

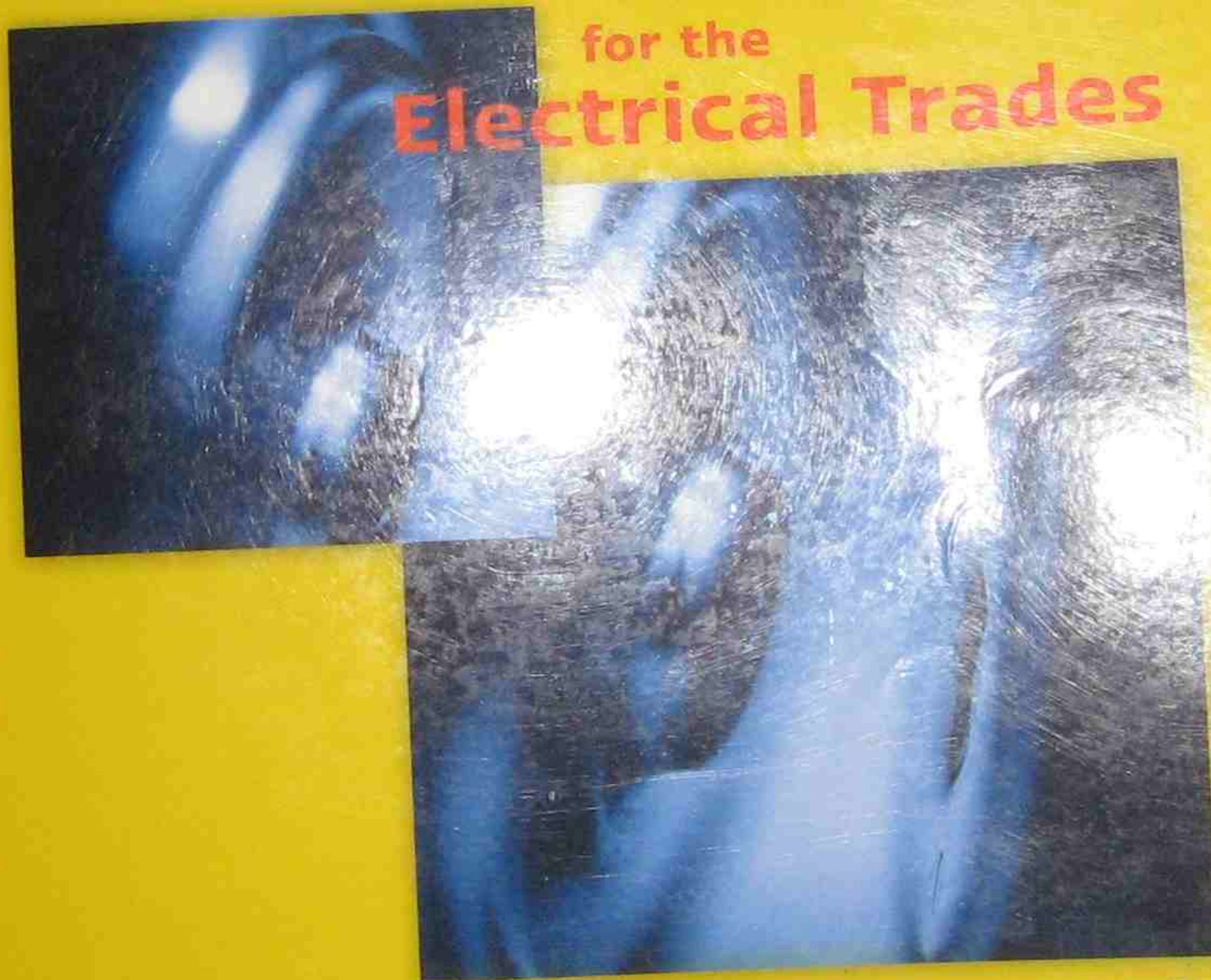
# Electrical Principles

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for the  
**Electrical Trades**



5th edition

**Jim Jenneson**

621.3



# Chapter 10

## Alternating current machines

### 10.1 INTRODUCTION

The majority of a.c. motors used in industry are of the induction type. They are rugged and have a high degree of reliability. A three-phase induction motor consists of a laminated stator with three identical windings placed symmetrically in slots within it. The rotor is also laminated and usually has single-turn conductors placed within its slots and short-circuited at the ends. To achieve special characteristics, conventional windings are sometimes used instead. The motor derives its name from the fact that the currents flowing in the rotor are induced and not drawn directly from the supply.

### 10.2 THREE-PHASE INDUCTION MOTORS

#### 10.2.1 Stator

The laminated stator core is made from sheet steel stampings with slots on the inner surface. Three identical windings are laid out in the same fashion as the alternator and synchronous motor. In motors of higher power ratings, the stator slots are of the open type to allow the insertion of pre-shaped and insulated coils, but in smaller sizes the slots are partially closed to reduce the air gap as much as possible.

The stator core is held in the motor frame, which also serves to carry the bearings holding the rotor, to protect the coils and to provide a means whereby the whole can be mounted (see Fig. 10.1).

The motor frame takes various forms, depending on the conditions under which the motor will operate. An open-type frame allows free ventilation; a drip-proof frame has a closed upper half, while allowing ventilation through the lower half; a totally enclosed type prevents the exchange of air between the inside and the outside of the frame.

#### 10.2.2 Rotor

##### Squirrel-cage rotor

The rotor of a three-phase motor consists of a shaft with bearings, laminated iron core, and rotor conductors. The most common type of construction is that with rotor bars in the lamination slots rather than a winding. The rotor bars, short-circuited at each end by a solid ring, are often made of copper strip welded to copper rings, but for small- to medium-size motors they may be cast in one piece out of aluminium. Usually included in the rotor casting is a series of vanes for creating air movement. Figure 10.2



Figure 10.2 • Squirrel-cage rotor for an induction motor

Pope Electric Motors

shows these vanes standing out from each shorting ring. The photograph also shows skewed conductors in the rotor.

The main purpose for slanting the conductors in the rotor is to ensure a smooth steady acceleration during starting. Varying the physical design features of the bars affects motor performance. Embedding them deeper into the rotor, for example, increases their inductance and gives a lower starting current but at the same time creates a lower pull-out torque.

This type of rotor is then restricted to loads requiring low starting torques, such as centrifugal pumps. The rotor windings, if assembled without the laminations, resemble a metal cage giving rise to the often-used name 'squirrel-cage' rotors, although the standards refer to them simply as 'cage' rotors.

##### Wound rotor

The wound rotor is fitted with insulated windings, similar to the stator winding and having the same number of poles. Usually the rotor winding has three phases, connected internally in star configuration, and terminating at three slip-rings. A typical wound rotor is shown in Figure 10.3.



Figure 10.3 • Wound rotor for an induction motor

Brook Crompton

The slip-rings are connected by means of brushes to a star-connected variable resistance, as in Figure 10.4. This rotor rheostat provides the means of increasing the

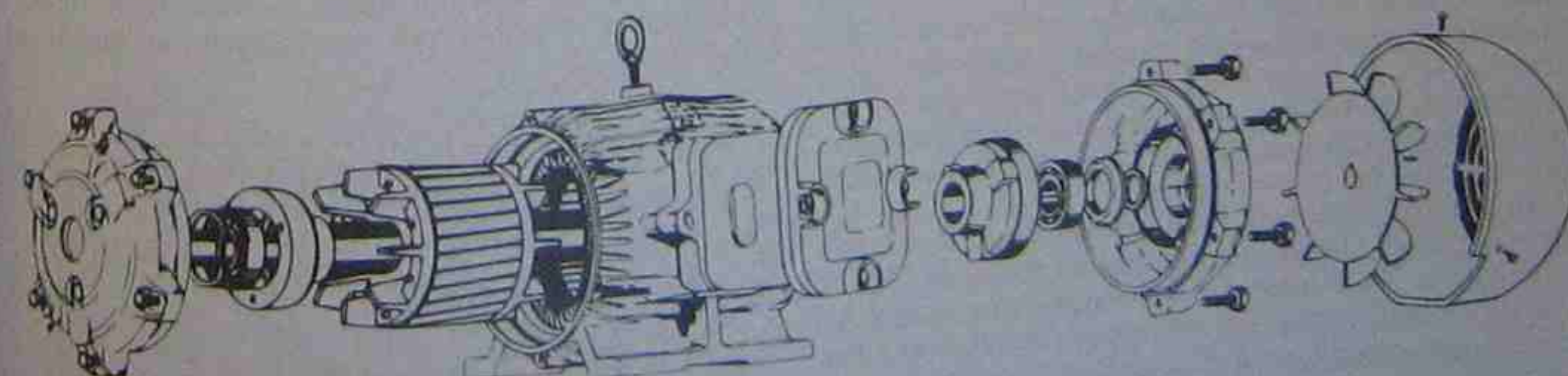


Figure 10.1 • Component parts of a three-phase induction motor mounted in a flame-proof housing  
Wernick E. H. (ed.) (1978), *Electric Motor Handbook*, McGraw-Hill Book Co./Brook Crompton



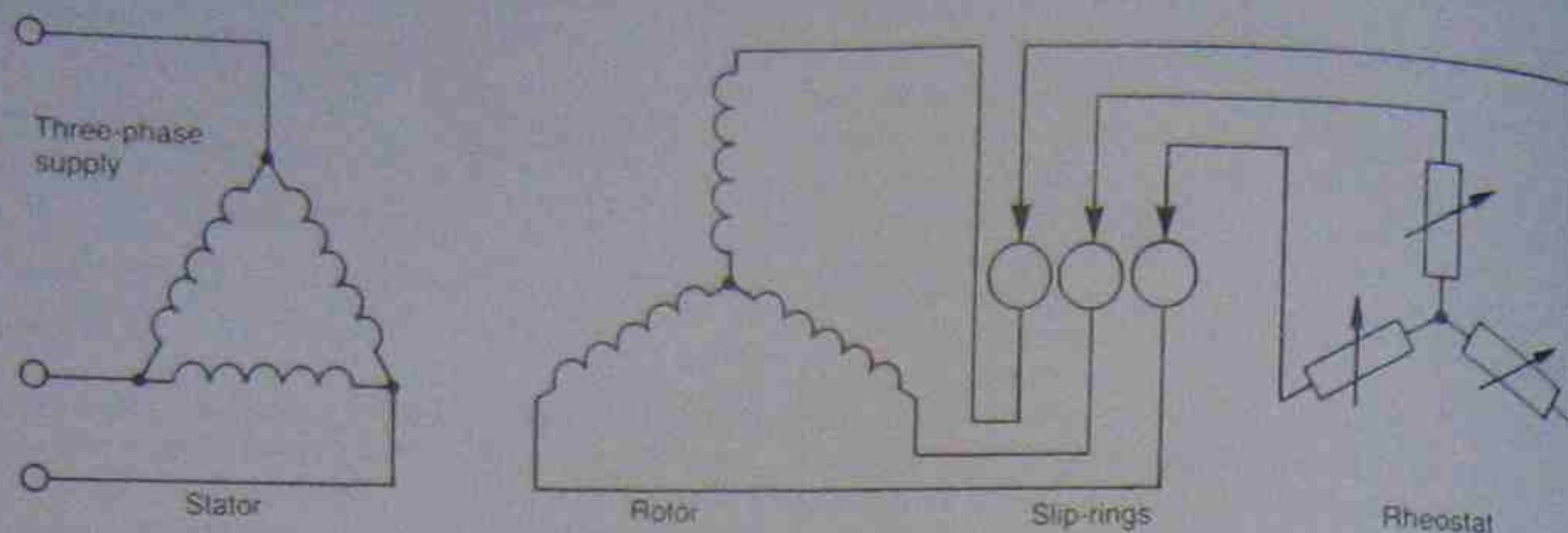


Figure 10.4 • Circuit for a wound-rotor induction motor

resistance of the rotor circuit during starting, thereby producing a high starting torque at a low starting current. As the speed increases, the external resistance is gradually reduced, lowering the rotor circuit resistance as the rotor reactance decreases.

Under operating conditions, the variations in rotor circuit resistance provide a means of controlling the speed of the motor—an increase in resistance produces a reduction in speed. This also produces a loss in efficiency due to the  $I^2R$  losses in the rheostat.

The wound-rotor motor is more expensive than the squirrel-cage motor, owing to the cost of manufacture of the wound rotor. It also has a higher starting torque and lower starting current, but poorer running characteristics than the squirrel-cage motor.

### 10.2.3 Motor enclosures

The conditions governing the actual installation of an induction motor are normally beyond the control of the motor manufacturer. As a result, the motor is manufactured in various enclosures. A motor driving a compressor for a refrigerated display cabinet, for example, may operate under such clean and dry conditions that the motor enclosure need only provide a mounting for the bearings and a means for fixing the motor in a horizontal plane. At the same time the enclosure provides mechanical protection against accidental spillage and enables cooling air to circulate freely through the motor windings.

Compare this situation with a water turbine pump used for irrigation purposes. In most cases the motor is mounted vertically at the bore head and is given no protection from the weather. The motor needs to be totally enclosed to prevent the entry of water, and cooling is by means of heat transfer through the motor housing. The air sealed within the motor housing is circulated by an internal fan, so transferring the heat generated by the windings to the housing. This heat is then transferred to the atmosphere by a second fan circulating free air across the outside of the motor housing.

For detailed information on electric motor standards, reference should be made to Australian Standard AS/NZS 1359 on the requirements for rotating electrical machines. It is an extensive standard with many sections and often calls up other standards that may be relevant to particular sections. Electrical rotating machinery is now classified by two letters followed by four numerals. This classifica-

tion number is different for such categories as cooling, mounting and protection.

### 10.2.4 Terminal block arrangements

#### Squirrel-cage motors

Most three-phase motors have all six winding ends brought out to a six-terminal block. The only exceptions are small dedicated-purpose motors that can be started directly on line and designed to run in either star or delta configuration at all times.

By custom and some attempts at standardisation, the phase ends are brought out to terminals in one of two possible arrangements. In Figure 10.5(a) the more usual arrangement is shown, while Figure 10.5(b) illustrates an alternative system of connections.

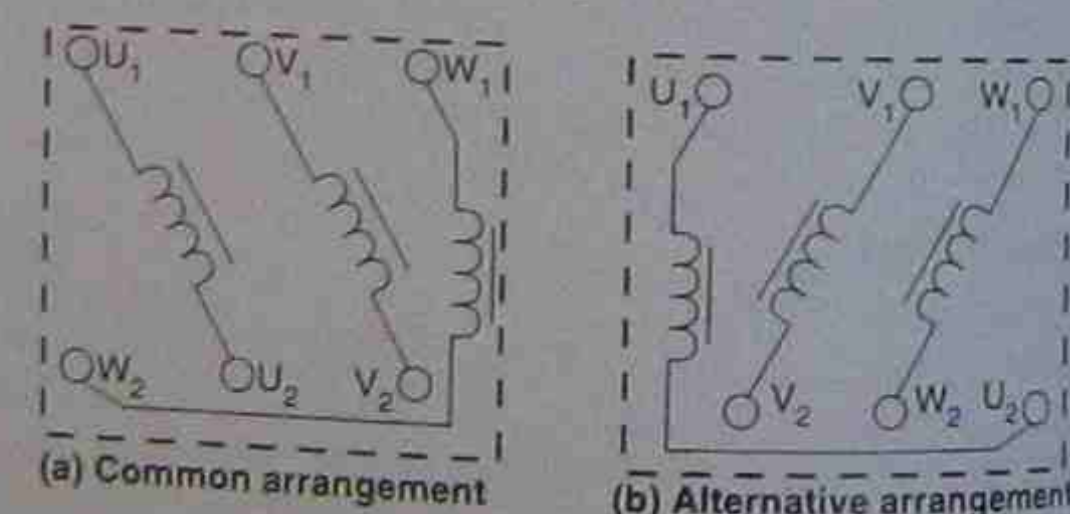


Figure 10.5 • Winding connections to the terminal block of a three-phase motor

The intention is to simplify connecting arrangements for personnel installing the motor or reconnecting it after maintenance. To connect a motor in either star or delta configuration, winding ends are bridged, as shown in Figure 10.6.

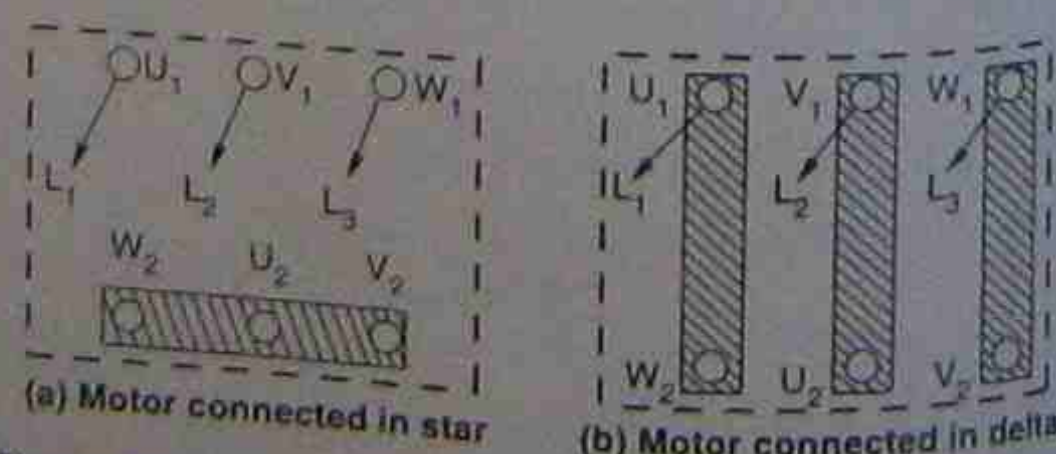


Figure 10.6 • Bridging connections in a three-phase terminal block

The points to note are:

1. Individual phase ends are not connected to terminal pairs but are 'offset' as shown.
2. Connecting a motor in star configuration means that the windings have only 58 per cent of the line voltage applied to them.
3. In star configuration, one bridge couples all three corresponding ends of each winding.
4. The bridge can be placed across the beginnings of the phase windings instead of the ends as shown. The lines are connected to the opposite ends to the bridge.
5. There is no alternative option for the bridges when connecting a motor in delta configuration. Each bridge connects to line voltage.
6. While bridges or shorting strips are shown in Figure 10.6, it might be necessary to remove the bridges so that all six ends of the windings can be connected to a starter, for example, a star-delta starter.

#### Wound-rotor motors

With wound-rotor motors it is common to connect the stator windings internally in either star or delta configuration as required—usually delta. The terminal block will still have six terminals because the three appropriate ends of the rotor windings are connected in star configuration internally and the other ends brought out via slip-rings to the terminal block.

It is usual to identify them in some way, such as separating them from the line terminals of the stator windings or using a different type of terminal connector. Care should be taken to observe that line voltages are not connected to the rotor terminals.

## 10.3 OPERATING PRINCIPLES

### 10.3.1 Rotating magnetic fields

For its operation, a three-phase induction motor is dependent on a rotating magnetic field being established by the a.c. windings. The three separate windings are installed in the stator at  $120^\circ$  intervals to one another and provide a fixed number of poles for each phase. This is shown diagrammatically in Figure 10.7(a) for one

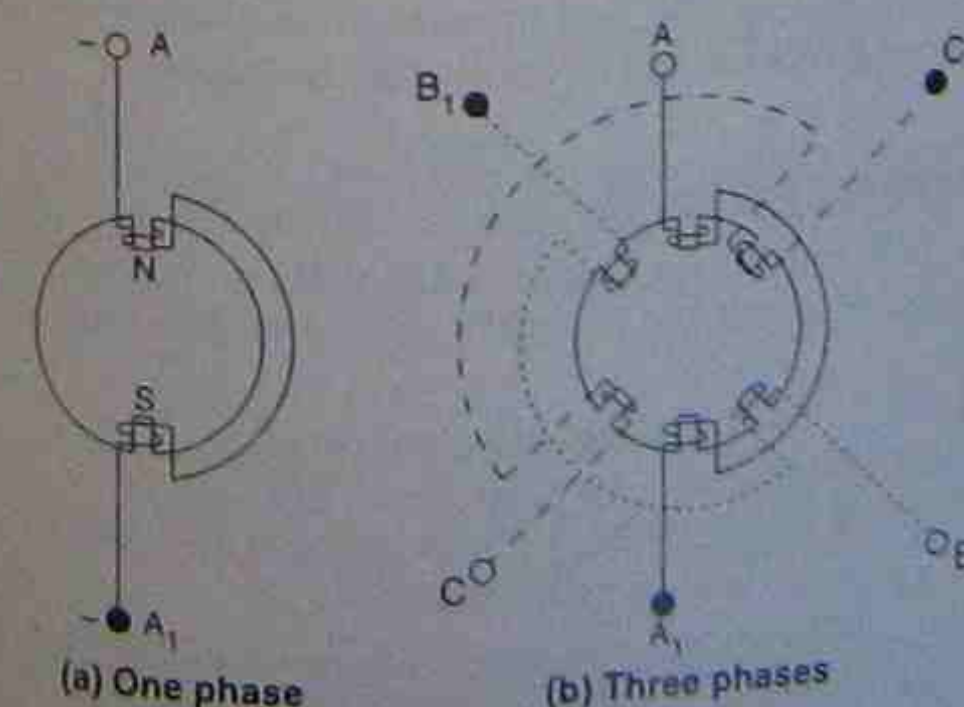


Figure 10.7 • Polarities and connections in a two-pole, three-phase motor

phase of a two-pole machine. Figure 10.7(b) shows three phases in relation to one another, giving six poles. Phase A is drawn as a solid line, phase B as a dotted line and phase C as a dashed line. Note the sequence is carried through for the explanation applies to the current waveforms, the magnetic field and the phasors.

#### Assumption

In the following explanation for the production of a rotating magnetic field, one assumption has been made as a starting point. That winding ends A, B, C, when connected to a source of voltage, makes the adjacent iron core a magnetic pole. From this it will follow that the other poles become south magnetic poles. These details are shown in Figure 10.7(a). If the current flow is reversed, then the magnetic poles are also reversed.

With the three windings connected in star configuration by joining ends A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub> together, and the ends A, B, C are connected to a three-phase supply, the currents  $I_A$ ,  $I_B$  and  $I_C$  are  $120^\circ$  out of phase with one another. These are shown in Figure 10.8.

Because each current is alternating, each phase sets up a magnetic flux that continually changes polarity to the other. Note that although the flux in phase A in Figure 10.7(b), for example, alternates in direction in the diagram, it does not rotate in space. It simply varies in strength and direction in time. Similarly, a pulsating flux is also established in the other two phases, giving a total of three magnetic fields that combine into one resultant flux. This flux rotates at synchronous speed. At reference position 1 in Figure 10.8, the current  $I_A$  is zero and no flux is produced by winding A-A<sub>1</sub>. Current  $I_B$  is negative and so will produce a south pole at B and a north pole at B<sub>1</sub>. Current  $I_C$  is positive and so will produce a north pole at C and a south pole at C<sub>1</sub>. Because currents  $I_B$  and  $I_C$  are equal in strength, the resultant magnetic field is shown in Figure 10.9(a). In the phasor diagram the addition of these three fields is shown, giving a resultant instantaneous field.

At position 2 in Figure 10.8,  $I_A$  is positive while  $I_C$  is zero. This produces a north

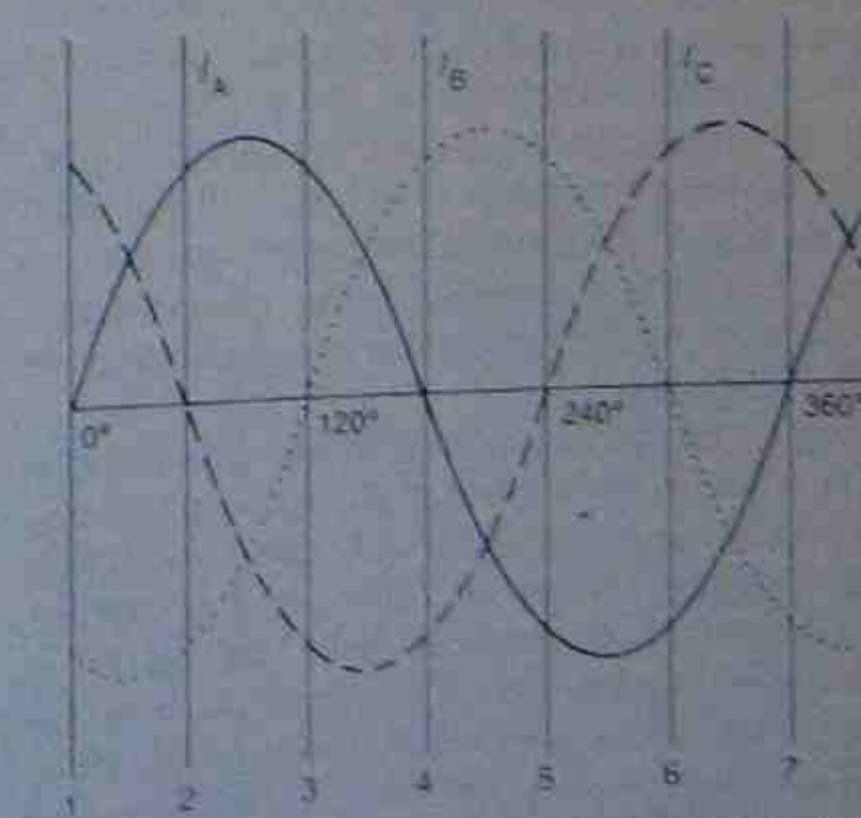


Figure 10.8 • Waveform diagram showing three-phase currents at  $120^\circ$  to one another (for reference see text)



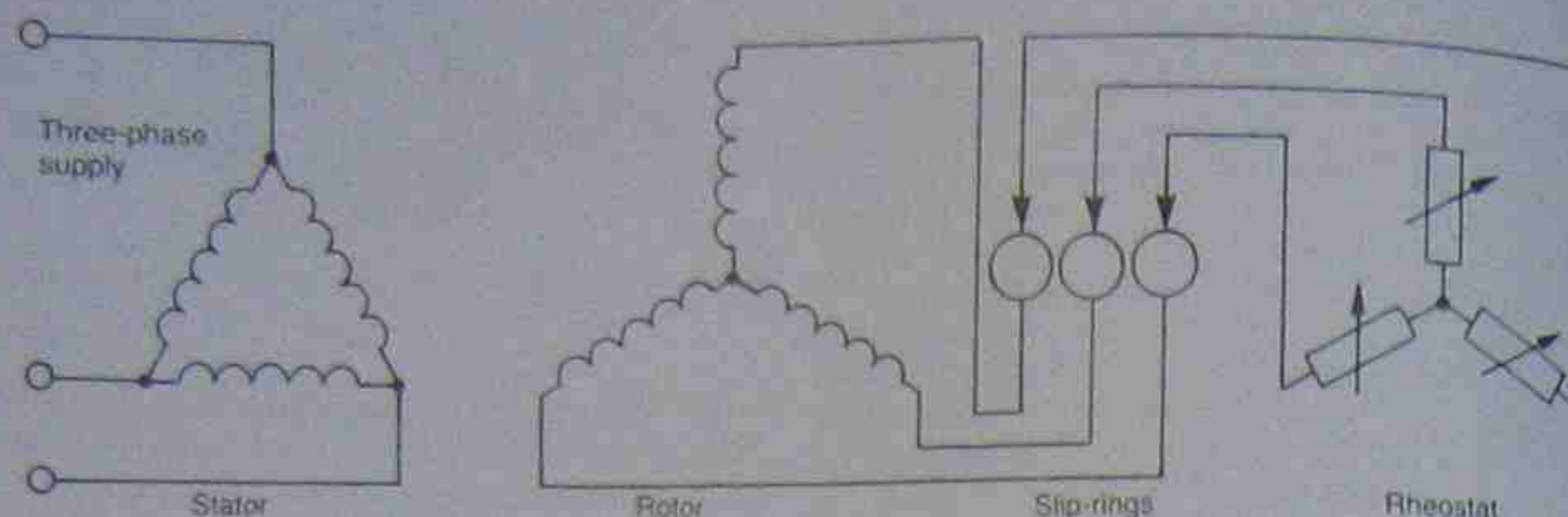


Figure 10.4 • Circuit for a wound-rotor induction motor

resistance of the rotor circuit during starting, thereby producing a high starting torque at a low starting current. As the speed increases, the external resistance is gradually reduced, lowering the rotor circuit resistance as the rotor reactance decreases.

