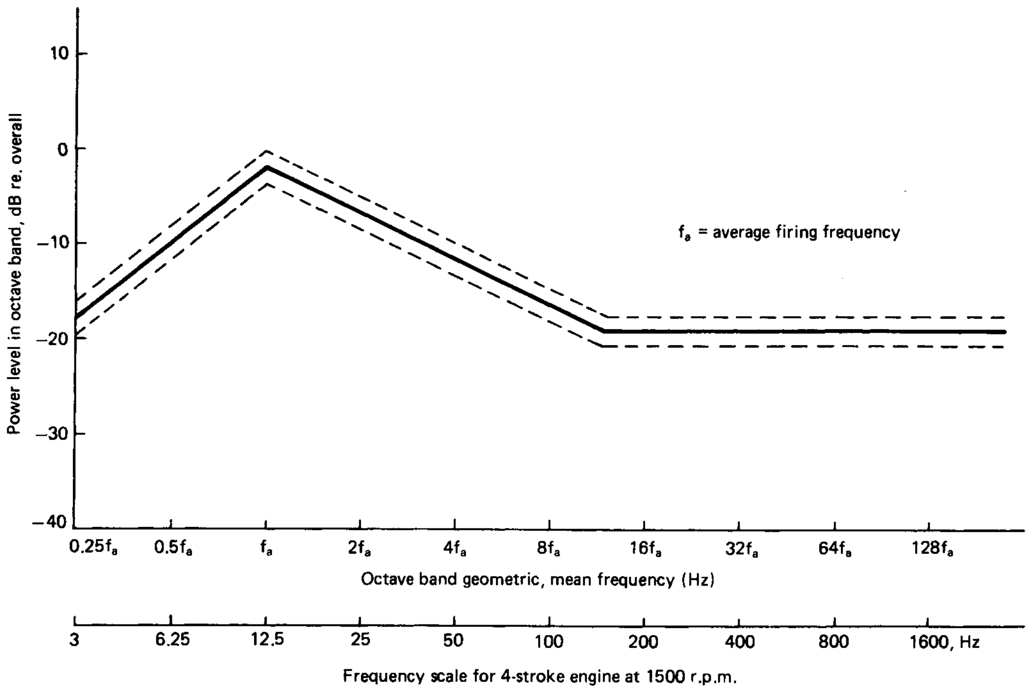



**Figure 14.42** Chart for determining the octave band sound power levels of engine exhaust noise [7]

attenuator of this type is illustrated in diagram (f) of Figure 14.43. The perforated tubes not only improve the gas flow but also provide some sound absorption. Because of their rather sinuous gas flow paths, reactive mufflers tend to have a higher back pressure than the absorptive types.

*Expansion chamber* types, illustrated in diagrams (i) and (j) of Figure 14.43 afford a means of dissipating energy when used upstream in an exhaust system, or act as resonators to give maximum attenuation at specific frequencies when used downstream of, and in line with, absorptive or reactive mufflers. Generally speaking, the ratio of muffler body diameter to inlet pipe diameter governs the level of attenuation, and the chamber length determines the frequencies attenuated.

Certain guide lines apply to the selection of mufflers:

1. The volume of the muffler should be of the order of 3-5 times engine cubic capacity - for both naturally-aspirated and turbo-charged engines.
2. The muffler's cross-sectional area should be large, and the ideal ratio of body diameter to inlet pipe diameter is between 4 : 1 and 5 : 1.

Muffler manufacturers provide attenuation and pressure loss data for their products. The more elementary silencers, illustrated in Figure 14.43, should give 10-15dBA attenuation, while the more complex forms may give up to 35 dBA reduction of open exhaust noise.

Opinions differ as to the ideal arrangements and positions for mufflers in exhaust systems. They may be used in series to give the best attenuation. Experience dictates that the first muffler, which may be an expansion chamber or a reactive unit, should be as near as possible to the engine's exhaust manifold (1.5-3m). The secondary, absorptive unit should be fitted directly downstream of it.

Tail pipe length should, at least, be equal to the length of the pipework between the engine exhaust manifold and the first muffler (see Figure 14.44). Long tail pipes may create obtrusive exhaust notes in certain conditions. This would necessitate fitting a *tuned resonator* of the expansion chamber type near the end of the exhaust system in order to suppress noise at particular frequencies. When mufflers are used in series, the final tail pipe exhausting to atmosphere should be at least as long as the last muffler in the system.

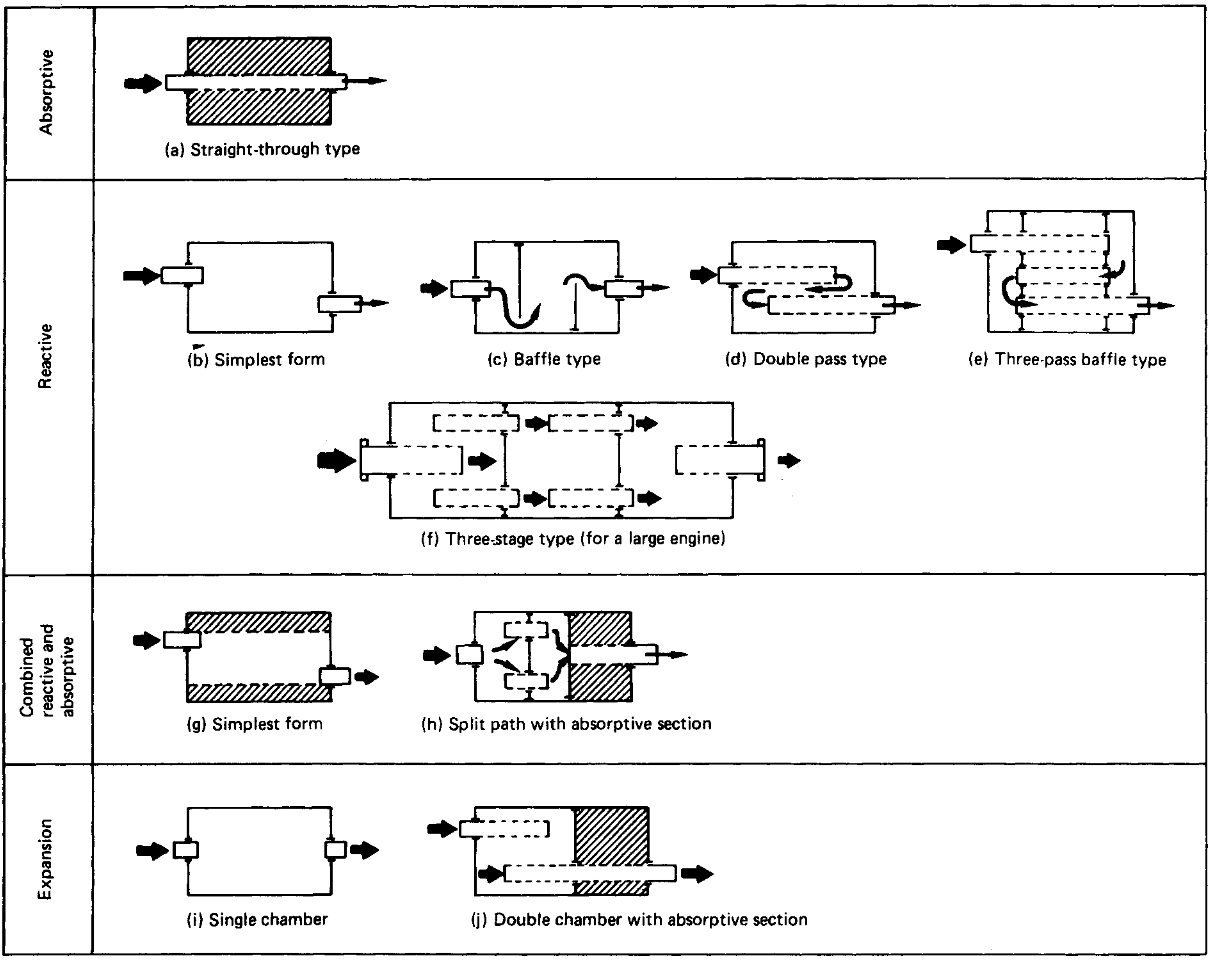



**Figure 14.43** Some general types of exhaust muffler (a) Straight through type (b) Simplest form (c) Baffle type (d) Double pass type (e) Three-pass type (f) Three-stage type (for a large engine) (g) Simplest form (h) Split path with absorptive section (i) Single chamber (j) Double chamber with absorptive section

## 14.6 Vibration control - principles and practice

### 14.6.1 Vibration sources

All reciprocating i.e. engines, by virtue of their design, are inherent sources of vibration. The nature and the magnitude of the vibration depend upon engine configuration. Two main disturbing forces need to be considered:

1. The first is produced by the firing cycle acting on the moving masses. This unbalanced force results in reactionary forces being passed through the engine-generator mountings in order to maintain equilibrium. **In** this group are the forces associated with combustion, which have a very steep pressure rise. Generated frequencies range (upwards) from the firing frequencies through successive harmonics, some of which are stronger than others. The firing frequencies for multi-cylinder engines are given by:

IF = $nxC/60$ Hz, for 2-stroke engines
IF = $nxc/120$ Hz, for 4-stroke engines

where $n$ is the rotational speed, in r.p.m.
C is the number of engine cylinders

Thus, for an 8-cylinder, 4-stroke engine, operating at 1500r.p.m., the disturbing frequency produced by the firing cycle would be 100Hz.

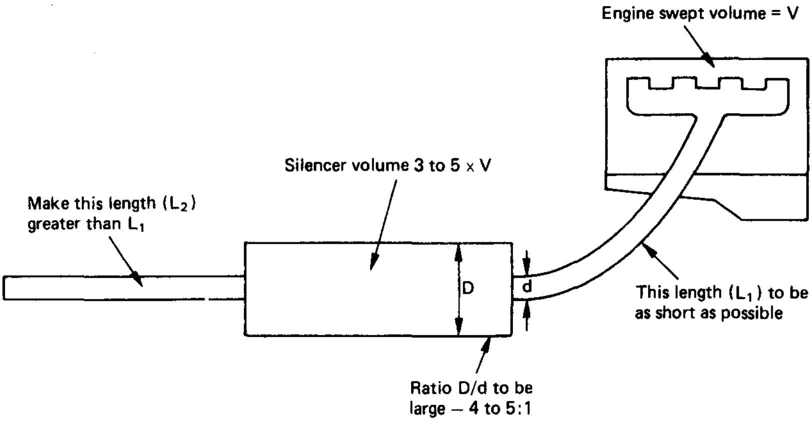



**Figure 14.44** Optimum dimensions for a single muffler exhaust system

2. The second disturbing force that may be present is that due to the imbalance of rotating or reciprocating parts, or to the misalignment of engine and generator. These forces are directly related to the rotational frequency of the engine (i.e. at 1500 rpm the frequency will be 25 Hz). Since this is the lower of the two disturbing frequencies (the other being 100 Hz - produced by the firing cycle), it should be used when selecting the natural frequency of the vibration isolation system. See the discussions which follow in Subsection 14.6.3.

### 14.6.2 Vibration control principles

Most structure-borne noise can be significantly reduced by mounting vibrating machines on flexible supports. The elastic devices used for this purpose are called *vibration isolators* (or *anti-vibration mountings).* Where auxiliary plant provides power for hospitals, computer installations, and laboratories, it is necessary to isolate vibrating equipment so that every region of the building likely to be affected is protected from structure-borne noise which may originate from this equipment. In some cases it may also be necessary to incorporate flexible mounting arrangements within the floor structures of receiving rooms (such as operating theatres, wards, rest rooms, offices, or areas housing delicate mechanical and electronic equipment).

#### *Transmissibility and efficiency of isolation*

The simplest flexibly-mounted system can be represented by a mass and a spring. If the mass is linearly displaced and then released, the 'system' vibrates freely at a *natural frequency (fo)* which is related to the weight of the mass and the *stiffness (k)* of the spring. In an undisturbed system the amplitude of this vibration will gradually decrease until the system eventually comes to rest. The rate of decay of the vibration is a function of the system's *damping* properties. If a vibrating force is applied to the system the system itself will be induced to vibrate. The nature of the resultant vibration is then governed by:

- the point of application of this input force;
- the frequency and magnitude of the input force; and
- the natural frequency and damping properties of the mass-spring system.

The idealized model of the simplest system (known as the *single-degree-of-freedom system)* is represented in Figure 14.45. It consists of a rigid mass constrained to move in a vertical direction only, and a massless spring and damper. Diagram (a) illustrates the case for an engine flexibly mounted on a rigid and immovable base, and where disturbing forces only originate from within the engine itself. Diagram (b) represents a mass isolated from structure- or ground-borne vibrations originating elsewhere. This condition exists, for example, on

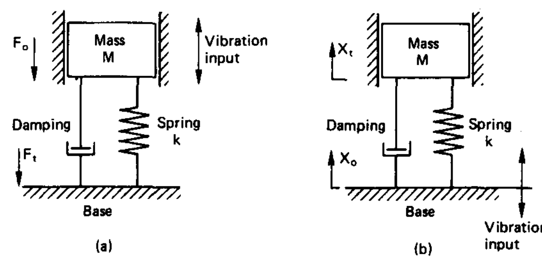



**Figure 14.45** Forced vibration of damped single-degree-of-freedom systems (a) Vibration input applied to the mass (b) Vibration input applied to the base

mobile applications (e.g. where road surface excitation or structure-transmitted vibrations, such as those from ship's propulsion gear, may exist) or on ductwork, pipes, and suspended ceilings, flexibly supported from structures which are subjected to vibration.

The effectiveness of a forced-vibration isolating system is measured by its *transmissibility*, defined by the ratio of vibration output to vibration input in the system. The *force transmissibility* ($T_f$) in the condition shown in diagram (a) is defined as:

$$T_f = \frac{\text{Force transmitted through the isolator to the rigid base}}{\text{Force applied by the isolated vibrating machine}}$$

$$= F_t/F_0$$

The *displacement transmissibility* ($T_d$) of the system in diagram (b) is defined as the ratio of the displacement transmitted through the isolator to the exciting displacement applied to it, from the supporting foundations, i.e.

$$T_d = \frac{\text{Dynamic amplitude of the isolated mass}}{\text{Dynamic amplitude of the supporting foundations}}$$

$$= X_t/X_0$$

The mathematics of the two cases is identical and the ratios are similar. The lower the ratio (usually expressed as a percentage), the more effective the isolator. The complementary term *efficiency of isolation* (or *degree of isolation*) defines the proportion of vibrational input (force or amplitude) which is not transmitted. An isolator which has a transmissibility of 4 % would therefore have an isolation efficiency of 96 %.

In order to achieve the desired efficiency in an isolating system it is necessary to know the forcing frequency ($f$) to be isolated, and to establish the natural frequency ($f_0$ or $f_n$) which is required of the mass–spring system. The natural frequency of a single-degree-of-freedom system is given by:

$$f_0 = (1/2\pi)\sqrt{k/m} \quad \text{Hz}$$

where $k$ is the static stiffness of the spring, N/m
$m$ is the mass of the mounted machine, kg

Developing this further, the *static deflection* ($d$) of a spring is given by:

$$d = m.g/k$$

where g is gravitational acceleration (9.81 m/s$^2$)

The expression for natural frequency may then be reduced to:

$f_0 = 15.8/\sqrt{d}$ Hz, where $d$ is in millimetres
$f_0 = 3.13/\sqrt{d}$ Hz, where $d$ is in inches

These relationships are true for steel springs over most of their operating range. The natural frequency for rubber-in-shear element isolators could be 15 to 20 % higher than the values given by these equations.

The transmissibility of any isolation system will vary with the ratio of its forcing and natural frequencies ($f/f_0$).

For undamped or very lowly-damped systems:

$$T = 1/[(f/f_0)^2 - 1]$$

When some degree of damping is present, transmissibility is expressed as:

$$T = \sqrt{\frac{1 + 4D^2(f/f_0)^2}{[1 - (f/f_0)^2]^2 + 4D^2(f/f_0)^2}}$$

where $D$ is the *damping ratio*: the ratio of damping actually present in the system ($C$) to that required for *critical* or *dead beat* damping ($C_0$), i.e.

$$D = C/C_0$$

$D$ is 0.005, for steel and 0.04 to 0.10, for rubber – depending upon the rubber compound.

The following points should be noted:

1. Resonance will occur when the forcing frequency coincides with the natural frequency of the mass–spring system (i.e. when the frequency ratio is unity), and resonant amplitude will be dependent upon the internal damping properties of the mounting system.
2. Amplification occurs at frequency ratios less than $\sqrt{2}$, and the lower the internal damping, the more severe the amplification.
3. Isolation only begins to become effective at frequencies greater than twice the resonant frequency (i.e. when $f > 2f_0$); the general rule-of-thumb in selecting flexible mounts is to ensure that the natural frequency of the chosen units is not greater than one-half (and, preferably, at least one-third) the lowest forcing frequency likely to be encountered.
4. In the region of useful isolation, the higher the internal damping the lower the degree of isolation. It may, however, be necessary to incorporate damping ($D \simeq 0.5$) in some systems in order to avoid problems during run-up and run-down of machinery – especially if the transition through resonance is slow. The condition is less likely to occur with medium- and high-speed engines which accelerate and decelerate rapidly on starting and stopping. Spring isolators incorporating a knitted wire mesh are available. The mesh provides high damping at a predetermined resonant frequency only, but gives reduced damping as frequency ratios rise above unity.

## *Compound systems*

We have assumed for the spring-mass system of Figure 14.45 that a rigid mass was mounted on an isolator which, in turn, rested on an infinitely rigid structure. Unfortunately, since modern buildings are less massive structures than they used to be, even basement floors cannot be considered to be rigid - certainly in the context of the audio-frequency range. In practice, one is faced with a double-spring system (Figure 14.46), since the floor under the machine isolator also acts as a spring.

Detailed analysis of multi-spring systems is outside the scope of this chapter. Suffice it to say that it is essential that the resonant frequency of the machine's isolating system is less than that of the floor. As a rule-of-thumb, the static deflection of the vibration isolators should be three to five times the expected, or probable, loaded deflection of the floor. In multiple spring systems those isolators nearest the floor should be the stiffest.

What is the floor deflection likely to be? Fry [10] offers some guidance on this matter. He has produced a table (Table 14.2) which gives the allowable, and probable maximum deflections for centrally-loaded floor spans ranging from 3 m to 15 m. The data are based upon guidelines in United Kingdom structural engineering and building regulations, which state that the maximum deflection due to load at the centre of a span should not exceed 1/250th of the span. In routine structural engineering, a safety factor of 500 % is usually applied to this figure. The probable maximum deflections of spans based on this safety factor are given in the third column of Table 14.2. The last column gives the lowest natural frequency for this probable deflection. It should not be assumed that all loaded spans of these sizes will have such low natural frequencies. On the contrary, lighter span loads and loads located off-centre of spans will result in natural frequencies greater than those listed in the last column. Those frequencies may be considered as worst-case with respect to building structure demands.

In basement areas, one needs to consider the natural frequencies of the soil upon which machinery is located. Precautions, similar to those for loaded floor spans, need to be taken in order to avoid resonance wih foundations. Table 14.3 lists the natural frequencies of typical soils.