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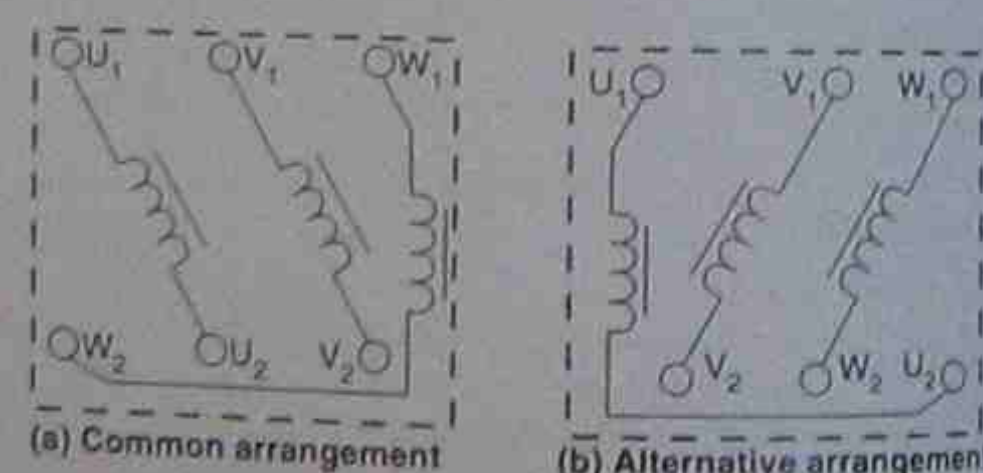


Figure 10.5 • Winding connections to the terminal block of a three-phase motor

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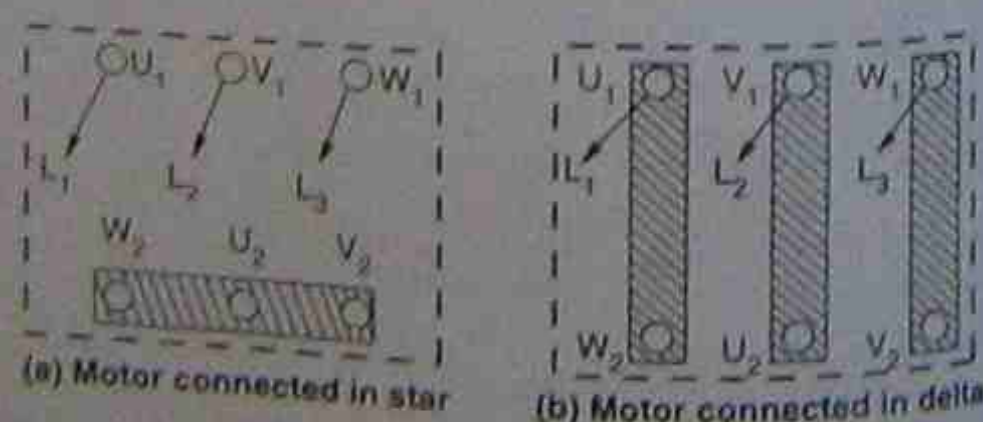


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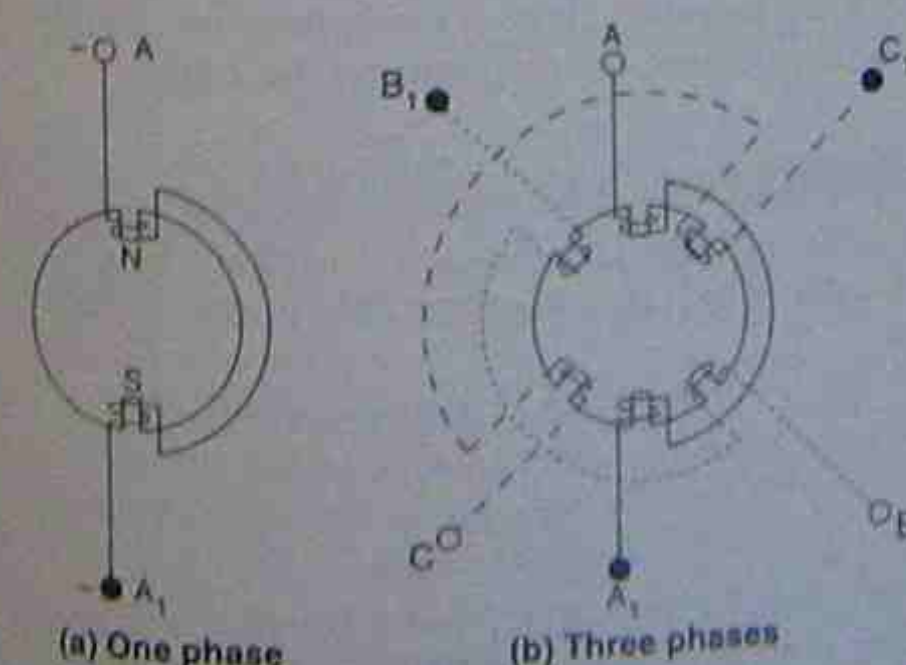


Figure 10.7 • Polarities and connections in a two-pole, three-phase motor

phase of a two-pole machine. Figure 10.7(b) shows the three phases in relation to one another, giving a total of six poles. Phase A is drawn as a solid line, phase B as a dotted line and phase C as a dashed line. Note that this sequence is carried through for the explanation and applies to the current waveforms, the magnetic fields and the phasors.

#### Assumption

In the following explanation for the production of a rotating field, one assumption has been made as a reference, that winding ends A, B, C, when connected to a positive source of voltage, makes the adjacent iron core a north magnetic pole. From this it will follow that the opposite poles become south magnetic poles. These details are also shown in Figure 10.7(a). If the current flow is reversed, then the magnetic poles are also reversed.

With the three windings connected in star configuration by joining ends A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub> together, and the ends A, B, and C are connected to a three-phase supply, the phase currents  $I_A$ ,  $I_B$  and  $I_C$  are  $120^\circ$  out of phase with one another. These are shown in Figure 10.8.

Because each current is alternating, each pair of poles sets up a magnetic flux that continually changes from one polarity to the other. Note that although the flux set up by phase A in Figure 10.7(b), for example, alternates in the direction in the diagram, it does not rotate in any way. It simply varies in strength and direction in the vertical plane. Similarly, a pulsating flux is also established by the other two phases, giving a total of three magnetic fluxes that combine into one resultant flux. This flux rotates at synchronous speed. At reference position 1 in Figure 10.8, the current  $I_A$  is zero and no flux is produced by the winding A-A<sub>1</sub>. Current  $I_B$  is negative and so will produce a south pole at B and a north pole at B<sub>1</sub>. Current  $I_C$  is positive and so will produce a north pole at C and a south pole at C<sub>1</sub>. Because currents  $I_B$  and  $I_C$  are equal, the two magnetic fields are equal in strength. The directions of these fields are shown in Figure 10.9(a). In the accompanying phasor diagram the addition of these two fields is shown, giving a resultant instantaneous field  $\Phi_R$ .

At position 2 in Figure 10.8,  $I_A$  is positive,  $I_B$  is still negative while  $I_C$  is zero. This produces a north pole at

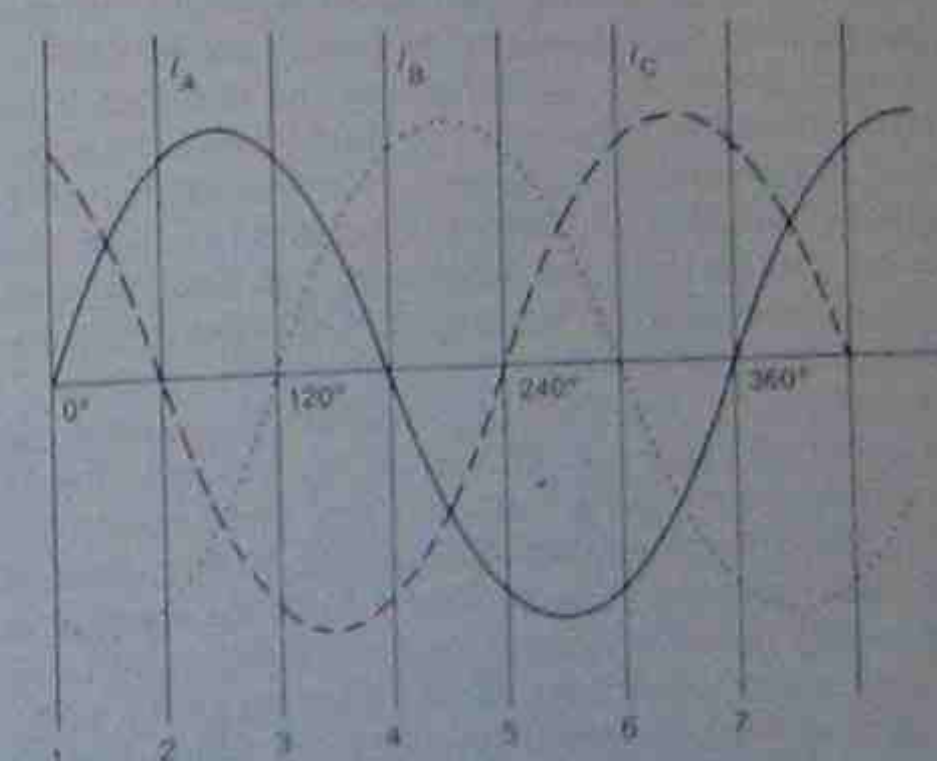


Figure 10.8 • Waveform diagram showing three-phase currents at  $120^\circ$  to one another (for reference numbers, see text)



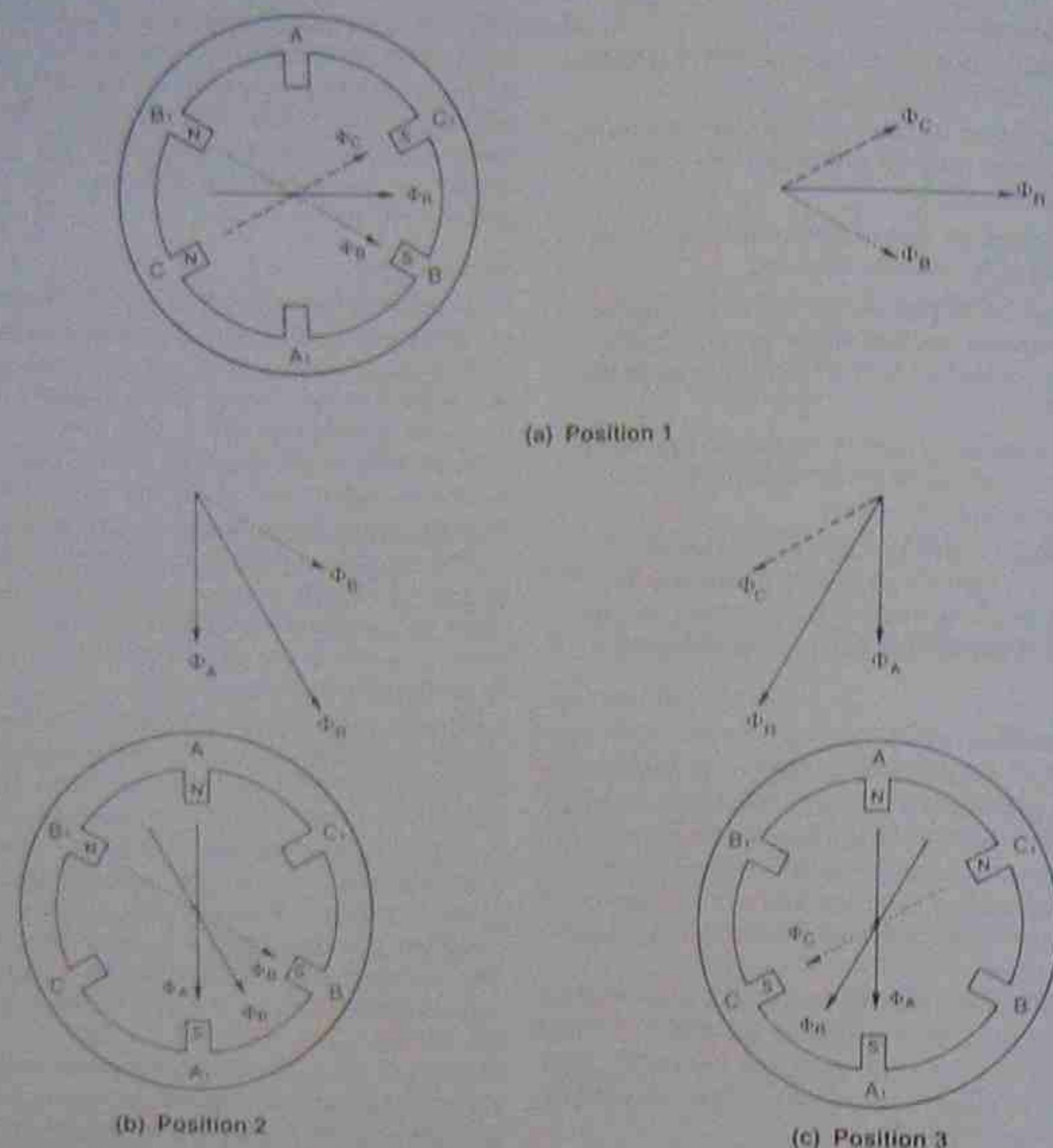


Figure 10.9 • Resultant flux produced at positions indicated from Figure 10.8

A, a south pole at B, and nothing at C. These are shown in Figure 10.9(b) together with the phasor diagram showing the addition of the phasors to give the resultant instantaneous magnetic field. Since all coils have an equal number of turns, the relative strengths of the magnetic fields can be gauged by measuring the vertical heights of the current waveforms at the positions indicated by the reference number. In this instance the direction of the resultant magnetic field has shifted 60° clockwise from that in position 1. If drawn to scale it can also be shown that the length of the resultant has remained constant, indicating that the field strength has remained constant.

At position 3 (Fig. 10.8),  $I_A$  is positive, producing a north pole at A and a south pole at  $A_1$ .  $I_B$  is zero, and  $I_C$  is negative, producing a south pole at C and a north pole at  $C_1$ . These fields are drawn in Figure 10.9(c) together with their phasors. The resultant field has rotated a further 60° in a clockwise direction. (There is a 60° difference between all the numbered positions in Fig. 10.8.) For each of the numbered positions, the resultant field rotates a further 60° in a clockwise direction. For one complete cycle of current (360°) the resultant magnetic field rotates 360°.

### 10.3.2 Rate of rotation and factors affecting it

By comparing Figures 10.8 and 10.9 it can be seen that for the time intervals of 60°E between positions 1, 2 and 3 the resultant field rotates an equal amount around the stator. For a complete cycle of a.c., a two-pole field rotates one complete revolution around the stator. The synchronous speed of the magnetic field in revolutions per minute can be determined from the frequency of the supply.

#### Example 10.1

A two-pole machine is connected to a 50 Hz supply. Find the speed at which the magnetic field rotates around the stator.

$$\begin{aligned} 50 \text{ Hz} &= 50 \text{ cycles per second} \\ \text{speed of rotation} &= 50 \text{ revolutions per second} \\ &= 50 \times 60 \text{ revolutions per minute} \\ &= 3000 \text{ r/min} \end{aligned}$$

With a four-pole machine, 360° represents one-half of a full revolution of the stator field, and the speed of rotation of the field is consequently halved. Similarly, the speed of field rotation for a six-pole machine is reduced

to one-third that of a two-pole machine. In each case the speed is usually expressed in revolutions per minute, whereas the frequency is in hertz (cycles per second). The speed in revolutions per minute can be found from the following formula:

$$n_{\text{syn}} = \frac{120f}{p}$$

where  $n_{\text{syn}}$  = number of revolutions per minute  
 $f$  = frequency in Hz  
 $p$  = number of poles

The speed  $n$  of the rotating magnetic field is called the synchronous speed of the motor. The synchronous speeds of common sizes of motors of a frequency of 50 Hz are given in Table 10.1. The formula above is identical to that shown in section 8.7.1.

Table 10.1 • Speed of the rotating field in an induction motor for various number of poles

Poles	2	4	6	8	10	12
Synchronous speed (r/min)	3000	1500	1000	750	600	500

### 10.3.3 Direction of rotation and reversal

The direction of rotation of a rotating field depends on the phase sequence of the three currents flowing through the windings. In Figure 10.10(a), the three supply lines R, W and B are connected to terminals A, B and C of the motor. The resultant magnetic field rotates clockwise.

In Figure 10.10(b), the supply lines to phases B and C have been changed over and, using the procedure from the previous section, it can be shown that the rotation of the magnetic field is reversed. That is, the direction of rotation of the field can be controlled by interchanging any two supply lines to the motor. In section 10.4.1 on torque, it is shown that the rotation of a three-phase induction motor is in the same direction as that of the rotating field.

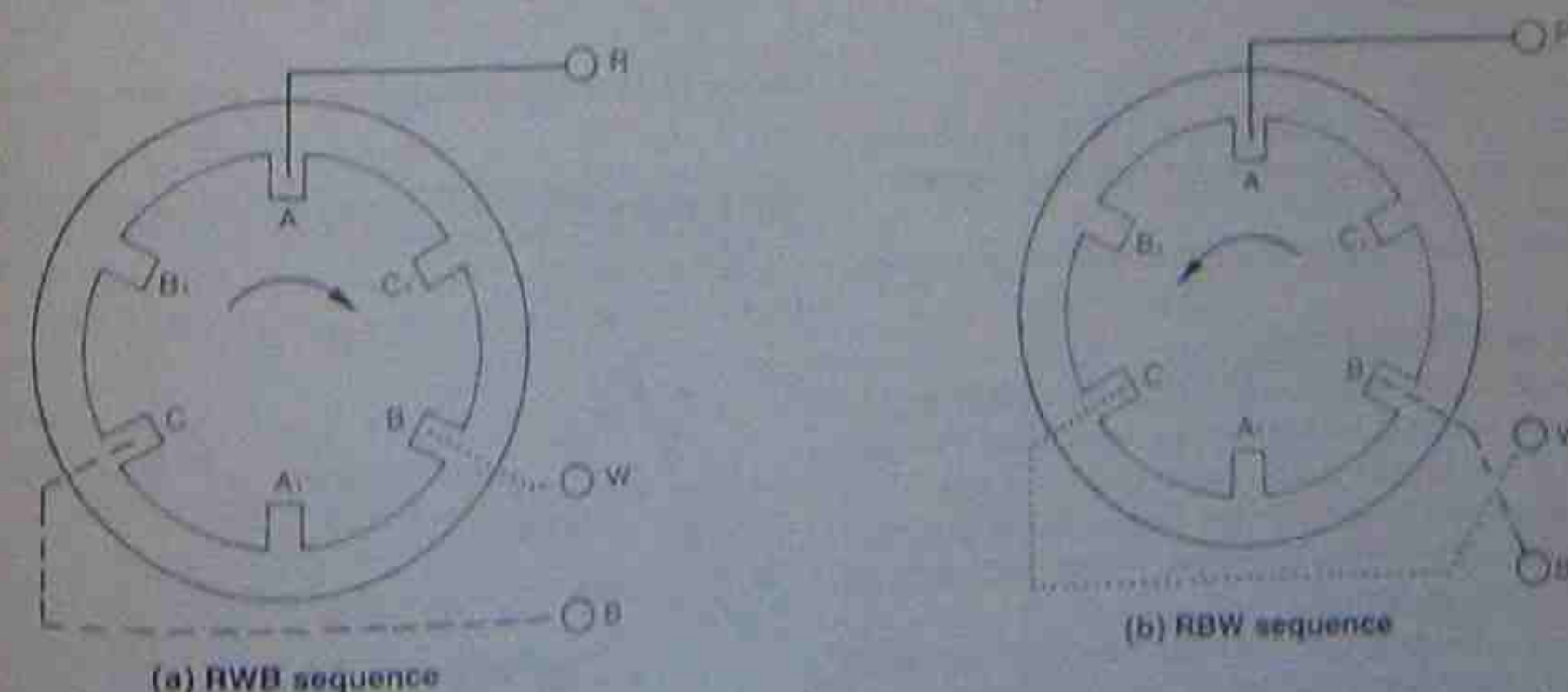


Figure 10.10 • Phase sequence and field rotation

## 10.4 INDUCTION AND ITS EFFECTS

When the stator windings of a three-phase induction motor are energised from a three-phase supply, a magnetic field is produced, rotating at synchronous speed. This rotating magnetic field crosses the air gap and cuts the rotor conductors, inducing a voltage in them (magnetic field, conductors and relative motion). When the rotor circuit is complete (through end rings in the case of the squirrel-cage rotor, or external resistance in the case of the wound rotor) the induced voltages cause high currents to flow in the rotor conductors.

### 10.4.1 Torque

Figure 10.11(a) shows a part of the stator and air gap of an induction motor with the stator flux rotating clockwise as indicated. When these lines of force cut the rotor conductors from left to right, the relative movement between the stator flux and the rotor conductor is from right to left. By applying Fleming's right-hand rule (section 8.3.3), the direction of induced current flow in the conductor is towards the reader. Owing to the comparatively high rotor currents flowing, a large flux is established around the conductor as shown in Figure 10.11(b). The stator and rotor fluxes react with each other as shown in Figure 10.11(c) to form a resultant field. This resultant field tends to straighten itself out, and in the process causes a force to be exerted on the rotor conductor, trying to force it to the right and out of the stator magnetic field. A similar force is exerted on all the rotor conductors as the field rotates, and if sufficient force is created, the rotor will commence rotating in the same direction as the rotating magnetic field. Provided it is free to rotate, the rotor will accelerate until it approaches synchronous speed.

This rotating force, called the torque of the motor, is the result of the interaction of the two fluxes. The stator flux remains fairly constant but the rotor flux varies with the rotor current, which is determined by such factors as the impedance, the induced voltage and the relative speed of the rotor conductors.

### 10.4.2 Slip

To produce torque, there must be a rotor flux caused by current flowing through the rotor conductors. If the rotor could run at synchronous speed, there would be no



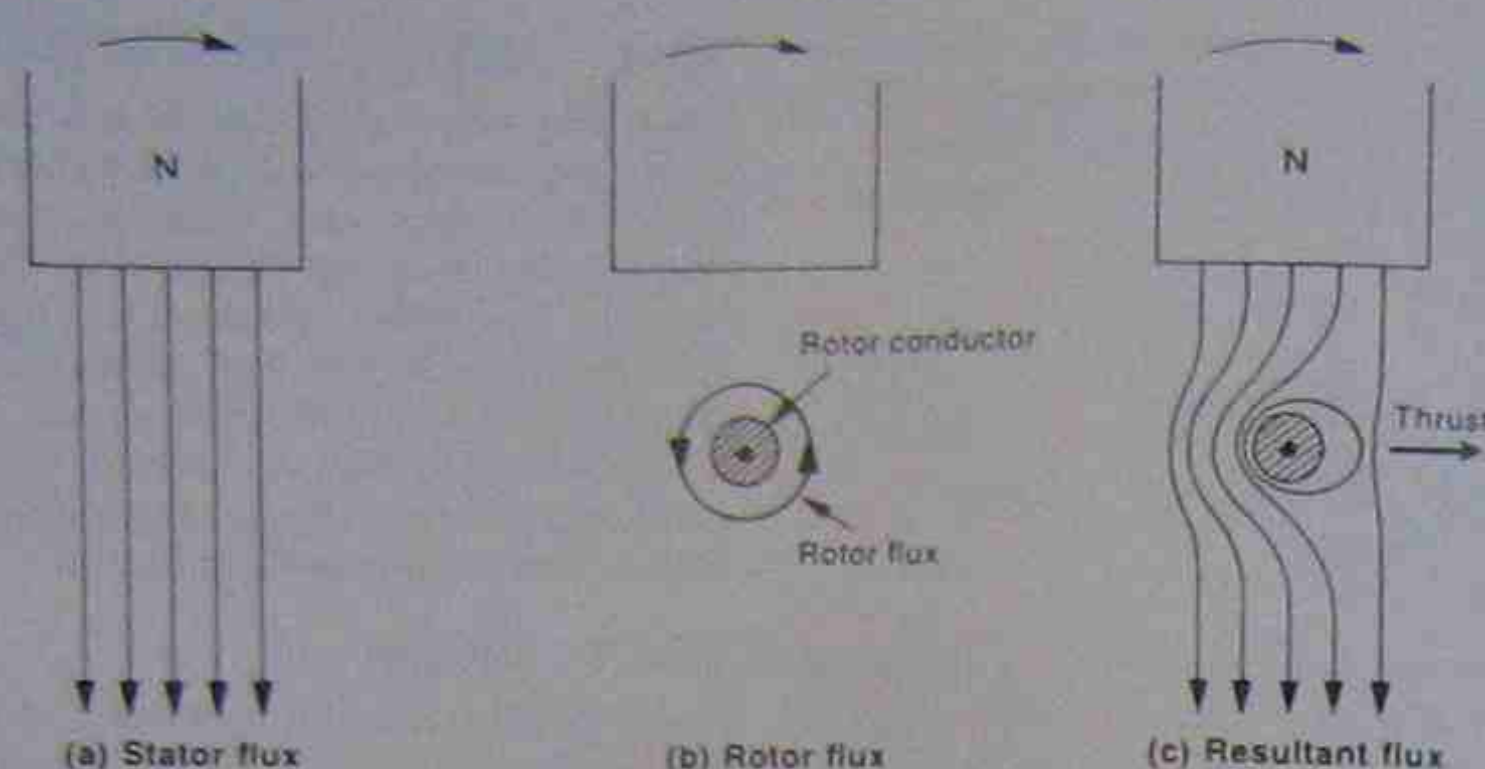


Figure 10.11 • Production of torque in an induction motor

relative motion between the stator flux and rotor conductors. Consequently there would be no induced voltage, no rotor current, no rotor flux, no torque developed, and so the rotor would slow down. An induction motor therefore cannot run at synchronous speed.

With the rotor running just below synchronous speed, relative motion exists and sufficient torque is developed to keep the rotor turning. The difference between the synchronous speed of the rotating field and the actual speed of the rotor is called the slip speed. It is commonly expressed as a percentage of the synchronous speed.

### Example 10.2

Determine the slip of a four-pole induction motor running at 1440 r/min when connected to a 50 Hz supply.

$$n_{syn} = \frac{120f}{p} = \frac{120 \times 50}{4} = 1500 \text{ r/min}$$

$$\text{slip speed} = 1500 - 1440 = 60 \text{ r/min}$$

$$\text{percentage slip} = \frac{1500 - 1440}{1500} \times 100 = 4\%$$

The formula for determining percentage slip is:

$$s\% = \frac{n_{syn} - n}{n_{syn}} \times 100$$

where  $s\%$  = percentage slip

$n_{syn}$  = synchronous speed

$n$  = rotor speed

At standstill (i.e. when starting) the slip is 100 per cent, whereas if the motor could run at synchronous speed, the slip would be zero.

### 10.4.3 Rotor frequency

When the rotor of a two-pole motor is at standstill and the stator is connected to a 50 Hz supply, each rotor conductor is cut by a north pole and a south pole at a rate of 50 times per second. At standstill, the frequency of the rotor voltage (rotor frequency) is the same as the frequency of the supply (stator frequency).

As the rotor speeds up to half the synchronous speed (1500 r/min), the rotor conductors are cut by only one-

half as many north and south poles per second as at standstill, and so the rotor frequency is one-half the supply frequency (i.e. 25 Hz). If the rotor were to revolve at synchronous speed, the rotor frequency would be zero. The rotor frequency depends on the differences in the speeds of the stator flux and the rotor (i.e. the slip of the motor), as shown in Figure 10.12.

The rotor frequency can be calculated using the following formula:

$$f_r = \frac{s \cdot f}{100}$$

where  $f_r$  = rotor frequency in Hz

$s$  = slip percentage

$f$  = supply frequency in Hz

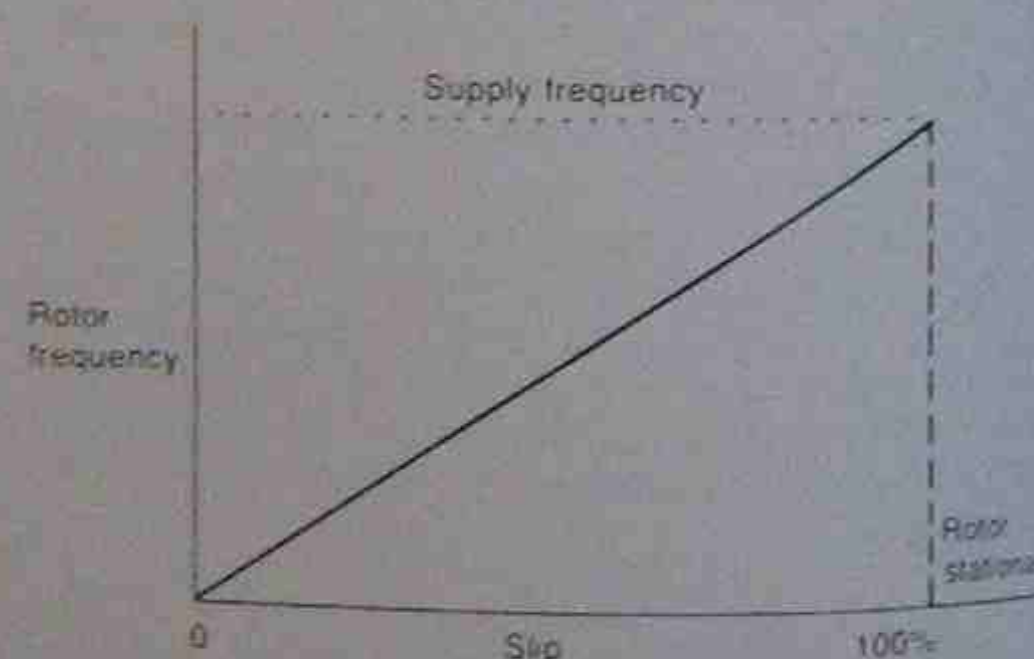


Figure 10.12 • Relation between rotor frequency and slip

### Example 10.3

Determine the rotor frequency of a two-pole, 50 Hz induction motor if the rotor speed is 2850 r/min.

$$s = \frac{n_{syn} - n}{n_{syn}} \times 100 = \frac{3000 - 2850}{3000} \times 100 = 5\%$$

$$f_r = \frac{s \cdot f}{100} = \frac{5 \times 50}{100} = 2.5 \text{ Hz}$$

As the rotor frequency varies, so does the rotor inductive reactance, and this affects the starting and running characteristics of the motor.

## 10.5 OPERATING CHARACTERISTICS

### 10.5.1 Squirrel-cage motors

When power is first applied to a stationary motor, the stator windings act as transformer primary windings with the resultant magnetic field rotating at synchronous speed. The rotor then behaves as a shorted secondary winding, causing a high circulating current in the rotor bars and a high starting current in the stator windings. As the rotor accelerates in the direction of the rotating field, the difference between its speed and the rotating magnetic field becomes less and the generated voltage causing the rotor circulating currents also becomes less. This in turn reduces the stator current.

The typical relationship between the stator current and the rotor speed is shown in Figure 10.13(a). The initial circulating current in the rotor is affected by the frequency of the supply, the resistance of the rotor bars, and the inductance of the rotor circuit—that is, the current-limiting factor is the impedance of the rotor circuit. With the usual type of power transformer, the frequency of the supply is the line frequency, but in this case the frequency commences at line frequency and steadily decreases as the motor speed increases. As a consequence the torque created can change as the speed changes. See Figure 10.13(b) for the typical relationships between speed and torque.

For small values of slip the torque is assumed to be proportional to the slip. As the motor load increases, the torque increases and the speed decreases, until the torque reaches a maximum value called the breakdown torque. If the motor is loaded beyond this point, the torque and the speed both decrease and the motor quickly comes to a standstill. An overall figure for starting torque is in the region of 1.5 times the rated torque, while the breakdown torque is usually about twice the rated torque. Australian Standard AS 1359.41 sets out minimum requirements for these torque values and provides a table for a range of motor sizes.

The resistance of the rotor conductors remains constant

at power line frequencies for all practical purposes, while the inductive reactance decreases as the rotor speed increases. As a guide, torque reaches a maximum when the rotor resistance in ohms is equal to the rotor reactance in ohms. Since the resistance is fixed, the breakdown torque can be altered only in relationship to the motor speed by altering the inductance of the rotor. In turn this affects the starting torque. Australian Standard AS 1359.41 allows for only two basic types of rotor—normal and high torque—and any other types necessarily require prior arrangement with the manufacturer. For the high-torque motor the required breakdown torque remains around twice the rated torque, while the starting torque is increased to approximately 2.5 times the rated torque.

### 10.5.2 Special purpose squirrel-cage rotors

In section 10.2.2, reference was made to the fact that the rotor bars in a squirrel-cage rotor can be designed and manufactured to suit different operating conditions. In general, for any one stator, only the impedance of the rotor can affect the current flowing in the rotor bars. Impedance can in turn be broken down into resistance and inductive reactance. Altering either one of these two elements affects the current flow.

Resistance can be altered by changing the cross-sectional area of the bars, while the inductive reactance can be altered by varying the depth and shape of the bar in the iron core of the rotor.

Figure 10.14 shows typically shaped rotor bars where the starting current is about 6–7 times the rated current and the motor has a starting torque of approximately 150 per cent of the rated running torque. Its use is restricted to very low starting torque requirements.

Figure 10.15 shows rotor bars of greater cross-section, where part is imbedded deeper into the rotor magnetic circuit. Starting torque is still about 150 per cent of running torque but the starting current is reduced to about five times the running current. It is suitable for use with equipment of low starting inertia such as fans, blowers and some types of machinery. Figure 10.16 gives one example of a rotor with two sets of rotor bars. The inner set is shown with half as many bars as the outer set and includes an optional air gap.

Depending on performance requirements, there may be

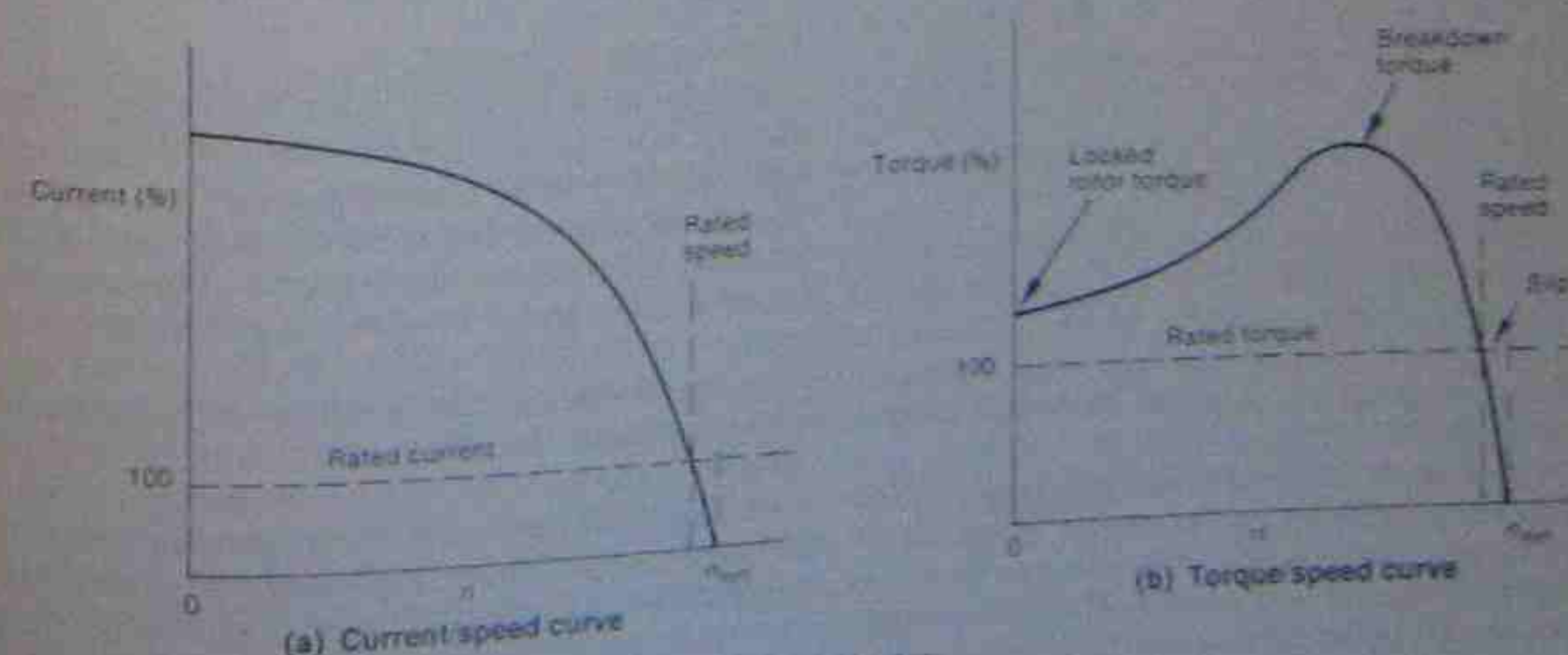


Figure 10.13 • Operating characteristics for a squirrel-cage induction motor



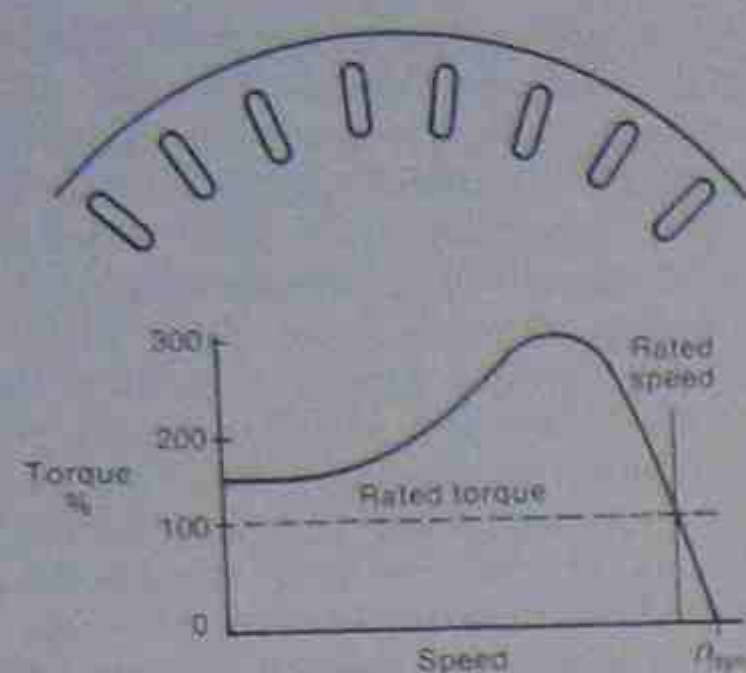


Figure 10.14 • Low starting torque rotor bars

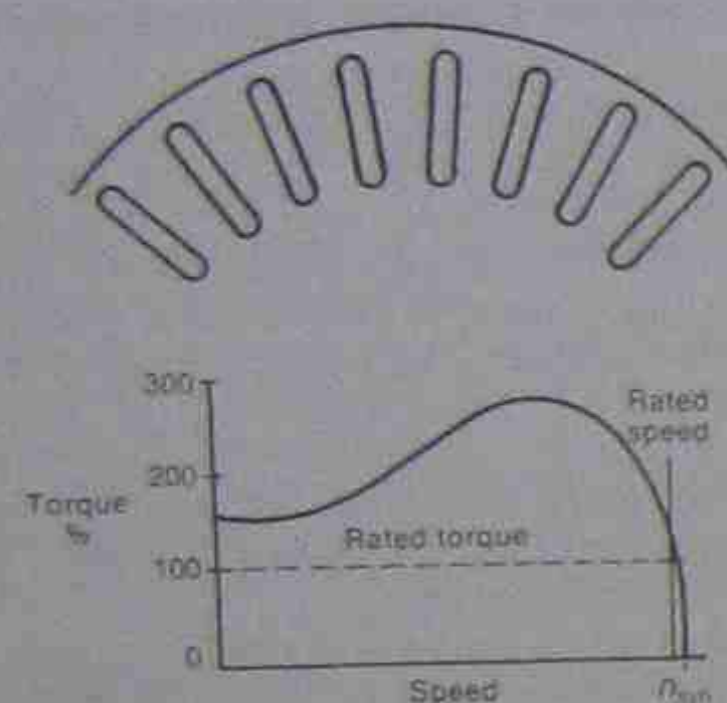


Figure 10.15 • Standard rotor bars

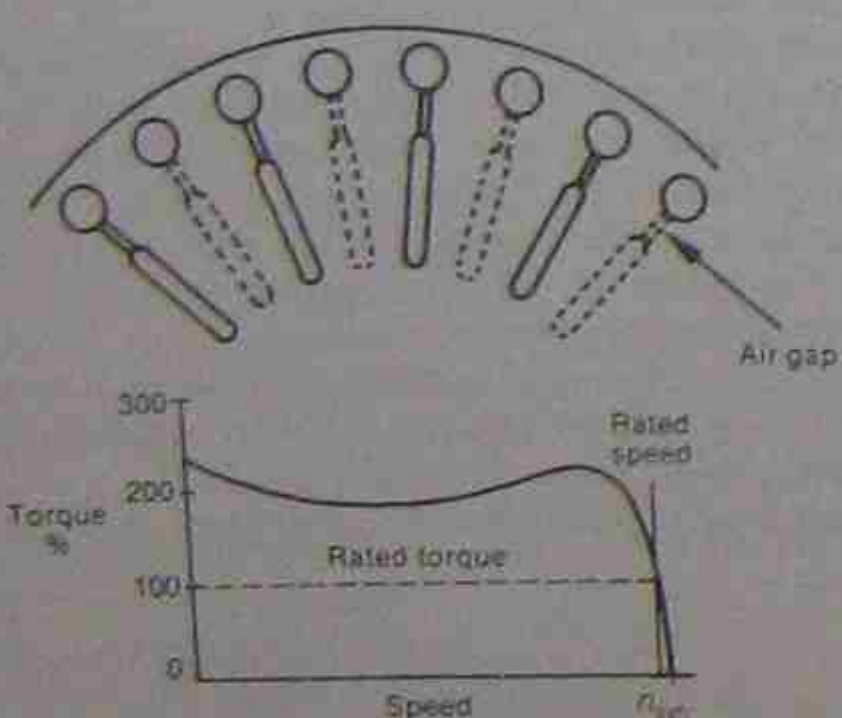


Figure 10.16 • Double cage rotor for high starting torque

different shaped bars, no air gap or a full set of bars in the cage. Starting torque is high—here it is 225 per cent of rated torque—and starting current is about five times the rated running current. Applications are in air compressors, crushers, refrigerator compressor motors or reciprocating force pumps.

A typical example of high resistance rotor bars with low starting current requirements is shown in Figure 10.17. With this construction the starting torque can be increased to about 275 per cent with fairly low starting currents. It is at the expense of a lower rated speed (i.e. increased slip).

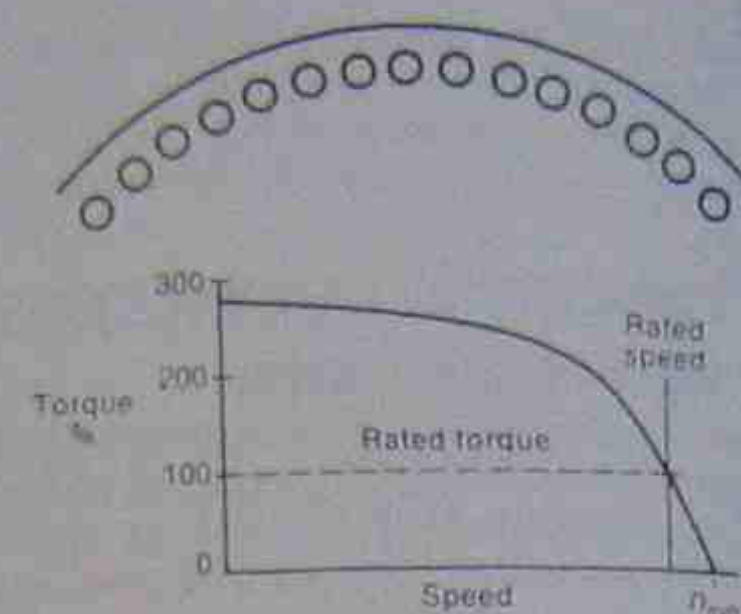


Figure 10.17 • High resistance rotor bars

Typical uses are flywheel-mounted machinery such as presses and punches. It is excellent with hoists where the maximum load occurs at the start of the lift. The above details apply particularly to copper rotor bars. If aluminium is used for the rotor bars, the cross-sectional area of the bars must be increased to allow for the metal's higher resistivity. The shape may also be changed to incorporate desired starting and running characteristics. Figure 10.18 shows a 'tear-drop'-shaped cast aluminium bar. In practice the shape may also be inverted to alter the characteristics to suit a particular purpose.

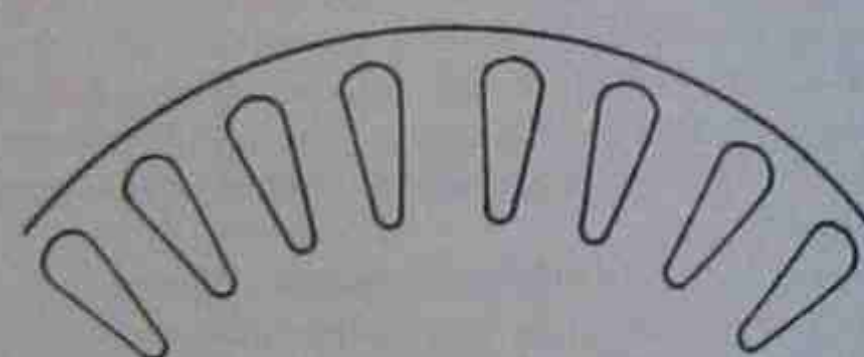


Figure 10.18 • Cast aluminium rotor bars

### 10.5.3 Wound-rotor motors

The introduction of resistance into the rotor circuit of an induction motor produces three effects:

1. the rotor current is reduced, resulting in less stator current
2. the starting torque is increased, because rotor and stator magnetic fields are more in phase with each other
3. the slip speed is increased.

An adjustable resistor is used external to the rotor, which is wound with comparatively low resistance windings. The value of the external resistance can be adjusted as required and, as the motor accelerates, the value is gradually reduced until all the resistance is out of the rotor circuit and the motor behaves as an ordinary induction motor.

The torque-speed characteristic of a typical three-stage wound-rotor motor is shown in Figure 10.19. When all the resistance is in the rotor circuit, the starting current is low and the starting torque is high, as shown by curve *a*. If this resistance is left in, the full-load torque would occur at approximately 25 per cent slip, resulting in extremely poor speed regulation.

If one stage of the resistance in the rotor circuit is

shorted out, the operating characteristics are modified as shown by curve *b*.

If all the external resistance in the rotor circuit is shorted out, the operating characteristic is shown by curve *c*.

The normal starting procedure is to start the motor with all the resistance in the rotor circuit. As the motor speeds up, the resistance is reduced and the motor increases in speed, but maintains a high torque. During the starting procedure the torque-speed curve is as shown by the thicker curve *d*.

By comparing Figures 10.13 and 10.19, it can be seen that full-load torque occurs at a greater slip in a wound-rotor motor than a squirrel-cage motor. This is due to the extra resistance of the windings in the wound rotor.

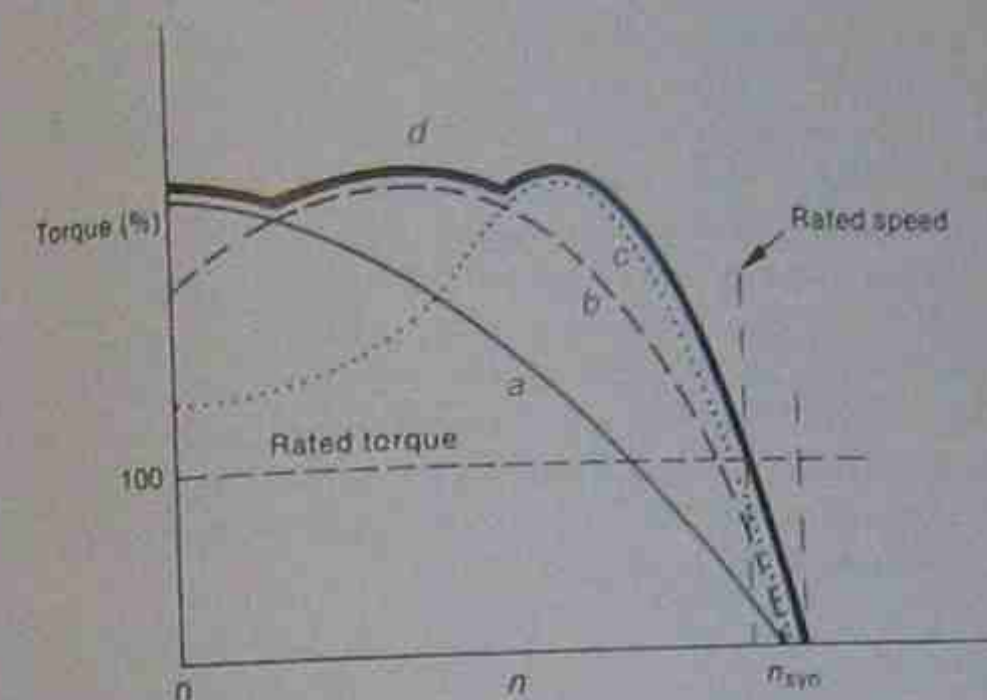


Figure 10.19 • Operating characteristic for a wound-rotor motor

The main use for wound-rotor motors is the starting of high inertia loads that may take several minutes to attain operating speed. The high starting torque and reduced starting current of this type of motor ensures that the motor windings are not subjected to excessive starting currents for any length of time.

Applications for wound-rotor motors invariably involve the need to get pairs of large flywheels up to speed. Once up to speed the flywheels can absorb the impact shock of sudden loads and so enable the machinery to continue operating. Applications include large air compressors, metal presses, and stone-crusher heads in quarries to reduce excavated material to suitable sizes before grading.

### 10.5.4 Operational parameters for induction motors

On no load, the stator current of any induction motor is largely a magnetising current, with a small energy component required to supply the no-load losses. Accordingly, the power factor of an induction motor on no load is very low. The no-load current is relatively high when compared with a transformer because of the high reluctance of the magnetic circuit, due to the air gap between the stator and rotor.

The stator flux remains fairly constant from no load to full load and so the magnetising current is also fairly constant. In Figure 10.20(a) the no-load stator current  $I_0$  lags the supply voltage by  $\phi$  degrees.

As a load is applied to the motor, a load current  $I_1$  is

required to accommodate that load. This load current  $I_1$  lags the supply voltage slightly, owing to the effect of the stator and rotor reactance. The two current components  $I_0$  and  $I_1$  combine to give the total stator current  $I_s$  at that load. The phase-angle decreases from  $\phi$  to  $\phi_1$  and the power factor of the induction motor increases as the load on the motor increases.

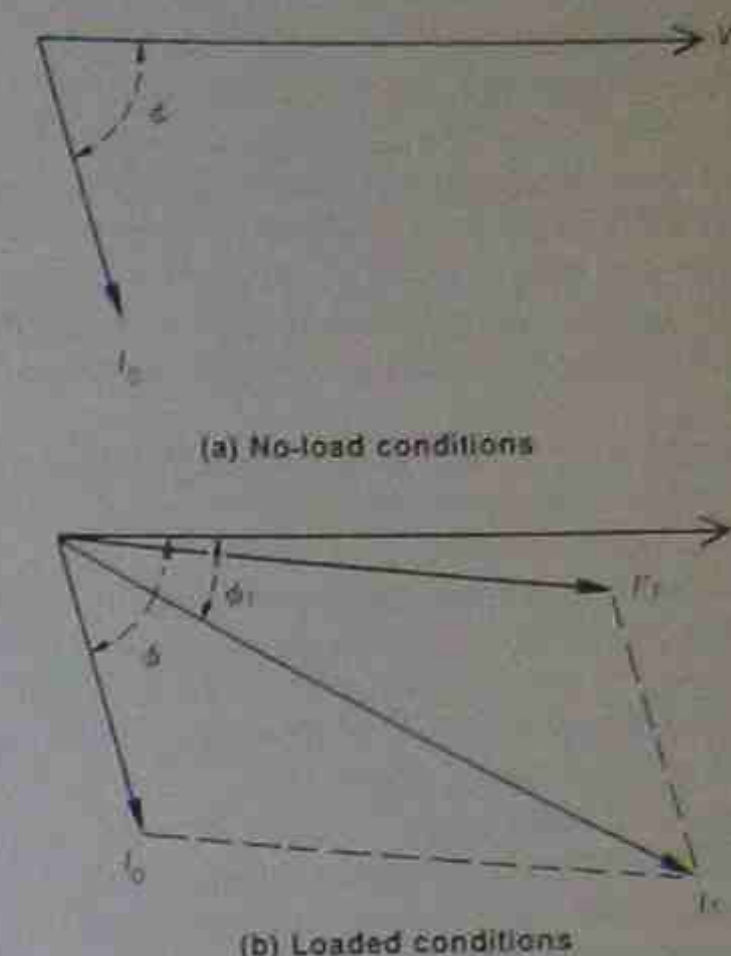


Figure 10.20 • Current phasors for an induction motor

Figure 10.21 gives representative characteristic shapes for some parameters of a three-phase induction motor. It shows the speed decreasing and the slip increasing as the load on the motor is increased. It also shows the line current increasing and the power factor improving at the same time.

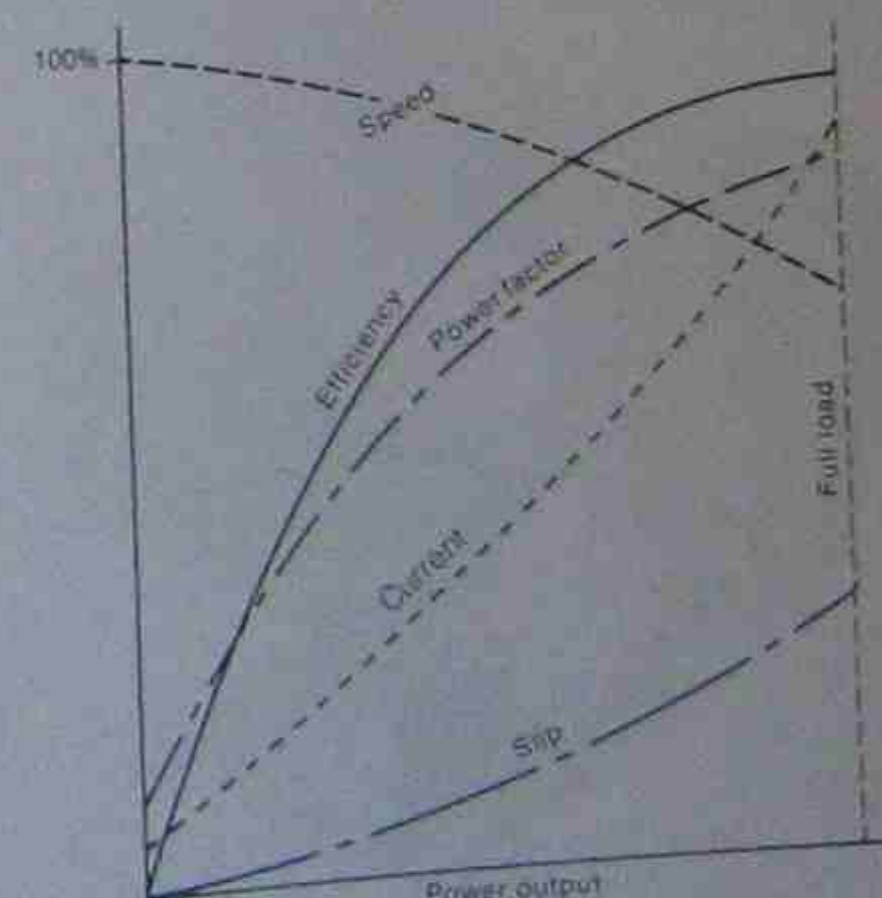


Figure 10.21 • Typical parameters for a three-phase induction motor, showing how they alter as the load varies



## 10.6 SINGLE-PHASE INDUCTION MOTORS

The induction motor is highly regarded because of its simplicity, ruggedness and reliability. The three-phase induction motors discussed above had inherent starting torque because of a rotating field. The single-phase induction motor initially has no rotating field and therefore no starting torque.

In the three-phase motor the supply consists of three identical currents being supplied to three identical windings in the motor. The resultant magnetic field rotates at a constant speed and strength. Similarly, if two identical currents at 90°E could be supplied to two identical windings displaced by 90°E in a two-phase motor, the magnetic field would rotate at a synchronous speed determined by the supply frequency and the number of poles in the windings.

A single-phase motor can be wound with two identical windings easily enough, but on connecting them to a single-phase supply, the individual winding currents may well be closely in phase with each other and not produce a rotating magnetic field. The two currents have to be displaced electrically from each other by some means to produce a rotating field. This can be achieved by having windings of different inductances and resistances. Sometimes a capacitor is also added in series with one winding to enhance the phase displacement. A single-phase motor of Australian manufacture is shown in Figure 10.22.

Once the motor is rotating at sufficient speed, one of the windings can be disconnected and the motor will continue to rotate. Because of the more uneven magnetisation of the iron core the motor develops a pronounced vibration that is a characteristic of the single-phase motor. This vibration is at twice the supply line frequency and tends to make the motor more noisy in operation than a three-phase motor.

The motor also develops a small amount of negative

torque, which is a function of the slip speed. It results in a rather high no-load current at low power factor. When a load is applied, the current increases only marginally but the power factor improves in a similar fashion to that of the three-phase motor.

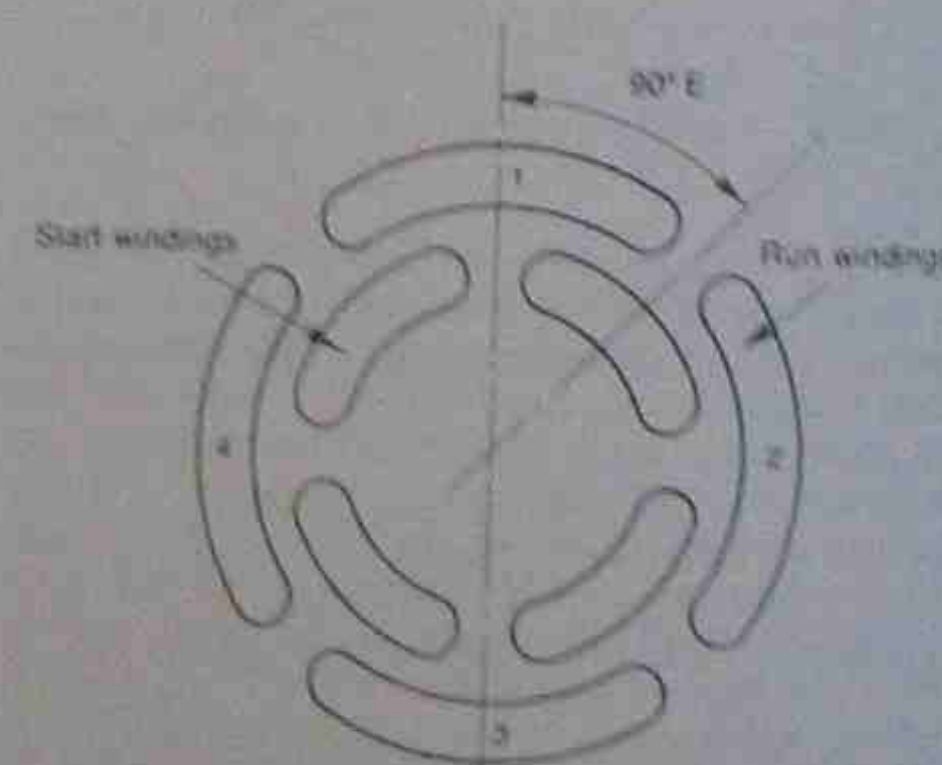
Owing to the above considerations, special techniques have to be adopted to ensure the starting of the single-phase motor. Because of the various starting methods employed there are several versions of the single-phase motor.