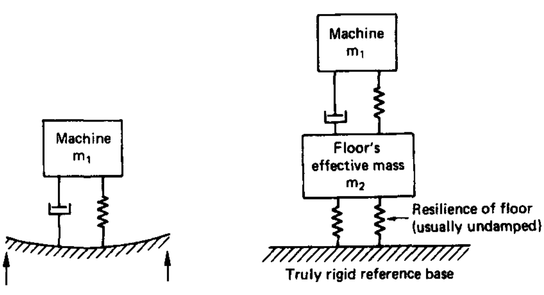



**Figure 14.46** The floor structure as a spring

**Table 14.2** Centrally loaded span natural frequencies

| *Span* (m) | *Allowable deflection (d(1/250 th)* (mm) | *Maximum probable d(20 %)* (mm) | *Minimum probable $f_o$* (Hz) |
|---|---|---|---|
| 3 | 12 | 2 | 12 |
| 5 | 20 | 4 | 8 |
| 10 | 40 | 8 | 7 |
| 12 | 50 | 10 | 6 |
| 15 | 60 | 12 | 5 |

**Table 14.3** Soil natural frequencies

| *Undersoil* | *Hz* |
|---|---|
| Silt | 10 |
| Sand | 15–25 |
| Clay (soft brown) | 15 |
| Clay (hard blue) | 30 |
| Gravel | 20–25 |
| Chalk | 30–35 |
| Limestone | 35–45 |
| Granite | 40–50 |

Fry [10] has also devised a chart to aid selection of resilient mounting systems, using four prime variables:

- equipment type;
- equipment power;
- equipment running speed; and
- floor plan.

The chart shows the minimum static deflection required from flexible mountings in each equipment category in order to provide isolation at the floor's lowest probable resonant frequency – at a mid-span location. The following table, based on Fry's chart, relates to recommendations for standby power generators with i.c. engines.

| *Generators* | *Minimum static deflection* (mm) | | | | |
|---|---|---|---|---|---|
| | | *Floor span* | | | |
| | *Basement* | *6 m* | *9 m* | *12 m* | *15 m* |
| Up to 20 kW | 9 | 12 | 50 | 60 | 60 |
| 25–75 kW | 12 | 50 | 60 | 90 | 90 |
| above 95 kW | 25 | 60 | 90 | 120 | 120 |

### *The six modes of vibration*

In preceding discussions we have considered vibratory motion in one direction only, the vertical. Any unbalanced forces in diesel-generators will produce both linear and rotational vibration, along and around the principal axes of inertia (i.e. longitudinal, vertical, and transverse). These are seen as a rocking motion.

The six basic modes of vibration (or *degrees-of-freedom)* that may occur are shown in Figure 14.47. The roll axis will always pass through the combined centre of gravity of the mounted assembly. Its precise orientation can only be determined by experiment. However, a very close approximation is obtained by using the line joining the centres of gravity of the engine and the generator - as shown in the inset diagram of Figure 14.47.

A schematic model for the vibrational modes is rather complex and is outside the scope of this chapter. Suffice it to say that the system may have a number of natural frequencies, each corresponding to a particular vibratory mode. See the family of transmission loss curves in Figure 14.48. The *total force transmissibility* curve represents a possible coupled combination of the six separate modes. Curve 3 is for the vertical-only mode of vibration - that which is normally considered. The natural frequency is $f_v$. In practice, instead of the expected isolation efficiency of 94 % (point A of Curve 3), only 50 % would be achieved (point B on the total force transmissibility curve). What can be done to minimize this disparity between expected and actual achievement? The answer is to ensure that the mounted natural frequencies in the rotational and rigid modes (Curves 4, 5 and 6) are as close as possible to that of the vertical mode. In order to achieve this, and to reduce the risk of high compound coupling between the various modes, it is necessary to select isolators whose horizontal and vertical stiffnesses are similar, and to ensure that the centre of gravity of the unit assembly is as low as possible and, preferably, in the plane of the top of the isolators. See Sub-section dealing with *inertia blocks.* Problems with 6-degrees-of-freedom vibration are usually only significant when mounted natural resonant frequencies are less than 7 Hz.

## 14.6.3 **Vibration control in practice**

### *Vibration isolators and materials*

The resilient materials most commonly used on diesel-generator applications are moulded rubber (natural or artificial) and steel springs. Foundation mats (or isolation pads) of cork, felt or fibre glass are sometimes used for the smaller plants - especially where static deflections of less than 6 mm are acceptable. These materials suffer from some of the following disadvantages:

- they do not give good isolation over a wide range of frequency;

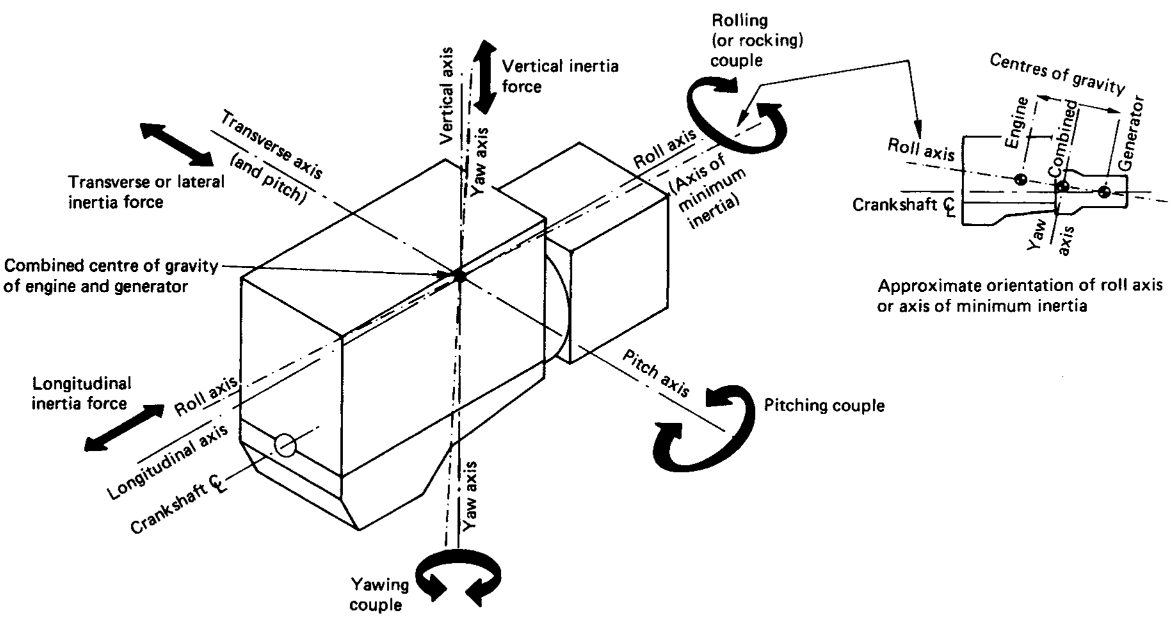



**Figure 14.47** Six basic modes of vibratory motion of a diesel-generator unit: three linear and three rotary motions

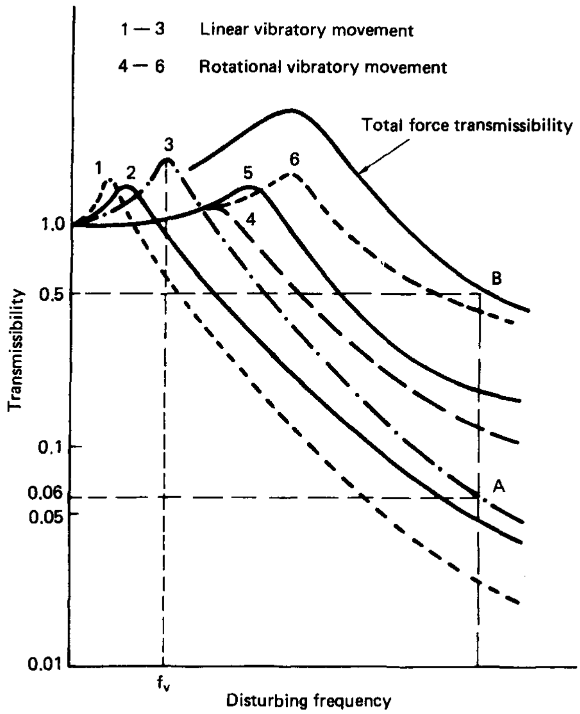



**Figure 14.48** Typical transmission loss curves for the six modes of vibration.

- their load deflection curves are not always linear;
- they may harden with age, or stiffen with dynamic load;
- they are moisture absorbent, and some may even deteriorate under the action of oils and water.

*Steel spring isolators.* Helically-coiled springs are generally used for isolators that carry heavy loads, and for those which must provide static deflections in excess of 15 mm. They have very little inherent damping. External dashpots or, more simply, steel mesh inserts may be employed for damping. Most commercial mountings have rubber or fibrous material pads in series with the springs to act as acoustic noise stops and prevent an all-metal vibration path from spring to loading plate.

*Elastomeric isolators.* The flexible mounts most commonly used for static deflections below 15 mm are those which incorporate moulded natural rubber or artificial rubber, such as neoprene, in a bonded-to-metal format.

When rubber is compressed its deformation is not directly proportional to the applied load. This is because the modulus of elasticity in compression increases with the stress. On the other hand, the shear modulus of rubber (or the *modulus of transverse elasticity)* is constant for the normal range of stresses. For a given load, however, both compressive and shear moduli increase with *shape factor.* This is defined as the ratio of one loaded surface to the total area of free surface. Very approximately, the shape factor varies linearly with the greatest dimension of the loaded surface, and inversely with the undeflected height of the rubber element.

For a given shape factor and hardness, rubber is some six to eight times softer in shear than in compression. For this reason, when high resilience is required, rubber is best employed in shear for vibration isolation. Many commercial designs use rubber-in-shear to provide the primary resilience, while rubber-in-compression is used as a secondary element to give a snubbing action should the mount be subjected to overload (such as may occur on mobile or transportable plant or on machinery installed in ships).

The elastic moduli, and hence the rigidity, of elastomers vary with the *hardness* of the material. Hardness is a measure of the resistance of the material to deformation under pressure and is characterized by a *durometer number.* The higher the number, the stiffer the material. The Shore durometer (or sclerometer), a cone-shaped instrument with a blunt spring-loaded tip, is used to test the hardness of sample materials. When the instrument is pressed into the material the indentation depth is read off a scale graduated from 0 to 100 in IRH degrees. A hardness of 0° IRH indicates an infinitely soft material, and 100° IRH, an infinitely hard material. Materials in commercial mounts generally have durometer numbers ranging between 30° and 70° IRH. Manufacturers use colour coding for unit type identification.

Durometer numbers may only be used to compare *similar* materials. Although a natural rubber and a neoprene elastomer may have the same durometer number, each will display considerably different dynamic stiffnesses. When subjected to rapid vibration, elastomers exhibit greater rigidity than when in the static mode. Due allowance should therefore be made for this when mount selection calculations are made. Isolator manufacturers state the multiplication factors that need to be applied to static deflection constants to obtain the dynamic equivalents. Typical factors are between 1.3 and 1.8 for good quality natural rubber compounds, 3 for natural rubber with high damping; and up to 9 for some synthetic elastomers.

When estimating for dynamic deflection, allowance should be made for the vertical accelerations that are likely to occur - because of full torque wind-up and maximum bump conditions. For example, on stationary plant, the vertical acceleration may be ±2 g, while on marine and mobile applications it may be ±6 g. The dynamic forces due to vertical acceleration may thus be between twice and six times the magnitude of any force due to the static mass of the machine itself. These figures refer to dynamic loading. They should be increased by 1g for downward loading, and decreased by 1g for upward loading in order to obtain the *total* (i.e. dynamic plus static) loading.

*Engineers' selection charts.* Transmission loss selection data (usually in chart form) are summarized in anti-vibration mount (AVM) manufacturers' product literature. They enable the installation designer to select the static deflection (or the mounted, natural frequency) for a given disturbing frequency and isolation efficiency required. In acoustically critical areas, isolator efficiencies should be of the order of 90--98% (transmissibility, $T$ = 0.10 to 0.02), and in non-critical areas 70--90% ($T$ = 0.30 to 0.10). In manufacturers' charts *deflection* usually refers to static deflection in the vertical plane, and vibration is assumed to be in the vertical mode only. On most diesel-generator installations, it is sufficient to allow for similar AVM resilience in both horizontal and vertical planes. Fortunately, this is an inherent feature of most spring and rubber-in-shear mounts.

*Mounting configurations and arrangements.* It is essential that the static deflection at each of the flexible mounts in the system is the same. If not, rocking or pitching motions may be induced. These may have natural frequencies higher than the simple vertical mode. Ideally, mounts should be symmetrically arranged about the combined centre of gravity of the engine and generator so that each carries the same weight. Examples of calculations for typical multi-mount configurations are given in Appendix 14.1 of this chapter.

The centre of gravity of the combined unit will rarely, if ever, coincide with its obvious geometric centre. Figure 14.49 shows a method for calculating the longitudinal location of the centre of gravity in relation to the centres of gravity of the engine and generator. For all practical purposes, the combined centre of gravity of the unit may be considered to be located along the longitudinal axis of the unit, but offset from the geometric centre towards the prime mover.

In a flanged diesel-generator arrangement, where mount locations are restricted to pads provided on the engine and the generator, the alternative method (Appendix 14.2) is to calculate the static load at each isolator mounting point, and select mounts of different stiffnesses to give eql,lal deflections on each. Appendix 14.3 defines the particular properties of symmetrical systems in which the mounts are arranged to be loaded with their principal axes vertical.

The compact flange-coupled arrangement in Appendix 14.2 is particularly suited to mobile and transportable plant. Engine and generator must be

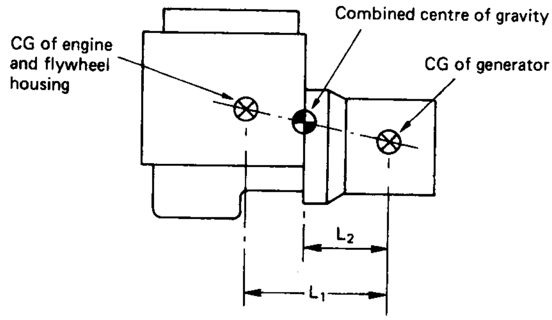



**Figure 14.49** Longitudinal location of the combined centre of gravity (Courtesy: Perkins Engines Ltd)

very carefully aligned to minimize the loadings on coupling and flywheel housing. Also, the bending moment at the cylinder block/flywheel housing interface (face X-X) must be within limits that are acceptable to the engine manufacturer. The method of calculation is shown in Appendix 14.2. With high speed engines, rigid assemblies of this type may be mounted at three or four points to reduce the cost of installation. Overload snubber devices should be fitted to the AVMs used on mobile and transportable equipment in order to limit mounting deflections in transit. Due allowance should also be made for the high lateral loads that result from vehicle cornering, and for the longitudinal loading (in a forward direction) caused by braking.

*Designing for flexible mounting.* The following checklist [11] will help to ensure that all those aspects which need to be considered are covered at the mounting design stage. The AVM manufacturer's confirmation should be sought that the optimum matching of mount properties with design requirements has been achieved.

1. Determine the combined centre of gravity of the diesel generator plant.
2. Establish the positions of the machinery supports relative to the centre of gravity.
3. Take moments to find the loads on the supports in the static condition.
4. Calculate the torque reactions at mountings and check against manufacturer's figures for maximum permissible deflections.
5. Where the generator is flange mounted to the engine flywheel housing, calculate bending moments *(in the static condition)* at the rear of cylinder block/flywheel housing interface (see Appendix 14.2 for the method).

6. Decide upon the 'g' value (the anticipated vertical acceleration) for the application and then calculate *the dynamic loads* on the plant supports and the bending moment at cylinder block! flywheel housing interface.
7. Select suitable mountings to withstand both static and dynamic loadings with required deflection.
8. Calculate the natural frequency of selected mountings.
9. Establish the lowest disturbing frequency for t!le plant being considered.
10. Establish the degree of isolation that will be achieved from data supplied by the AVM manufacturer.

*Inertia blocks.* When discussing the simple mass-spring system of Figure 14.45 we considered the effects of disturbing forces applied either to the mass itself or to the foundation. If the vibro-isolated mass is subjected to an oscillatory motion under the action of a disturbing force $F_0$, it can be shown that the amplitude of the motion is given by the expression:

$$X = (F_o/K)\{1/[1 - (f/f_o)^2]\} \qquad \text{for low damping.}$$

Clearly, the amplitude increases with the strength < the disturbing force and is inversely proportional t the stiffness *(K)* of the spring. Increasing vibn isolator stiffness is, therefore, one way of reducin the amplitude of the forced vibration. This is n< always practicable, especially when mounts hay already been selected to meet a required resonar frequency *(fo).*

The rotating parts in reciprocating i.c. engin{ may account for up to one-third of the total engin mass. These parts may be out-of-balance (more s on engines with an odd number of cylinders), an any unbalanced external couples could be quit significant. In such cases, and where the mass of th machinery is small, the movement of a vibr< isolated power unit could be quite unacceptable. 1 satisfactory isolation system cannot be obtaine without incorporating a high degree of damping int it. However, the additional damping required i usually so great that the isolated unit may be cor sidered as (virtually) being bolted down solid ont its foundations.

One way of increasing the stiffness of give mounts is to add mass to the vibro-isolated machir ery. This is done by means of *inertia blocks* (als known as *pendulum masses).* If vibratory motion i to be kept within controllable limits, a block of th order of two to three times the mass of the machir ery is required. The addition of such mass inevitabl necessitates re-selection of AVMs to give the sam static deflection as previously obtained; unless c course the original mounts were very much undel deflected in the first instance.

If a machine's centre of gravity is above the line of action of the horizontal forces from its mountings, there is the danger that a rolling motion may be induced. This can be particularly troublesome on systems where the mounted resonant frequency is below 5 Hz, as this necessitates large static deflections and the use of large mounts which tend to be inherently unstable. In such cases, mounting the machine on an inertia block not only lowers the unit's centre of gravity but also allows AVMs to be placed further apart - giving added stability to the system. Ideally, the centre of gravity should be below the plane of the top of the mounts. The argument is developed in Figure 14.50. Diagram (a) illustrates a potentially unstable arrangement, in which the machine is directly supported on free-standing mounts. Diagram (b) shows the addition of an inertia base frame which effectively lowers the centre of gravity so that it now falls fractionally above the plane of the mounts. Prefabricated inertia base frames specifically designed to receive poured concrete are constructed from welded steel channels with in-built reinforcing rods. Pre-located equipment anchor bolts and vibration isolator brackets are provided to suit the equipment to be supported. Diagram (c) illustrates the use of a precast reinforced concrete block set into a foundation pit in the plant room floor. The heavier block gives the ideal arrangement, in which the combined centre of gravity coincides with the plane of the top of the mounts. Obviously, this solution is less cost-effective than that illustrated in diagram (b) because of the additional civil engineering work associated with the foundation pit.

Another advantage with the inertia block is that it can move the centre of gravity of the mounted machinery towards its geometric centre (see diagram (d». This enables the use of equal-resilience mountings, placed symmetrically about the inertia block. Diagram (e) illustrates an arrangement that is often employed on plant using large slow-speed engines. The reinforced concrete inertia block has built-in beams projecting on all sides. Tie bolts connect these beams to the stationary supporting blocks through leaf springs.