### 10.6.1 The split-phase motor

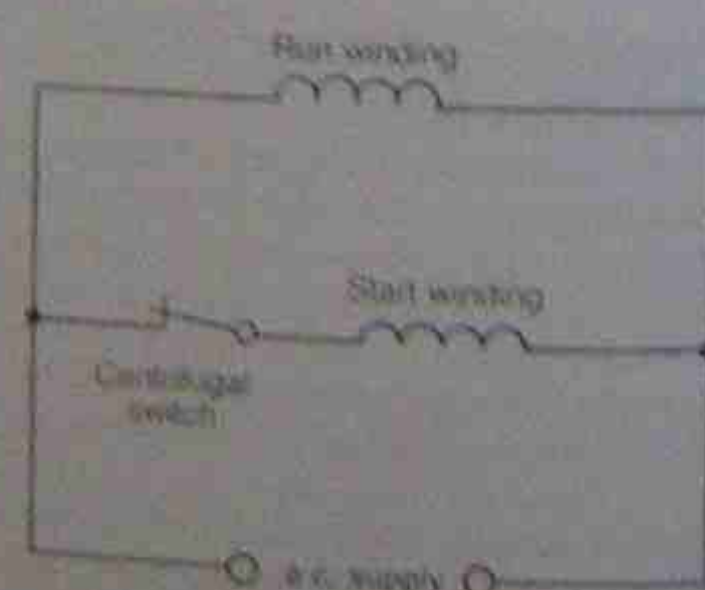
The standard split-phase induction motor has two separate windings (start and run) connected across the supply during the starting process. For normal running, however, only the run winding is used.

The run winding consists of a number of coils connected in series to form a set number of poles. A four-pole machine, for example, has four groups of coils all in series and physically displaced around the stator to form four separate poles as shown in Figure 10.23(a).

The run winding is wound with a heavier gauge wire to reduce its resistance. To increase the inductance of the run winding, the coils are embedded deep into the slots of the iron core and usually have more turns than the start winding. The current  $I_R$  flowing through the run winding is highly reactive and so it lags the applied voltage  $V$  by a considerable angle  $\phi_R$  (Fig. 10.24).



(a) Start and run windings displaced by 90°E



(b) Internal connections

Figure 10.23 • Electrical details of a split-phase motor

The start winding also consists of a number of coils connected in series to form a set number of poles. If the machine has four poles in the run winding, it will also have four poles in the start winding. However, the start winding is physically displaced by 90°E around the stator core, as shown in Figure 10.23(a).

The start winding of the standard split-phase motor is wound with finer gauge wire, increasing the resistance of the winding. When compared with the run winding, the start winding has fewer turns, and the coils are placed nearer the surface of the slots in the stator core, reducing the inductance of the winding. The net result is that the current  $I_S$  flowing in the start winding is more in phase with the voltage  $V$  than  $I_R$  in the run winding. In Figure 10.24,  $I_R$  lags  $V$  by  $\phi_R$  and  $I_S$  lags  $V$  by  $\phi_S$ . This produces a phase displacement of  $\phi$  between the two currents, so producing a phase displacement between the respective fluxes of the two windings.

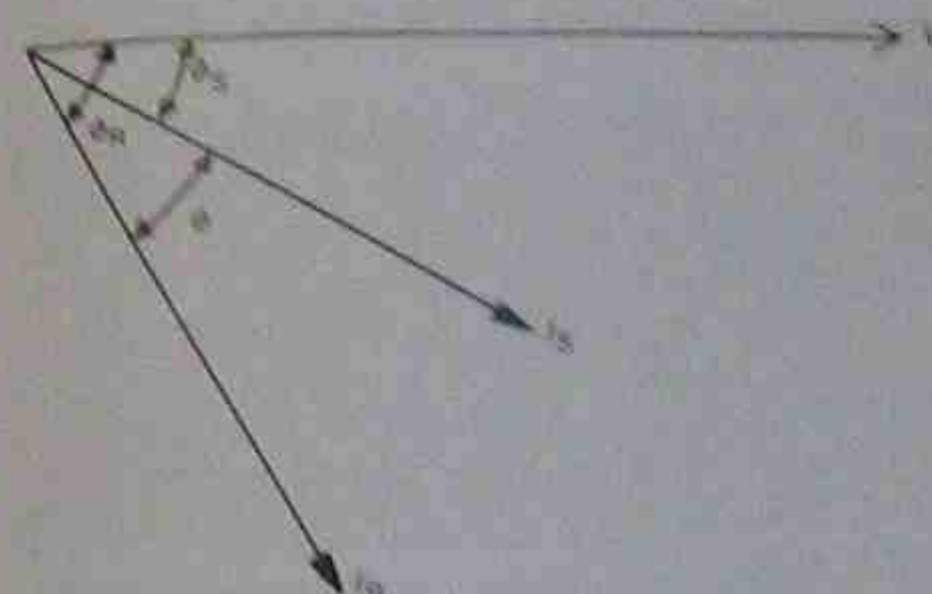


Figure 10.24 • Phase relationships between starting and running winding currents for a split-phase motor

### Starting

For a two-pole machine, the windings are also physically displaced by 90°E. Assuming a 30° phase displacement between the two fluxes, at position  $a$  in Figure 10.25 the run flux  $\Phi_R$  is zero and the start flux  $\Phi_S$  is 50 per cent of the maximum value in a positive direc-

tion. The resultant stator flux is shown at position  $a$  in Figure 10.26(b).

At position  $b$  in Figure 10.25,  $\Phi_R$  is 50 per cent of its maximum value and  $\Phi_S$  is 86.6 per cent of its maximum value, and these combine to form the resultant stator flux  $\Phi$  in Figure 10.26(b). At position  $c$  in Figure 10.25,  $\Phi_R$  is 86.6 per cent of its maximum value and  $\Phi_S$  is 50 per cent, and the resultant stator flux  $\Phi$  is shown in Figure 10.26(b). By taking each position from  $a$  to  $e$  in Figure 10.25 it can be seen that the stator flux rotates one half revolution for one full cycle. The direction of rotation is the same direction as that of the resultant magnetic field.

The stator flux rotates at a speed governed by the supply frequency and the number of poles in a winding:

$$\text{that is, } n = \frac{120f}{p}$$

where  $f$  = frequency  
 $p$  = number of poles  
 $n$  = speed in r/min

For a two-pole machine on a 50-Hz supply:

$$n = 3000 \text{ r/min}$$

For a four-pole machine:

$$n = 1500 \text{ r/min}$$

If the direction of current flow through one winding is reversed, the resultant magnetic field rotates in the reverse direction. That is, the direction of rotation of the motor is reversed by changing the direction of current flow through one winding. This is done by exchanging the two end connections of any one winding.

As seen in Figure 10.26(b), the rotating stator flux is not of uniform value and an elliptical field pattern is produced. This produces considerable vibrations and humming noise during starting.

The rotating stator field cuts the rotor bars and induces a voltage in them and, because they are shorted out, a current flows through the bars and produces a rotor flux. The stator flux and the rotor flux interact to produce a

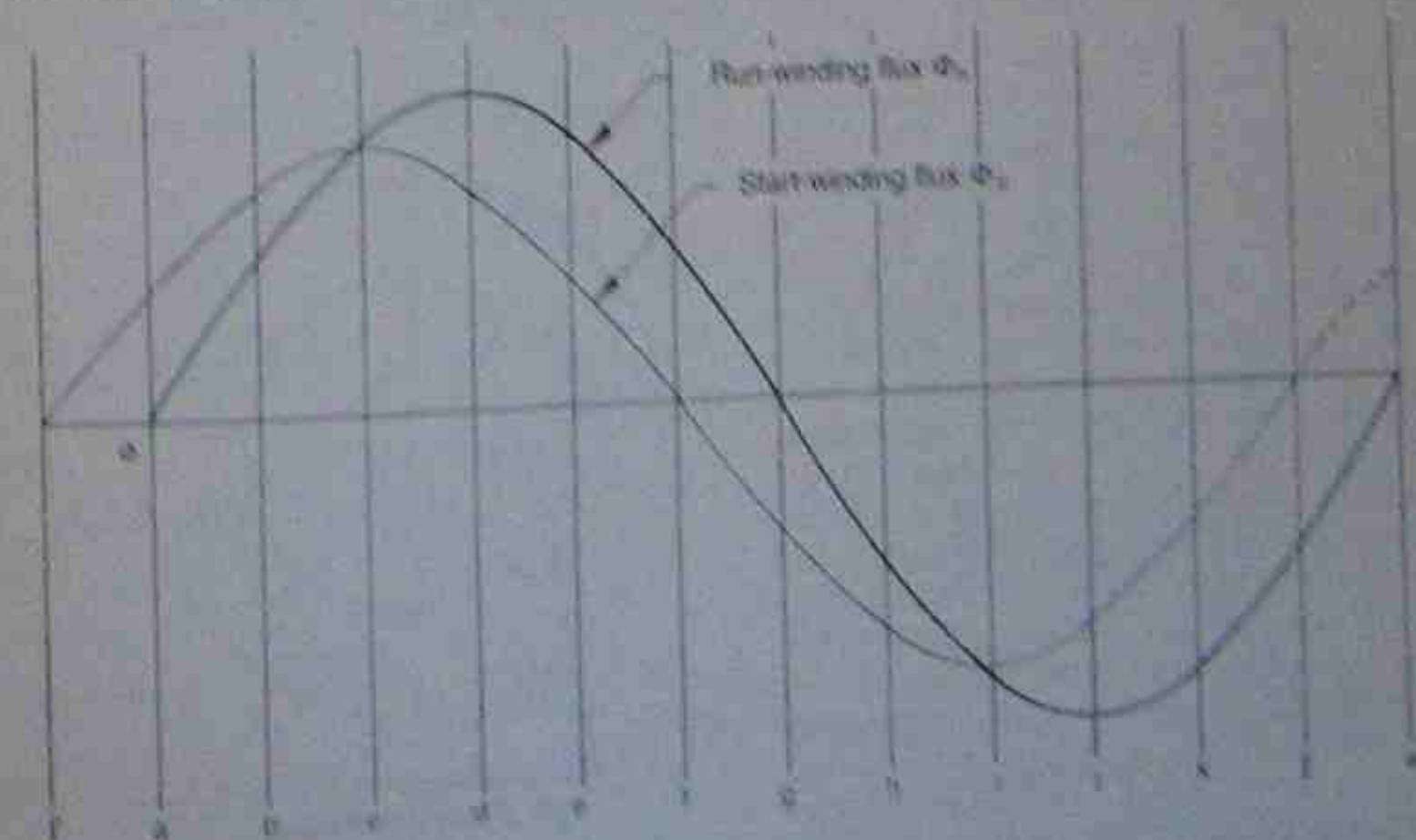


Figure 10.25 • Flux waveforms



Figure 10.22 • Single-phase split-phase 160 W motor



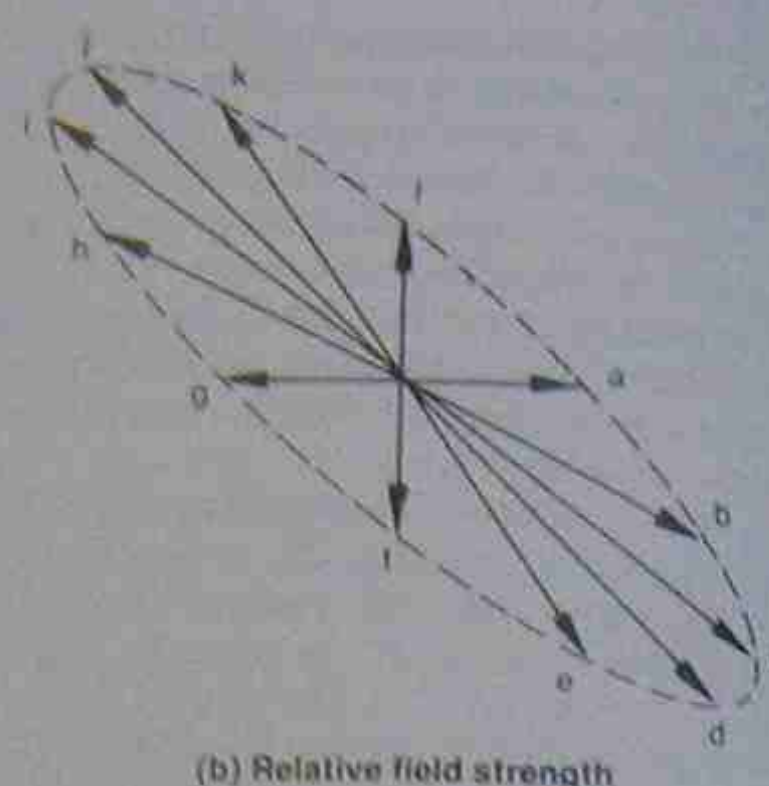
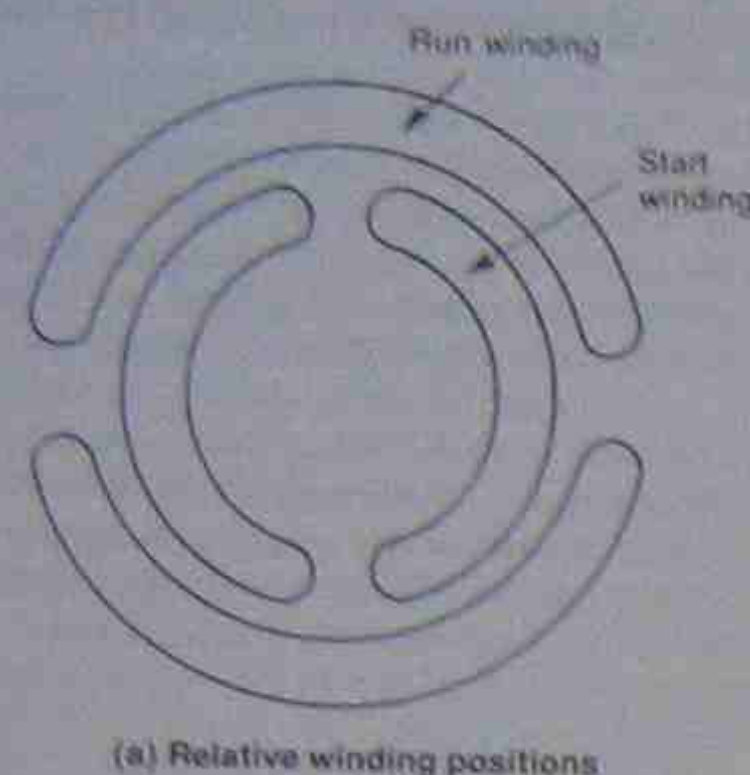


Figure 10.26 • Rotating field in a split-phase motor

force on the rotor bars, causing the rotor to turn in the direction in which the stator flux is rotating. This rotating force is called the starting torque and largely depends on the relative strengths of the start and run fluxes, and the phase displacement between the currents flowing through both windings.

The start and run windings are connected in parallel across the supply voltage. When the rotor has reached sufficient speed to provide a strong cross-flux, the start winding can be open-circuited. This is usually done by connecting a centrifugally operated switch in series with the start winding.

The centrifugal switch is usually set to open when the rotor speed reaches approximately 75 per cent of the rated speed of the motor. When the motor is switched off, the rotor slows down and the centrifugal mechanism operates, closing the switch contacts again in readiness for the next starting operation.

Because the start winding is only connected during the starting procedure, it is designed for a very short duty cycle. If the centrifugal switch fails to operate, the start winding will quickly overheat and burn out.

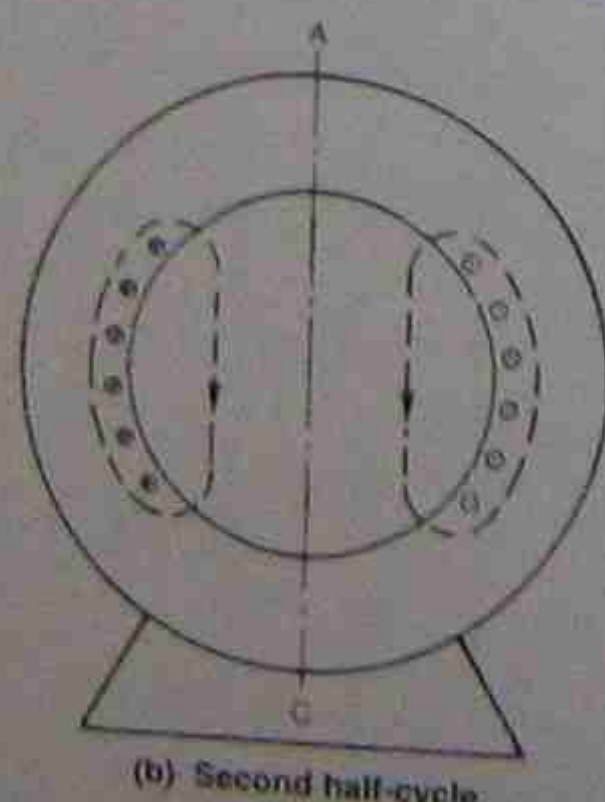
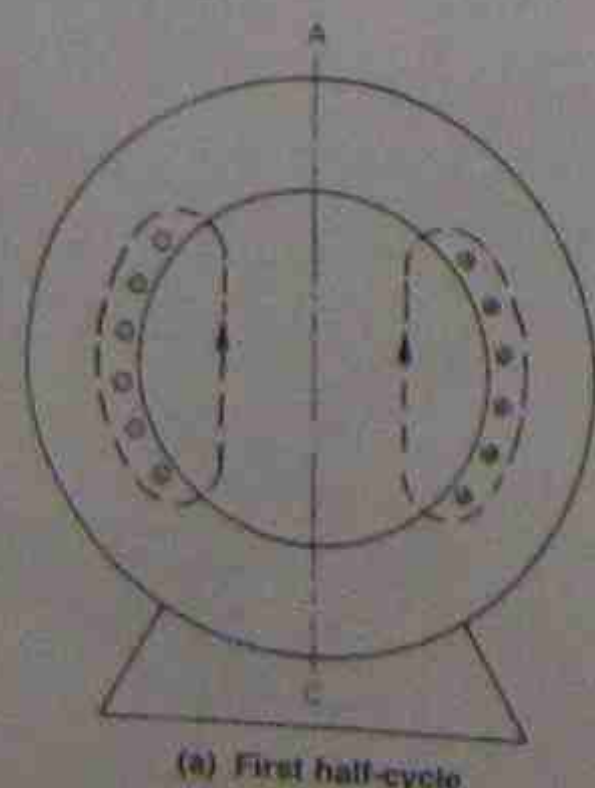


Figure 10.27 • Pulsating stator field

### Running

When the rotor speed of the standard split-phase motor reaches approximately 75 per cent of the synchronous speed, the centrifugal switch open-circuits the start winding and only the run winding is connected to the supply.

For a two-pole motor, when the stator current flows in one direction for one half-cycle, a magnetic field is produced in the direction C-A in Figure 10.27(a). During the next half-cycle when the stator current is reversed, the magnetic field also reverses and is in the direction A-C in Figure 10.27(b).

This stator field, produced by the run windings, varies in strength and direction according to the supply, but it does not rotate. It is a stationary pulsating field. This is the reason why some form of starting (i.e. start winding) is required for split-phase motors.

When the stator winding is connected to the a.c. supply and the rotor is turning, the rotor bars cut the stator flux, causing an e.m.f. to be generated in them. In Figure 10.28(a) the rotor is revolving clockwise, and the stator field is acting in the direction C-A. By Fleming's right-hand rule, the generated e.m.f. in the rotor acts in

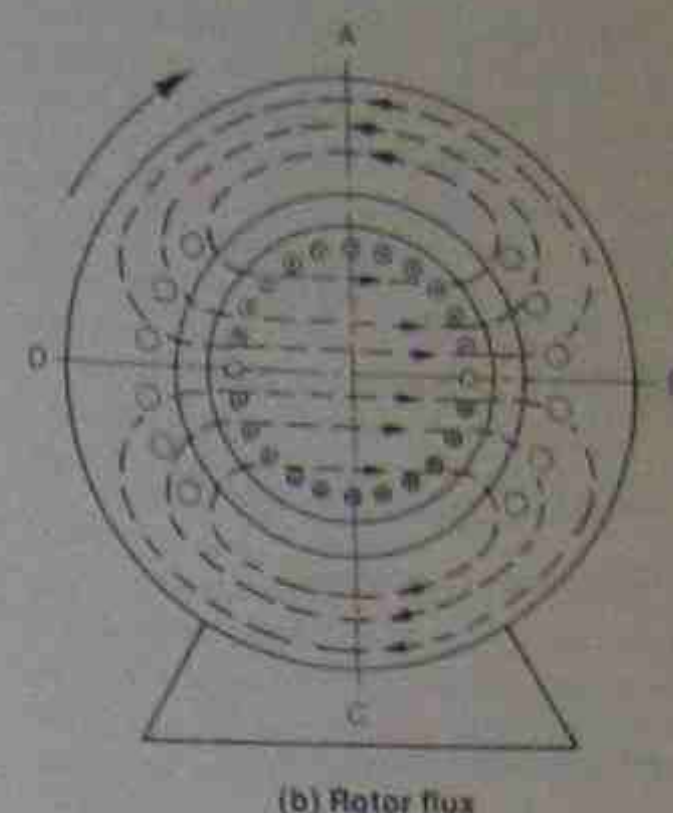
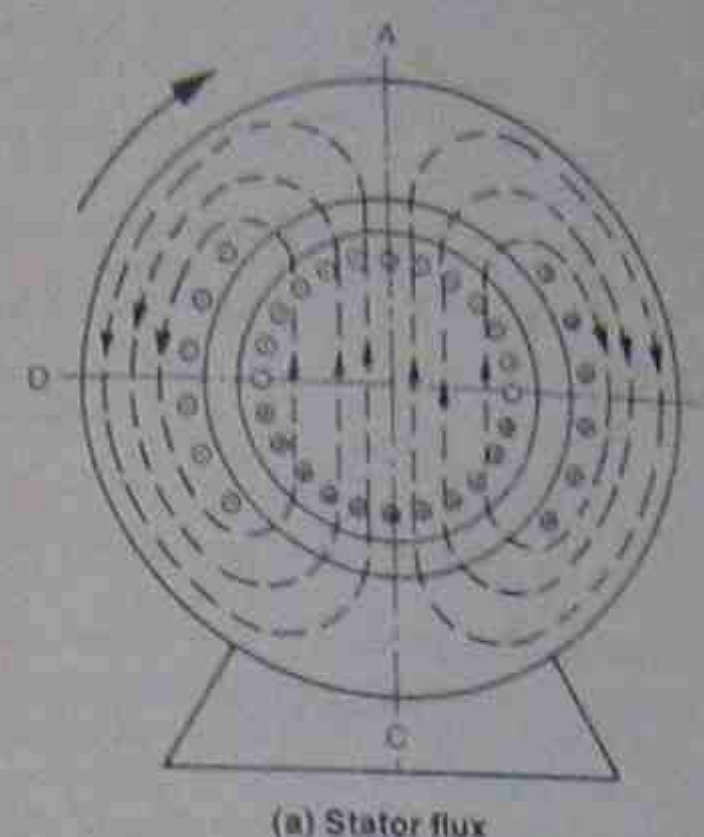


Figure 10.28 • Magnetic fields in a rotating single-phase motor

the direction shown (out of the page) in all rotor bars above the axis D-B (indicated by the dots), and into the page in all rotor bars below the axis D-B (indicated by +).

The induced rotor voltages are in phase with the stator flux and cause a rotor current to flow. Because of the low resistance and high inductance of the rotor bars, these currents lag the induced rotor voltage by nearly 90°. Consequently, the rotor currents produce a rotor flux lagging almost 90° behind the stator flux, and acting in the direction D-B, as shown in Figure 10.28(b).

Because the rotor flux is at right angles to the stator flux it is often referred to as the 'cross-field'. The two fields effectively combine to form a rotating field, which tends to force the rotor bars in the direction in which the field rotates.

For one full cycle of the a.c. supply, the resultant field rotates 360°. For the two-pole machine described, this constitutes one full revolution. For a four-pole machine, it will rotate a half-revolution for each full cycle of the a.c. supply.

Owing to the internal losses within the rotor, however, the rotor itself will not rotate at synchronous speed but at a slightly slower speed.

Figure 10.29 shows a typical torque/speed characteristic

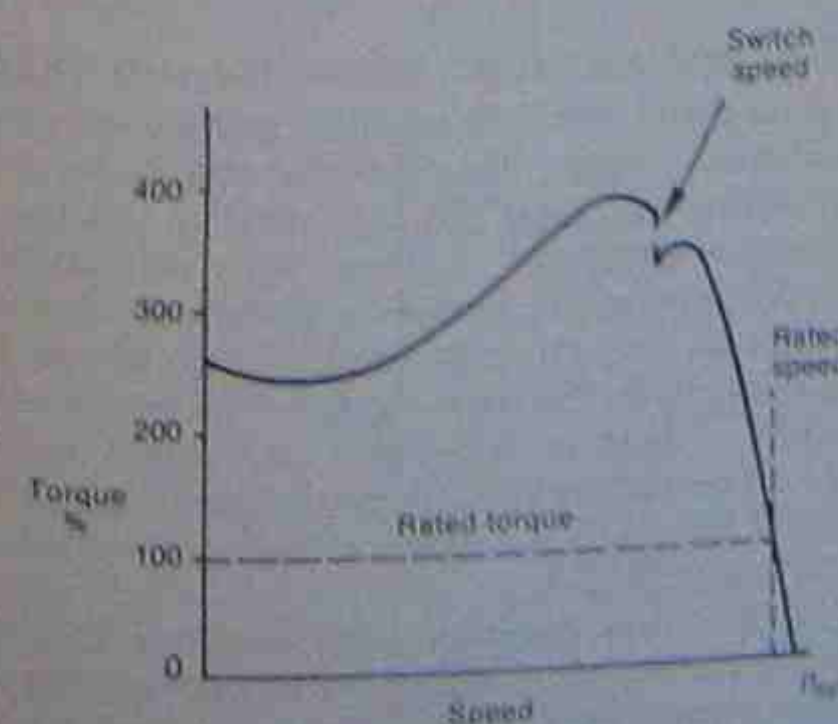


Figure 10.29 • Speed/torque curve for a split-phase motor

for a split-phase motor. The break in the curve is caused by the switch operating to disconnect the starting winding. This is necessary to limit the losses in the motor and to protect the starting winding. The torque curves between the running and starting sequences normally do not coincide, so the speed and torque values have to be adjusted when the switch operates. The values shown on the curve must be considered only as representative. They will vary from one make to another and even within the one make because of design changes.

### Uses

Split-phase motors have only moderate starting torque, so they are limited to such typical uses as washing machines, blowers, buffing machines, grinders and machine tools.

### 10.6.2 Capacitor-start motor

Design limitations restrict the split-phase motor to a maximum of about 30° between the starting and running winding currents. To increase this angle and produce improved starting characteristics, a capacitor is connected in series with the starting winding (Fig. 10.30(a)). A capacitor-start motor is identical in appearance to a split-phase motor but with the addition of a capacitor usually mounted on top of the motor. Refer back to Figure 10.22. If the correct size capacitor is selected, the two currents will be at 90° to each other and improved starting torque is obtained.

Any value capacitor will increase the angle, but values that enable the starting winding to approach resonance must be avoided. For this reason it is advisable that a capacitor much larger than necessary be used to ensure that resonance does not occur. The phasors in Figure 10.30(b) indicate the ideal phase displacement of 90°. This angle of phase displacement between  $I_s$  and  $I_r$  provides a more uniform strength of stator flux during starting—compare Figures 10.26(b) and 10.31(b). Owing to this more even field strength, the starting torque is higher than for the equivalent size split-phase motor.

Figure 10.32 shows the speed/torque curve for a capacitor-start motor. It is drawn to the same scale as that of Figure 10.29 to give a framework for comparison. It



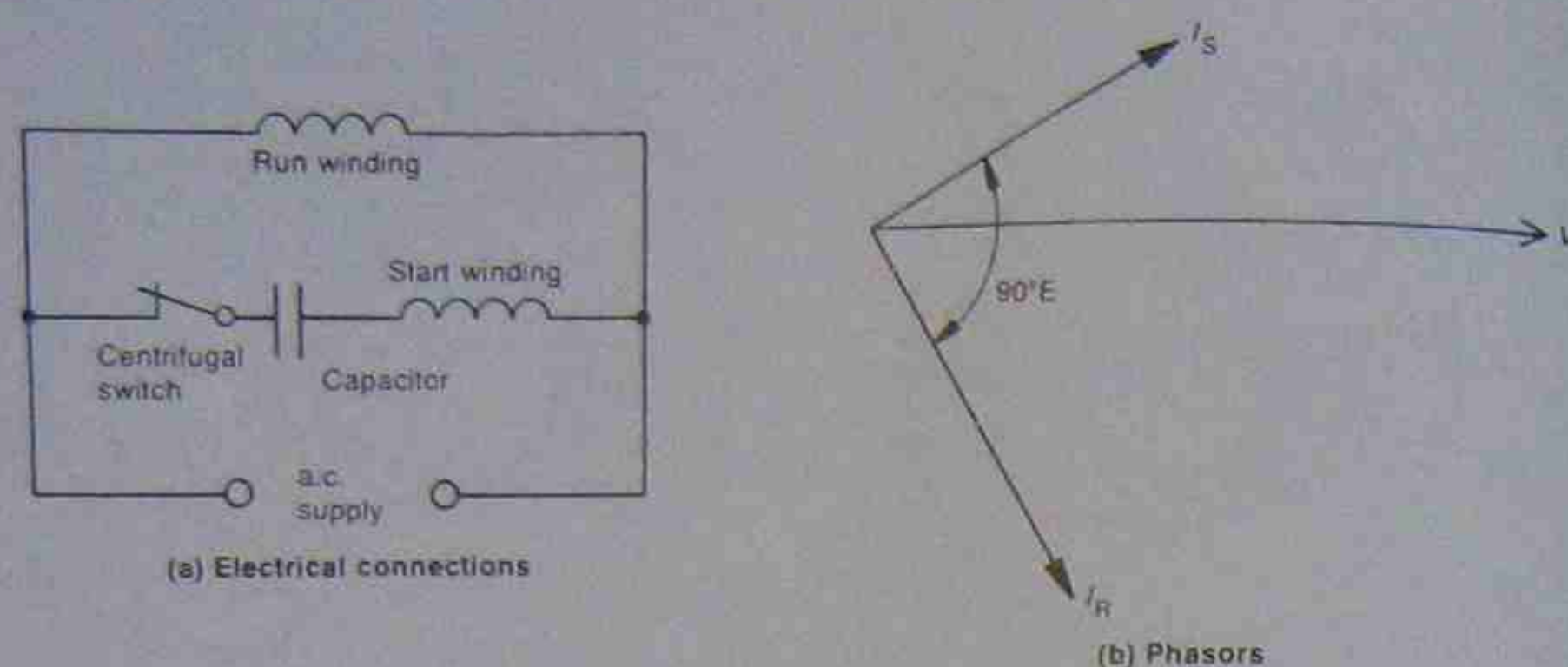


Figure 10.30 • Capacitor-start, induction-run motor

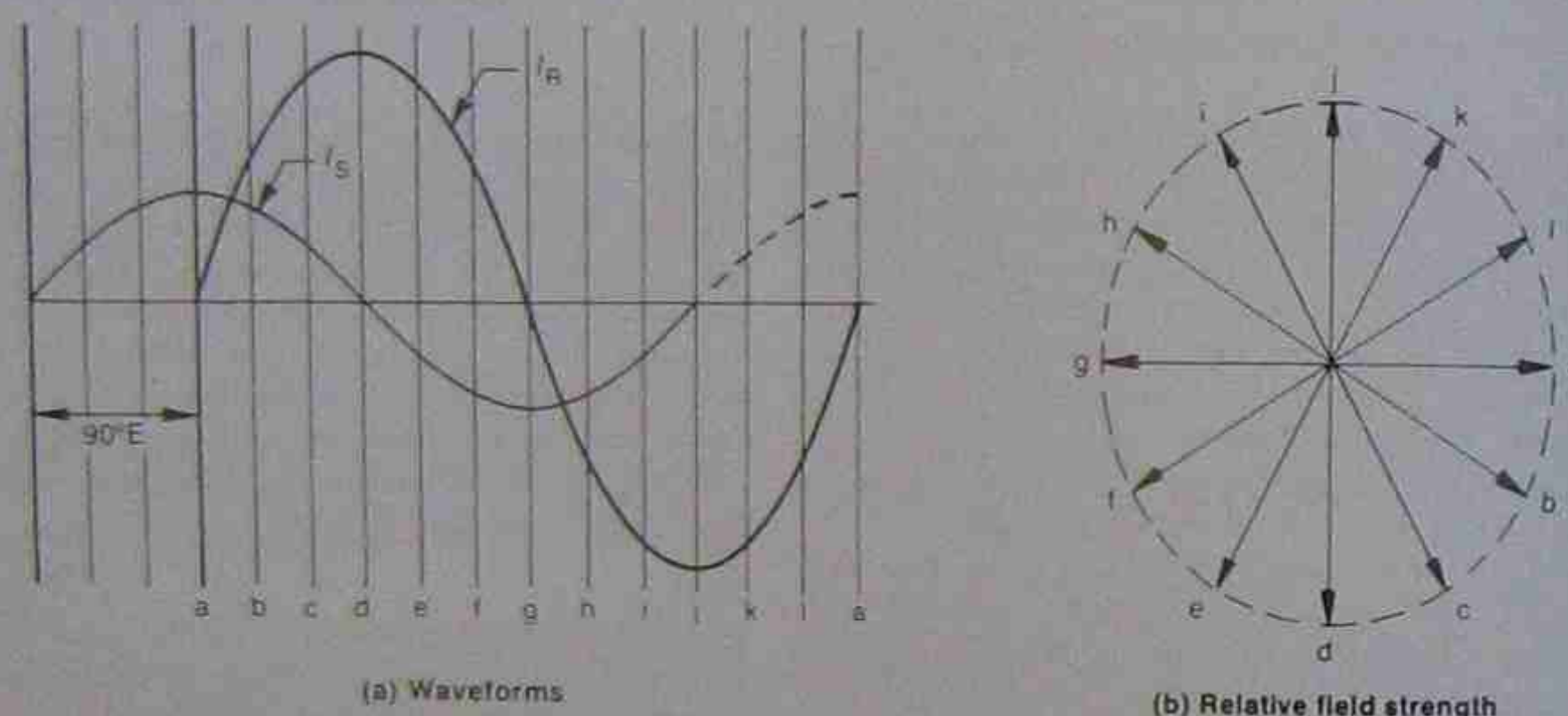


Figure 10.31 • Rotating field in a capacitor-start motor

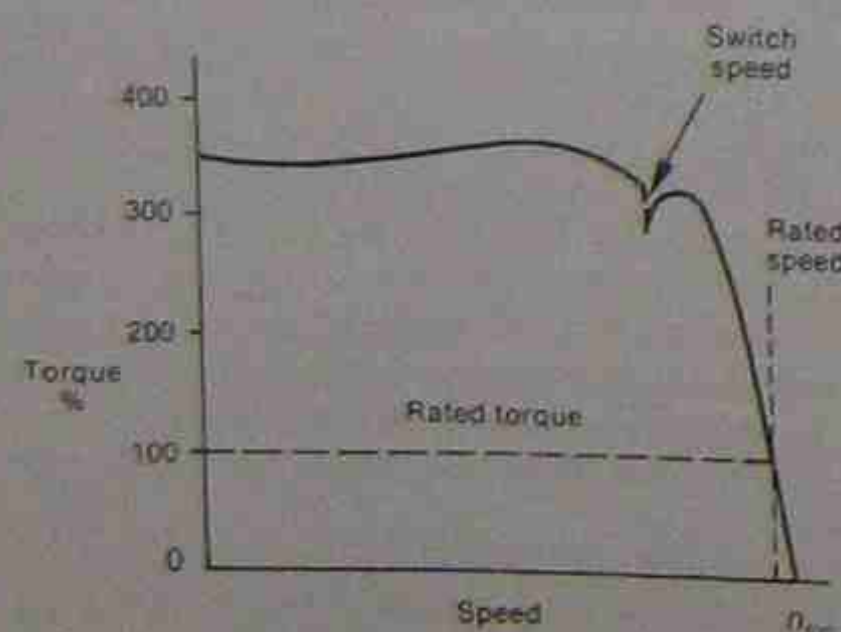


Figure 10.32 • Speed/torque curve for a capacitor-start motor

can be seen that there is a large increase in starting torque due to the addition of the capacitor, while the torque is the same as for the split-phase motor after the switch has operated. In a similar fashion to the split-phase motor, the switch operates at approximately 75 per cent of full-load speed. The actual starting windings for the two types of motor may consist of different data. The reversal of rotation is achieved by the same principles that apply to the split-phase motor. That is, the motor

can be reversed by changing over the two leads of any one winding, but not both.

#### Uses

Capacitor-start motors are used in general-purpose heavy-duty applications requiring high locked-rotor starting torque, such as for starting refrigerators and air compressors.

### 10.6.3 Capacitor-start, capacitor-run motor

This type of motor has both windings permanently connected across the supply; these are referred to as the main and auxiliary windings. During starting, additional capacitance is connected in series with the auxiliary winding to provide the necessary phase displacement between the winding currents for maximum torque. The starting capacitor is therefore connected in parallel with the running capacitor. When the rotor speed reaches about 75 per cent of the rated speed, the centrifugal switch disconnects the starting capacitor from the circuit, as shown in Figure 10.33.

During operating conditions the running capacitor ensures the correct phase displacement between the two currents in the windings, so providing a constant-strength rotating magnetic field.

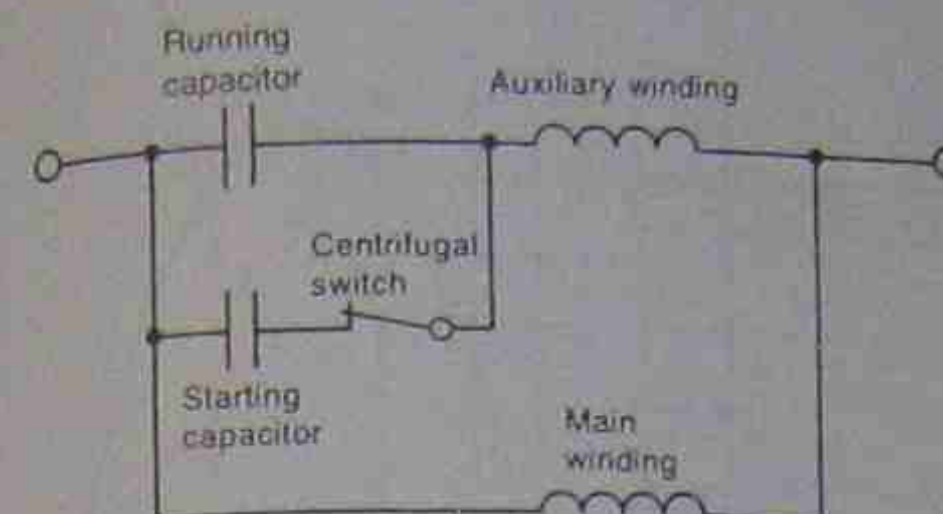


Figure 10.33 • Capacitor-start, capacitor-run motor

It should be noted that the starting capacitor can be rated for intermittent duty but the running capacitor must be of a construction suitable for continuous rating, such as the paper-spaced oil-filled type. The two-capacitor motor provides substantially the same running torque as the capacitor-starting, induction-run type, but there are beneficial effects. Adding the second capacitor:

1. increases the breakdown torque
2. improves full-load efficiency and power factor
3. reduces operational noise and vibration
4. increases locked-rotor torque.

The direction of rotation can be reversed by changing over the two leads of any one winding but not both. This changes the direction of rotation of the magnetic field in the stator.

#### Uses

The capacitor-start, capacitor-run motor is suitable for heavy-duty loads where quietness is a consideration and substantial starting torque is necessary, for example, wall-mounted air-conditioning units where high head pressures are encountered in hot weather.

### 10.6.4 Permanently-split capacitor motor

The permanently-split motor also has both windings permanently connected across the supply, with a capacitor in series with one of them as shown in Figure 10.34.

For this type of motor, both windings are identical in wire size and the number of turns, and they are also referred to as the main and auxiliary windings. Because the capacitor is in series with one winding, the current in that winding leads the current in the other, providing the

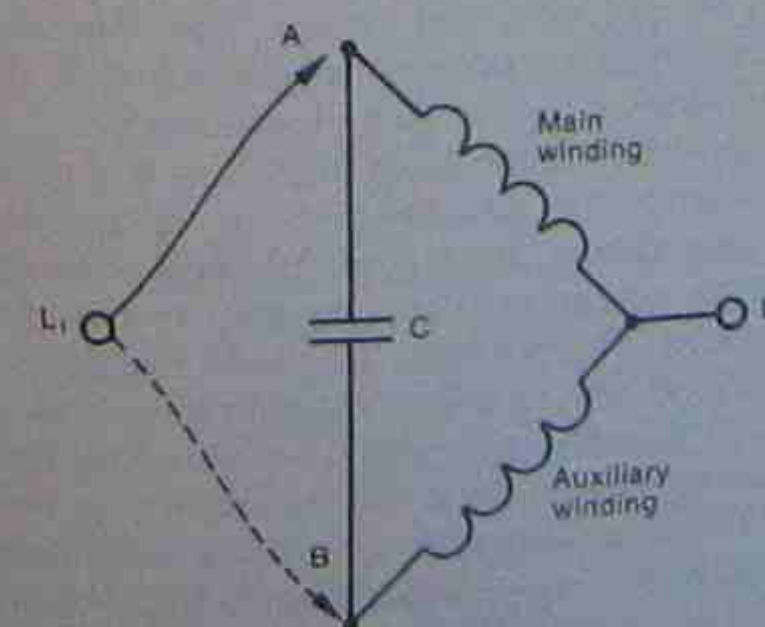


Figure 10.34 • Permanently-split motor circuit

necessary phase displacement to produce a rotating stator field. However, the phase displacement between the two fluxes is relatively small, and so the starting torque is low.

By interchanging the line connection from A to B in Figure 10.34, the capacitor is then in series with the main winding instead of the auxiliary winding. The current in the main winding leads that in the auxiliary winding and the rotor runs in the reverse direction.

These motors are suitable for unit heaters and fans because their speed can be varied fairly easily with series inductances.

#### Uses

The permanently split capacitor motor is suitable for light applications with low starting torque; for example, fans and blowers, which might need to be reversed frequently, and for remote control of induction regulators and dampers for regulating air flow in air-conditioning systems.

### 10.6.5 Shaded-pole motor

The shaded-pole motor has a cage rotor with salient poles in the stator. On one side of each pole a slot is cut and a shading ring is embedded into it, as shown in Figure 10.35. The shading rings are made of copper bar formed into a closed loop, providing a low resistance path through the ring.

The supply current produces an alternating flux in each pole. This alternating flux cuts the shading ring, inducing an e.m.f. in it. Because of the low resistance path, the current flowing through the ring is relatively high. Also, according to Lenz's law the induced current in the shading ring will produce a flux that will tend to oppose the change of the main flux.

When the supply current rises rapidly from A to B as in Figure 10.36(d), an induced voltage is established in the shading ring. The current in the ring produces a flux that opposes the build-up of the main flux. As a result, the main flux is concentrated in the unshaded section of the pole, as in Figure 10.36(a).

When the current changes from B to C, there is little change in value of current and very little voltage is induced in the shading ring. Consequently, practically no current, nor flux, is produced in the shaded ring. The

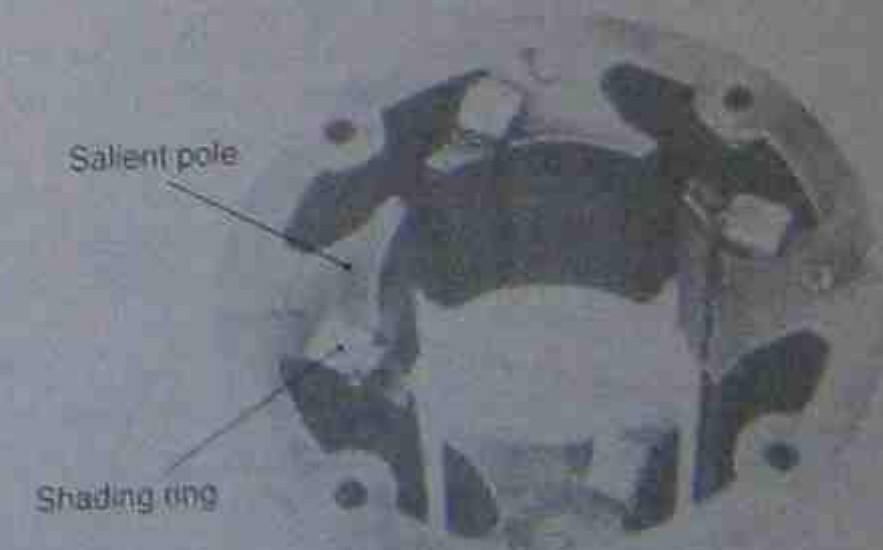


Figure 10.35 • Salient poles and shading rings



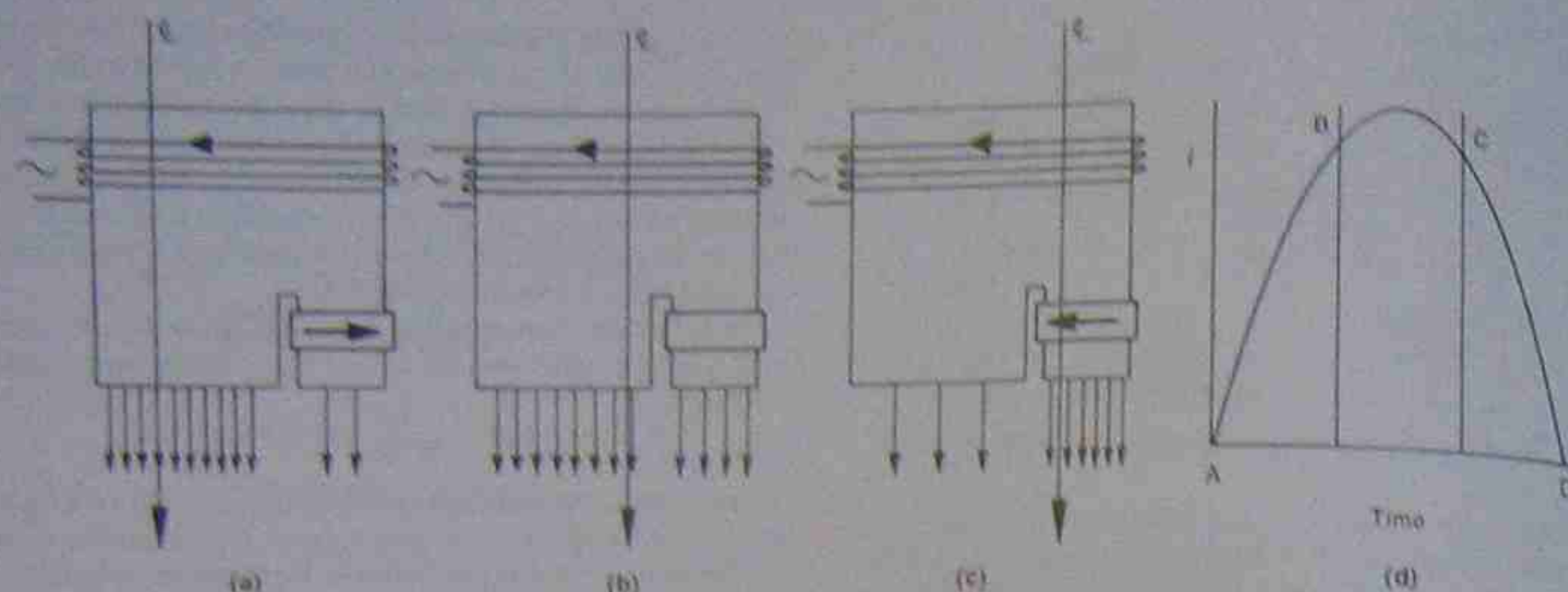


Figure 10.36 • Centre line of flux moves towards the shading ring, giving the effect of a moving field

main flux is at this time nearly always at maximum value, and is uniformly distributed over the whole pole face, as seen in Figure 10.36(b).

When the supply current drops rapidly from C to D an induced voltage is established in the shading ring. The current in the shading ring produces a flux that opposes the collapse of the main flux. The concentration of flux therefore occurs in the shaded section of the pole, as shown in Figure 10.36(c).

The magnetic axis shifts across the pole face from the unshaded part to the shaded part of the pole. This shifting flux is similar to a rotating field and produces a small torque, causing the rotor to rotate in the direction of the flux, towards the shaded section of the pole.

The starting torque is very low, as indicated in Figure 10.37, and the motor runs with a slip speed slightly higher than the single-phase motors described above. It is simple in construction, low in cost and reliable. There are no switches, slip-rings, brushes or capacitors that might require maintenance. The motor efficiency is down and this tends to restrict its use to low power ratings.

The direction of rotation has to be reversed by altering the direction of the rotating magnetic field across the pole face. This is done by shifting the shading ring to the other side of the pole face. Some poles are fitted with slots on both sides for this purpose but with others the only method is to remove the stator from its housing and replace it the other way around in the frame.

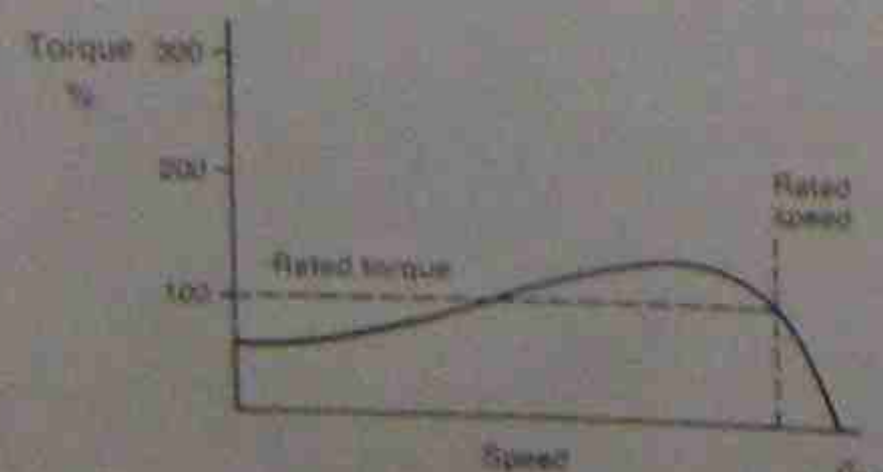


Figure 10.37 • Speed/torque curve for a shaded-pole motor

#### Uses

Because its speed can be varied within a limited range by a series resistor or inductor, the shaded-pole motor is suitable for fans and blowers, advertising signs, damper controllers, hair dryers and other uses where the starting torque requirements are minimal.

## 10.7 SERIES MOTOR

The series motor is often called a universal motor because it can operate effectively on d.c. and a.c. up to power line frequencies. Like the normal d.c. series motor it has a highly variable speed characteristic, with speeds up to 15 000 r/min in domestic appliances. Under some circumstances, governors have to be used to restrict speeds to safe values. Field pole construction consists of a number of lamination stampings riveted together to form salient poles. The field coils are concentrated-type windings fitted closely around the salient poles.

The armature construction is similar to that of a d.c. armature, with laminations, commutator and windings. The armature windings are connected in series with the two field coils by means of carbon brushes running on the commutator (see Fig. 10.38).

There is a common current flowing through both windings, so the two magnetic fluxes produced are in phase with each other. Interaction of the fluxes produces torque to turn the armature. As the a.c. supply alternates, the fluxes change in unison, so remaining in phase.

When the line current flows from A to B in Figure 10.38(a), north and south poles are produced as shown. Assuming that the armature current is in the direction indicated by the dots and crosses, the flux produced around the armature conductors interacts with the field flux, producing an anticlockwise rotation.

When the line current flows from B to A on the alternate half-cycle, the polarities of the main fields are reversed, as shown in Figure 10.38(b). The current through the armature also reverses, so reversing the armature flux. The resultant torque is still in the anticlockwise direction so a steady rotation in one direction is maintained. Rotation is reversed by changing the direction of current flow through the armature with respect to the field, that is changing over the leads to the armature, or the fields, but not both (refer to Fig. 10.39). The speed/load characteristic for the series motor is shown in Figure 10.40. When the load is heavy, the speed is low, at

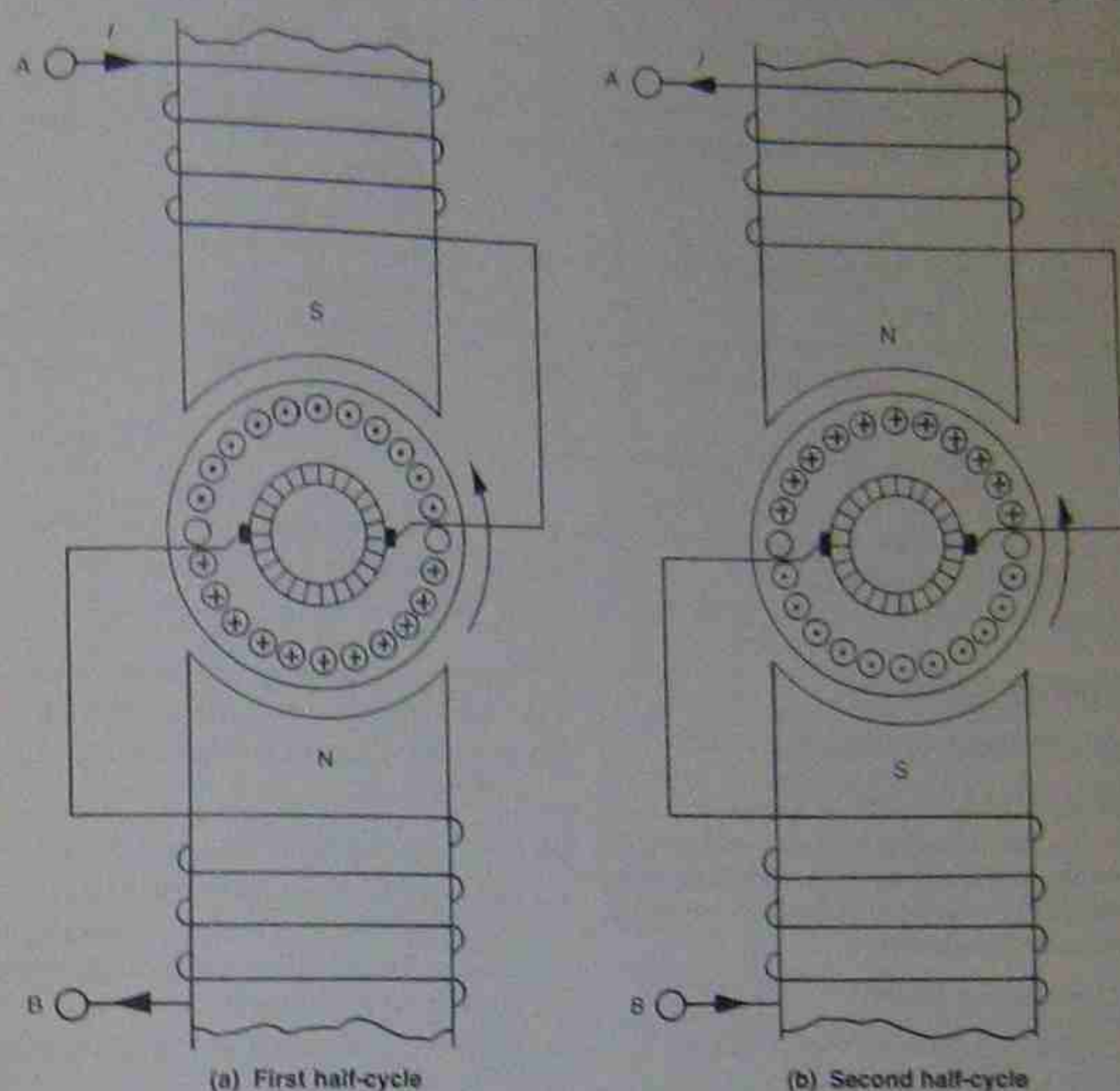


Figure 10.38 • Torque production in a universal motor

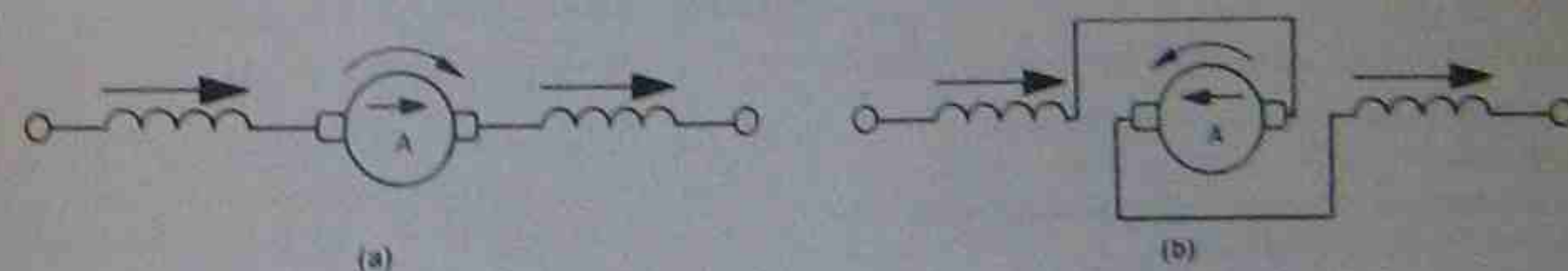


Figure 10.39 • Reversing the direction of rotation in a universal motor

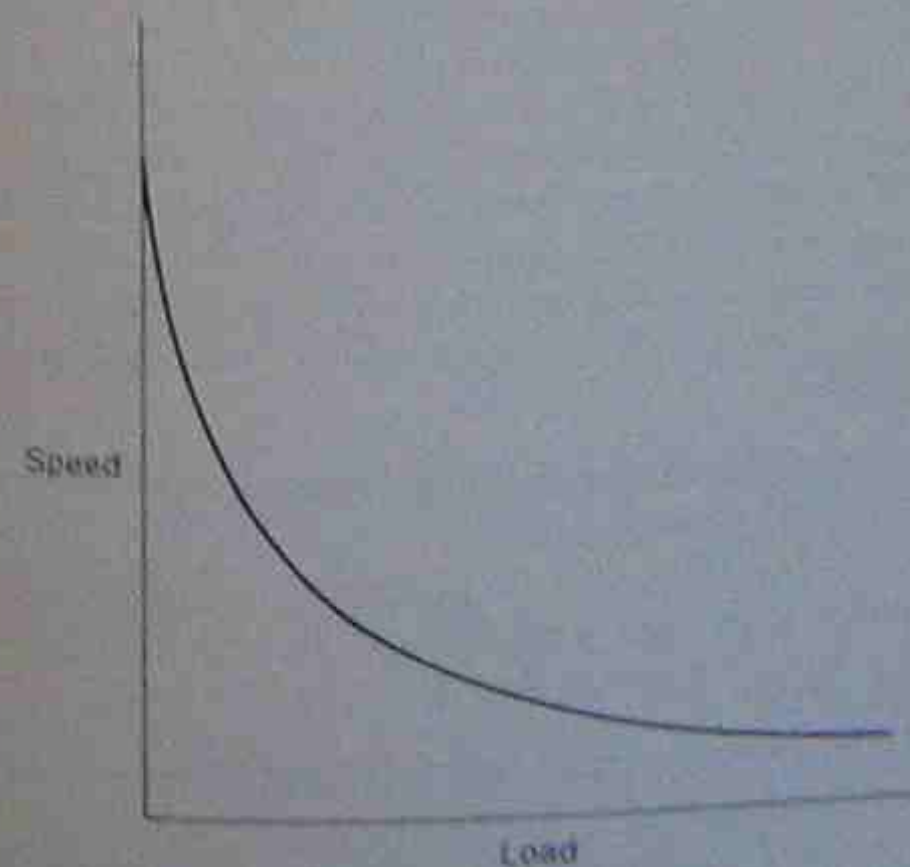


Figure 10.40 • Universal motor speed/load characteristics

light loads the speed is very high. With the very small series motor in domestic use, the internal losses (such as friction and windage) are large enough to limit the speed to a safe value. The motor runs at a relatively high speed and has good starting and running torque characteristics considering its small size.