In summary, the major benefits of inertia bases are:

1. to limit the amplitude of machinery vibration;
2. to add stability to a system;
3. to give better weight distribution and so allow the use of equally loaded and symmetrically disposed mounts;
4. to minimize the effects of any errors in centre of mass location calculations by moving the centre of mass towards the centre of force in the system.

*Floating floors.* There are often very good reasons for locating mechanical services equipment, indud-

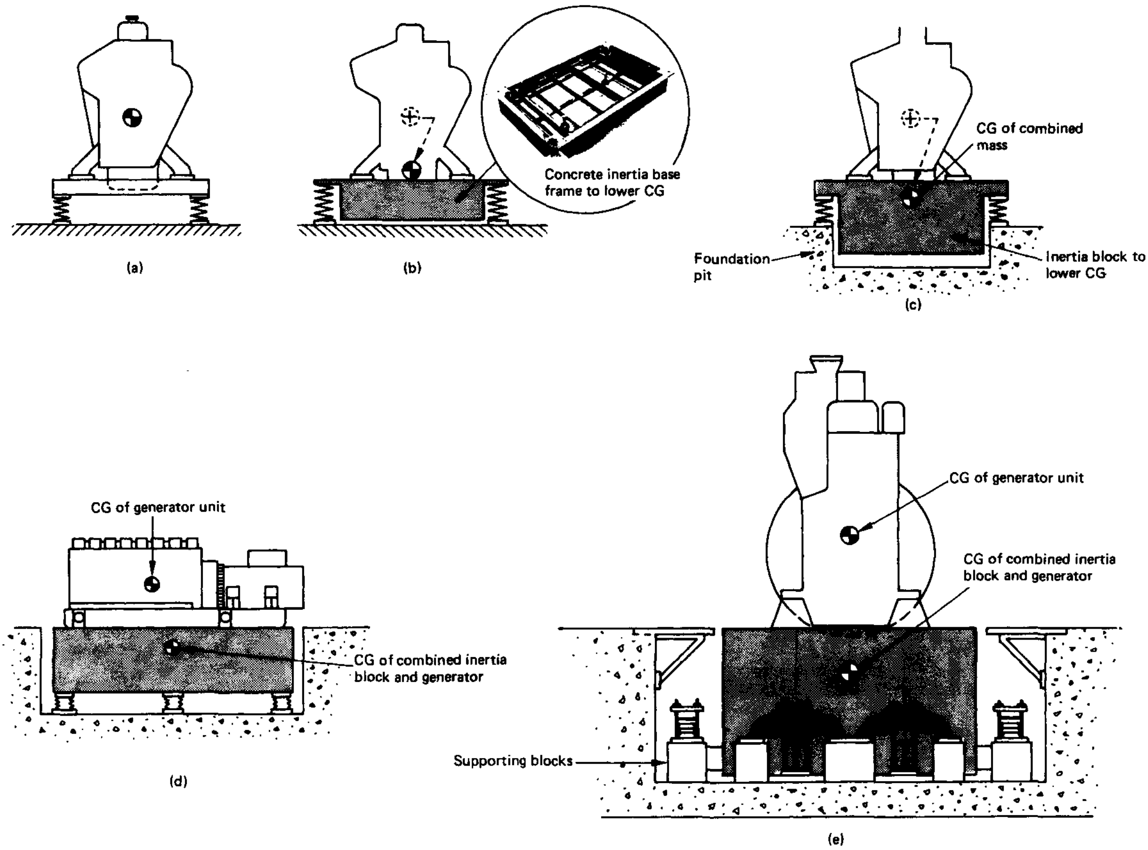



Figure 14.50 Typical applications of inertia blocks

ing standby generators, in plant rooms on the top floors of multi-storey buildings. It is, of course, necessary to provide efficient sound barriers between these noise sources and any sensitive receiving areas immediately below them. Constructions must be consistent with the weight limitations that apply to structural floors at these levels.

Merely increasing the mass of the plant room floor itself gives diminishing returns in terms of noise-reduction performance, besides being economically and technically undesirable. For example, whereas a 150 mm thick concrete slab weighing 365 kglm$^2$ gives a sound reduction index (SRI) of 45 dB at 500 Hz, a 300 mm slab will only increase the mean SRI to 50dB, and a further doubling of the mass using a 600 mm slab only increases the SRI to 55 dB. This attenuation obeys the mass law discussed in Sub-section 14.5.3.

A *floating floor* construction gives SRI values exceeding mass law capability. It does this by providing a floating mass which is effectively isolated from the building structure itself. The essential elements of typical constructions are shown in Figure 14.51. The floating floor is supported, but isolated, from the structural floor by a resilient quilt or by flexible mounts. Any impacts or vibrations induced in the floating floor are only partially transmitted to the structural floor. Control of flanking transmission is essential.

Successful insulation depends very much upon the selection and loading of the resilient quilt, and on the distribution of the isolation pads - to give the correct loading on each. These isolators may be helical steel springs, neoprene pads or, as in the construction in (c), pre-compressed glass fibre pads 50 mm thick and coated with a flexible, moisture-impervious, elastomeric membrane. In this context, it is best to use non-linear mounts in order to obtain isolation over a wide range of loadings and to give more flexibility for any future use of the floor.

Plant room floors need to be waterproof. Careful attention must therefore be paid to edge seal detail. Construction (c), for example, employs a 20mm thick, closed-cell, sponge neoprene (cut-back and top-sealed) for perimeter isolation.

Floating floors generally have natural resonances in the region of 20 Hz and give good acoustic isolation at frequencies above 30 Hz. With a

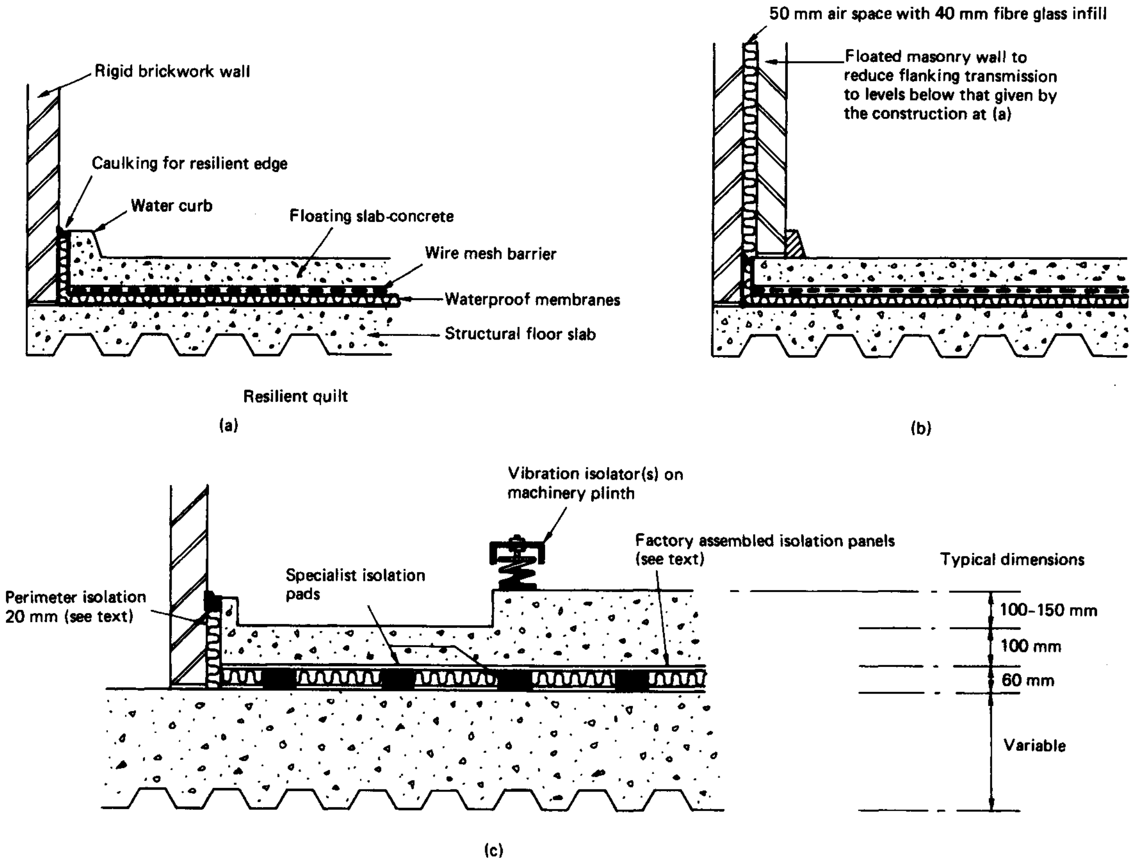



**Figure 14.51** Typical examples of floating floor construction

proprietary construction of the type marketed by the Consolidate Kinetics Corporation (and illustrated in diagram (c» it is possible to achieve a mean SRI of the order of 75 dB for a composite system mass of 6OOkglm²· The isolation panels consist of lOmm exterior grade plywood, factory-bonded to, and supported by, the glass fibre isolation pads. A low density, glass fibre sound absorbent material (40 mm thick) is also pre-bonded to the areas between the isolation pads. *(Note:* Chapter 23 [8] gives an excellent checklist for floating floor constructions, summarizing some of the measures to be taken to minimize the probability of mistakes during construction. )

Do remember that machinery vibro-isolators must be selected to follow the principles for compound spring systems discussed earlier in this chapter. They should be less stiff than the resilient supports incorporated within the floating floor construction.

*Isolation bridging.* The most common installation fault (negating the correct selection of vibration mountings) is the mechanical *bridging* of the vibro-isolators by rigid connections between the mounted machinery and its foundations. Care must be taken to eliminate all vibration paths that may bypass or bridge the isolators. Flexible sections should therefore be included in all electrical cables, conduits, trunking, ductwork, or piping between isolated and un isolated areas of plant. The flexible connections should not, of course, increase the overall stiffness (and therefore the natural frequency) of the mounted system, nor should they add damping to lower the efficiency of the isolation system. The manufacturer's advice should always be sought on the correct selection and installation of proprietary flexible connectors and expansion joints. This particularly applies to bellows fitted in exhaust pipework, where special care should be taken with the installation of flexible expansion joints which use tie rod assemblies, as these can serve as vibration transmission paths.

## 14.7 Sources of noise in engine-generator plant

### 14.7.1 The diesel engine

The engine is the major noise-producing source in generating plant. We have established that the exhaust gas noise is a key factor (see Sub-section 14.5.4). Other noise-producing constituents are:

1. Intake air.
2. Casing noise - arising from out-of-balance vibration from rotating parts, especially the crankshaft and the camshaft.
3. The mechanical forces caused by the impact of pistons, tappets and valves, fuel-injection systems, gears, bearings and chains. In this category of so-called mechanical noise, the predominant source is the combustion-induced *diesel knock* which is of an impulsive nature and is produced by abrupt pressure rise in the cylinders. Considerable success has been achieved over the years in reducing this combustion-induced noise by controlling fuel-injection characteristics to give a smoother pressure rise and minimize combustion irregularities. Such improvements, however, are ultimately limited by engine performance requirements. See Section 1.3 of Chapter 1.

In general, engine structures have modes of vibration that are responsible for much of the noise that is produced. Most research directed towards making conventional diesels quieter has concentrated on modifying engine structures to reduce the vibration levels of external surfaces - particularly in thinly-panelled areas [12, 13, 14 and 15]. For example, the exploitation of reinforced plastic materials (as an alternative to pressed steel and die case covers) on production engines is one outcome of such research. The various damping treatments applied in research on proprietary engines may have given overall noise reductions of 10 dBA or more at full rated speed and load, but continuous development and production engineering is necessary before research techniques are fully translated to production engines. There is also a commercial limit to the amount of attenuation that can be achieved by these methods.

It is essential to have the noise spectra of engines at the noise attenuation design stage. Total noise frequency analyses in well defined conditions are usually obtainable from engine manufacturers. See Figure 14.41 for a typical example. If this information is not available at the plant's conceptual design stage, a very good prediction of the selected engine's overall noise level may be obtained by using formulae published by researchers at the Institute of Sound and Vibration Research, University of Southampton, England [14]. They concluded, from work on engines in the volume range 0.375 to 30 litres per cylinder, that:

1. The intensity of engine noise due to combustion is determined by a simple relation, $I \propto (\text{speed})^n \times (\text{bore})^5$, where the value of the speed index, *n*, can be between 2.8 and 3.0 for conventional direct injection engines with 4-hole injectors, and 4.0 for both direct injection pressure charged engines with smoother pressure development and for two-stroke diesel engines.
2. The engine configuration (i.e. in-line, vee-form, etc.) and the details of design, for the same stroke-to-bore ratio, may affect the characteristics (the spectrum) of the noise emitted, but not its overall level - in dBA. The noise generated is independent of the power produced by the engine. More power may be obtained without an increase in noise by the addition of cylinders. For example, 4 and 6 cylinder in-line and V 8 engines will produce the same level of noise if they have the same bore, and run at the same speed.

The following empirical formulae devised by these researchers may be used to predict overall combustion-induced noise (within 2dBA) at 1 m from engines with toroidal combustion chambers and with 4-hole injectors.

1. For 4-stroke naturally aspirated diesel engines

   $$\text{dBA} = 30\log_{10} n + 50\log_{10} B - 31.5$$

2. For 4-stroke turbocharged diesel engines

   $$\text{dBA} = 40\log_{10} n + 50\log_{10} B - 66.5$$

3. For 2-stroke diesel engines

   $$\text{dBA} = 40\log_{10} n + 50\log_{10} B - 54.5$$

where $n$ is engine speed, in revolutions per minute
$B$, the cylinder bore, is in inches

The noise level of an engine is therefore determined by its speed, its bore, and its combustion system (i.e. the form of the cylinder pressure diagram). It must be emphasized that the relations given in the above formulations are for combustion-induced noise, and that, on some large low-speed engines, mechanical noise may predominate. In such cases, care must be exercised when applying these formulae.

#### *Other noise sources*

The other significant noise-producing elements in diesel-generator plant are the generator and the aerodynamic fans of radiators and cooling towers associated with engine coolant, lubricating oil and charge air circuits. The overall sound levels of any of these elements is of the order of 15-20 dBA less than that of the engine's combustion-induced noise. So that, taken in aggregate, engine noise is certainly predominant in situations where the heat exchanger element is in close proximity to the diesel generator itself.

By way of illustration, the comparative noise ratings, each taken in isolation, of an engine developing 700kW at 1500r.p.m., a matching standard generator, and the engine's coolant radiator (using a crankshaft-driven 'pusher' fan) would be as follows:

1. Engine spectrum: within an NR 100 curve.
2. Generator spectrum: falling between NR 85 and NR 90 curves.
3. Radiator fan: approximating to an NR 85 curve.

It is clear, therefore, that the worst-case conditions are those attributable to the diesel engine. However, interface with the environment makes noise control of the total system a more complex task than this bland conclusion may suggest. It should not, therefore, be implied that the generator and heat exchanger elements may be conveniently ignored in any noise attenuation studies. On the contrary, full spectral analyses of all the noise producing elements of the plant (this would also include, for example, any compressors for starting air systems, exhaust gases, and intake air) must be obtained, either from measurements on combined tests or from data on each element, if any noise rating target is to be achieved. This is particularly important where heat exchanging elements are remotely sited and must, therefore, be attenuated in their own right to comply with any environmental noise level limits relating to their location.

## 14.8 Plant noise control in practice

### 14.8.1 Site planning and preliminary design

Decisions on plant room locations should be made in the full knowledge of their impact on environmental noise control requirements. Much can be achieved by the suitable location of plant in buildings. For example, plant areas may be separated from very quiet areas by buffer zones, in which intermediate noise levels are tolerable. Decisions on the location of offices and other noise-sensitive areas, relative to the plant, must be made early in any building design studies. If detailed selection of plant has not been made at this stage, estimates of sound power output based on the best possible information will be necessary. Noise measurements from similar plants operating elsewhere or the use of manufacturer's noise data for the machinery under consideration will suffice.

Obviously, one needs to have a clear idea of the (acoustic) design target for the installation as a whole. In many instances, a local authority may have prescribed noise limits at the boundary of the site. If so, measurements of the background noise levels at all sensitive locations, such as local housing, must be made in order to assess the effects of the proposed installation at those locations.

Most plant noise problems will have very practical control solutions. These would involve standard construction materials (subject to any limitations on freedom of choice imposed by fire precautions, the presence of oil mist, etc.) and many of the noise control techniques we have discussed. The following logical steps must be taken in order to determine which noise control measures are appropriate to the plant under consideration.

1. Measure (or estimate) the noise output of the plant. This may also include vibration measurements to evaluate the effect of structure-borne vibrations on the total noise emitted.
2. Establish a design target level (expressed in the A-weighted scale, octave band sound pressure or sound power levels, or in terms of noise rating (NR) and noise criterion (NC) curves) that would be acceptable at noise-sensitive areas in the neighbourhood.
3. Compute, from the first two steps, the amount of noise reduction that is desired or required, i.e. calculate the difference between the measured (or estimated) level and the design target level.
4. Select the appropriate control measures required to limit the transmission and radiation of noise from the plant and its constituent parts. Noise levels would have been quantified by the measurements (or estimates) made at Step 1 above. Treatments must then be chosen so that their total effect is to limit the output noise to the design target (established at Step 2). These must be commensurate with the lowest possible costs and without prejudice to the efficient operation, maintenance, and safety of the plant.

### 14.8.2 Noise control measures

Plant noise will be transmitted both as airborne (primary) sound and as structure-borne sound (secondary air vibrations). One, basically, has two options for reducing the noise output. The first is to reduce the strength of the noise energy from within the diesel-generator itself; the second is to impede the transmission of this energy along its paths to the receivers.

Consider the first of these options. There is little scope, as we have seen, for reducing the sound energy level from a proprietary engine - apart from selecting a quieter unit of lower speed or smaller bore. But this inevitably introduces penalties in first cost, bulk, and weight. It is far more practical to concentrate on impeding the transmission of the to seek help from those knowledgeable and experienced in acoustics, if the best results are to be obtained.

1. The use of concrete and masonry walls and barriers - remembering the benefits of stiffness, weight and cavity construction, and the need to provide well-sealed, sound-attenuating doors and windows where these are included.
2. The use of complete or partial enclosures.
3. Attenuation by use of sound absorbents on walls and fixed or suspended ceilings.
4. The introduction of control and monitoring rooms having good sound insulation properties.
5. The reduction, or elimination, of noise leakage paths.
6. The use of vibration isolation techniques such as resilient mountings, flexible floors, flexible connections and vibration breaks, and vibro-isolated inertia blocks.
7. The use of ducts and plenum chambers incorporating sound absorbent materials.
8. The use of mufflers, sound attenuators, and acoustic louvres in airflow paths, taking particular care to direct inlet and discharge air openings away from critical areas wherever possible, so as to take advantage of directivity effects.

Another very obvious measure is to site plant so as to increase the distance between it and receivers. This is not always possible. For noise reductions greater than 5 dB, one would have to double the distance between source and receiver. Any gain in attenuation by re-siting the source must inevitably be limited by practical considerations.

Noise control is a matter of applied common sense, once an appreciation of the capabilities and limitations of the various control forms has been developed. Dr. T.J.B. Smith, formerly Research Director of the Sound Research Laboratories, Sudbury, England, suggests that each case should be systematically analysed in terms of sources, paths, and receivers, and that corrective action should be tailored to the particular problem [16]. Figure 14.53 [16] charts a typical analysis, of noise control procedures, for a diesel generator plant.