#### Uses

The series motor is popular in portable appliances such as saws and drills, sewing machines, business machines, food mixers, small washing machines and vacuum cleaners.

## 10.8 SUMMARY OF SINGLE-PHASE MOTORS

Refer to Table 10.2 on the next page.



Table 10.2 • Single-phase motors

Motor type	Reversal	Applications	Torque
Split phase	Interchange connections of one winding	Washing machines Blowers Bench grinders	Moderate
Cap. start	Interchange connections of one winding	Pumps and small compressors	Moderate increase
Cap. start, cap. run	Interchange connections of one winding	Air conditioning units	Substantial increase
Permanently split	Interchange connections of one winding	Light loads subject to regular reversals	Very low
Shaded pole	Move shading rings to opposite side of pole or reverse stator in body	Fans	Low
Series	Interchange connections of either field or armature	Domestic appliances Hand tools	Low

## 10.9 COMPARISON OF SINGLE-PHASE AND THREE-PHASE MOTORS

The following comparison is a general guide only and will not necessarily be applicable in all cases. What would be the most suitable motor to select in one case would not necessarily be the same in another.

### Advantages of three-phase motors

1. For the same power output, a three-phase motor is physically smaller and lighter.
2. More efficient use of the iron core.
3. Higher efficiency—less input power for the same output power.
4. For the same output power, line currents are smaller.
5. Suitable for power line frequencies in excess of several hundred hertz.
6. Less mechanical vibration, owing to magnetic fields of more constant strength.
7. Inherently self-starting, owing to naturally rotating magnetic field.
8. No starting mechanism or switches required.
9. No additional wiring of extra conductors for fully sealed motors, and reducing complications of difficult installations such as submersible pumps.
10. Direction can be reversed externally by interchanging supply lines.
11. Starting currents are more easily controlled without great loss of starting torque.

### Disadvantages of three-phase motors

1. Three identical windings are needed.
2. Three active conductors are needed.
3. Not conducive to machine winding—more labour intensive.

### Advantages of single-phase motors

1. Only two windings in use, one of which can be of lighter construction.

2. More amenable to automatic machine winding; reduced construction costs in many cases.
3. Only one active and one neutral conductor needed in most cases.

### Disadvantages of single-phase motors

1. Higher line currents for the same power.
2. Larger-size motors sometimes need higher line voltages to reduce line currents. Stricter limitations on their use by supply authorities.
3. Single-phase motor reversal is usually done internally.

## 10.10 ABNORMAL OPERATING CONDITIONS FOR THREE-PHASE MOTORS

Satisfactory operation of three-phase motors on a three-phase supply depends on several factors, described below.

### Three equal voltages at the correct phase displacement

Under normal operating conditions the phase displacement is a function of the generating equipment and stays relatively fixed, but the line voltages can vary depending on the individual loads connected at that time. For balanced loads, such as three-phase motors, unbalanced phase voltages lead to unbalanced currents flowing in the motor windings. As a consequence, circulating currents are set up, heating is increased and uneven, and torque is reduced.

### Stator windings being correctly connected in either star or delta configuration

If phase currents become unbalanced, windings generate increased heat, and torque is greatly reduced. Refer to section 10.10.1 for more details.

### Three line voltages being connected to the motor windings

When any one supply line is not able to supply current to the winding to which it is connected, the condition known

as 'single phasing' occurs. For further details refer to section 10.10.2.

### Condition of all four windings in the motor

The stator windings connected to the supply are prominent and obvious areas of concern. Noisy operation and reduced torque of a three-phase motor can mean that the bars of the rotor might be in need of attention. Many cages consist of aluminium cast into shape in the laminations and little can be done in the way of maintenance; many of the larger motors, however, have prefabricated bars and rings of copper, which are welded into place. It is possible to repair or replace damaged items, whether broken or simply loose in the rotor.

## 10.10.1 Phase reversal

Previously in this chapter, description of the operation of the induction motor has been based on the assumption that the motor has three identical windings and three equal currents flowing in them, all spaced at  $120^\circ\text{E}$  to each other. If one phase is reversed, however, as shown in Figure 10.41(a) for a star connection, these conditions no longer hold true. Two of the three currents that flow are at  $60^\circ\text{E}$  to each other and the load system is unbalanced (Fig. 10.41(b)). The same condition applies to delta-connected loads.

As a result of this incorrect connection, the motor loses most of its torque and is often unable to start against even a light load. If able to start at all, it usually rotates very slowly and has unequal values of current in the phase windings. The values of current approach those drawn during normal starting, but remain high. The motor usually emits a 'growling' noise and has an associated vibration due to the sustained high current values.

## 10.10.2 Single phasing

Single phasing is a condition that occurs when one line of a three-phase supply is open-circuited and is not able to supply current to a three-phase load. The term is also used when one of the three-phase windings in a load is open-circuited.

The condition for single phasing in a star-connected load is shown in Figure 10.42(a), and it can be seen that a break in either the line or the phase winding reduces the circuit to a single current path.

Figure 10.42(b) shows an open-circuited line for a delta-connected motor. There is one main current path from  $L_1$  to  $L_2$  through phase A and another path from  $L_1$  to  $L_3$  through phases B and C in series. Both currents are in parallel with each other, although not necessarily in phase with each other. In Figure 10.42(c), a delta-connected induction motor is shown with phase C open-circuited. There are two current paths— $L_1$  through phase A to  $L_2$  and  $L_2$  through phase B to  $L_3$ .

In each of the cases shown in Figure 10.42, the rotating magnetic field is either destroyed or unbalanced, and causes unsatisfactory operation of the motor. The motor rotates at slower speeds, if it is able to start at all, because of a much reduced starting torque. It usually draws higher than normal currents in the parts of the circuit still operating, with values approaching starting current values in some circumstances. It can also emit a low-pitched 'growling' noise similar to that which occurs during a phase reversal. If single phasing occurs while the motor is operating at normal speeds, the normal humming sound often changes to a higher-pitched whine. For any of the conditions for single phasing outlined above, the  $\sqrt{3}$  ratios between line and phase values are no longer valid.

## 10.10.3 Overloading

As indicated in section 10.5.1, standards are laid down for the operation and performance of induction motors. In particular, standards are set for the starting and running torques of these motors. There are also stated limits for the amount of torque a motor can exert when it is unable to start, or is stalled by the connected load. The limits are of course variable, depending on the size or rating of the motor.

These requirements are built into the motor design and beyond the control of anyone attending to the maintenance or installation of a motor. Overloading is a

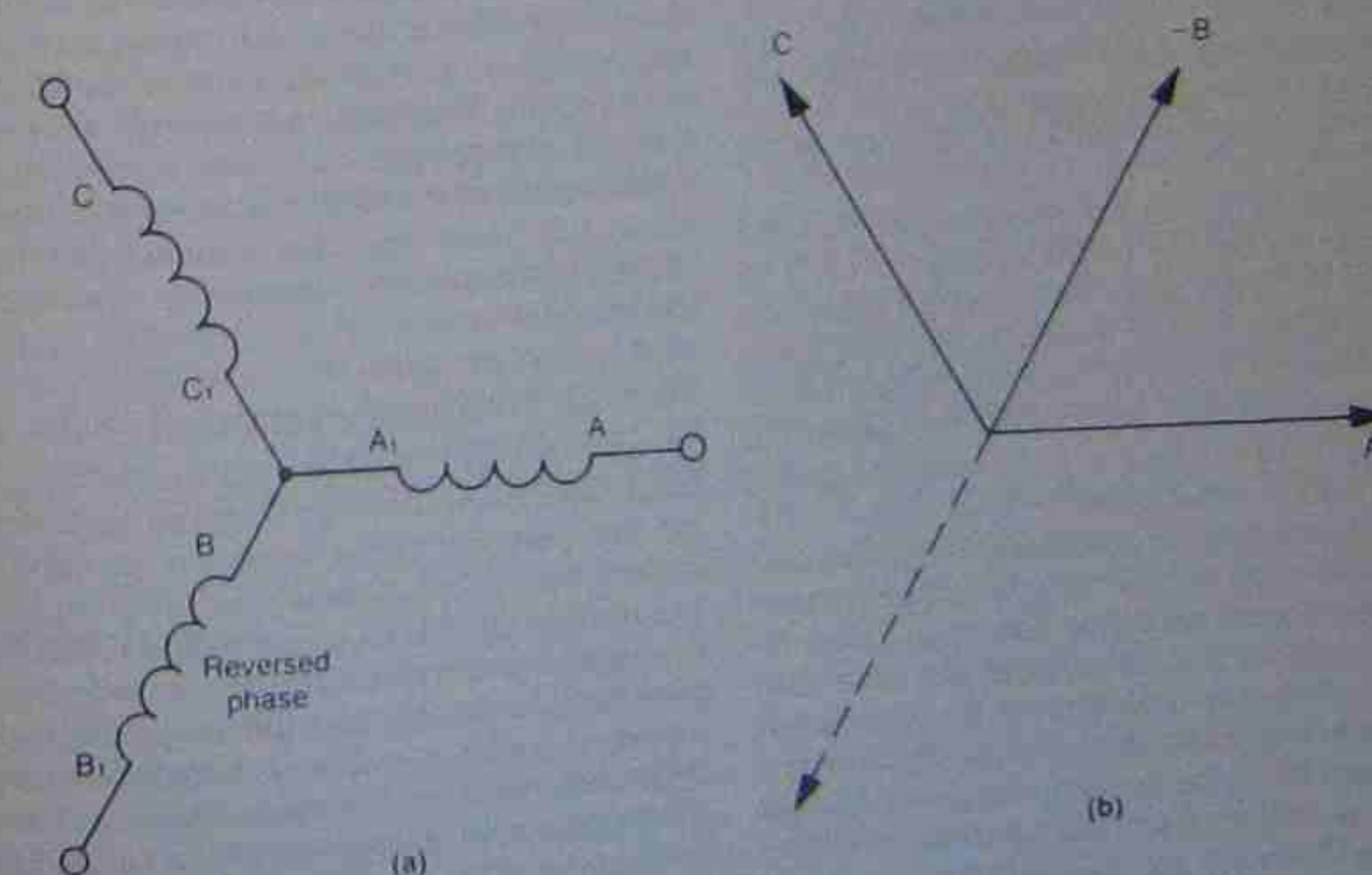


Figure 10.41 • Reversal of one phase for a star-connected motor



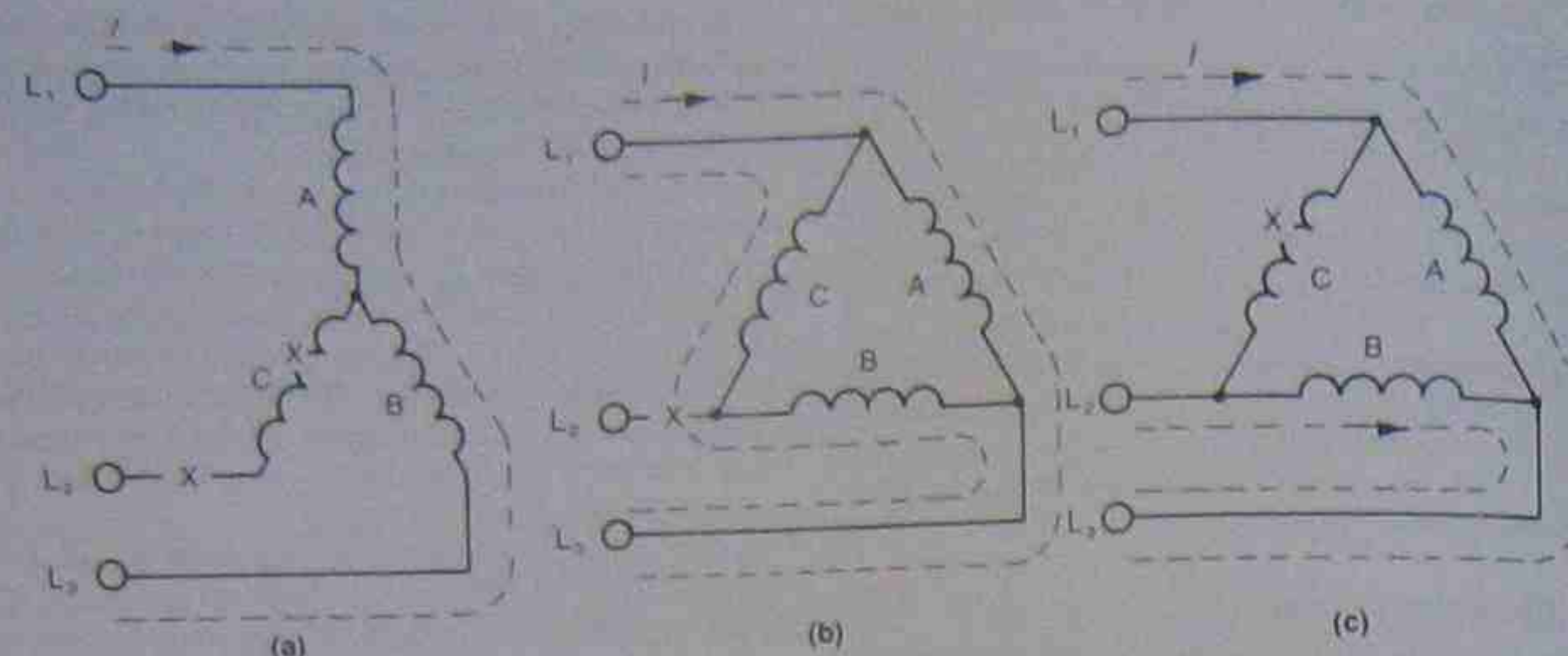


Figure 10.42 • Circuit conditions causing single phasing with a three-phase motor

condition normally brought to the attention of a technician only when a motor is behaving in an abnormal manner.

As a general guide the motor may run at a slower speed and higher temperature than normal. The varnish used on the windings might start to smell, while in extreme cases smoke might start to issue from the windings.

Once a motor is unable to meet the requirements of the applied load, it will come to a rapid stop and locked-rotor conditions then apply. Refer to 'breakdown torque' in Figure 10.13(b). Current in excess of normal full load will then be drawn and the installed motor protection must rapidly disconnect the motor from the supply, in order to prevent damage.

## 10.11 ABNORMAL OPERATING CONDITIONS FOR A.C. INDUCTION MOTORS

### 10.11.1 Voltage fluctuation

Voltage fluctuation can be of two types: voltage rise or fall, where the voltages remain symmetrical, or variations in individual phase voltages might occur. The latter is especially detrimental to the performance of three-phase motors.

It will be shown in section 13.4 that the torque produced is proportional to the square of the voltage. That is, if the voltage drops to 90 per cent of its nominal value, the torque reduces to 81 per cent of its rated value. Similarly, if the voltage rises to 110 per cent, then the torque increases to 121 per cent of its rated value. For example, a 10 kW motor with a 10 per cent voltage variation should now be rated at 8.1 kW or 12.1 kW.

Under normal operating conditions a voltage variation of this magnitude should make only minor differences to the motor's characteristics. With a voltage increase, for example, the increased torque reduces the slip only slightly, so a motor rotating at 1450 r/min on 50 Hz would increase its speed to approximately 1455 r/min. If advantage is taken of the increased torque, the operating temperature could be expected to increase. With voltage variations greater than 10 per cent the motor must be

derated to prevent excessive temperature rise. Motors are normally given a full-time rating for a specified temperature rise and under these conditions might have to be switched off after a duty period and be allowed to cool down.

Starting and breakdown torque values are also affected. A voltage rise increases torque, while a voltage reduction decreases torque. In the latter case, care must be taken to see that the motor does not stall while under load.

For three-phase motors a more serious problem occurs when only one phase shifts in value. The phase current is affected to a greater degree, which affects the rotating magnetic field in the motor. This results in reduced starting, running and breakdown torques, increased running noise and vibration, full-load speed reduction and a higher operating temperature.

### 10.11.2 Higher operating temperatures

Common causes of overheating in motors are inadequate or restricted ventilation and overloading. Apart from accelerated deterioration of lubricants, possibly the most serious effect is on the insulation. At increased temperatures there is a marked reduction in the life of insulation. For example, insulation designed to work at 90°C may have an expected life of 25 years. If the operating temperature is doubled to 180°C, the life expectancy is reduced to about 1.25 years. The cure is increased efficiency of the cooling system and a decrease in the load applied to the motor.

### 10.11.3 Frequency variation

Motor speed can be regulated by the frequency of the supply and allowances are made when selecting a motor for this purpose, but a variation in supply frequency under other circumstances can affect motor operation. The obvious effect is a change in speed, but there are also changes in power factor, efficiency and torque. A higher frequency causes an increase in power factor, a slight increase in efficiency and a decrease in torque. With a decreased frequency the opposite occurs. A variation in the frequency of supply usually occurs where there are comparatively few large loads connected to a smaller supply.

### 10.11.4 Overloading

Manufacturers build into their motors the capability to handle short duration overloads, as specified in AS/NZS 1359.41. In broad general terms the standard requires the motor to be able to withstand 1.5 times full load for a period of 15 seconds without appreciable change in speed or excessive heating. For a motor to operate under these conditions, it must also have a breakdown torque in excess of the overload test figure.

The heating effect in a machine winding is related to the square of the current and the time it is flowing, so any excess current must result in a temperature rise. With short time overloads the amount of heat generated is small and can be expected to be dissipated by the normal cooling process. Long periods of overload, however, can lead to excessive increases in temperature, in turn leading to a shortened motor life. Other effects are a slight decrease in speed, decreased efficiency, decreased power factor, and an increased possibility of stalling because the working torque is closer to the breakdown torque. When the motor stalls it draws starting current at full line voltage until its protection system operates. Large amounts of heat can be generated in short periods of time under these conditions. It should be noted that special types of motors are given restricted duty cycles. In effect they are overloaded for short periods of time, after which they must be switched off and allowed to cool down to room temperature. If this type of motor is required to run on a continuous duty cycle, it must be derated to a lower power value.

### 10.11.5 Frequent starting

Motors in general are mechanically strong enough to handle normal loads with a fair safety factor. The number of times a motor is started, however, cannot be provided for by the manufacturer unless specifically requested at time of purchase or manufacture.

When a motor is started there is a high current flow that decreases as the motor accelerates up to its operational speed. While this current is flowing, heat is being generated within the windings at a rate in excess of the usual heat dissipation rate. Under normal conditions this excess heat is removed by the cooling system while the motor is in operation. With repetitive starting, however, the heat generated does not have sufficient time to be removed and the temperature of the motor rises.

The circumstances are similar for repeated reversing and plug braking. Starting current values, whether being used for starting, reversing or braking, repeatedly stress the windings. Unless the coils are firmly braced, they rub against one another, eventually rubbing through the insulation and so causing short-circuits within the windings of the motor.

### 10.11.6 Other factors

Motors are designed to withstand normal operating conditions. Other conditions must be considered abnormal and need special consideration. Some of these are exposure to corrosive fumes, explosive vapours, dust, steam, salt air, high humidity, operation in ambient temperature of below approximately 10°C or above 40°C, or operation at altitudes in excess of 1000 metres. Generally, all these

factors can subject a motor to damage of some kind, but initially they are due to selection of the wrong type of stator housing at the time of purchase. Even motors selected for operation at elevated altitudes are subject to the same restrictions and must be rated by the manufacturer at the time of purchase for the conditions under which they will work.

Probably the most common abnormal operating condition for single-phase motors is encountered with centrifugal switch failure.

In general terms, for single-phase motors there are two major conditions, described below.

#### Starting switch contacts remain closed after motor starts

A starting switch that remains closed effectively prevents the isolation of the starting winding from the power after the starting process has been achieved. Since most, if not all, starting windings are designed with a limited duty cycle, there is very little tolerance in the amount of time they can remain energised. After a period of about 20 to 30 seconds the starting windings overheat and can be permanently damaged.

#### Starting switch contacts open-circuit

A fault of this nature usually occurs when the switch becomes jammed in its running position. The next time the motor is required to start, the starting windings are unable to function. The motor is unable to commence its rotation and remains stalled with full line voltage applied. A high starting current is maintained and is not able to reduce to a normal running value. The effect is that the excessive current continues, and overheats the running winding, leading to possible burnout.

In either instance there is also the real possibility that the heat generated in one winding can be transferred to the other, damaging it as well. Without suitable motor protection, only prompt action on the part of the operator will prevent further damage.

## 10.12 MOTOR MAINTENANCE

### 10.12.1 Electrical tests for three-phase motor windings

The tests applicable to an electric motor are either electrical or visual—usually both. Electrical tests are possibly the easiest to carry out (assuming that the equipment is available) because it often means there is no need to dismantle the motor; the testing can be done at the terminal box. Subject to the results of the electrical test, it may then be necessary to dismantle the motor.

### 10.12.2 Continuity tests

Low voltage sources such as multimeters are suitable for continuity testing. The regular multimeter is of the series ohmmeter type and care must be exercised in taking any resistance readings as absolute readings, particularly at very low values. If a winding is supposed to read 1 Ω, then a meter reading of say 0.7 Ω is pointless, since the accuracy of the meter itself might be in question. All it will establish is that there is some resistance and some form of electrical continuity between the two leads being checked.



Without some knowledge of the motor circuit it cannot be established whether the correct part of the circuit is actually being tested. For example, if a three-phase motor connected in delta configuration is being tested, an ohmmeter would give a reading across any pair of terminals even if one phase winding was an open circuit. In Figure 10.43, phase winding A is open circuit, yet a reading can be obtained between  $L_1$  and  $L_2$  (phase B), also between  $L_2$  and  $L_3$  (phase C), and between  $L_1$  and  $L_3$  (phases B and C in series). If the motor is large, the winding resistance is low and it might be difficult for ohmmeters to detect the difference in readings. Then it might be necessary to disconnect the delta bridges and check the phases individually.

A similar situation occurs with single-phase motors. When testing the motor it must be known whether the two windings are in parallel, whether there is a capacitor in the circuit, if the motor has a starting switch and if it is operational.

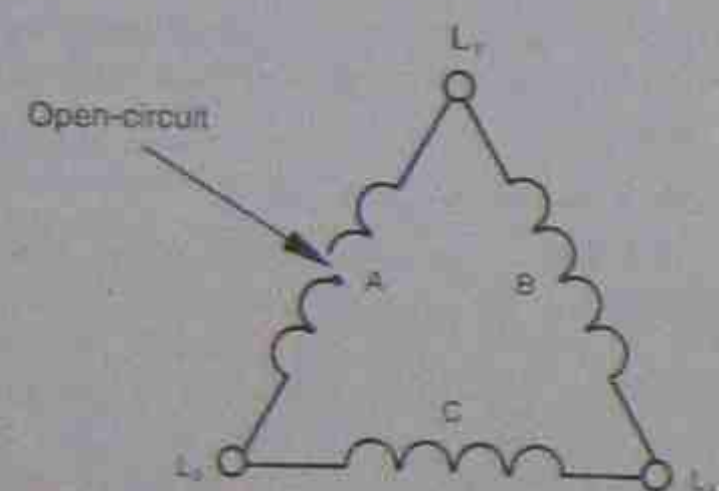


Figure 10.43 • Delta-connected motor with one phase winding open-circuited

### 10.12.3 Insulation-to-earth test

An insulation-to-earth test must be made with instruments of the correct voltage. A 415 V circuit, for example, cannot be tested satisfactorily with a 3 V ohmmeter. Similarly a small-town local supply with an exciter rated at 24 V should not be tested with an insulation tester of 500 V. Again there should be some prior knowledge of the circuit of the motor. Each phase or winding should be tested separately and the results compared. One phase with a reading considerably different to the other two could indicate a problem.

### 10.12.4 Insulation test between windings

For an insulation test between windings, the windings should be disconnected from each other and the supply source to enable a meaningful test. Again a suitable test voltage should be used and the relative readings compared for variation. A low reading between two phases is an indication of a problem.

### 10.12.5 Visual inspection

If after electrical testing a further check is required, the motor is usually dismantled for a visual inspection. With very large machines a limited visual inspection is possible by removing covers and looking inside without dismantling the complete machine. In the greater proportion of instances burnt-out motors have a characteristic smell that is quite easy to detect.

Probably most obvious is the sign of heat within the windings and associated with the burnt smell. Insulation can be charred, and windings can consist of bar copper wire with all covering burnt off. The burning smell is not an infallible indication, however, because the fault can trip the supply before the burning becomes appreciable.

Non-electrical tests indicating burnt insulation include pressing the winding with the hands and listening for a crackling noise (a winding in good condition should make no noise), rubbing the bindings with the fingers to see if they crumble, and on larger motors tapping the windings lightly with a small hammer (a faulty coil group sometimes gives a flatter sound than the rest of the windings, so giving a lead to a fault).

Where windings have short-circuited to earth, small holes in the windings, with associated copper globules, can occasionally be seen. With lighter-coloured enamels and varnishes, faulty turns and coils can be clearly seen as very much darker than the rest of the windings.

### 10.12.6 Specialised test equipment

There are times when the above checks do not give a definite answer as to the condition of the windings. If a motor is faulty in operation and passes the above tests, then further testing is necessary. One popular method involves using the windings as the secondary of a transformer with a piece of equipment called a growler—a name given for the noise made when it is in operation.

One type is designed for the testing of armature windings and has a vee-shaped gap in which to place the armature. When alternating current is applied to the growler an alternating voltage is induced in the armature windings. The induced voltages on opposite sides of the armature are equal and opposing, so no circulating current flows. If there is a short-circuit in the windings, this balance is upset and a circulating current flows. The faulty coil can be detected by a light-gauge strip of steel held against the armature—it vibrates when laid along the slot holding the faulty coil. One variation of this is where the vee-shaped gap is rounded to sit inside the stator of a motor and a similar operating procedure is followed.

Some models of growler have the vee on one side and the rounded section on the other. Another piece of test equipment, the Profex, is sometimes used with motor stators. It is plugged into an a.c. supply and moved around inside the stator. If a short-circuit exists in the stator windings, the circulating currents upset the magnetic field of the tester and a light flashes, indicating the location of the fault. A piece of test equipment called an Induktor is shown in Figure 10.44. It is used in a similar way to the Profex.

### 10.12.7 Dismantling three-phase motors

When dismantling an electric motor, the main aim after any inspection or repairs is to reassemble it in the original form. To make it easier than just relying on memory or previous experience, it is a common practice to mark the end-shields and other pieces in some way.

Probably the most common method is to use a centre punch and make adjacent punch marks on matching surfaces. They should not be placed on machined surfaces.