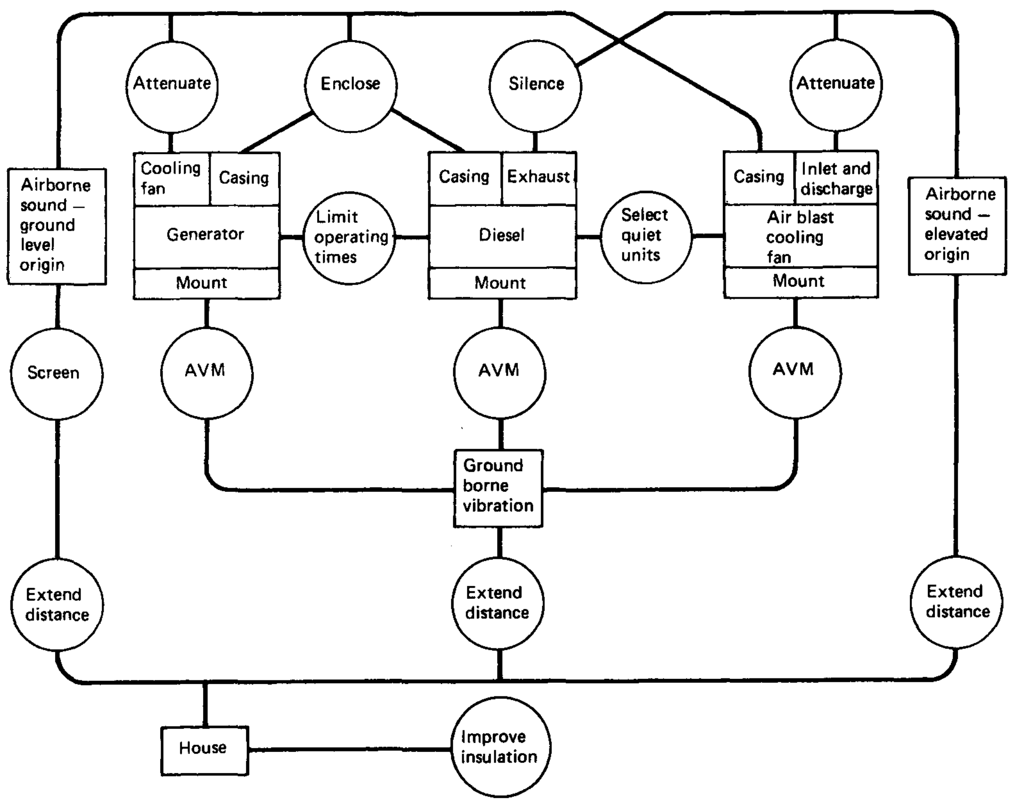



**Figure 14.53** Systematic analyses of noise control procedures for diesel-generator plant (After Dr. T.J.B. Smith – Sound Research Laboratories)

## 14.9 Noise masking

The European Community regulations limiting noise in the workplace (Directives 84/535/EEC and 84/536/EEC) came into effect in January of 1990. Employers and public authorities are legally responsible for protecting employees and the general public from the noisiest environments - factory floors, airports, etc. Reporting on the potential of a new technology originally designed for military environments, Steve Connor [17] states that it is creating considerable interest in the non-military field. The technique involves the creation of sound waves that are a mirror image of the noise to be eliminated. The *anti-noise* so created works best on low-frequency sounds, and has been successfully employed in military personnel carriers and helicopters. The sound waves of the extraneous noise in the working environment are processed by computer and mirror image waves are generated to cancel out the sound waves. Anti-noise headsets worn by the individuals protected are not cheap. Current costs are between £500 and £600, but the potential non-military market could bring down the prices considerably. Researchers at the Institute of Sound and Vibration Research at the University of Southampton have been working on the problem of generating anti-noise through loudspeakers so that it would be possible to create quiet in a room previously full of noise [17]. This would be of obvious benefit in plant control rooms.

A British firm (Sound Masking Ltd, of High Wycombe) markets a system which works on the same principle, in that entire working areas are 'bathed' in a constant background sound which is electronically generated and distributed by a grid of speaker units. The output from the speakers is tuned to blend with the residual background noise in the area of concern, to produce the maximum possible privacy for personnel working in that environment. Sound masking does not 'get rid of', or cancel, unwanted sound. It is a conditioning treatment, i.e. it covers or conceals sound, and has been appropriately described as 'acoustic fog' or 'acoustic perfume' .

## 14.10 Referenced standards

Reference has been made in this chapter to the following British Standards. The identical or (technically) equivalent documents of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (lEC) are shown in brackets.

BS3045 (ISO 131) - *Method of expression of physical and subjective magnitudes of sound or noise in air*

BS 3383 (ISO 226) - *Normal equal-loudness contours for pure tones and normal threshold of hearing under free-field listening conditions*

BS 3638 (ISO 354) - *Method for measurement of sound absorption in a reverberation room*

BS 4142 (ISO 1996/3) - *Method of rating industrial noise affecting mixed residential and industrial areas*

BS4196 - *Sound power levels of noise sources*

- Part 0 (ISO 3740) - *Guide for the use of basic standards and for the preparation of noise test codes*
- Part 1 (ISO 3741) - *Precision methods for determination of sound power levels for broad-band sources in reverberation rooms*
- Part 2 (ISO 3742) - *Precision methods for determination of sound power levels for discrete-frequency and narrow-band sources in reverberation rooms*
- Part 3 (ISO 3743) - *Engineering methods for determination of sound power levels for sources in special reverberation test rooms*
- Part 4 (ISO 3744) - *Engineering methods for determination of sound power levels for sources in free-field coditions over a reflecting plane*
- Part 5 (ISO 3745) - *Precision methods for determination of sound power levels for sources in anechoic and semi-anechoic rooms*
- Part 6 (ISO 3746) - *Survey method for determination of sound power levels of noise sources*
- Part 7 (ISO 3747) - *Survey method for determination of sound power levels of noise sources using a reference sound source*

BS5%9 (lEC651) - *Specification for sound level meters*

## 14.11 References and bibliography

### 14.11.1 References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2. Robinson, D.W. and Dadson, RS. A redetermination of the equal loudness relations' for pure tones, *British Journal of Applied Physics,* (1956)
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4. *Noise and the worker.* Health and Safety Booklet No. 25, HMSO
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15. Diehl, G.M. Think Quiet. An eleven-part series of articles in *Compressed Air (1971)*
16. Dr. Berkovitch. Quieter please ! A review article in *Engineering,* May (1974)
17. Connor, S. When no noise is good noise. An article in *The Daily Telegraph,* 4th December (1989)

### 14.11.2 Bibliography

The text-books listed in the references contain many sugestions for further reading. Other useful sources of information are:

(1) The Technical Reviews, published quarterly by Bruel and Kjrer, covering advance techniques in acoustic measurement.

(2) The following Oil Companies Materials Association (OCMA) publications:

- NWG-l Procedural specification for limitation of noise in plant and equipment for use in the petroleum industry.
- NWG-2 Equipment vendors' extract from NWG-l
- NWG-3 Purchaser's and Contractors Guides to use of NWG-l.

The Author found the following published papers and articles to be useful sources of information, in the preparation of this chapter.

(3) Dawson, H. Industrial Noise control - a guide for Works Engineers. *The Plant Engineer,* 16 (7) July (1972)

(4) A series of articles in *Engineering Materials and Design,* June 1977, pp. 35-49, entitled:

Industrial noise
Acoustic materials
Valve noise
Hushing the diesel
Quiet compressor, and
Keeping the peace

(5) Moir, J. On-site power measurement. *Proceedings I.Mech.E.* Ref *C224178 (1978)*

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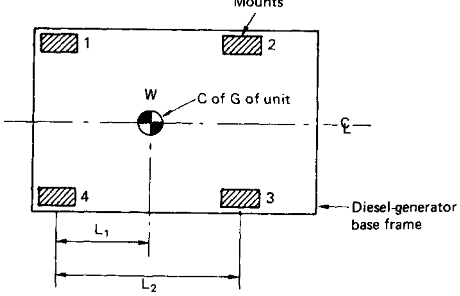
# Appendix 14.1

4-point mounting

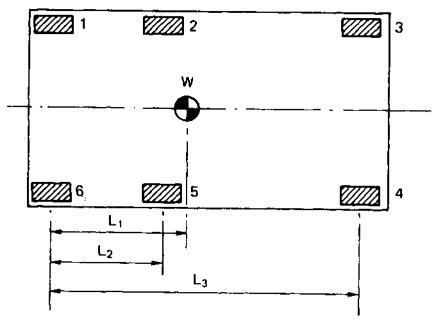



In each case the weight (W) of the diesel-generator is supported equally by the mounts

Taking moments about a line joining mounts 1 and 4:

$\frac{2W}{4} . L_2 = W.L_1$ so that $L_2 = 2L_1$

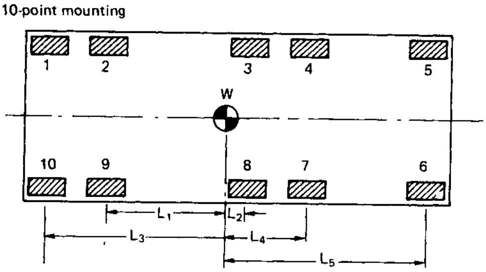
6-point mounting




The longitudinal dimension of the unit baseframe will determine the maximum valuve of $L_3$. To establish where mounts 2 and 5 are to be placed to give an equal loading of W/6 on all mounts, take moments about the line joining mounts 1 and 6:

$2. \frac{W}{6} . L_3 + 2. \frac{W}{6} . L_2 = W. L_1$ so that $L_2 + L_3 = 3L_1$
or $L_2$, the required dimension $= 3L_1 - L_3$

10-point mounting



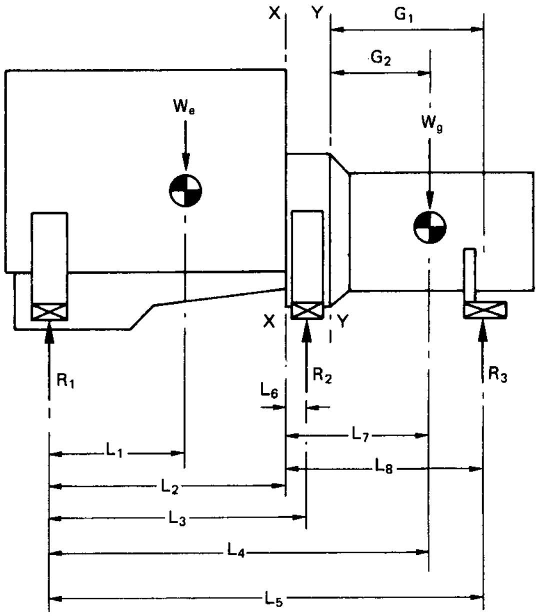

Taking moments about a line through the unit's centre of gravity:

$2. \frac{W}{10} . L_1 + 2. \frac{W}{10} . L_3 = 2. \frac{W}{10} L_2 + 2. \frac{W}{10} . L_4 + 2. \frac{W}{10} . L_5$

so that, for the condition of equal loading on each mount $\left(\text{i.e. } \frac{W}{10}\right)$
$L_1 + L_3 = L_2 + L_4 + L_5$

**Figure 14A** Typical calculations for multi-mount configurations where mounts are equally loaded

## Appendix 14.2




Since standard engine and generator mounting location points are fixed and unchangeable, it is necessary to find the static load to be carried by each mount at the given locations.

$W_e$ = total weight of engine.
$W_g$ = weight of generator.

acting through their respective centres of gravity

The reaction at $R_3$ will have a predetermined value obtained by taking moments at the flanged interface between generator stator frame and flywheel housing (face Y–Y)

i.e. $R_3 . G_1 = W_G . G_2$

and $R_3 = \frac{W_G . G_2}{G_1}$

To find $R_2$ take moments about $R_1$:

$$R_2 = \frac{W_e . L_1 + W_g . L_4 - R_3 . L_5}{L_3}$$

To find $R_1$ take moments about $R_2$:

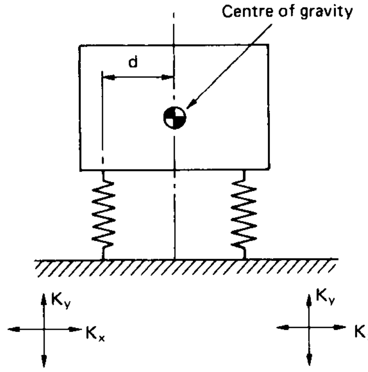
$$R_1 = \frac{W_e(L_3 - L_1) - W_g(L_4 - L_3) + R_3(L_5 - L_3)}{L_3}$$

The bending moment ($M_x$) between the cylinder block and flywheel housing interface (X–X) is given by:

either, $M_x = R_2 . L_6 + R_3 . L_8 - W_g . L_7$
or $M_x = R_1 . L_2 + W_e(L_2 - L_1)$

**Figure 14B** Method of calculating loads on mounts at stated locations, and the bending moment across the engine flywheel housing [14]

## Appendix 14.3




$K_y$ = vertical stiffness

$K_x$ = transverse stiffness (both expressed in units of force deflection)

Total vertical stiffness $= 2K_y$
Total lateral stiffness $= 2K_x$
Torsional stiffness $= 2K_y . d^2$

**Figure 14C** Properties of a vertical mounting arrangement

# 15 Operation and maintenance

**Contents**

## 15.1 Introduction

This chapter first establishes the importance of comprehensive technical manuals to efficient and trouble-free operation of a power plant, and lists the sort of information that should be contained within them.

The key to good operation is regularity in procedures - involving the regular inspection and servicing of all items of plant within the facility. Operating staff must be capable of recognizing trouble symptoms and of taking speedy corrective action.

Equipment that is required to function efficiently must be well maintained. Maintenance strategies need to be established in the earliest phases of a contract. Planned preventive maintenance, preferably based on plant condition monitoring, reduces the probability of failure in service, and extends the operating life of a plant.

In discussing programme planning and maintenance schedules, emphasis is placed on the need for keeping comprehensive records. Various methods may be used for recording data (e.g. card files, ledgers or computer storage). Manual or automatic means may then be employed to alert staff when particular tasks need to be performed.

Staff must be instructed and trained in the operation and maintenance of all equipment within the plant. Training during erection and work up of the plant should be supplemented by courses arranged with key equipment manufacturers.

## 15.2 Technical manuals

Users, consultants and main contractors are often guilty of giving less than due consideration to comprehensive manuals for generating plant. Manuals should be treated as an important element of any contract and should be delivered before contract works can be accepted.

Users' and consultants' specifications should define precisely what is required, and when. Contract conditions should require a draft copy (or copies) of manuals to be provided for approval by the user or his consultants, some six to three months before the commencement of commissioning. Too often, unvetted manuals appear after the event or, at best, during the commissioning phase. Frequently, they are a loose collection of general instructions which refer to ranges of equipment produced by manufacturers, leaving the plant user to sort out what sections of the literature apply to his specific equipment.

Manuals should be designed as a ready reference to all mechanical and electrical equipment in the power generating complex. They are intended to assist plant personnel during the early stages of takeover and during subsequent operation and maintenance.

British Standard 4884: Part 1 *(Technical Manuals - Content)* makes recommendations as to the scope and content of manuals intended to explain the use, maintenance and repair of products ranging from domestic appliances to the complex systems of our context. The standard suggests that product information may be conveniently divided into categories, as follows:

| | |
|---|---|
| • purpose and planning information | (what it is for) |
| • operating information | (how to use it) |
| • technical description | (how it works) |
| • handling, installation, storage and transit | (how to prepare it for use) |
| • maintenance instructions | (how to keep it working) |
| • maintenance schedules | (what is done when) |
| • parts lists | (what it consists of) |
| • modification instructions | (how to change it) |

These categories may be presented in any order in manuals, and any category may be combined with any other. The extent of information will depend upon the nature of the specific product, the user's needs, and his maintenance strategy.

Documents may vary in form from one comprehensive manual for a standby generator installation, to several volumes for a base-load power station. In the latter case, a typical set of Operation and Maintenance (0 & M) Manuals may comprise:

Volume 1 -A User Guide to the Complete Works (prepared by the main contractor):
- (a) outlining the basis for design and providing a brief technical description of the major items of plant and their associated auxiliaries, cross-referenced to record drawings (in Volume 2);
- (b) listing, in data sheets, the function, size, capacity and model number of the plant items;
- (c) describing the method of overall plant control and the controls for each unit;
- (d) giving, where applicable, the initial setting of equipment which requires periodic adjustment;
- (e) covering general safety aspects; and
- (f) including a master index of the contents of all volumes in the 0 & M instructions package.

Volume 2 - All M & E record drawings of the plant.
Volume 3 -Suppliers' Literature.
Volume 4 -Commissioning Test Results (see Chapter 13, Sub-section 13.10.5)

Volume 3 should only include O & M information specific to the plant supplied. General instructions referring to a range of the supplier's equipment should only be accepted if suitably marked-up to indicate the specific equipment supplied, and if inapplicable descriptions are deleted.

The Supplier Manuals should include all the (BS4884: Part 1) categories of information listed above. They must contain, in particular:

- the checks required before start-up;
- start-up and shut-down procedures;
- operating procedures;
- hazards in operation, and safety precautions
- normal operating checks;
- procedures in the event of malfunction - fault conditions, fault diagnosis, and rectification procedures;
- maintenance instructions defining tests, checks and inspections, and maintenance tasks (routine schedules and overhauls);
- schedules giving the maximum permissible wear of moving parts;
- comprehensive lists of all part numbers of items supplied - for the ordering of spare parts; and
- factory test results.

Concerned at the failure of its suppliers of electrical and other control systems to provide documentation meeting its needs for the understanding and maintenance of these systems, British Steel Pic introduced the concept of *Functional Systems Documentation* (FSD) in the mid-1970s. (Corporate Engineering Instruction CEI 1 (July 1974) - *An outline to functional systems documentation.* Copies may be purchased from British Steel Pic., Head Office Standards, 9 Albert Embankment, London SEI 7SN.) It was based upon the functional concept developed by the Royal Navy (described in the *New Guide to F.I.M.S.* (2nd Edition, HMSO) - F.I.M.S. is *Functionally Identified Maintenance Systems).*

The main objectives of FSD are:

1. To ensure that systems are described in terms of function so that the user has a quick and clear understanding of the function of components within systems.
2. To provide a logical fault-finding and maintenance procedure directly related to the specific construction and operation of the plant.
3. To provide means for monitoring the system and adjusting it, when appropriate, to maintain optimum performance.
4. To ensure that maintenance and test needs are fully recognized at the design stage and thus allow supplier and user to agree upon engineering requirements, and maintain a continuous design history.

Considerable benefits evolve from documentation which achieves these objectives:

1. a clearer understanding at the design stage of the facilities to be supplied;
2. speedier plant commissioning; and
3. reduced plant downtime, i.e. high plant availability.

The key to success is that FSD must be integrated with the initial design of the system/equipment. FSD sets out to describe the operation of systems in logical steps that directly relate to the method of operation, and to the construction of the plant and its control equipment. There is a marked difference between the circuit diagrams normally provided for plant, and the functional diagrams which form the basis of FSD. The functional diagrams aim to reduce the apparent complexity of systems to a level which is understandable to staff and maintenance craftsmen. They serve to guide diagnostic exercises to a successful conclusion, in a logical and pre-planned manner.

A plant's FSD manuals would be based upon a collection of functional block diagrams arranged in a hierarchical or ladder form - each level being a detailed expansion of the level above it. There would be a number of other diagrams and charts to support these functional diagrams, in particular:

- safety instructions;
- general arrangement drawings;
- charts of test and signal data for each functional diagram;
- location diagrams for equipment and test points;
- procedures for adjustments and examination;
- procedures charts for replacement and repairs;
- spare parts lists.

FSD should not necessarily be a contractual condition for all types of generating plant. It should certainly be considered for the more complex systems and those where high plant availability in operation is an essential requirement.

## 15.3 Plant operation

Operation entails the methods of starting up, running, shutting down, controlling and monitoring the plant under all foreseeable conditions. Plant details will vary from one installation to the next. The equipment manufacturer's Operator Handbook should be studied for specific procedures. The key to good operation is *regularity.* One needs to establish sound procedures and stick to them [1].

Start, run, and stop procedures would be fully automatic in the case of emergency generators on standby to a utility supply. In continuously manned base-load power stations these procedures may or may not be automatic, depending upon the control systems used. For example, in a fully automated scheme, generators may be started, synchronized, and connected to the busbars without any action on the part of the plant's operating personnel (see Section 9.16 of Chapter 9). On others, the procedures may be carried out by switchboard attendants, who make the decisions as to when generators should be started or taken off line.

On the larger installations, condition monitoring and data logging with integral alarms and protection may replace the need for constant vigilance by attendant staff. In the context of marine plant, Wilbur and Wight [2] observe that 'notwithstanding the inevitability - not to mention the ingenuity, and in several cases the noteworthy dependability of data logging or condition monitoring installations - the presence of skilled ears and eyes in the engine room is on occasion sorely missed'.

### 15.3.1 Fault diagnosis

Not every installation can justify the cost of automatic monitoring systems, and reliance is placed on the ability of plant operators to recognize and remedy minor troubles in their early stages before they develop into major breakdowns. Operating personnel must then be capable of recognizing trouble symptoms and of quickly determining what adjustments or repairs are needed. This requires a systematic and logical approach to fault-finding.

Equipment manufacturers' manuals usually contain fault diagnosis charts or check lists which table the most common symptoms, itemize possible causes, and suggest responses. A typical example of a troubleshooting chart (for a high-speed engine) is shown in Figure 15.1

The fault finding charts for generators would list, against common symptoms and faults, the possible causes and the tests and remedies for each. They would include, but not be confined to, such faults as:

- failure to excite;
- low generator voltage or high, uncontrollable, voltage;
- poor voltage regulation;
- voltage instability;
- component failures, such as main rotating diodes and voltage control units (or AVRs).

Plants are usually most vulnerable to failure immediately after commissioning, and after general overhauls. Table 15.1 based on four years of analyses (prior to 1985) of the excellent annual *Working Cost and Operational Report* published by the Institution of Diesel and Gas Turbine Engineers, shows the major classes of failure reported by over 100 diesel and gas engined plants, worldwide. Failures are expressed as rounded-off percentages of total unscheduled stoppages.

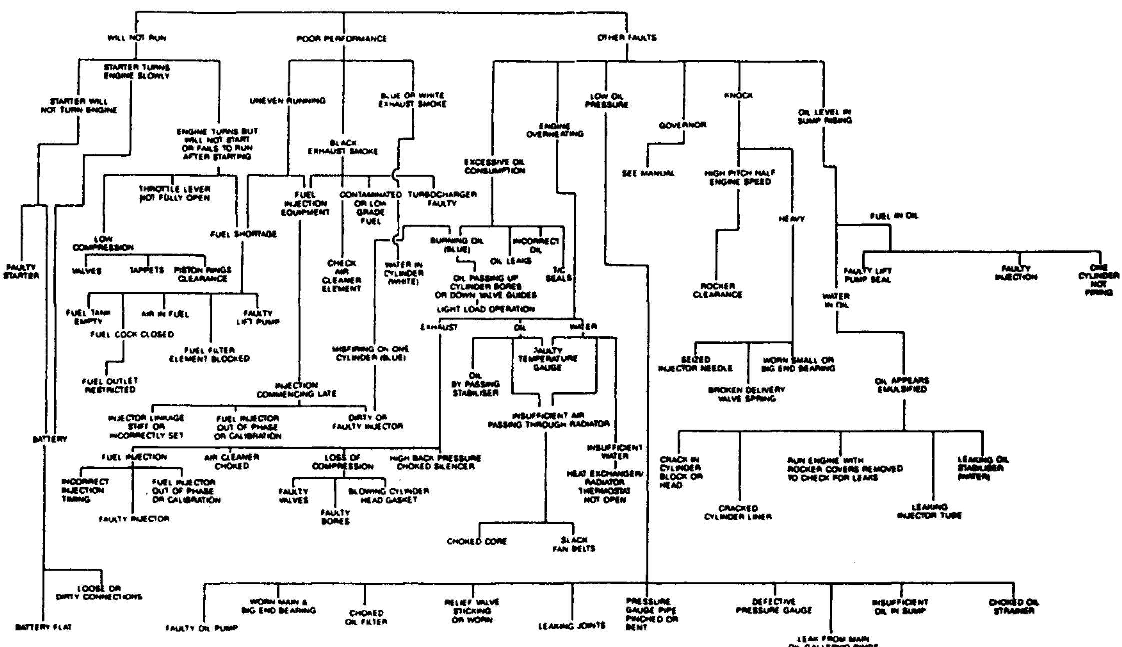


**Figure 15.1** A typical fault diagnosis chart for a high-speed engine (Courtesy: Dorman Diesels Ltd)

**Table 15.1** The major classes of failure at diesel and gas engined plants

| *Class of failure* | *Percentage of total stoppages* |
|---|---|
| Fuel injection equipment and fuel supply | 26 |
| Water leakages and cooling | 16 |
| Valve systems and seatings | 13 |
| Bearings | 7 |
| Governor gear | 6 |
| Turbocharger/lubrication/piston assemblies/gearing and drives | 4 each |

## 15.3.2 Operating records

In fully-manned plants it is important to initiate and maintain Operating Logs. These may vary in sophistication from a simple notebook to carefully designed forms. Whatever method is employed, regular entries are essential. Figure 15.2 shows a typical form that might be used in a base-load power station.

In addition to these daily logs, it will be necessary to keep periodic 'accounting records' to cover:

1. the station's output in terms of kWh;
2. costs in terms of:
   - operating labour;
   - maintenance labour;
   - spares;
   - fuel and lubricating oil consumption;
3. the cost of depreciation, interest, insurance and rates.

The significance of the costs at 3 are not often appreciated by engineers. The annual sum can be as high as 70% of the combined total of the other running costs at 2.

When combined with the operating logs and the maintenance records, these accounting records provide station management with the complete picture of what it takes to ensure trouble-free, low-cost performance [1].

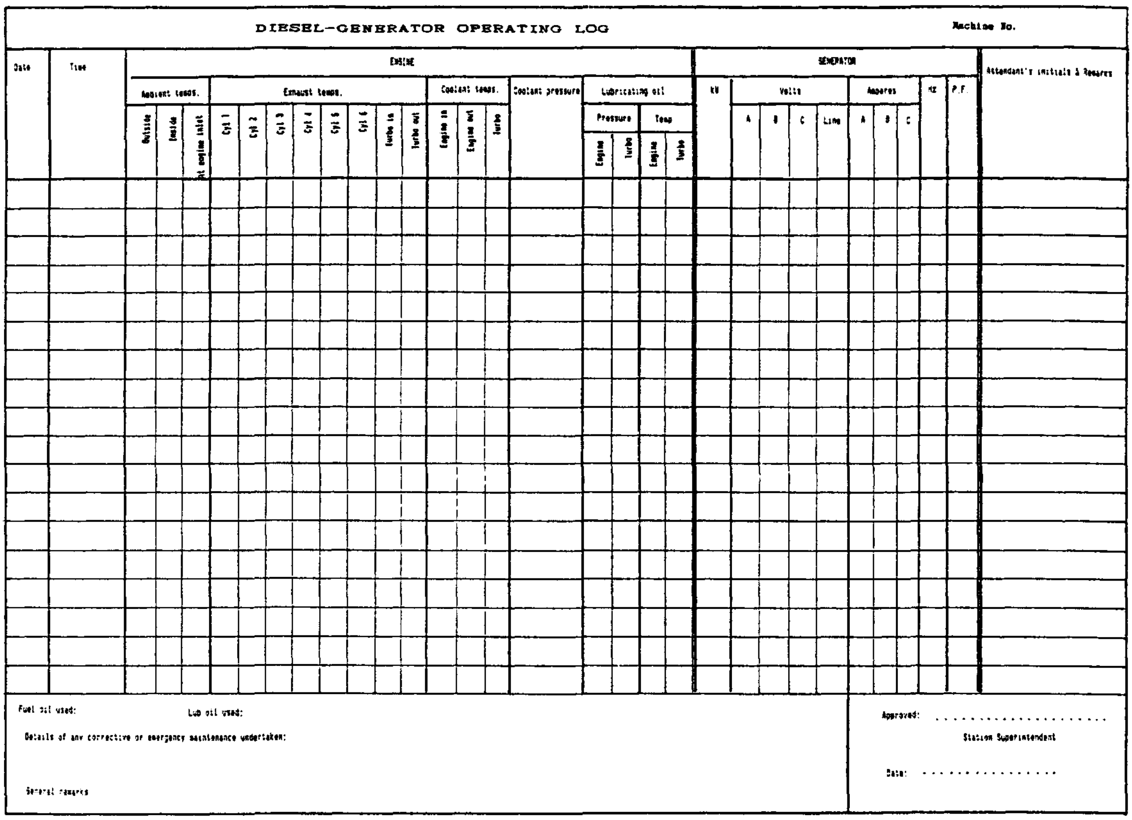

DIESEL-GENERATOR OPERATING LOG
Machine No.
Date
Time
ENGINE
Ambient temps.: Outside, Inside, At engine inlet
Exhaust temps.: Cyl 1, Cyl 2, Cyl 3, Cyl 4, Cyl 5, Cyl 6, Turbo in, Turbo out
Coolant temps.: Engine in, Engine out, Turbo
Coolant pressure
Lubricating oil: Pressure (Engine, Turbo), Temp (Engine, Turbo)
GENERATOR
kW
Volts: A, B, C, Line
Amperes: A, B, C
HZ
P.F.
Attendant's initials & Remarks
Fuel oil used:
Lub oil used:
Details of any corrective or emergency maintenance undertaken:
General remarks
Approved: ....................
Station Superintendent
Date: ................

**Figure 15.2** A typical operating log for a diesel-generator set

## 15.4 Maintenance

BS 3811 (see Section 15.6) defines maintenance as 'the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function'.

The service life of plant is influenced by:

- wear and tear resulting from usage;
- natural wear due to such factors as corrosion; and
- damage or destruction due to operating errors.

A degree of indemnity against the first two is provided by:

1. the right choice of materials;
2. careful design; and
3. specifying both the operational duty and the maintenance strategy for the plant.

Potential damage due to operating errors is minimized by effective staff training, and by the provision of safety circuits. Underestimating the importance of maintenance can lead to chronic neglect. This may result in irreparable damage to plant, with serious consequences for the power networks it supplies [3].

### 15.4.1 Maintenance strategies

It is important to establish, at the project conception stage, what maintenance strategy is to be adopted for the economic operation of the plant. The choices are shown in the diagram of Figure 15.3. The terms are defined as follows.

Maintenance may be organized and undertaken to a predetermined plan, using forethought, control and good documentation and recording systems. It is then said to be *planned.* It is *unplanned* where no predetermined or formalized plan exists.

Anyone adopting the 'unplanned' route for generating plant is courting disaster. It usually means running plant without maintenance or repair until and unless there is a failure or breakdown [4]. It implies a fault-related strategy, embracing both *corrective* and *emergency* maintenance forms. In the first, the corrective work is done after a failure has occurred. In the second, the maintenance is put in hand only after a disturbance, in order to avoid serious consequences. This is not to say that corrective and emergency action well never be required in a planned-maintenance regime. Even in the best of organizations, such actions may be necessary. But they should occur only in exceptional circumstances and not be the accepted norm.

There is an unfortunate tendency in some developing and newly industrialized countries to neglect the maintenance aspects of plant operation. A *breakdown maintenance* strategy is usually adopted because the prime cost of maintenance is excessive, and down time can be high for even a relatively minor service. Whilst this philosophy may conceivably be justified for very small, low value, or second-hand plants, it should be deprecated for the larger and more expensive ones.

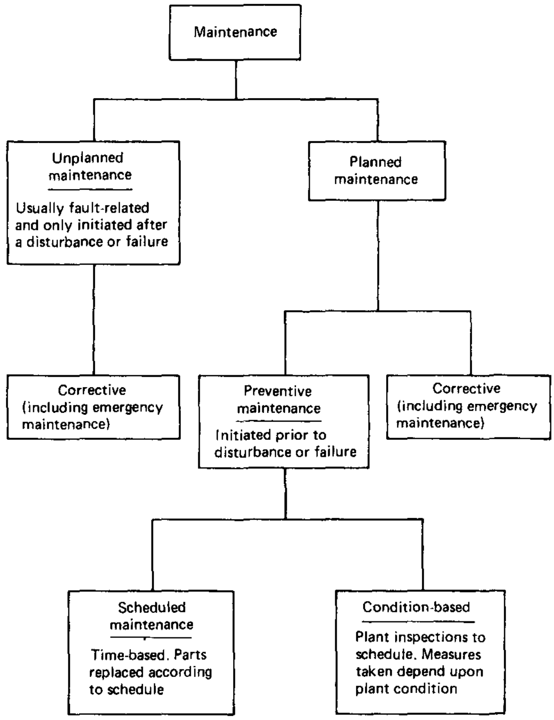



**Figure 15.3** Maintenance strategies

The aim of planned maintenance is to reduce or eliminate breakdowns and failures and to minimize the resulting plant stoppages or damage. *Preventive* maintenance is always part of planned maintenance, whereas, corrective maintenance may or may not be.

Preventive maintenance, as the term implies, is intended to reduce the probability of failure and to extend the operating life of an item. It is carried out at predetermined intervals or at intervals corresponding to prescribed criteria. It may be performed with the item of plant on load or on line *(running maintenance),* or may require the item to be out of service ( *shut-down maintenance).*

Statutory inspections of items on auxiliary services may be required, to comply with national regulations such as the Factories Act in the UK. This may necessitate taking equipment or auxiliary plant out of service. Items such as air receivers, cranes and lifting tackle, and fire warning devices would come within this category.

If high plant availability is to be achieved, as much maintenance work as is possible must be done whilst generators are in commission. Minor faults, representing an unexpected deviation from requirements and requiring plant unit outage to correct, should be left until a sufficient number have accrued. The unit may then be taken off line at a convenient time to suit system conditions and costs [5].

Preventive maintenance may be time-based and/or condition-based. Where it is time-based, it is carried out at predetermined intervals *(scheduled maintenance).* For example, the attention required on engines, and the parts to be replaced at various intervals of time, are scheduled in the maintenance information supplied by manufacturers. More on this later. *Condition-based maintenance* is that initiated as a result of knowledge of the condition of an item from routine or continuous monitoring. It is the current 'state of the art' and is, increasingly, the preferred type of maintenance [3].

*Condition monitoring* (CM) is the continuous, or periodic, measurement and interpretation of data to indicate the condition of an item in order to determine the need for maintenance. It is normally carried out with the item in operation, in an operable state, or removed but not subject to major stripdown (BS3811). In a well-planned condition monitoring system, diagnosis should be possible without dismantling so that plant overhauls can be safely deferred. This makes for more cost-effective maintenance.

When ratings rise on machinery, faults are likely to develop more rapidly into failure. It is now possible to monitor directly, reliably, and continuously, the most sensitive parameters on plant, rather than only the more conventional, such as the pressure and temperature of cylinder gases or lubricating oil- all of which react relatively late [2].

Various techniques are used in monitoring the dynamic condition of critical components in machinery. Examples are:

1. vibration monitoring (using piezo-electric transducers or accelerometers);
2. shock pulse monitoring for rolling bearings;
3. side-band analysis (of frequencies near to the fundamental) for checking gear teeth condition;
4. proximity probes to check the correct functioning of piston rings by detecting rings not in contact with the running surface of cylinders, as well as broken rings [6];
5. flush-mounted surface thermocouple sensors to detect wear rate - for instance, in cylinder liners;
6. sound monitoring, in a similar manner to vibration monitoring, to obtain characteristic signatures of engines;
7. the detection of the gaseous products evolved in the breakdown of electrical insulation due to arcing or overheating - using chromatographic techniques; and
8. the detection of high frequency emission from generator stator windings, signalling the inception of electrical discharge from voids in the insulation.

By monitoring performance in this way, and comparing parameter values with preset base values (at regular time intervals), trend analyses are possible. Analogue signals from plant sensors are sampled by a computer to present trend diagrams for various data. The calculations processed from the scanned data can be evaluated for their significance within the central processing unit (CPU). This enables operating staff to determine what cautionary or preventative measures, if any, need to be taken to prevent failures which may have serious consequences on plant operation. The other significant advantage of automatic monitoring is that it eliminates the several hours of labour, and the plant outages that are required for manual inspections.

Some proprietary performance monitoring systems are described by Collacott [6] who acknowledges the leading role taken by the Scandinavian countries in the development of computerized multi-logging scanning systems for diesel engines. See also entry (17) in the Bibliography.

Regular chemical analyses of lubricant samples may be taken to detect contamination using spectroscopy. Wilkie describes, in [7], an oil analysis service (provided by Century Oils of Stoke-on-Trent) which can pinpoint wear and failure in equipment. The Company's Controlled Engineering Tribological Service (CENT) uses automatic testing and robotics facilities to analyse small samples of oil in just four minutes.

The nub of the diagnostic facility is an inductively coupled plasma spectrophotometer (ICP) which identifies 26 metals in a sample of oil. It can detect some trace elements in concentrations as low as 1 part per billion. The service hinges on a central computer system which brings together the results of all the tests. A database of information on the equipment's operation, working environment, maintenance procedures and metallurgical and elastomeric data on the equipment's components, assists experienced personnel to draw the right conclusions from the analysis.

For example, the presence of sodium or boron in an engine oil sample would indicate that coolant has found its way into the oil since these elements are present in engine coolant inhibitors. High levels of iron and chrome would point to excessive wear on the piston rings, and the presence of excessive lead, copper and tin would indicate big end bearing wear. Rises in water and solubles contents would suggest a pump seal failure, while a rise in nickel and molybdenum would point to wear on the pump shaft.

Century Oils condenses the information generated by the analyses into a programme of charts which uses a 'traffic light' system to advise clients of the action to be taken for each piece of equipment 'sampled'.

- GREEN indicates normal running, or an acceptable condition, and implies that no action is needed, other than the usual maintenance.
- AMBER indicates caution and suggests unusual factors which require special attention and possible adjustment.
- RED signifies critical situations demanding immediate action to avoid imminent failure; client's maintenance management is normally notified by telephone when such action is necessary.

With regular airline service connections between most countries, the small samples required (about 5 $cm^3$) can be transported expeditiously, and a 'red-alert' telephone message should be received no more than an hour or two after results have been analysed.