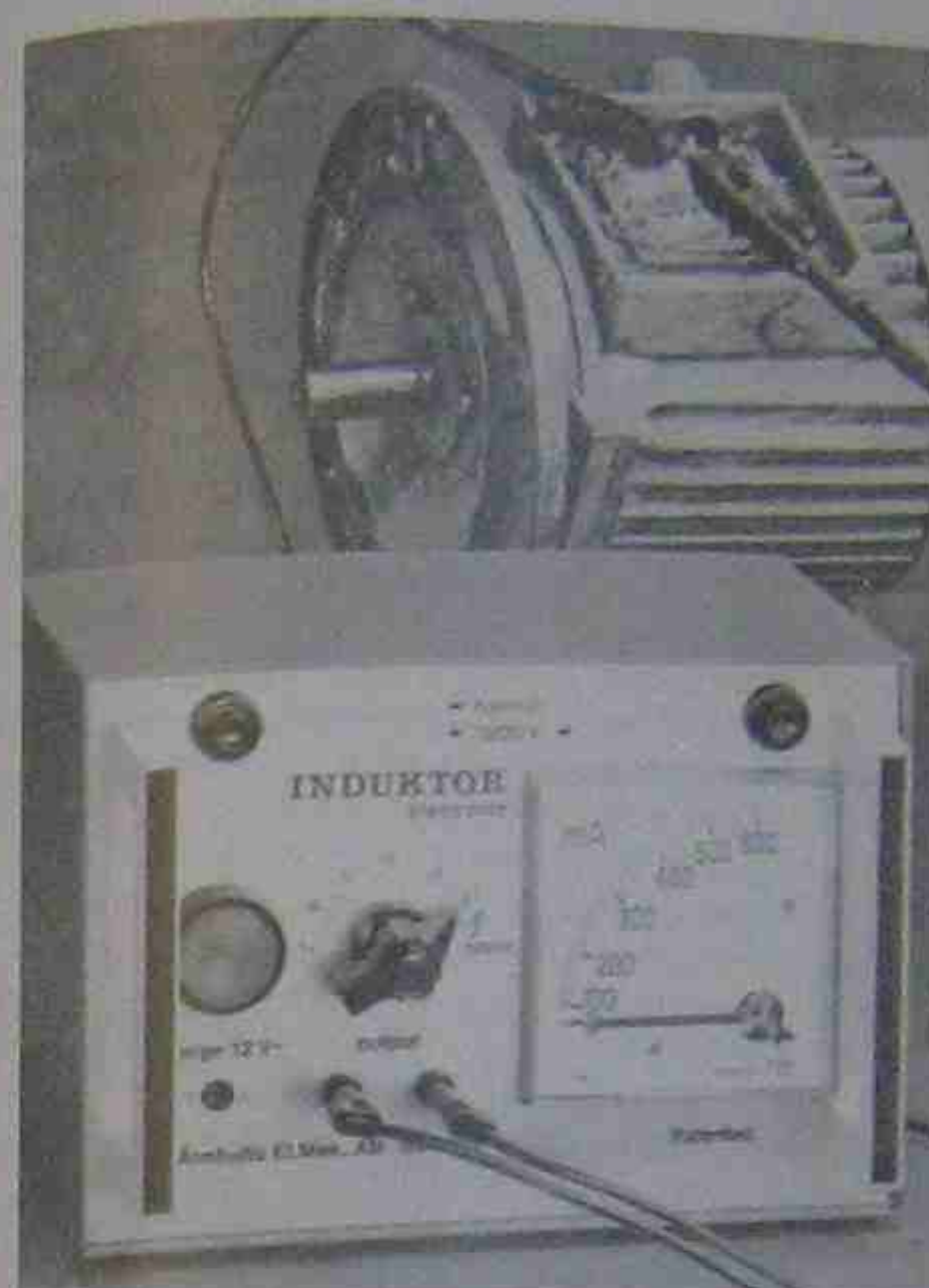


Figure 10.44 • Tester for comparing relative inductances of motor windings

ASEA Pty Ltd

Some technicians prefer to use a cold chisel and make one mark across two surfaces, the intention being to be able to reassemble the motor more accurately. In either case only a light mark is needed so long as it can be used on reassembly. It is not recommended that large deep marks be made because of the possibility of damage to the casing. Called 'witness marks' by some, it is nevertheless good practice and is used extensively by experienced technicians.

For example, an end-shield could be marked with a single centre-punch mark on both the end-shield and the motor frame. It is quite customary to place these marks at the top of the motor where they can be easily seen. The opposite end-shield could then be marked with two closely spaced punch marks. A similar method could be used on the bearing covers.

If in a position to do so, an experienced operator will often keep components of subassemblies separate from other subassemblies as they are removed. It is bad practice to put all components in one container and then have to attempt to sort them out when required for reassembly.

Withdrawal of the rotor from the stator calls for some care to ensure that no damage is caused by the worker to either the rotor or the stator and its windings. A mechanical and electrical examination of the motor can then take place.

Matching punch marks when rebuilding is a quick and accurate method of ensuring that the motor is assembled in its prescribed condition and manner. It also ensures that the motor shaft is protruding from the right end and the terminal block and housing is in the correct position.

Bearings should be checked for wear and regreased on assembly with just the right amount of correct-grade grease.

### 10.12.8 Electrical tests for single-phase motor windings

As a general guide, any electrical tests applicable to three-phase motor windings are also applicable to single-phase motor windings. The major problem is that it is common practice for one of the starting winding leads to be firmly connected to the starting switch behind the terminal strip. Since the motor is at rest and the switch contacts closed, this means that there is a feedback path to the other winding. It can and does lead to false continuity readings.

Separation of these leads is not straightforward. With the current lack of standardisation in single-phase motor terminal arrangements, it is sometimes difficult to distinguish between running and starting winding leads. The matter is further complicated by the presence or otherwise of any capacitors that might be connected to the windings.

When added to the fact that provision has to be made for all leads to be brought out to the terminals to allow for motor reversal, it is occasionally easier to dismantle the motor to avoid confusion over which lead belongs to which winding.

A method applicable only to armatures is called the 'drop-test', where the armature has a d.c. voltage applied to sections of the commutator, so causing a current flow through the windings. The readings (voltage-drop) across adjacent segments are compared as progress is made around the commutator. An armature in good condition will have similar readings right around the commutator.

High, low and reverse readings indicate faults that must be interpreted according to the local circumstances. For example, a high reading across two segments can indicate a poor joining of leads to the commutator bar or it can indicate an open circuit. A reverse reading can indicate a coil connected in reverse, or it might merely mean that the operator has the two supply leads more than one pole pitch apart. Experience is necessary to interpret test results accurately from drop-testing, as indeed it is from any test equipment. A circuit for drop-testing an armature is shown in Figure 10.45.

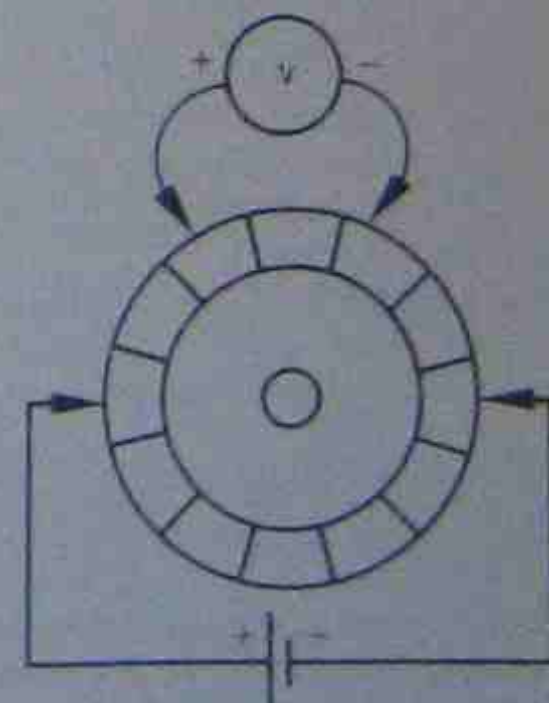


Figure 10.45 • Circuit for voltage drop-testing of armatures



### 10.12.9 Dismantling single-phase motors

The basic procedure for dismantling three-phase motors applies also to single-phase motors, with one possible precaution. The starting switch is usually centrifugally operated and attached to the shaft at the terminal end of the motor.

In some makes of motor the rotor and the end-shield

have to be withdrawn from the stator with some care because of the winding leads and the switch connections. They might even have to be withdrawn together to ensure that there is no damage to the switch. In many instances the rotating mechanism and the stationary mechanism overlap and have to be separated carefully.

## SUMMARY

- The stator core is made from laminations pressed into a frame.
- The rotor is laminated and pressed on to a shaft that is free to rotate in bearings.
- The rotor windings are usually single copper conductors shorted at the ends with copper rings. This construction is called a squirrel-cage rotor.
- There are special types of rotor constructed to produce various amounts of torque. There are only two major types—standard and high-torque rotors, although some may be designed only for either star or delta starting.
- Wound rotors have three identical windings, usually connected in star configuration internally and the other ends brought out of the windings to slip-rings.
- Stator winding leads are brought out to terminal blocks and arranged in a standard manner for ease of connection in either star or delta configuration.
- Motor enclosures are made to AS/NZS requirements. They range from an open type to completely sealed. See AS/NZS 1359.
- A three-phase motor has a rotating magnetic field, which gives the motor an inherent starting torque. The motor always rotates in the direction of the rotating field.
- Reversal of rotation of the field and the rotor is achieved by interchanging any two lines of the supply to the motor.
- The rate of rotation of the field depends on the frequency of the supply and the number of poles in each phase winding.
- The synchronous speed of an induction motor can never be achieved because the motor relies on a certain amount of slip to generate torque. Within the capacity of the motor, the greater the slip, the greater is the torque. Once a maximum value is exceeded, the motor stalls and excess current flows.
- The rotating field cuts the conductors of the rotor, generating a voltage in the rotor conductors by induction. This causes currents to flow in the rotor bars and creates a magnetic field that reacts with the rotating field to produce the torque.
- Slip causes an alternating current to be generated in the rotor bars.
- Slip is the difference in speed between synchronous speed and actual speed.
- As a general guide, when the resistance of the rotor bars equals the inductive reactance of the rotor bars, maximum torque is created.
- Wound-rotor motors have a much higher starting torque than squirrel-cage rotors. Reducing the external resistance in the rotor circuit allows the rotor to get up to speed gradually without excessive currents flowing.
- Wound-rotor motors have poorer speed regulation than squirrel-cage motors.
- A three-phase motor needs to have all three windings correctly connected to operate properly. Reversal of one phase winding leads to flow of unequal phase currents and greater heat generation.
- A similar situation occurs when one phase winding has no current flowing in it. Unequal currents flow, and greater heat is generated. Torque in both cases is greatly reduced. This also applies in the absence of one supply line.
- Single-phase squirrel-cage motors have no rotating field or starting torque.
- A rotating field has to be created by starting the motor as a two-phase motor. Once up to speed, the motor is able to create torque to keep rotating and the second winding can then be disconnected.
- Reversal of motor rotation is achieved by reversing one of the windings. This reverses the direction of the rotating field.
- The second winding has to have a current flow at sufficient phase displacement to the running winding current. This gives rise to different windings. The phase displacement can be enhanced with the addition of a capacitor in series with one winding.
- There are different arrangements and connections for single-phase induction motors, depending on the use for the motor.
- One method for starting single-phase induction motors is the shaded-pole method. It provides only a limited rotating field and so only a limited starting torque. Its use is limited to smaller motors. To reverse this type of motor, the shading rings must be shifted to the opposite side of the pole.
- Overloading of both single- and three-phase motors causes high temperatures to be created in the motor windings. This can damage the windings permanently. Single-phase motors will stall more quickly than three-phase motors of equal size.
- A series motor is a single-phase motor that relies on its high speed for its power. Its uses are limited to small motors, usually of the hand tool variety.
- A series motor is not an induction motor.
- The speed regulation of a series motor is very poor and the greater the load, the lower is the speed.
- Reversal of rotation is achieved by reversing the connection of either the field or the armature—not both.
- Electrical tests for single-phase and three-phase windings involve continuity and insulation tests both between windings and to earth.

## EXERCISES

- An additional test for an a.c. motor winding is for the detection of short-circuits between the turns or coils. Short-circuits in this case lead to high circulating currents and heat generation, causing breakdowns.
  - When dismantling a motor, care should be taken to ensure that it can be reassembled correctly in its original form. The use of punch marks is one method of ensuring this. Good technicians will try to keep components in separate units to avoid confusion on reassembly.
- 10.1 Briefly describe how the rotating magnetic field is produced in a three-phase motor.
  - 10.2 (a) Define the term *synchronous speed*.  
(b) Make a table showing the synchronous speeds of two-, four-, six- and eight-pole induction motors for frequencies of 40, 50 and 60 Hz.
  - 10.3 Explain why an induction motor runs at less than synchronous speed.
  - 10.4 Explain why the power factor of an induction motor increases with the load.
  - 10.5 Briefly describe the construction of the squirrel-cage and the wound-rotor motors.
  - 10.6 What is meant by:  
(a) synchronous speed of an induction motor?  
(b) actual speed?  
(c) slip speed?  
What is the relationship between each of these speeds?
  - 10.7 Sketch a typical torque/speed curve for an induction motor having a normal squirrel-cage rotor. At low values of slip, how does the torque vary with load? What occurs when breakdown torque is reached?
  - 10.8 Why do squirrel-cage motors draw relatively large amounts of current when first connected direct to the supply?
  - 10.9 What is meant by the term *split phase*?
  - 10.10 Briefly describe the split-phase method of starting single-phase induction motors.
  - 10.11 Why is a centrifugal switch used in most single-phase induction motors?
  - 10.12 Name one type of single-phase induction motor which does not use a centrifugal switch.
  - 10.13 Why is the starting winding of a split-phase motor disconnected under running conditions?
  - 10.14 Briefly describe the principle of operation of the capacitor-start, induction-run motor.
  - 10.15 What is the main advantage of capacitor-start, induction-run motor, compared with the standard split-phase motor?
  - 10.16 How is the direction of rotation reversed in a split-phase motor?
  - 10.17 Explain the principle of operation of the shaded-pole motor.
  - 10.18 Explain why it is possible for a d.c. series motor to operate on an a.c. supply.
  - 10.19 How can the direction of rotation be reversed in an a.c. series motor?
  - 10.20 With the aid of diagrams, explain how a shading ring provides starting torque for a shaded-pole motor.
  - 10.21 Discuss, with the aid of circuit diagrams, how the following motors can be reversed: split phase, series type, shaded pole.
  - 10.22 Why are the armature and field fluxes in phase with each other in an a.c. series motor? Explain also why it is necessary that they be in phase with each other.
  - 10.23 Explain why a capacitor-start motor has more starting torque than a split-phase motor.
  - 10.24 Draw a simple circuit diagram for a permanently split capacitor motor. Give the typical operating characteristics, and list an application for this type of motor.
  - 10.25 Describe a method for finding which phase has an earth fault in a three-phase delta-connected motor.
  - 10.26 State a reason for not using a 500 V insulation tester on a motor that runs on 110 V.
  - 10.27 Give a list of items to look for when inspecting a motor for a suspected faulty winding.
  - 10.28 Describe a procedure for testing an armature with a growler.
  - 10.29 List three types of single-phase induction motors and briefly describe the characteristics of each one.
  - 10.30 Why is the shunt field of a direct current motor unsuitable for alternating current operation?
  - 10.31 Describe the operation of a universal motor. How is it reversed? Include a circuit diagram with your answer.
  - 10.32 Why can the starting winding of a single-phase induction motor be employed only for intermittent duty?
  - 10.33 What is the purpose of connecting a capacitor in series with the starting winding of a single-phase induction motor?
  - 10.34 What would be the result of connecting a capacitor in series with the starting winding of a single-phase motor if it produced resonance in that winding?
  - 10.35 Describe the operation of a shaded-pole motor. Include in your explanation how starting torque is produced.



## TESTING PROBLEMS

- Determine the percentage slip for the following three-phase, 50 Hz motors:
- four-pole, 1420 r/min
  - six-pole, 960 r/min
  - eight-pole, 720 r/min.
- At full load the efficiency of a 15 kW motor is 83 per cent. If the power factor is 0.84, calculate the current drawn.
- The rotor speed of a 10 kW, 415 V, three-phase, four-pole motor is 1455 r/min when it operates from a source of 50 Hz. Find:
- the synchronous speed
  - the slip speed
  - the frequency of rotor currents.
- Calculate the synchronous speed for a ten-pole 60 Hz motor. What would the speed be if it is run on 50 Hz?
- A ten-pole motor has a synchronous speed of 720 r/min and an actual speed of 695 r/min. Find:
- the slip speed
  - the percentage slip
  - the frequency of the supply.
- A four-pole motor when connected to a 50 Hz supply runs at a speed of 1440 r/min. Calculate the slip speed and the rotor frequency.
- The rotor frequency of a two-pole motor is 2.5 Hz when connected to a 50 Hz supply. Calculate the motor speed and slip percentage.
- The rotor frequency of a two-pole motor is 0.5 Hz when running on a 50 Hz supply. Calculate:
    - the synchronous speed
    - the actual speed
    - the slip as a percentage of synchronous speed.
  - A 50 Hz three-phase motor supplies 2 kW of power at a torque of 20 N m. Find the speed of the motor, and so deduce the number of poles in the motor.
  - A three-phase 415 V motor supplies a load of 19 kW at a power factor of 0.82. Calculate the current flow to the motor if the motor efficiency is 85 per cent.
  - A 415 V three-phase delta-connected motor delivers a starting torque of 76 N m. What starting torque would be produced if a star/delta starter was used?
  - Calculate the power input to a three-phase motor if it has to drive a load at 1440 r/min and supply a torque of 47 N m. Efficiency is 83 per cent.
  - A six-pole motor runs at 875 r/min on a 50 Hz supply obtained from a diesel-powered alternator. Calculate:
    - the synchronous speed of the motor
    - the slip speed, rotor slip frequency and percentage slip.
 What would be the synchronous speed of the motor if the frequency was allowed to drift to 55 Hz?

# Chapter 11

## Synchronous machines





## 11.1 INTRODUCTION

It was shown in section 8.2 that an alternator driven at a constant speed produces an alternating voltage at a fixed frequency, dependent on the number of poles in the machine. A machine designed to be connected to the supply and run at synchronous speed is called a synchronous machine. The description applies to both motors and generators. A synchronous condenser is a special application of a synchronous motor.

While the synchronous motor has only one generally used name, the synchronous generator is on occasion referred to as an alternator or as an a.c. generator. The term alternator has been used in previous chapters and will be used in this chapter, but it should be remembered that other terms are in use. In general the principles of construction and operation for alternators and generators are similar.

While alternators were once seldom seen outside power houses, and whole communities were supplied from a central source, there is now an expanding market for smaller-size alternators suitable for the production of power for portable loads. With the growth in computer control, there is a further need for standby generating plant to ensure a continuity of supply and prevent loss of data from computer memories. So much information is now being stored in computers that even brief interruptions to the power supplies can have serious consequences for the accuracy and extent of information stored.

## 11.2 THREE-PHASE ALTERNATOR CONSTRUCTION

The three-phase synchronous machine has two main windings:

1. a three-phase a.c. winding
2. a single winding carrying d.c.

In most cases the pole has the d.c. winding and the stator the a.c. winding. An alternator with a rotating d.c. winding and a stationary a.c. winding, while suitable for smaller outputs, is not satisfactory for the larger outputs required of power stations. With these machines the output can be so inordinately large that it is impractical to handle with brushes and slip rings. Because the terminal voltages range up to 15 kV, the only satisfactory construction is to have the a.c. windings stationary and to supply the rotor with d.c.

This arrangement has the following advantages:

1. extra winding space for the a.c. windings
2. easier to maintain for higher voltages
3. simple, strong frame construction
4. lower voltages and currents in the rotating windings
5. the high current windings have solid connections to the 'outside' circuit
6. better suited to the higher speeds (and smaller number of poles) of turbine drives

### 11.2.1 Stator

The stator of the three-phase synchronous machine consists of a skirted laminated iron into which the stator winding is fitted. The stator winding consists of three

separate windings physically displaced from each other by 120°. Each phase winding has a number of coils connected in series to form a definite number of magnetic poles. A four-pole machine, for example, has four groups of coils per phase or four 'pole-phase groups'. The ends of the three-phase windings are connected in either star or delta configuration to the external circuit.

Details of phase windings for a three-phase machine were shown in Chapter 9 to consist of three identical windings symmetrically distributed around the stator. A typical three-phase stator is shown in Figure 11.1.



Figure 11.1 • Stator for a low-speed 415 V three-phase 150 kVA alternator

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### 11.2.2 Rotor

The alternator rotor can be of two types—low speed and high speed.

#### Low speed (salient pole)

This type usually consists of a 'spider' similar to that used in d.c. machines, on which are bolted the field poles and the field coils (see Fig. 11.2a). Physical constraints limit the use of this type of rotor to low-speed machines.

#### High speed (cylindrical)

The cylindrical rotor was developed to meet the need of higher-speed prime movers. To counteract centrifugal forces its diameter must be small compared to its length (see Fig. 11.2b).

### 11.2.3 Prime movers

#### Low speed

Most diesel engines used as prime movers for driving alternators operate within the range 500–1000 r/min and the necessity for the use of rotors with many pairs of poles.

Hydroelectric turbines have water-driven impulses that operate at low speeds; consequently they also have rotors with many poles. While the diesel-driven alternator usually has its shaft in the horizontal plane, the

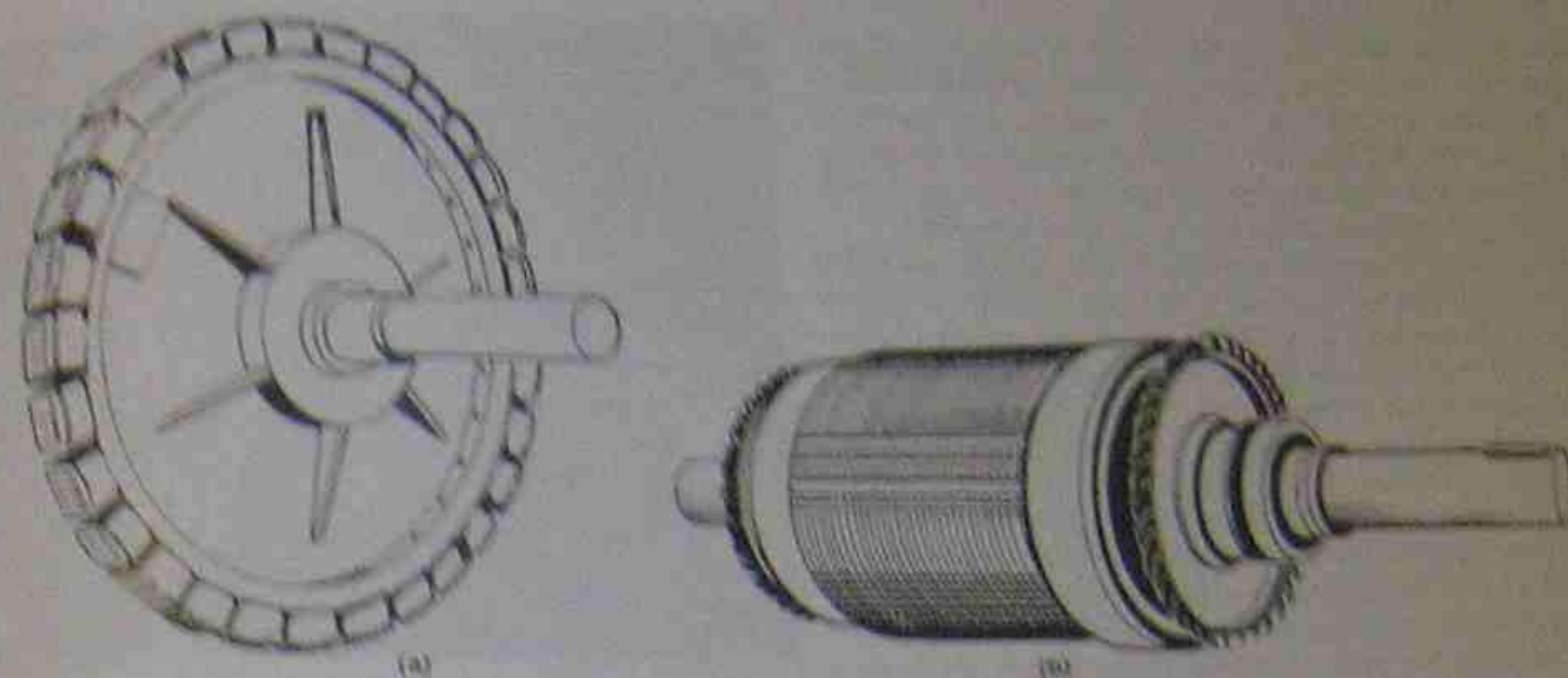


Figure 11.2 • Main types of alternator rotors: (a) low speed—salient pole; (b) high speed—cylindrical

hydroelectric unit has its shaft in the vertical plane. This method of construction means that special thrust bearings have to be fitted to take the end thrust of the rotating component.

#### High speed

Turbine prime movers, whether steam or gas, operate efficiently at speeds of about 3000 r/min. An alternator driven by a turbine and producing a frequency of 50 Hz at 3000 r/min must consist of only two poles.

In Chapter 8 the relationship between speed, frequency and the number of poles was shown to be:

$$f = \frac{n}{120} p$$

By transposition:

$$n = \frac{120f}{p}$$

where  $n$  = r/min

$f$  = frequency in hertz

$p$  = number of poles

For a large-diameter rotor of 24 poles at 50 Hz:

$$n = \frac{120 \times 50}{24} = 250 \text{ r/min}$$

For a turbine-type rotor of two poles at 50 Hz:

$$n = \frac{120 \times 50}{2} = 3000 \text{ r/min}$$

### Example 11.1

At what speed would the governor of a twelve-pole diesel-driven alternator have to be set to enable a frequency of 60 Hz to be generated?

$$\begin{aligned} n &= \frac{120f}{p} \\ &= \frac{120 \times 60}{12} = 600 \text{ r/min} \end{aligned}$$

An alternator in this speed range will have a large diameter and a comparatively short axial length. With turbines, the extra expense and auxiliary machinery needed restricts their use to larger sizes. Higher outputs mean that the length of the alternator must be increased, and the increase in length causes complications in cooling.

### 11.2.4 Alternator cooling

#### Low speed

With engine-driven or hydroelectric alternators there is no great difficulty in providing adequate ventilation because of the characteristically large diameter and short axial length. In addition to the large surface area available for direct radiation of heat there is a fanning action due to the rotation of the fields, an action that can be increased by the addition of fan blades if necessary.

When the axial length is short, the heat developed in the unbedded windings is quickly conducted to the ends where the fanning action can dissipate it. As the machine size becomes larger it is often necessary to provide ventilation ducts within the core to provide paths through which cooling air can flow.

#### High speed

The provision of adequate cooling facilities is a problem in high-speed machines of large capacity if the operating temperature of the windings is to be kept within safe limits. The surface area available for cooling in a high-speed machine is less than that in a low-speed machine of the same capacity.

The diameter of the rotor must be small enough to keep the surface speed down to a safe value, so its large capacity for the length of the machine must be considerable. This long axial length causes difficulty in cooling the central portion of the core because the heat generated cannot be conducted away quickly enough to limit the temperature rise in the core to a value that will protect the windings and the insulation.

These considerations gave rise to the necessity for completely enclosing the alternator and allowing the use of forced ventilation to carry away the heat produced. When



cooling air is used it must be filtered to keep it clean and sometimes washed by passing it through a spray chamber to prevent a build-up of dust within the machine. Washing the air has the added advantage of cooling it, and so further reducing the temperature of the alternator, allowing the rating of the machine to be increased.

To increase alternator ratings still more, hydrogen gas is used instead of air because of its greater ability to absorb heat. The machine is completely enclosed and the hydrogen is blown through the alternator and then through a heat exchanger before being recycled through the alternator again. The total exclusion of air from a fully sealed machine is necessary to prevent an explosive mixture from forming. Considerable care is taken to ensure the purity of the hydrogen gas. The oil pressure for the bearings is at a higher value than the pressure of the hydrogen being pumped through the machine. This ensures the oil flow through the seal is towards the hydrogen gas so that it is retained in the machine. The oil may then be passed through a vacuum process to remove any hydrogen gas or air before being reused in the machine.

These cooling methods require considerable power and auxiliary equipment, so the output from the alternator must be increased an appreciable amount for the method to be economically feasible. Accordingly, it is used only on very high capacity machines.

### 11.2.5 Excitation

The usual method for d.c. excitation of the rotor windings is for each machine to have its own d.c. generator called an exciter. The exciter can be belt driven or geared down from the synchronous machine but the usual practice is for the exciter to be directly coupled to the rotor shaft.

The exciter armature rotates within the influence of the exciter field, causing a d.c. voltage to be generated in the armature. The exciter output is fed into the field windings of the synchronous machine. By adjusting the rheostat in the exciter field circuit, the strength of the magnetic field in the rotor can be varied.

With very large alternators, the d.c. excitation requirements are substantial. This means that the d.c. generators have to be large also; so large that they might not be able to self-excite. Because of this, the d.c. generator might



Figure 11.3 • Slip-mounted generating unit. These are used as stand-by generating power supplies as backups in the event of power failures

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need an exciter of its own—one that is able to self-excite and provide power for the field of the main generator, which in turn supplies the rotor field of the alternator.

Some alternators use a 'brushless' excitation system in which the exciter armature has been replaced by a small three-phase alternator that rotates within the influence of a small residual magnetic field. This causes a small three-phase voltage to be generated in the exciter. When rectified by an internal rectifier and converted to d.c. it is supplied to the main field of the alternator, resulting in an a.c. output voltage. A sensor unit connected to the output of the machine monitors the output voltage and load current of the alternator and sends electrical signals to a controlled rectifier, which in turn controls the strength of the exciter field. The sensor unit and the controlled rectifier are in a sense the voltage regulator of the machine. (For more information on rectifiers and controlled rectifiers, see Chs 15 and 16.)

A basic circuit of a brushless generating system is shown in Figure 11.5.