Table 15.2 [3] summarizes the advantages and disadvantages of various maintenance strategies.

The reader will come across the term *terotechnology* in his/her researches into maintenance management. It is a title created to cover the combined technology of installation, commissioning, operation, maintenance, modification and replacement of plant, machinery, and equipment, with feedback of information on design, performance, and costs. Derived from the Greek root 'tereo' (caring), it means the 'technology of caring for' and extends to the whole life-cycle of an asset. Its objective is the pursuit of economic total life-time costs for (fixed) capital assets [4].

### 15.4.2 The preventive maintenance programme

The objectives in planning a preventive maintenance system for a power plant are as follows:

1. to determine the scheduled maintenance requirements for each item of plant;
2. to establish a maintenance programme which is a time-based plan allocating specific maintenance tasks to specific periods;
3. to ensure that scheduled maintenance is undertaken as planned; and
4. to provide an accurate and detailed record of the preventive and corrective maintenance tasks that have been undertaken, on all equipment within the plant.

The starting point of any preventive maintenance programme must be the equipment manufacturer's Operator and Service Manuals. They provide full maintenance and overhauling information, indicating what needs to be checked and how frequently. The strategy should be to collate the schedules for each item of plant within the complex so that a programme can be arranged for maintenance tasks to be carried out in sequence, and at the correct intervals of time.

The important role of lubrication in preventive maintenance cannot be overstressed. See Subsection 15.4.5 for further details.

When drafting the overall maintenance programme, it is logical to use the engine schedules as the base for the time plan since engines demand the most frequent attention. Plant service intervals should therefore be designed around the engines' requirements. These range from daily, through weekly, and monthly, to 6-monthly and 12-monthly servicing, for engines in intermittent use - such as those driving emergency generators. Schedules for engines in constant use are usually presented in intervals of running hours, or of 'engine service counter' units (ESe). The latter are read off an engine-driven instrument which is geared to record one hour for each hour of running at the engine's rated speed. Maintenance management must use its judgement in converting ESe units to chronological periods - based on knowledge of the plant's

**Table 15.2** Comparison of various maintenance strategies

| *Criterion* | *Maintenance strategy*<br>*Fault-related (corrective/emergency)* | *Time-based (scheduled)* | *Condition-based* |
|---|---|---|---|
| Work performed at convenient time | No | No | Yes |
| Plant availability | Low | High | High |
| Spares inventory | Large | Medium | Small |
| Overtime hours | Very many | Many | Few |
| Personnel occupied constantly | No | Little | Yes |
| Maintenance costs | Low | Very high | High |
| Production losses (outages) | Very high | High | Medium |
| Use made of spares | Little | Great | Medium |
| Possibility of scheduling work | No | Yes | Yes |
| Forced outages | Many | Few | Few |
| Scheduled outages | None | Few | Few |

tions. See Section 15.4.4 for typical service tasks required at various intervals.

Planned schedules should, at first, rigidly adhere to the engine manufacturer's recommended frequencies for inspection checks and maintenance tasks. Only after sufficient operational experience has been accumulated should one contemplate any modification to fit the particular installation and its operating conditions. This would also apply to those plants which use condition monitoring systems.

If the manufacturer's schedule is to be modified, the appropriate time to do this is after the first general overhaul, i.e. stripping to crankshaft bearing level. This gives the opportunity to assess achievement against the maker's wear and renewal limit schedules. The base data fed into the microprocessor of the condition monitoring system may then be up-dated if necessary.

While the service intervals recommended by manufacturers are conservative, and are based on average experience and temperature conditions, periodicity of inspection and service may need to be increased where, for instance, the quality of fuel is in question, or where very corrosive and very dusty environments exist, or where less than 50 % loads are initially expected. Wilbur and Wight [2] suggest that manufacturer's recommendations are sufficiently pessimistic (compared with average achievements) to give even the operator who has the worst conditions to contend with the assurance that he will undertake his first overhaul well in advance of any indication of trouble.

Servicing schedules will differ in detail between slow-speed, medium-speed, and high-speed engines. Intervals between major overhauls on well-maintained engines have widened considerably over the years. Typically, one expects intervals of 10000 - 15000 hours for high-speed engines, and between 20000 and 30000 hours for medium- and slow-speed engines.

Users, particularly those with single standby sets, may accept the option of a maintenance contract with the generating set manufacturer. Service technicians then visit the site at times and intervals to suit the planned maintenance programme. Manufacturers also offer service back-up in emergency situations. Where service technicians are located on a regional basis rather than operating from a central base, the response to call-out can be fast because the travelling time is reduced. Besides having sound experience of their company's products, these technicians usually carry specialist equipment in their service vans - this can make the difference between hours and days in getting generators back on line [8].

Having said that condition monitoring is more appropriate to the larger installations, fairly inexpensive microcomputer-based control systems are now available which use serial communication interfaces to monitor several individual generating sets from one (remote) operation and maintenance centre. The systems give advance notice of maintenance due and, by recording salient details of plant condition and running-hour information, provide the basis for centrally controlled maintenance schemes.

One such system (called *Sigmus)* is that developed by Petbow Limited - a founder member of the Association of British Generating Set Manufacturers (ABGSM). It is a remote, condition monitoring system which seeks to eliminate sole dependence on in-house maintenance by providing 24-hour, year-round vigilance over emergency generating sets. The condition of installed generators is continuously monitored to provide predictive maintenance protection in support of the regular planned maintenance programmes. Strategic sensors fitted to the generators provide analogue and digital signals, via the plant room's local management control console, to the network of control computers at Petbow's HQ centre. The link is through auto modems into the public switched telephone network.

Operators manning the service centre analyse and evaluate incoming data and initiate corrective action before problems arise. They are able to interrogate the central computer and obtain trend analyses - in graphical colour form. The system also has learning capacity, in that correct running patterns, once established, become a reference base for future monitoring tolerances.

The sensors have parameters which are set for normal conditions in both the passive (standstill) and operating modes. Provision may be made to monitor:

- battery voltage and battery chargers;
- engine coolant, lubricating oil, and exhaust temperatures;
- lubricating oil pressure;
- engine coolant and lubricating oil levels;
- daily service fuel tank levels;
- fuel head (i.e. pressure at the fuel injectors);
- drip tray levels (to detect low level leakage of fuel, oil or coolant);
- plant room ambient temperature;
- generator winding temperature;
- rotating diode failure;
- generator speed/frequency;
- generating set vibration;
- electrical parameters such as kW, kVA, etc.;
- status of plant room ventilation louvres, and plant room security;
- switchgear status (e.g. to ascertain if key isolators are in the correct positions); and
- fire valve status.

Users may also take advantage of engine manufacturers' service exchange schemes in which engines built to the same specification and in all ways updated and new, may be used to replace engines which are due for major overhaul. Exchange engines are built and tested to the same standards as new engines and usually carry a six-month guarantee. Such schemes are usually operated by high-speed engine makers. Exchange schemes on major components are more widely available.

### 15.4.3 Maintenance records

Documentation should be designed to fit the particular power installation's purpose. In the largest and most complex plants the organization of preventive maintenance may require critical path planning methods and the use of a computer to store and process information on maintenance procedures, covering scheduling, materials management, etc. A typical software package would offer the following facilities:

- print works orders
- print reports for control and follow-up
- provide a parts inventory
- store equipment history
- create a detailed database
- pinpoint problems by reports, and
- provide other detailed reports.

More commonly, programming is adequately handled by a punch card system which can be sorted out by a simple office machine of the type marketed by Kalamazoo Ltd [9]. Where job cards of this type are used, it is often possible to incorporate a history of the item of plant behind the card.

A simple and effective method of displaying the maintenance programme is on a composite wall chart, listing every major item of plant (and its associated equipment). A vertical 'date' cursor is re-positioned on the chart at weekly intervals.

While a recording system is inherent in the concept of planned preventive maintenance, it should not be over-ambitious. There is always the danger of creating more paperwork than is absolutely necessary or that can be sustained in day-to-day operations. Also, it is possible to obscure essential data with too much detail. The aim, initially, should be to keep it as simple as possible and provide a framework to which further sophistication may be introduced as and when necessary.

Whatever the system, maintenance records should provide the following:

1. an information index;
2. a record of past performance;
3. an analysis of historical information;
4. a timely indication of future events.

The sort of detailed information that might be included under each of these requirements is given below [5].

*The information index*

1. An inventory of installed plant.
2. Salient data on each item of plant.
3. The location of related drawings and workshop manuals.
4. Any limitations regarding access for maintenance, e.g. only available when its associated generator is shut-down.
5. The form of maintenance applicable to each item, i.e. scheduled, condition-based, fault-related, etc.
6. The nature of work to be performed where items are to be serviced on a regular scheduled basis.
7. Any other specific information, such as special service tools required, spare part numbers, modifications made, etc.

*Past performance*

1. A record of the nature, and dates, of all previous maintenance work.
2. Condition of the item/equipment at the last inspection, e.g. critical (wear) dimensions; insulation value, etc.
3. A record of maintenance costs on the item: labour, materials and spares.
4. A record of behaviour, or the results of any tests using different materials, lubricants, etc.

*Historical analysis*

1. Frequency of component breakdowns.
2. The total cost of maintaining each major element within the plant complex.

*Future events*

1. When the next scheduled maintenance work is due on an item.
2. Statutory inspection is due on an item, e.g. lifting tackle, air receivers, etc.
3. Spares need to be ordered, or are due on site.

As far as maintenance documentation is concerned, the engines will require the most detailed attention. In addition to the scheduled routines that are carried out between overhauls, the key consideration must be the overhauls themselves. When these are done, it becomes necessary to examine engine components in some detail and to record the amount of wear on moving surfaces. If the integrity of any part is suspect, non-destructive testing techniques may need to be applied to establish suitability for further service [10]. Hodge [10] recommends that details of the work done and the data obtained during overhauls are recorded on a set of sheets specifically created for the purpose. He gives typical examples of sheets which cover the following aspects:

Sheet 1 - Data extracted from the plant's operational logs/records such as total hours run, running hours since last overhaul, type of fuel and quantity used, type and grade of lubricating oil and quantity consumed.
Sheet 2 - Cylinder wear measurements.
Sheet 3 - Piston and gudgeon examination; piston ring data
Sheet 4 - Crankshaft measurement and alignment.
Sheet 5 - Main bearing and big end bearing clearances.
Sheet 6 - Cylinder head valves and details.
Sheet 7 - Miscellaneous components and assemblies.
Sheet 8 - Initial running: balancing cylinders and load testing.

These sheets would then supplement those documents which record the between-overhaul operations in the maintenance cycles.

### 15.4.4 Servicing schedules

In a work such as this, it is not possible to give comprehensive recommendations for a maintenance schedule that would be correct for similar equipment and in all applications. Schedule tasks will vary in frequency and complexity with the particular manufacturer's requiremen;s, and are determined by equipment rating, duty, and environmental conditions.

Maintenance and overhaul schedules and procedures are detailed in equipment manufacturers' instruction and workshop manuals. All operation and maintenance personnel should have ready access to copies of those manuals which are applicable to the equipment in their charge.

Certain basic principles will apply to the maintenance of the major items of equipment, regardless of their type and make. We shall consider engines, generators and switchgear, in turn, and list those inspection routines and servicing tasks which are commonly included in their maintenance schedules.

*Engines*

BETWEEN OVERHAULS

*Lubrication system*

- Check, top-up or renew lubricating oil in the engine and turbo-charger systems.
- Service the filters - check pressure drops; fit new elements and joints; clean bowls.
- Take oil samples for laboratory analysis.
- Inspect for leakage.

*Fuel system*

- Drain water and sediment from filter bowls and water traps.
- Service the filters - renew elements and joint rings; clyan bowls.
- Check fuel pump(s) drives.
- Service or renew fuel injectors (if a cloudy exhaust, or increased exhaust temperatures, suggest it is necessary).
- Check injection pump timing.
- Check/adjust control linkages between governors and injection pumps (where applicable).

*Cooling system*

- Check coolant levels; top-up where necessary.
- Check specific gravity of coolant mixture and its pH value.
- Service raw water pumps: replenish oil cups; drain system; clean filters and refit.
- Service heat exchanger tube packs.
- Where 'wet-spray' cooling towers are employed, consideration should be given to establishing schedules for the regular cleaning and disinfecting of the raw water systems (towers, heat exchangers, pumps and pipework). Such precautions are necessary in order to reduce the risk of *legionella* (Legionnaires' disease).
  The principal guides and codes of practice published in the United Kingdom are those listed below [11]. That which is most appropriate to power plant installations is the first of these documents, published by the Chartered Institution of Building Services Engineers (CIBSE). Plant maintenance personnel should be given procedural instructions based on its recommendations, with appropriate reference to the other two guidance codes.
  (a) Minimizing the risk of Legionnaires' disease. Technical Memorandum TM 13 published by the CIBSE.
  (b) Legionnaires' disease. Guidance Note EH 48, published by the Health and Safety Executive (HSE).
  (c) The control of *legionella* in health care premises. Health Circular HC(88)47 published by the Department of Health and Social Security (DHSS).

  The last two publications are available from Her Majesty's Stationery Office (HMSO).

*Air induction system*

- Check restriction indicators; reset after filters have been serviced.
- Service air cleaners; wash elements in warm solution of detergent or paraffin (as applicable); check sealing rings; clean intake ducting.

of inspections and service tasks should be adjusted to match the associated engine's maintenance programme. Typically, six-monthly schedules might be as follows:

- Clean exterior and check holding-down bolts/dowels.
- Clean air grilles/meshes and air filters (if fitted); replace filter elements, if necessary.
- Inspect tubes of air-cooled (CACA) or water-cooled (CACW) heat exchangers; clean, if necessary, with compressed air or a non-metallic tube brush (see Section 3.5 of Chapter 3).
- Check security of terminals and clean out terminal box, if necessary.
- Check insulation resistance and winding continuity.
- Check continuity of conditioning heaters, if fitted.
- Check embedded (stator) temperature detector circuits.
- Check frame earth connection for security and continuity.
- Grease bearings with approved grease using a gun.
- Drain oil from sleeve bearings; inspect for signs of uneven wear or overheating; clean with flushing oil; record salient dimensions; refill with the specified grade of oil, to the correct level.
- Check stator/rotor radial air gap readings and record results.
- Check all rotating diodes on brushless machines; care should be taken when screwing diodes back into their assemblies, since excess torque may damage the diode internally; use a torque spanner for the purpose.
- Inspect the automatic voltage regulator; check for loose connections and retighten if necessary; dry out if any moisture is present; remove any dirt with a fine brush.

On modern machines, it should not be necessary to undertake a complete overhaul at less than 4- to 5-yearly intervals. The frequency can only be determined by experience. Environmental factors will playa large part in a decision. Where there is high humidity, a dirty or dusty environment, or oil laden atmospheres (always a possibility with poorly maintained engines), overhauls may need to be reduced to 3-yearly or even 2-yearly intervals. The overhaul should be carried out in a clean and dry workshop. If this is not practicable, every effort should be made to keep the area in the immediate vicinity of the generator as clean as possible during the dismantling and reassembly operations described below. Typical *overhaul procedures* might be as follows:

- Clean exterior and blowout any fitted air ducts.
- Isolate the machine from the switchgear and controlgear by disconnecting main, and auxiliary cables; mark cables for future identification and ensure that they are protected from moisture and mechanical damage during the overhaul.
- Withdraw the coupling from the shaft; check keyway and shaft for burrs; and check the coupling for wear. Dismantling will usually be in the following sequence [12]:
  (a) external ducts and air filters;
  (b) heat exchanger;
  (c) end covers and/or bearings;
  (d) rotor.
- Check sleeve bearings for wear; ensure lubrication holes and oilways are not obstructed.
- Check ball and roller bearings; renew if required; otherwise degrease, pre-oil and repack with approved grease, ready for reassembly.
- Remove rotor. The method used will depend upon the particular machine. Manufacturers' maintenance and installation manuals should be consulted. Typically, on machines which have bearings fitted within the endshields, the procedure is as follows:

  (a) turn the main rotor assembly so that a full pole face lies at the bottom of the main stator case;
  (b) remove the non-drive end, and drive end, bearing brackets;
  (c) using a shaft extension tube at the non-drive end, support the rotor weight between two slings - positioned on the extension tube, and the shaft at the opposite end;
  (d) carefully withdraw the rotor, until a point is reached where half of it has emerged from the stator. The rotor weight can now be supported by the full pole face on the bottom of the stator core (see (a) above);
  (e) remove, and reposition, the slings tightly around the main rotor poles, endeavouring to select the rotor's centre of gravity;
  (f) manually steadying both ends of the rotor, carefully withdraw the rotor core clear of the stator. Then, using a sling suspended from a different hoist or crane jib, lift the rotor clear of the stator. Great care should be taken not to allow rotor assembly contact with the stator end-windings.

- Check rotors (main and exciter) for any signs of rubbing with their stators.
- Before cleaning, examine the stator windings for any signs of visible damage (e.g. loose or charred insulation; tightness of binding tapes/cords, packing blocks, wedges, and mouth-of-slot blocks; signs of electrical discharge between phases and at the slot exits).
- Check that stator laminations are free from burrs and that the ventilation airways are free from obstructions.

- Thoroughly clean all major components of the machine. If steam cleaning or hot water/detergent cleaning is contemplated, check the manufacturer's instructions to ascertain if any parts may not be so treated, e.g. core plates manufactured with water-soluble, interlaminar surface, insulating coatings. There is always a risk associated with water and steam treatments, because of the possibility of porous inclusions in insulation systems. The subsequent drying-out process can prove difficult. It is better to use proprietary cleaning fluids (based on mixtures of trichloroethylene and white spirit). Unfortunately, these are not always readily available in some developing countries and it may be necessary to ship quantities of the fluid to site in advance of overhaul or to hold quantities on site. Airline regulations prohibit the transportation of cleaning fluids [12].
- Reassemble the machine, following the reverse sequence to that of dismantling, and refit the coupling.
- Replace gasket materials, sealing compounds or strips, where applicable.
- Check relative positions of rotor and stator both radially (air gaps) and axially; and record on a sketch.
- If the machine has been removed for overhaul, replace it on its baseframe (or the composite baseplate) and realign it to the coupling of the prime mover; refit shims and dowels, where applicable; and record results.
- Reconnect all cables and test generator stator windings and cables, for insulation resistance and continuity.
- Check cleanliness of terminal boxes, before replacing covers.
- Check that sleeve bearings are filled with the specified oil.
- Check winding insulation values before run-up and re-commissioning load tests. (On very large power stations it may be possible to get the original machine manufacturer(s) to assess the condition of the insulation on critical machines in the plant. In addition to a thorough visual examination, their non-destructive test procedures enable the internal condition of coils to be evaluated and the detection of weak areas in the major insulation [13]. The on-site time for such tests are minimal (1 to 2 days). Long outages are therefore avoided. )

*Switchgear*

Switchgear should be inspected every six months. A typical schedule of work would include:

1. Clean equipment and check all connections for tightness.
2. Test all main and control fuses.
3. Check indicator lamps at all local and remote positions; replace where necessary.
4. Check the insulation resistance of all control wiring.

Annual checks and overhauls should be made on circuit breakers, contactors and isolators. Schedules of work would, typically, include:

1. Thoroughly cleaning the device.
2. Removing the arc chutes (where applicable) and inspecting the main contacts; and renewing these where necessary - always replace in complete sets.
3. Checking contact alignment, contact pressure and blow-out arc chutes.
4. Checking main and auxiliary connections for tightness.
5. Cleaning insulators and visually inspecting them for cracks.
6. Inspecting operating mechanisms for signs of wear on moving parts; lightly lubricating (with light machine oil) all moving parts and bearing surfaces - including those on isolating and shutter mechanisms.
7. Using a 'ductor' tester, check contact resistance, with the breaker, etc. closed.
8. Checking insulation resistance of each phase to earth, and between phases.
9. Inspecting, and lightly polishing if necessary, all auxiliary contacts; renew in sets, where necessary.
10. Checking insulation to earth of all auxiliary and control wiring; and checking the resistance of shunt trip and closing coils.
11. Checking operation of the power switching device from all control points, including emergency stop stations; and from protection relays. Flexible jumpers may be fitted to breakers for these tests.

Busbars should be cleaned annually and their connections checked for tightness. Protection relays should also be checked out annually, to ensure correct operation using injection test equipment to simulate fault conditions. Relay operating times should be recorded and compared with relay characteristic curves. Time delay differences point to either relay or circuit faults. These should be rectified. See also Sub-section 13.10.1 of Chapter 13.

Inspections and tests should be conducted by qualified and competent electrical staff. The local rules and regulations for safety during maintenance work should include:

1. Avoiding, as far as possible, any work on live circuits above ELV potential (50 V a.c. or 120 V d.c.).
2. Checking circuits with voltage testers to confirm that they are de-energized.

3. Locking-out main disconnecting and isolating devices, and tagging them with warning notices. It is prudent to remove fuses from circuits, as an added precaution.
4. Exercising particular care when working on breakers which have stored energy closing! opening mechanisms.
5. Tagging breakers and contactors when arc chutes have been removed. The tags should display this fact and warn against operation without replacing the chutes.
6. Prohibition of work on HV systems by an unaccompanied person. On routine tests, where circuit conditions are not being changed, the presence of another worker in the immediate area is an acceptable alternative to two persons at the work station. Permits to work should be issued; and only by designated and authorized supervisors.

Codes of Practice BS 6423 (for equipment up to 650 V) and BS 6626 (for voltages up to 36 kV) should be consulted for the maintenance of switchgear and controlgear of the type to be found on generating plants. These codes record matters that experience has shown to be important in keeping switchgear and controlgear in an acceptable condition.

### 15.4.5 Supporting schedules

It may be convenient on the very largest plants to keep separate records for certain general items of equipment and services. These may include spare parts schedules, specialist tools and equipment schedules, drawing registers, valve schedules, and lubrication schedules.

#### *Lubrication schedule*

This is perhaps the most important of the supporting schedules. In some power stations, lubrication is the responsibility of the operating staff; in others, it is a function of the maintenance department. In any event, a comprehensive schedule is necessary to ensure that all items in the plant are correctly and regularly lubricated.

The schedule should indicate [5]:

1. the plant item to be lubricated;
2. the points of lubrication for each item;
3. the application method, e.g. grease gun, oil can, etc.
4. the lubricant to be used;
5. the frequency of application; and
6. for items such as engines and compressors, the frequency of lubricant sampling or of oil changes.

On the larger stations, it is well worth planning 'lubrication routes' into the overall maintenance programme. The route schedules should then identify those items on the routes requiring a particular type of lubricant and its method of application. A separate grease gun or oil can (suitably labelled) should be used for each type and grade of lubricant, to avoid the possibility of improper application.

If possible, a *lubricator* should be assigned to each route in order to narrow the range or responsibility for lubrication activities. Lubricators should be required to confirm, by signature, that all tasks have been completed. The route schedule should then be returned to records and filed.

The oils and greases specified by equipment manufacturers are based on plant duties and ratings. The need to use specified or equivalent lubricants cannot be overstated. Lubrication requirements should be discussed with the representative of a local oil company, in the context of the equipment manufacturers' recommendations, in order to try to rationalize the number of products and grades used.

#### *Spares schedule*

Plant manufacturers issue standard lists of recommended spares for their equipment. The lists are based on the manufacturer's experience and usually assume 'continuous' running of the plant. Lists typically cover one, two or three years of operation, and form the basis for setting-up the original spares stocks on site.

Lists should be critically examined by operations and maintenance managements and orders only placed for those items considered to be essential, bearing in mind their importance to the plant and their delivery periods. Each manufacturer's list should be compared with those from other equipment suppliers to check for duplication of identical items. Fuses and indicator lamps are the more obvious items.

Careful consideration should then be given to the extent of the original spares holding. A more comprehensive stock would be necessary at remote sites or in certain developing countries where there are no local, accredited-spares stockists for some plant items. At locations where there is ready access to good stockists, a much-reduced inventory on consumable items is justified.

Having deteimined the extent of the spares holding, it is necessary to establish maximum and minimum stock levels. These levels should be periodically reviewed in the light of experience gained in the operation and maintenance of the plant. Large amounts of capital can be tied-up in spares stock. If too many items remain unused for long periods, the capital wastage can be high.

A comprehensive spares schedule should be maintained. It should list all the items on inventory and indicate, for consumables, the max-min stock levels and the economic re-order quantity levels. Periodic inventories will provide the necessary recording data for keeping a check on spares to meet planned maintenance requirements. They will also assist in controlling holdings to desired levels, and help in preparing future budgets.

### *Schedules of specialized tools and equipment*

The specialist tools necessary for certain maintenance tasks on particular items of plant should be housed in a 'Special Tools Store', under the control of the Maintenance Department. Engine manufacturers, for example, have developed tools and fixtures specifically designed to facilitate dismantling and re-assembly of their engines. Such tools would be held in this store. They might include valve extractors, inertia extractors (for injectors), valve spring compressors, valve and injector seat cutters, and specialized lifting tackle.

Other tools and equipment needing to be held in a centralized store might include:

- Portable electrical testing instruments. (In the largest plants, these may extend to Schering bridges and dielectric loss analysers - for the evaluation of coil insulation on machines).
- Measuring instruments such as micrometers, caliper gauges, depth gauges, sets of feeler gauges, square sets, drill gauges, precision spirit levels, etc.
- Pulling tools for bearings and couplings.
- Borescopes, fibrescopes and fibre optic torches.
- Portable diesel engine diagnostic kits.
- Engine cylinder maximum pressure indicators.
- Torque spanners.
- Tap and die sets.
- Magnetic retrieval tools.
- Portable power tools such as angle grinders, shears, nibblers, jig saws, and circular saws.
- Portable welding and brazing kits.
- Lifting beams for generator rotors (these would usually be stored in the machinery hall, adjacent to the plant).

Effective controls must be established for such equipment. A schedule should be prepared, and maintained, listing:

1. items and their cost;
2. supplier/maker and date of purchase;
3. location within the stores;
4. item plant or code number.

All items should be checked in and out of storage. This gives an immediate indication of where tools are being used, and provides an incentive to personnel to return items to their designated places, and in a satisfactory condition.

All test and inspection equipment should be regularly checked by maintenance supervisors and any deficiencies made good. Also, a system for periodic calibration should be established and records maintained as evidence of calibration status.

## 15.5 Staff instruction and training

Contract conditions should include the requirement for the instruction and training of the user's operating and maintenance personnel during erection, site testing, and the setting to work of the plant.

Further training should also be arranged for key personnel at the major suppliers' works. Engine, generator, and switchgear manufacturers usually have Product Training Centres at which users' personnel are offered courses in the maintenance and overhaul of the company's products. Although practical work is the keynote of these courses, sufficient theoretical instruction is included to help define the functions of various components.

Taking engines as a typical example, courses may range from those of four to six weeks duration which give comprehensive instruction in operation, maintenance, repair, and overhaul - including fuel injection testing; to those of one or two weeks duration covering scheduled maintenance and overhauls. Trainees are given the opportunity of stripping and re-assembling the engine types specific to their own installations.

Some manufacturers can provide instructors to visit home or overseas sites to give convenient on-the-spot training to users' personnel.

British Electricity International (BEl), a company established by the Electricity Supply Industry, is able to offer training courses in all aspects of power supply operations. This includes the maintenance of power plant and the planning of maintenance work, distribution and transmission systems, instrumentation and control, and protection. Programmes provided in the UK can be matched to the needs of clients' staff. Typically, two UK-based training programmes (each of one year's duration) are designed for recently graduated engineers employed on the staffs of electricity supply undertakings. They cover 'Power Station Plant', and 'Distribution Engineering'. In conjunction with the British Council, BEl also offers shorter programmes of integrated training in electrical engineering. These are designed for students with qualifications below degree level.

Overseas services include the design of initial training schemes for new entrants to power supply undertakings, the design and commissioning of training centres, and the provision of training instructors to run courses. The highest importance is attached to the preparation of local staff to continue the training arrangements initiated by BEL

## 15.6 Referenced standards

Reference has been made in this chapter to the following British Standards:

BS 3811 - *Glossary of maintenance management terms in terotechnology*
BS 4884 - *Specification for technical manuals*
Part 1 - *Content*
BS 6423 - *Code of practice for maintenance of electrical switchgear and controlgear for voltages up to and including 650 V*
BS 6626 - *Code of practice for maintenance of electrical switchgear and controlgear for voltages above 650 V and up to and including 36 kV*

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8. Mackenzie, P. Maintenance and servicing of a generating set. A paper presented to the 4th Power Conference, INPOWER '88, jointly organized by the IDGTE and FMJ International Publications Ltd, September (1988)
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11. Sykes, J.M. Legionnaires' disease: applying the guidance, *Health Service Estate* (published by HMSO on behalf of the Department of Health, Health Building Directorate) 65, 28 - 29, February (1989)
12. Watson, S.P. Maintenance and failures. Chapter 10 of *Electric Motor Handbook* edited by B.J. Chalmers, Butterworth (1988)
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### 15.7.2 Bibliography

There is a wealth of literature on the subject of maintenance. The following selection, arranged in groups to cover the topics discussed in this chapter, will provide the reader with practical information and data in his or her research.


*Maintenance management*

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(2) Kelly, A. and Harris, M.J. *Management of Industrial Maintenance* Butterworth (1978)
(3) Mann, L. *Maintenance Management,* Lexington, (1978)
*(4) Burton, R.* From manual to computer - the easy way. Paper 37 presented to the conference on Maintenance Management by Computer organized by the British Council of Maintenance Associations, London (1977)
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*Preventive maintenance*

(7) Clifton, RH. *Principles of planned maintenance,* Edward Arnold (1978)
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*Technical Manuals*

(10) Technical manuals: a guide to users' requirements. Institution of Plant Engineers, Ref: TMG/9/74 (1974)

*Electrical equipment*

(11) BS CP 1011: 1961 *Maintenance of electric motor control gear,* British Standards Institution
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## *Diesel engines*

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## *Condition monitoring*

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## *Maintainability practices*

(19) Williams, D. Reliably informed. *Electrical Design,* a journal of the Chartered Institution of Building Services, pp. 19-23 September (1987)

Useful guidance on specifying and contracting maintainability requirements is given in the following British Standard. The equivalent International Electrotechnical Commission publication is shown in brackets.

(20) BS 6548 - *Maintainability of equipment*
Part 1: 1984 (IEC 706-1: 1982) - *Guide to specifying and contracting for maintainability* (This Publication is currently in three sections - it will eventually comprise seven.)

## *Periodicals*

Specialist articles and papers on topics relating to the installation, commissioning and maintenance of plant are regularly published in the following journals and magazines:

- *The Plant Engineer* - the Journal of the Institution of Plant Engineers
- *Power Engineering Journal* - published monthly by Peter Peregrinus for the lEE
- *Diesel & Gas Turbine Worldwide* - published by Diesel Engines Inc., Milwaukee, Wis. U.S.A.

# A

# Conversion factors and formulae

## A.1. **Useful conversion factors**

### Energy

1 kilowatt hour (kWh) = 3.6 x $10^6$ Joules (J)
= 859.85 x lO3 calories (cal)
= 2.65 x lO6 foot pound force (ft Ibf)
= 3412 British thermal units (BTU)

### Force

1 Newton (N) = 0.lO2 kg-force (kgf)
= 0.225 Ib-force (Ibf)
= 1 x lO-4 ton-force (UK) (tonf)

### Pressure and stress

1 Pascal = 1 Newton per square metre *($N/m^2$)*
= 1 x lO-6 Newton per square mm *($N/mm^2$)*
= 1 x lO-5 bar (bar)
= 1.02 x lO-5 kg-force per square cm *(kgfl* $cm^2$)
= 1.45 x lO-4 Ib-force per square inch ($Ibf/in^2$)

also

1 bar = 29.53 inches mercury (in Hg)
= 750mm mercury (mm Hg)
= 100 kilopascal (kPa)
= 401.5 inches water (in $H_2O$)

### Power

1 Watt (W) = 0.lO2 kg-force metre per second (kgf m/s)
= 0.737 foot lb-force per second (ft lbf/s)
= 1.34 x lO-.1 horsepower (hp)
= 1.36 x lO-3 metric horsepower (ch, PS or CV)
= 0.239 calorie per second (calls)

### Torque

1 Newton metre (Nm) = O. 7376 lb-force foot (lbf ft)
= O. lO20 kg-force metre (kgf m)

### Angular velocity

1 radian per second *(rad/s)* = 0.159 revolution per second (rev/s)
= 9.55 revolutions per minute (r.p.m.)
= 57.3 degrees per second *e/s)*

### Linear velocity

1 metre per second (m/s) = 3.6 kilometre per hour (km/h )
= 3.28 feet per second (ftls)
= 2.24 miles per hour (m.p.h.)

### Volume flow

1 cubic metre per second *($m^3/s$)* = 2119 cubic feet per minute *($ft^3$1 min)*
= 35.3 cubic feet per second *($ft^3/s$)*

### Quantities involving heat and heat flow

1 kilojoule = 0.948 British thermal units (BTU)
= 0.239 kilocalorie (kcal)

1 kilocalorie per minute (kcal/min) = 0.698 kilowatt (kW) (Note: 1 kW = 1 kJ/s)
= 3.969 British thermal units per minute (BTU/min)

1 kilocalorie per kilogram (kcal/kg) = 4.196 kilojoules per kilogram (kJ/kg)
= 1.804 British thermal units per minute (BTU/min)

### Specific fuel consumption

1 gram per kilowatt hour (g/kWh) = 0.00164 pounds per horsepower hour (lb/hp h)
= 0.7355 gram per metric horsepower hour (g/ch h)

### Moment of inertia

It is important to differentiate between *moment of inertia* and *flywheel effect* since the terms are often confused. The flywheel effect involves diameter and not radius. It is therefore four times greater than the moment of inertia. When using the terms, one should indicate whether calculations have been based on radius or diameter – $mk^2$ or $GD^2$

1 lb in$^2$ ($mk^2$) = $0.2926 \times 10^{-3}$ kgm$^2$ [$mk^2$]
= $1.1706 \times 10^{-3}$ kgm$^2$ [$GD^2$]

1 lb in$^2$ ($GD^2$) = $0.2926 \times 10^{-3}$ kgm$^2$ [$GD^2$]
= $0.0732 \times 10^{-3}$ kgm$^2$ [$mk^2$]

## A.2. Useful formulae

### Power

$$\text{hp} = \frac{\text{torque (lbf ft)} \times \text{r.p.m.}}{5252} = \frac{\text{swept volume (in}^3) \times \text{bmep (lbf/in}^2) \times \text{r.p.m.}}{792000}$$

$$\text{kW} = \frac{\text{torque (Nm)} \times \text{r.p.m.}}{9549} = \frac{\text{swept volume (l)} \times \text{bmep (kN/m}^2) \times \text{r.p.m.}}{120000}$$

### Torque

$$\text{Torque (lbf ft)} = \frac{\text{bmep (lbf/in}^2) \times \text{swept volume (in}^3)}{150.8}$$

$$\text{Torque (kgf m)} = \frac{\text{bmep (kgf/cm}^2) \times \text{swept volume (l)}}{1.257}$$

$$\text{Torque (Nm)} = \frac{\text{bmep (kN/m}^2) \times \text{swept volume (l)}}{12.57}$$

### Alternating current

To determine current ($I$), horsepower (hp), true power (kW) and apparent power (kVA).

| | *Single phase* | *Three phase* |
|---|---|---|
| $I$ when hp is known | $\frac{\text{hp} \times 746}{V \times \%\ \text{eff} \times \text{pf}}$ | $\frac{\text{hp} \times 746}{1.732 \times V_L \times \%\ \text{eff} \times \text{pf}}$ |
| $I$ when kW is known | $\frac{\text{kw} \times 1000}{V \times \text{pf}}$ | $\frac{\text{kw} \times 1000}{1.732 \times V_L \times \text{pf}}$ |
| $I$ when kVA is known | $\frac{\text{kVA} \times 1000}{V}$ | $\frac{\text{kVA} \times 1000}{1.732 \times V_L}$ |
| kW | $\frac{V \times I \times \text{pf}}{1000}$ | $\frac{1.732 \times V_L \times I_L \times \text{pf}}{1000}$ |
| kVA | $\frac{V \times I}{1000}$ | $\frac{1.732 \times V_L \times I_L}{1000}$ |
| output hp | $\frac{V \times I \times \%\ \text{eff} \times \text{pf}}{746}$ | $\frac{1.732 \times V_L \times I_L \times \%\ \text{eff} \times \text{pf}}{746}$ |

Power Factor (pf) is the ratio of true power to apparent power

$$= \frac{\mathrm{W}}{\mathrm{VA}} \text{ or } \frac{\mathrm{kW}}{\mathrm{kVA}}$$

Ohm's Law : $I = V/R$ where $R$ is the unit of resistance (ohm)

The impedance of a circuit

$Z = [R^2 + (X_L - X_C)^2]^{1/2}$

where $X_L$ is inductive reactance
$X_C$ is capacitive reactance

# B Batteries

The application of storage batteries falls into three categories:

1. *High rate discharge service:* typically, for engine starting, switchgear operation, and uninterruptible power supplies.
2. *Medium rate discharge service:* such as emergency lighting central battery systems, and telemetry.
3. *Low rate discharge service:* those low pressure systems calling for low voltage current to alarm and protection systems such as those for engines and fire-detection apparatus.

We shall concentrate on engine starter batteries.

The *rate of discharge* is the current at which a battery is discharged expressed as a function of its rated capacity. Thus the l;2-hour discharge rate of of a 300 Ah battery would be 300/0.5 = 600 amperes. A battery's *capacity rating* is obtained by multiplying the output current (in amperes) by the length of time the current is flowing. It is expressed in *ampere-hours* (Ah).

A *high rate discharge* implies withdrawal of a large amount of current for a short interval of time - usually, at a rate that would completely discharge the battery in less than an hour.

## B.1. Types of storage battery

The two principal battery systems in use are lead acid systems and alkaline or nickel cadmium systems. There are others such as silver zinc, *ztnc* air, zinc chloride and sodium sulphur, but they are, relatively, more expensive. They are used for special applications and not usually in run-of-the-mill generator plants.

### B.I.I Lead acid batteries

The several types of lead acid battery may be classified under two groups:

1. those of the vented type; and
2. those of the sealed type.

#### *Vented lead acid batteries*

In these, the sulphuric acid electrolyte is in liquid form. They are available in several arrangements: with Plante positive plates; with tubular positive plates; or with flat pasted plates. They are either of low antimony lead alloy, or lead-calcium alloy construction to give increased life.

In terms of engine starting, particularly for standby and peak lopping applications (where it is essential that the battery is always capable of providing its required duty immediately), a high degree of reliability is essential. While the tubular battery offers robustness and a small plan area, its performance at the high rates of discharge required in engine starting is poor compared with the other two types of vented cells. Indeed, battery capacities of twice those required from high performance Plante or flat plate engine starter batteries may be required [1].

A note of warning is appropriate in the context of standby generators. Automotive-type batteries should not be used because they are not intended for trickle charge duties. The alloys used in the construction of their plate grids are, by necessity, other than pure lead. Where impurities of this nature are present, trickle charging is not recommended. The only safe way to treat an automotive-type battery on standby duty is to leave it on open-circuit between engine starts and to subject it to periodic *freshening* charges. Batteries are notoriously susceptible to neglect, and where one has to rely on the efficiency of personnel, routines can be forgotten - with disastrous results [2].

The high performance Plante battery is perhaps the best choice for standby generator applications. When operated with constant voltage chargers (see Section B.3.) these batteries may have a life in excess of 20 years and may only need topping-up with distilled or de-ionized water at 6-monthly intervals. The major disadvantages of the Plante type battery are:

- its relative expense;
- its bulk for given ampere-hour capacity;
- its proneness to damage if left discharged; and
- its relatively poor mechanical strength.

This last characteristic requires that it should not be subjected to excessive vibration or movement. It should, therefore, not be located on an engine-generator baseplate.

Where space is limited, or if baseplate mounting is ideal, the recommended battery must be the flat plate type using high capacity positive plates of pasted grid construction, designed specifically for continual service involving high rates of discharge. It is worth noting that most post office telephone exchanges and hospitals use high performance Plante cells for their emergency generators.

### *Sealed lead acid batteries*

The term *sealed* tends to be euphemistically applied to cells varying from those of the so-called *maintenance-free* and *ultra-low maintenance* types to those large capacity cells of orthodox design which have sealed lids, but with vent plugs or explosion inhibitors to prevent acid spray or the ignition of internal gases.

Some ultra-low maintenance types (which are really semi-sealed units) employ a wet electrolyte and a facility for adding occasional drops of water, while others simply use an excess of electrolyte to minimize periods between topping-up with pure water.

The term sealed cell is now more usually applied to those cells which use gas recombination technology, and in which water loss is effectively eliminated and flammable gas emissions negligibly small. Cells are provided with venting devices which are designed to allow for release of gas if the cell is *abused.* The electrolyte may be in thixotropic gel form or it may be a liquid absorbed in a microporous matrix. Cell recharging needs careful control (current limited, constant potential charging) otherwise service life may be reduced. The only way to check capacity is by actual test discharges. Available capacities, at 8 hour rates, are as high as 8000 Ah for power cells on communications applications. This form of battery is also widely used in switchgear and UPS installations.

### B.1.2 Nickel cadmium batteries

Cells are usually of one of two types: *pocket-plate* or *sintered plate.* In the former, the plates, which are made of finely perforated nickel plated steel strip, are filled with the active materials (compressed into flat pellets): nickel hydroxides for the positive plates, and cadmium hydroxides for the negative plates. Sintered plate cells use a very porous matrix obtained by sintering special types of nickel powder. The plates contain voids into which the nickel and cadmium hydroxides are introduced by impregnation. The electrolyte (potassium hydroxide with lithium hydroxide added) plays no part in the chemical activity of the cell. It merely acts as a carrier of ions between the plates. Charge and recharge cycles result in only very small amounts of water being transferred between the electrolyte and the active materials of the plates. The specfic gravity of the electrolyte is, therefore, little affected by the cell's state of charge. Manufacturers recommend renewal of electrolyte when its specific gravity has dropped to about 1.16.

Cells suitable for the peak currents of engine starting duty employ a large number of closely-spaced, very thin, positive and negative plates. This speeds up the exchange of ions and gives a large effective-surface area for high performance.

## B.2. Sizing the battery for the application

### B.2.1 Capacity

The capacity (ampere-hours) which a cell supplies varies with the discharge rate which may be 3 hours, 5 hours, 8 hours, 10 hours, and so on - as indicated by the battery manufacturer. A 250 Ah battery may give 25 amperes at the 10 hour rate, but it doesn't follow that it will have an output capability of 250 Ah at the 1 hour rate. In practice, it will give less than 250Ah, and a *capacity factor* is generally applied by the manufacturer.

The battery capacity is therefore affected by discharge curren~. It is also affected by the battery temperature and, especially with lead acid batteries, by the strength of the electrolyte.

The data, tabled at the top of the next page, for a high performance Plante cell will illustrate the point [3].

Lead acid batteries are particularly affected by low-temperature environments. As the battery's stjlte of charge falls, the density of its electrolyte falls, and its freezing point rises. There is always, therefore, the risk of the electrolyte freezing as the battery discharges in low ambient temperatures. The problem is not so crucial with nickel cadmium cells since the density of their electrolyte varies very little with temperature. Normal specific gravity of 1.19 corresponds to a freezing point of about -25°C.

| | *Capacity in ampere-hours* *at 15°C* | | | *at 25°C* | | |
|---|---|---|---|---|---|---|
| Discharge time (hours) | 10 | 3 | 1 | 10 | 3 | 1 |
| Final voltage per cell (V) | 1.85 | 1.80 | 1.75 | 1.85 | 1.80 | 1.75 |
| | 500 | 406 | 300 | 536 | 438 | 327 |

For very low temperature applications, a stronger electrolyte, which has a freezing point of about -42°C, may be used [4].

The output capability of the selected battery must be such that if the engine does not start at the first attempt, there is sufficient capacity in the battery for further starting attempts (i.e. crank the engine above firing speed). The minimum number of repeat starts required, each of 10 seconds duration, should be three. This, in the context of the Fire Officers Committee (FOe) requirement that an emergency engine should have *two* separate batteries each capable of giving six starting attempts of 15s duration at 4°C. The American National Fire Pumps Association (NFPA), responsible for the National Electrical Code (NEe), also requires two separate batteries, each capable of twelve starting attempts of 15s duration at 4SC.

Bear in mind that the breakaway current demand of an engine may be 1.5 times its steady cranking current demand. Batteries should be sized so that lead acid cells are not discharged below 75 % of their nominal voltage, and nickel cadmium cells not below 50 % of nominal, after the repeat start requirements of the specification have been met.

### B.2.2 Voltage

Starter motor windings will determine the voltage of the system: 12 volts on the smaller engines and 24 or 32 volts on the larger high-speed engines, and on medium-output medium-speed engines, are common ratings.

The open-circuit voltage of a fully charged lead acid cell is 2 V; that of an alkaline cell is 1.2 V. This means that more nickel cadmium cells are required to make up a given battery than would be required for a lead acid battery. The number of cells normally used in 12, 24, and 32 volt systems are shown in the following table.

| | *12* | *24* | *32* | *Volts* |
|---|---|---|---|---|
| Number of cells | | | | |
| Lead acid | 6 | 12 | 16 | |
| Nickel cadmium | 10 | 19 | 24 | |

## B.3. Battery charging

Starter batteries rarely become more than 10 % discharged. The commonest means of recharging them is by the use of an engine (vee belt) driven alternator fitted with a rectifier and voltage regulator. The battery may also be charged through a transformer/rectifier deriving its power from the main a.c generator. The constant-voltage charging mode is recommended. This method of charging involves the application of a constant voltage to the battery, and charge current is allowed to vary according to battery demand.

For vented lead acid batteries, the charge should be set at 2.25 to 2.30 V per cell and it should be capable of providing a current of 7 % of the nominal battery capacity, i.e. 7 A for a l00AH battery. A boost circuit should be incorporated to raise the cell voltage to 2.70V per cell. The voltage setting must be carefully selected for nickel cadmium batteries so as to obtain the optimum performance against the minimum watering requirements. Typically, charging is at 1.35 to 1.50 V per cell, with boost facilities at around 1.60 V per cell. Fast recharging of gas recombination lead acid cells is not recommended. If it is absolutely essential, the maximum constant voltage should be 2.4 V per cell and the maximum current should be of the order of 35 A/l00 AH (35%). Normal charge voltage is between 2.25 and 2.27 V per cell and current is limited to 10 % of capacity (AH).

## B.4. References

1. Batteries for engine starting. Engineering Note S.211C, Chloride Industrial Batteries Ltd, February (1981)
2. Barraclough, T. Standby Plante gives high reliability. *Electrical Review,* 205(10), 14 September

(1979)
3. Tungstone Batteries Limited Publication T 203/4, February (1984)
4. Hodge, D. Starting gear and starting aids. Chapter 14 of *Diesel Engine Reference Book,* 1st edn, Butterworth, (1984)

# C

# Soil resistivity measurements and surveys

## C.1. Measurement of soil resistivity

The several methods of measuring soil resistivity are all variants of a 4-electrode arrangement originally developed by Dr. F. Wenner of the US Bureau of Standards. The recommended method involves the use of an earth testing instrument and four test electrodes driven into the ground in a straight line at equal distances apart (see Figure C.!). The depth of insertion of the test electrodes should not exceed 1I20th of the electrode spacing, *s*.

A current is passed between the two outer electrodes ($C_1$ and *Cz)* and the resultant voltage is measured between the inner pair (PI and $P_2$). The meter reading expresses the ratio of voltage to current in a direct-reading ohmic resistance value. On some null-balance earth test instruments the guard-terminal must be connected to a spike inserted midway between $C_2$ and $P_2$.

The resistivity of the soil at a depth equivalent to two-thirds of the spacing between the test electrodes, is given by:

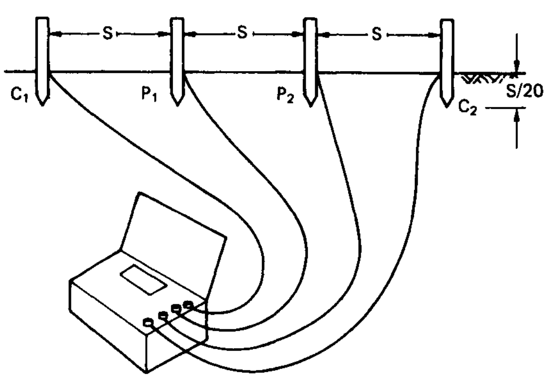


**Figure C.1** Method of measuring soil resistivity

p = 21Ts *Rm* (ohm-em)

where *Rm* = the earth test meter reading (ohms)
*s* = the test electrodes' separation distance (em)

Soil resistivity at greater depths may be explored by increasing the electrode spacing, *s*. One may then decide if there is any advantage to be gained by deep-driving earth electrodes or even going down to the maximum depth that earth rods can be driven at that particular location.

The formula may be re-written using a term for rod electrode length rather than test electrode spacing:

p = 31T*L* *Rm* (ohm-em)

where *L* = the proposed site earth rod electrode depth (em)

It is important that the electrode configurations CPPC or PCCP are observed during the tests. Departure from either arrangement could give very misleading results. For example:

- for arrangements CPCP and PCPC, p = 31Ts *Rm'* and
- for arrangements CCPP and PPCC, p = 61T *s* *Rm.*

Inadvertent transposition of test electrodes (or cross-connection of test leads) could, therefore, give resistivity values three times greater than actual.

## C.2. Survey techniques

There are, basically, two methods of obtaining site soil resistivity information: by *line traverses* or by *expanded traverses.* The first is used when horizontal earth electrodes (such as tapes and strips) are to be installed, and the latter when vertical electrode installations are planned.

## C.2.• Line traverse

This method uses a constant test electrode separation distance, *s*. The electrodes are usually driven-in at separation distances equal to the depth at which it is intended to bury or drive the permanent earth electrodes.

Readings are made with the electrodes positioned along a straight line. In practice, between 8 and 10 test electrodes are used. The earth test meter is initially connected to the first four electrodes and the first resistance reading taken. Meter connections are then transferred to electrodes 2, 3, 4 and 5 and a second reading taken. Progressive readings are made by moving along, an electrode at a time, until the planned traverse is completed. As readings proceed, the disconnected electrode is 'retrieved' and driven-in ahead of those already in position. The average resistivity of the traverse is equal to the mean of the readings taken.

It is usual to make a number of parallel line traverses - if possible - in a grid format, the distance between each traverse being equal to either *s* or *L*. Data may then be expressed in the form of resistivity contour maps, using lines of *equal resistivity* (either in terms of p or the direct meter reading, *Rm*). The permanent earth electrodes would then be installed in the areas of low resistivity identified on the site plan.

## C.2.2 Expanded traverses

In this method, the four equally-spaced test electrodes are separated in increasing, equal increments about the mid-point of the traverse line. The maximum electrode separation for all practical purposes is between 12 and 15 metres. Since the depth of test electrode penetration *(s/20)* must be proportional to the electrode separation distance, it is important to remember that the penetration must vary with each reading, i.e as the separation distance 'expands'.

The method gives resistivity readings for increasing depths and therefore allows vertical (or depth) changes in resistivity to be investigated. It is recommended that at least one expanded traverse is made on site.

## C.2.3 Equipment and procedures

### *Equipment*

In addition to the portable earth test meter, the following equipment will be required:

1. test electrodes;
2. cables;
3. stakes, pegs, tapes and measuring equipment,

with adequate spares for each of the above items. Test electrodes, made from 20 mm galvanized conduit and flattened at one end to facilitate driving, should be about 300 mm long for line traverses and about 1.25 m long for expanded traverses. Cables should be single core, flexible, and no longer than necessary. Identification by sheath colours is desirable. Battery clips, fixed to one end of the cable, give the most convenient form of connection to the test electrodes.

Other esssentials are:

- hammers;
- wire cutters;
- adhesive tape and labels;
- a compass;
- a small tin of white paint, and a paint brush - for identification of particular pegs or stakes;
- a camera to record the location of the surveyed site, relative to any topographical or building landmarks.

### *Procedures*

Surveys are time-consuming. It would take a party of three more than two days to complete the readings on a hectare site on which test electrode separations are about 5 m. It is important to stress at briefings the need to maintain correct electrode separation and penetration depth. A simple explanation of the purpose of the survey, supported by a few exploratory demonstration runs, will pay dividends in the long run.

The lines of traverses and the salient identification points on the site should be marked-out with pegs, stakes and/or tapes. These should be left *in-situ* until the survey's findings are completed. It is a good idea to photograph the pegged and taped-out site for record purposes.

Cable leads may have the electrode spacings premarked on them, in paint. This removes the need for extraneous measuring tapes and each lead is, effectively, its own tape measure.

# D Device function numbers

## 0.1. Purposes

A device function number, with appropriate suffix letter or letters where necessary, is placed adjacent to the device symbol. It is intended to identify the function of each device on arrangement drawings, connection diagrams, in instruction books and in specifications, for all types of switchgear. The device function number is also attached to, or located adjacent to, each device in the assembled equipment so that it may be readily identified.

## 0.2. Related standards

The American Standlard ANSI C37.2 is recognised as the definitive publication on the subject. British Standard BS 3939 (Appendix II of *Guiding principles)* follows it almost entirely, with only minor differences in wording on some function titles and definitions.

## 0.3. Suffix letters

Suffix letters are used with function numbers for various purposes. There are so many specific component references related to functional use in different applications that it is 'impracticable to quote or attempt to standardize any complete list' (BS 3939). ANSI C37.2lists auxiliary device letter designations from 'A - Air, automatic, or accelerating' to 'X, Y and Z' for separate 'auxiliary devices'. In the protective relaying context, the letter 'N' is generally used if the device is connected in the secondary neutral of current transformers.

Manufacturers will often compile their own lists of functional component (letter) references. It is then important that they are clearly identified in the relevant drawings, or group of drawings. For example, one may find that the letters L, U, G and P may be intended by a manufacturer to differentiate between 'line', 'utility', 'generator' and 'plant' circuits; whereas in ANSI C37.2 codes 'U' is 'upper operating coil', 'P' is 'power', and 'line' is not included among the recognised designations for 'L'.

Where several devices with the same function number and suffix letter are present in the same equipment, it is customary to use numbered suffixes to distinguish between them (e.g. 27-1 and 27-2; 59X-l and 59X-2).

## 0.4. Standard device function numbers

Tabulated below are some of the numbers, and the corresponding functions, that are most lik-ely to be found on engine-generator protection schemes.

2. Time-delay starting or closing relay
3. Checking, or interlocking, relay
5. Stopping device
12. Over-speed device
13. Synchronous-speed device
14. Under-speed device
15. Speed, or frequency, matching device
20. Electrically operated valve
25. Synchronizing or synchronism-check device
26. Apparatus thermal device
27. Undervoltage relay
30. Annunciator relay
32. Directional power relay
37. Undercurrent or underpower relay
38. Bearing protective device
39. Mechanical condition monitor (e.g. excessive vibration)
40. Field relay
41. Field circuit breaker

44. Unit sequence starting relay
45. Atmospheric condition monitor (e.g. smoke or fire)
46. Reverse phase or phase-balance current relay (e.g. unbalanced currents or those containing n.p.s. components above a given amount)
49. Machine or transformer thermal relay
50. Instantaneous overcurrent or rate-of-rise relay
51. A.C time overcurrent relay
52. A.C circuit breaker
53. Exciter or d.c. generator relay
55. Power factor relay
56. Field application relay (e.g. pole-slip protective relay)
57. Short-circuiting or earthing device
59. Overvoltage relay
60. Voltage balance relay
61. Current balance relay
62. Time-delay stopping or opening relay
63. Liquid or gas pressure or vacuum relay (would be used for pressure switches)
64. Earth-fault protective relay [Note: this is not applicable to 'a device connected in the secondary circuit of a c.t., or in the secondary neutral of a c.t., connected in the power circuit of a normally earthed system' (BS 3939)]
65. Governor
67. A.C. directional overcurrent relay
68. Blocking relay (defined in BS 3939 as a 'relay that initiates a pilot signal for blocking or tripping on external faults ... under predetermined conditions')
69. Permissive control device (generally a manually operated two-position switch that gives ON/OFF type control)
70. Electrically operated rheostat
71. Liquid or gas-level relay (in our context, a level switch, for example)
74. Alarm relay
76. D.C. overcurrent relay
77. Pulse transmitter (in our context, could be applied to a magnetic pick-up)
78. Phase-angle measuring or out-of-step relay (one that functions at a predetermined phase angle between two voltages or between two currents or between voltage and current)
80. Liquid or gas flow relay (would be used for a flow switch)
81. Frequency relay
83. Automatic selective control or transfer relay [ a relay that operates to select automatically between certain sources or conditions in an equipment, or perform a transfer function automatically' (BS 3939)]
84. Operating mechanism ['the complete electrical mechanism or servo-mechanism ... for any piece of apparatus which otherwise has no device function number' (BS 3939)]
86. Locking out relay
87. Differential protective relay
89. Line switch ['a switch used as a disconnecting, load-interrupter, or isolating switch in a ... power circuit, when this device is electrically operated or has electrical accessories, such as auxiliary switch, magnetic lock etc.' (BS 3939)]
90. Regulating device (in our context would be applied to an a.v.r.)
92. Voltage and power directional relay
94. Tripping or trip-free relay ['a relay that functions to trip a circuit breaker, contactor, or equipment, or to permit immediate tripping by other devices ... ' (BS 3939)]

(95-99 are used only for specific applications in individual installations, where none of the assigned number functions from 1-94 are suitable.)

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