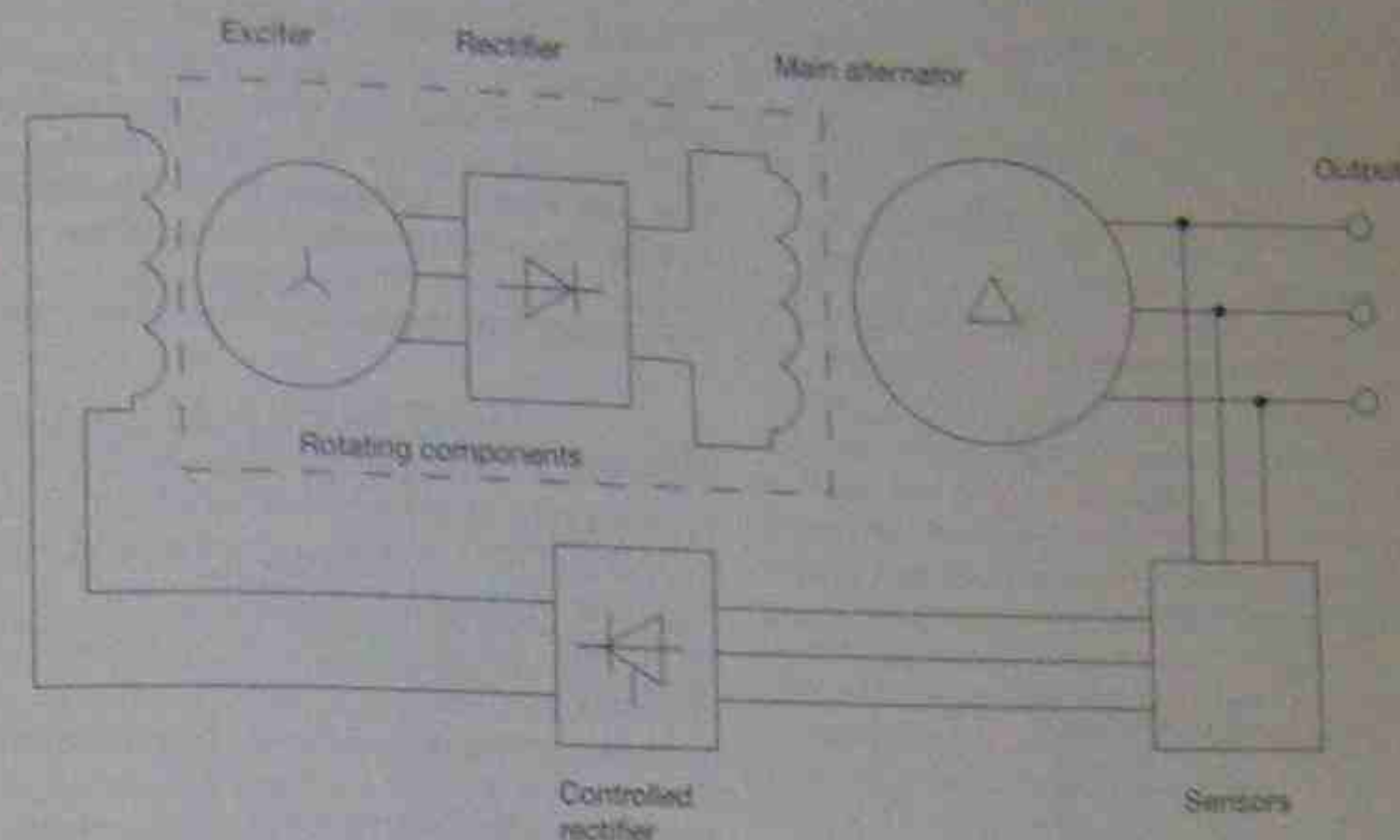


Figure 11.5 • Brushless excitation

### 11.2.6 Generated voltage

The value of the generated a.c. voltage depends on the strength of the rotor flux and the speed at which it cuts the windings. Because the speed must be constant (and is linked to the frequency required) the sole remaining factor determining the value of the generated voltage is the strength of the rotor flux.

For an alternator, the generated voltage is found from:

$$V_g = 4.44 \Phi f N k_d k_p$$

where  $V_g$  = generated voltage per phase (r.m.s.)

$\Phi$  = flux per pole in webers

$f$  = frequency in hertz

$N$  = number of turns per phase

$k_d$  = a constant, dependent on winding distribution

$k_p$  = a constant, dependent on coil pitch

### Example 11.2

Calculate the line voltage of a 50 Hz star-connected alternator given the following details:

$$\Phi = 0.67 \text{ Wb/pole}$$

$$\lambda_d = 0.85$$

$$k_p = 0.98$$

$$N = 36 \text{ turns/phase}$$

$$V_g = 4.44 \Phi f N \lambda_d k_p \\ = 4.44 \times 0.67 \times 50 \times 36 \times 0.85 \times 0.98 \\ = 4460 \text{ V}$$

$$\text{Then: } V_L = \sqrt{3} \times V_g \\ = 1.732 \times 4460 \\ = 7725 \text{ V}$$

### 11.2.7 Effect of load on alternator voltage

An alternator can be considered to consist of three components in series:

1. an a.c. generating source
2. a resistor—representing iron and copper losses
3. an inductor—representing the inductance of the windings and magnetic leakage.

Any load placed on the alternator must be assumed to be in series with these components as shown in Figure 11.6.

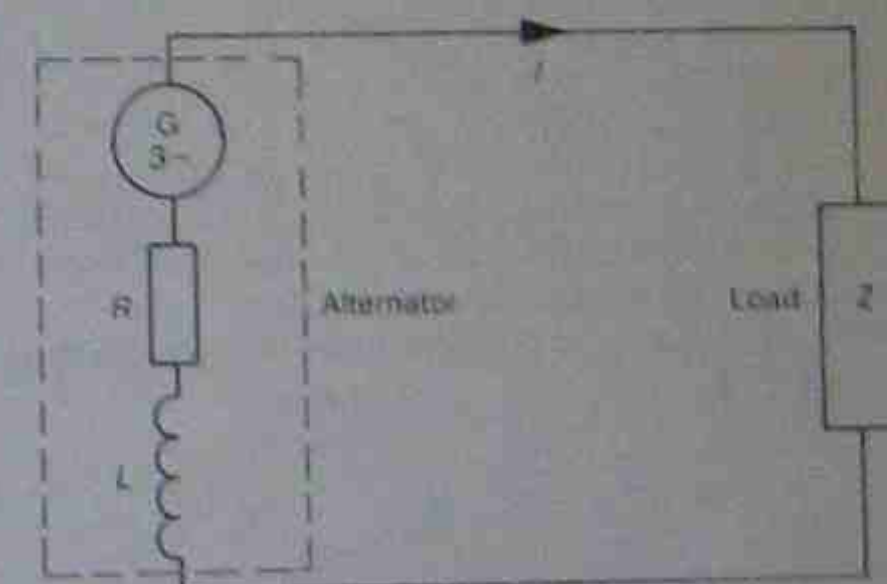


Figure 11.6 • Equivalent circuit of an alternator

The series impedance of the resistance and inductance provides a drop in voltage before the generated voltage can reach the connected load. Additionally the load current in the a.c. windings produces an armature reaction, which also affects the output voltage.

With a unity power factor load, the armature reaction merely distorts the main field and the effect on voltage is minimal, the voltage drop in the main being due to the series impedance. Figure 11.7(a) shows that the resistive voltage drop  $IR$  is in phase with the load current  $I$  and the voltage drop due to the reactance  $IX$  is at  $90^\circ$  to the  $IR$

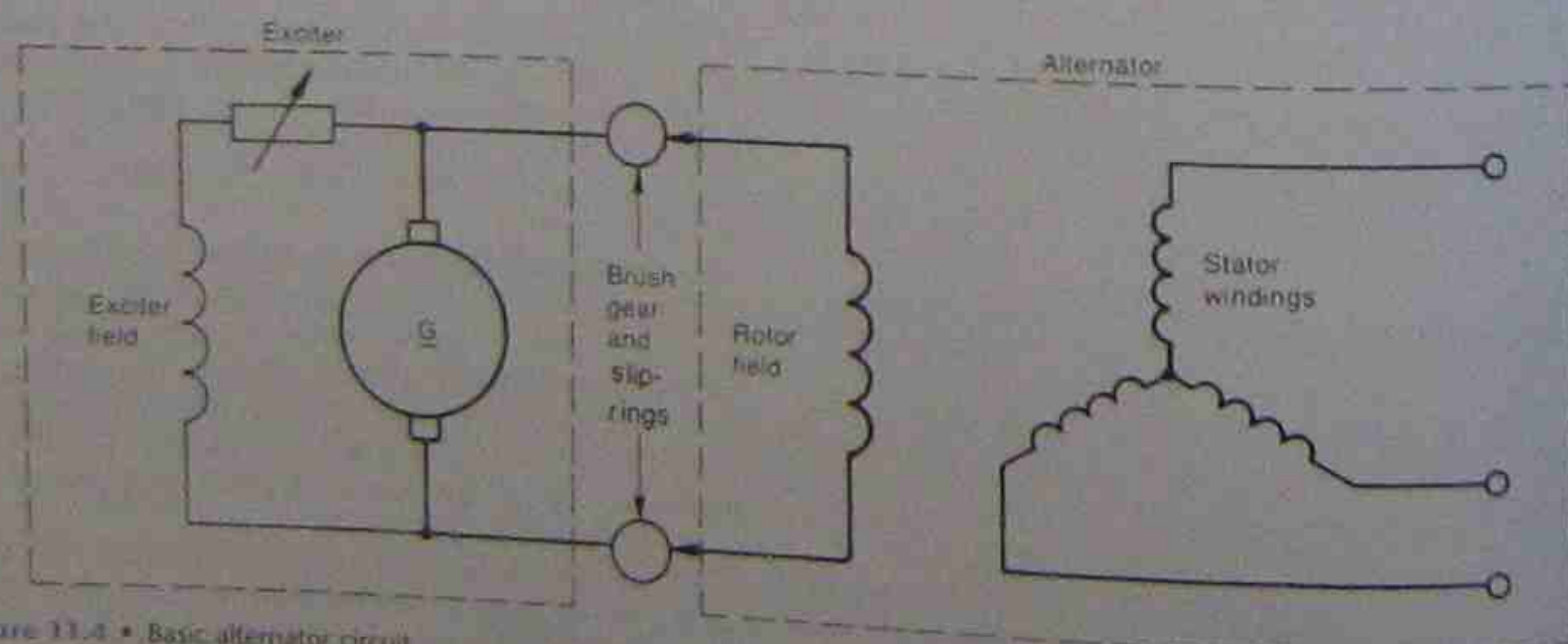


Figure 11.4 • Basic alternator circuit



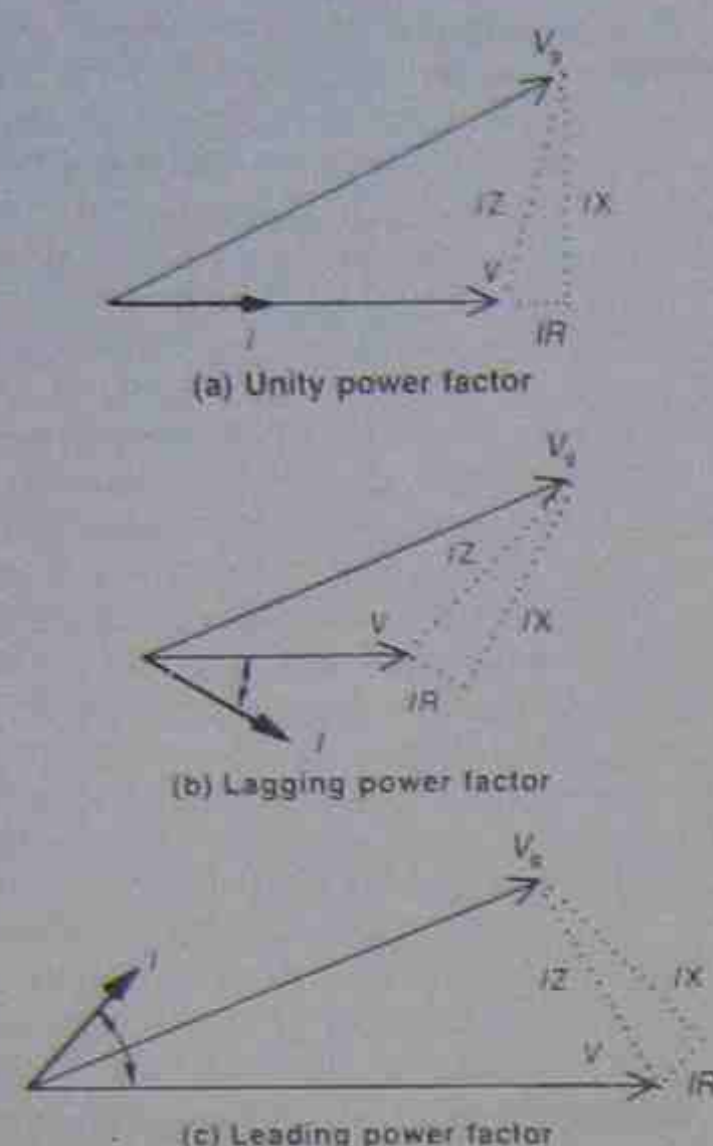


Figure 11.7 • Phasors for various power factor loads on an alternator

drop. These two values combine to form a voltage drop  $IZ$  due to the impedance of the alternator windings. The phasor sum of the output voltage and  $IZ$  gives the generated voltage  $V_0$ . For a load with a lagging power factor, however, the magnetic effect of the stator currents opposes that of the rotor, resulting in a weakened rotor field and reducing the output voltage further than did the resistive load alone (see Fig. 11.7(b)). As before,  $IR$  is in phase with the load current  $I$ .  $IX$  is at  $90^\circ$  to  $IR$ , so placing  $IZ$  at a different angle to the previous case. In a similar manner,  $V_0$  is equal to the phasor sum of the output voltage and  $IZ$ . For a load with a leading power factor, the flux caused by the stator currents assists that of the rotor, resulting in an increased output voltage (see Fig. 11.7(c)).

The characteristics of the three types of loads are shown in Figure 11.8.

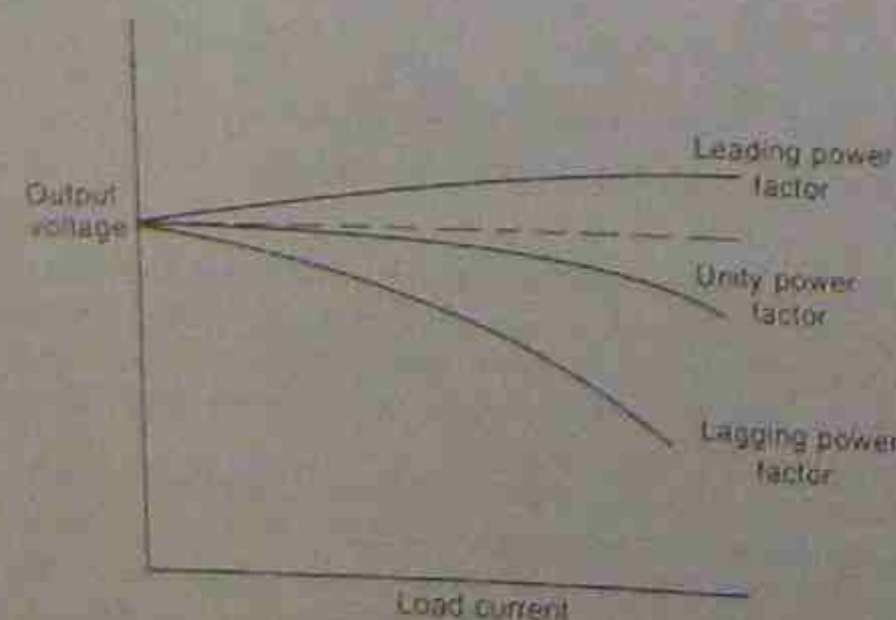


Figure 11.8 • Effect of power factor on output voltage of an alternator

### 11.2.8 Voltage regulation

An alternator is required to give a prescribed terminal voltage at full load. The difference in output between no load and full load is a measure of its voltage regulation. The difference is compared to the full-load value in a similar manner to that for d.c. machines:

$$\text{voltage regulation} = \left[ \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \right] \%$$

#### Example 11.3

A three-phase star-connected alternator has an output voltage of 3300 V at full load, with unity power factor. When the load is removed and the excitation is unchanged, the voltage rises to 3350 V. Find the percentage regulation.

$$\begin{aligned} \text{change in voltage} &= 3350 - 3300 = 50 \text{ V} \\ \text{regulation} &= \frac{50 \times 100}{3300} \\ &= 1.5\% \text{ at unity power factor} \end{aligned}$$

*Note:* The regulation must also be referred to the load power factor because these figures at any other power factor would be different.

### 11.2.9 Alternator ratings

An alternator is rated according to three basic factors:

1. frequency
2. voltage
3. current.

The first fixes the speed at which the alternator must be driven; the second states the designed output voltage; and the third is the full-load current output. The last two factors help establish the volt-ampere rating, usually expressed in kVA.

The power factor of any load placed on the alternator is beyond the control of the manufacturer and because it could vary considerably, the alternator rating cannot be given in kilowatts.

#### Example 11.4

Find the power loading in kilowatts of a three-phase, 415 V 50 Hz alternator rated at 150 kVA at 0.8 power factor, if when fully loaded the load has a power factor of:

(a) 0.8

(b) 0.6

The machine is rated at 150 kVA and 0.8 power factor so at this load:

$$\text{power output} = 150 \times 0.8 = 120 \text{ kW}$$

At 0.6 power factor:

$$\text{power output} = 150 \times 0.6 = 90 \text{ kW}$$

In both cases, the current flowing will be the full-load current value, which should not be exceeded because of cooling problems within the windings.

At 0.8 power factor:

$$P = \sqrt{3}VI$$

that is,  $120\,000 = \sqrt{3} \times 415 \times I \times 0.8$

$$I = \frac{120\,000}{\sqrt{3} \times 415 \times 0.8} = 208 \text{ A}$$

This is the full-load current rating for each phase winding of this particular alternator and it applies irrespective of the load power factor or of the load power.

## 11.3 PARALLEL OPERATION OF ALTERNATORS: SYNCHRONISING

Most commercial power stations are designed to have a number of alternators operating in parallel, supplying a common load at constant voltage. Because alternator efficiency is maximum near its full-load capacity, it is more economical to have each machine delivering its approximate rated output. During the early hours of the morning, for example, when there is a light load, it might be necessary to have only one machine connected to the line, delivering its rated output. As the load varies during the 24-hour period, so the number of machines connected in parallel is determined.

Before a three-phase alternator can be connected in parallel with another three-phase supply, the following conditions must be fulfilled:

1. The output waveform of each supply must be identical. This is determined by the design features of the alternators. It is standard practice to generate a sinusoidal waveform supply.
2. The phase sequence or rotation of each supply must be the same, and this ensures that the e.m.f.s of each supply reach their maximum values in the same sequence; for example, R, W, B. The phase sequence is determined by the method of connection of the alternator phase windings to the terminals of the machine. This check is carried out during the commissioning process after the initial installation, or following a major maintenance overhaul, and it

is not necessary to do it each time the machine is connected in parallel with others.

3. The alternator and supply voltages must be the same.
4. The alternator and supply voltages must also be in phase.
5. The alternator and supply frequencies must be identical.

The last three conditions can be adjusted by the operator. The voltage of the incoming alternator is adjusted by varying the field excitation, and the frequency is determined by the speed of the prime mover.

To ensure that the alternator and supply voltages are in phase with each other before connecting them in parallel to the load, some method of indicating the phase relationship is required. Smaller-size alternators can be synchronised with lamps, but for larger machines a more exact method is required.

### 11.3.1 Synchronising alternators with incandescent lamps

#### Three dark' method

Voltages for synchronising purposes can be checked by connecting a voltmeter to each machine in turn, but this does not give any indication of polarities or phase relationships. Incandescent lamps can be used to indicate this and the circuit is shown in Figure 11.9.

The voltage rating of the lamps needs to be twice the alternator phase voltage and the simplest way to achieve this is to connect two lamps of equal wattage in series. The lamps can be observed as three pairs of lamps, or three can be covered, leaving only three visible (as shown by the dotted box in the diagram).

If the alternator is properly connected, the three lamps should all become bright and dim simultaneously. If they brighten and dim in sequence, it means that the phase rotation of the alternator is opposite to that on the distribution system, so the phase rotation of the incoming alternator must be reversed.

The lamps flicker at a rate equal to the difference in

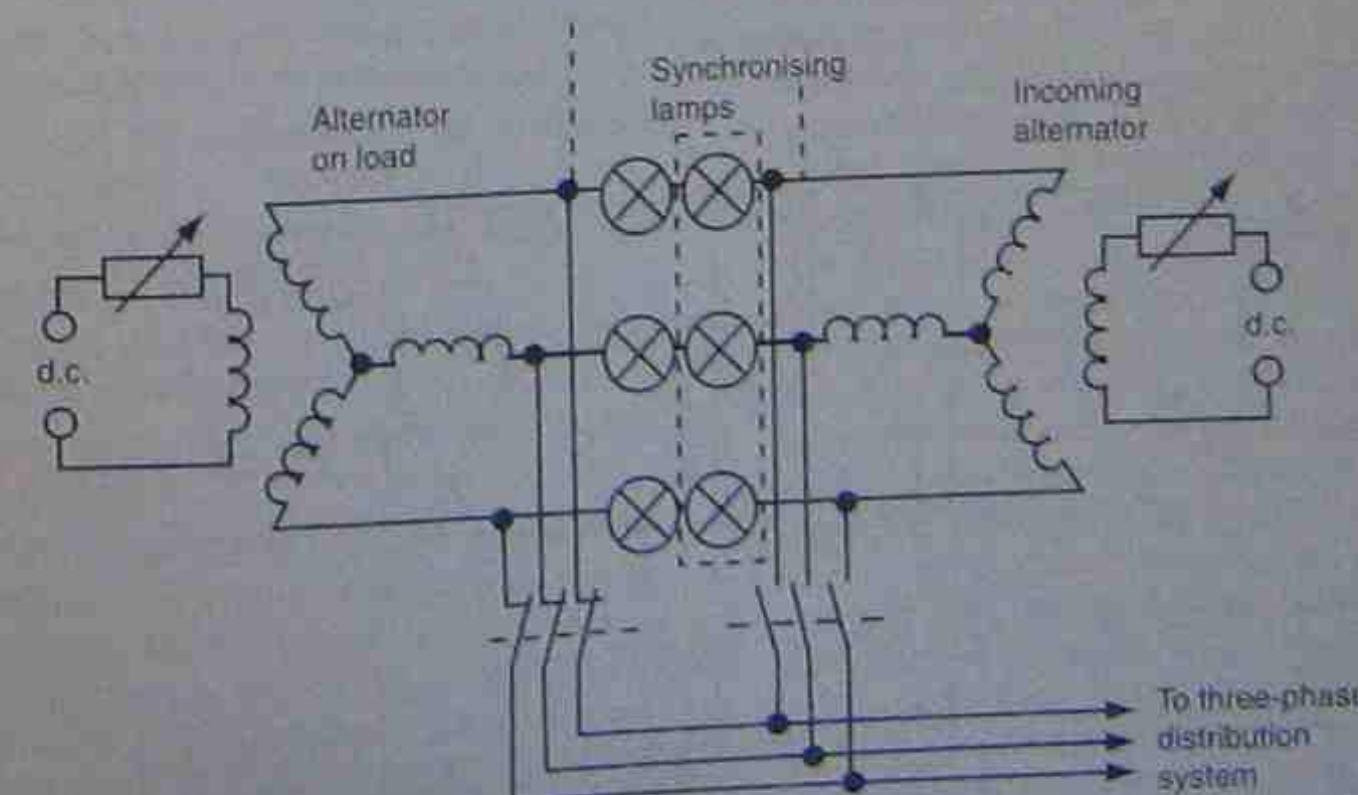


Figure 11.9 • 'Three dark' lamp method for synchronising alternators



frequency between that of the incoming alternator and the busbars leading to the distribution system. As the alternator frequency approaches that of the busbars, the rate of flickering slows down; when the two frequencies are equal, the flickering stops. When the lamps are out (dark), the connecting switch can be closed and the two machines will remain synchronised. When all the lamps are dark, there is no potential across the lamps, indicating that the two voltages are in phase with each other.

The disadvantage of this connection is that the lamps can be dark even with a 'small' voltage across them. With smaller alternators the two a.c. sources can synchronise themselves if the difference is not too great, but with larger alternators the mechanical and electrical forces created by a phase displacement between the two sources can cause considerable damage.

### Two bright, one dark' method

The circuit for this method is shown in Figure 11.10 and can be seen to be similar to that of the previous circuit except that the connections for two of the lamps are crossed. Again two lamps are in series and it is usual to cover up three lamps, leaving only three visible (as shown by the dotted box in the diagram).

To use this circuit it is essential to check the phase rotation by the 'three dark' method first. Having established that the phase rotation is correct and with the lamps reconnected, it will be found that the lamps go dark and bright in sequence. By noting the order of brightness, it becomes a reference in determining whether the incoming alternator is fast or slow.

Synchronism occurs when the lower lamp in Figure 11.10 is dark and the other two are of equal brilliance. Then the switch can be safely closed.

The significance of the correct lamp being dark lies in the fact that it is connected between two similar phases. When these two phases are synchronised, the voltage difference between them is zero. This cannot apply to the other lamps since they are connected across dissimilar phases.

The 'two bright, one dark' method gives greater accuracy, both in determining the relative speeds and frequen-

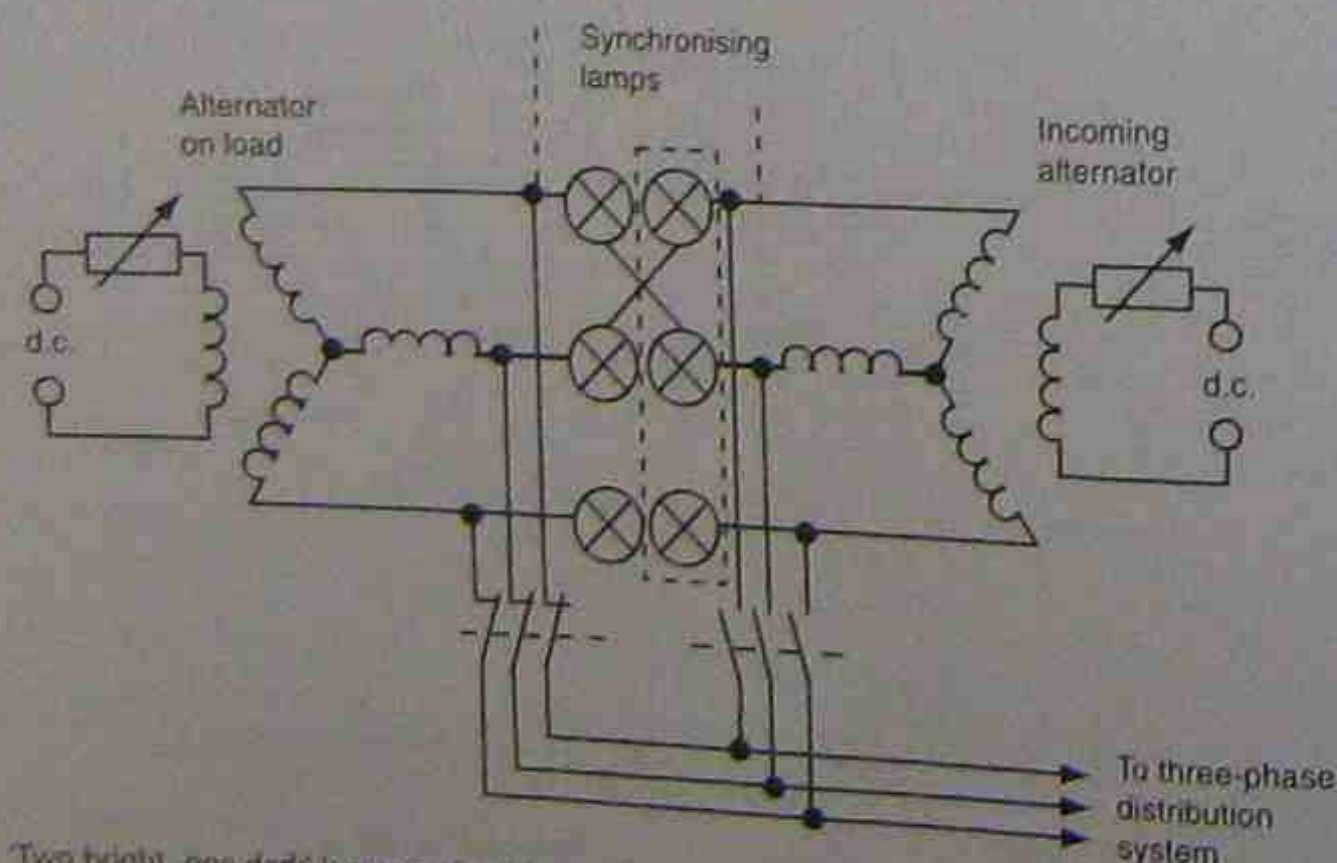


Figure 11.10 • 'Two bright, one dark' lamp method for synchronising alternators

cies, and in showing fairly accurately the instant for synchronising.

### 11.3.2 Synchronising alternators with a synchroscope

A synchroscope is an instrument that indicates both phase relationships and relative speed for an incoming alternator. There are variations between manufacturers in the operating principles but in general a synchroscope consists of a two-phase stator connected to the incoming alternator, with the rotor wound with a polarising coil and connected to the supply source. Some models use rotating vanes with no actual electrical connection to the rotor.

If there is any difference between the frequencies of the supply and the incoming alternator, a pointer attached to the rotor of the synchroscope will rotate at a speed proportional to this difference. Its direction of rotation indicates whether the incoming machine is running fast or slow (i.e. above or below synchronous speed). At synchronism the pointer will remain stationary, but it must be brought to an indicated position on the scale before the main switch of the incoming alternator is closed.

### 11.3.3 Automatic synchronisation

Modern generating systems are usually microprocessor controlled. Manufacturers use dedicated microprocessors to control their systems. The buyer is supplied with sufficient information to operate the system and re-programme it if and when necessary. Confidential information regarding the details of the individual circuits are not released. The following material is only a general guide.

An installed unit continually monitors the mains voltages. This is often done by using transformers to detect the presence of mains voltages and reduce them down to about 5 V<sub>p-p</sub>, which is then converted to pulses. These pulses are connected to the inputs of the microprocessor or a programmable logic controller. It is then processed by the manufacturer's software, which in turn controls all operations of the processor and the generating unit.

The majority of generating sets are diesel engine driven brushless alternators with single-bearing overhung alter-

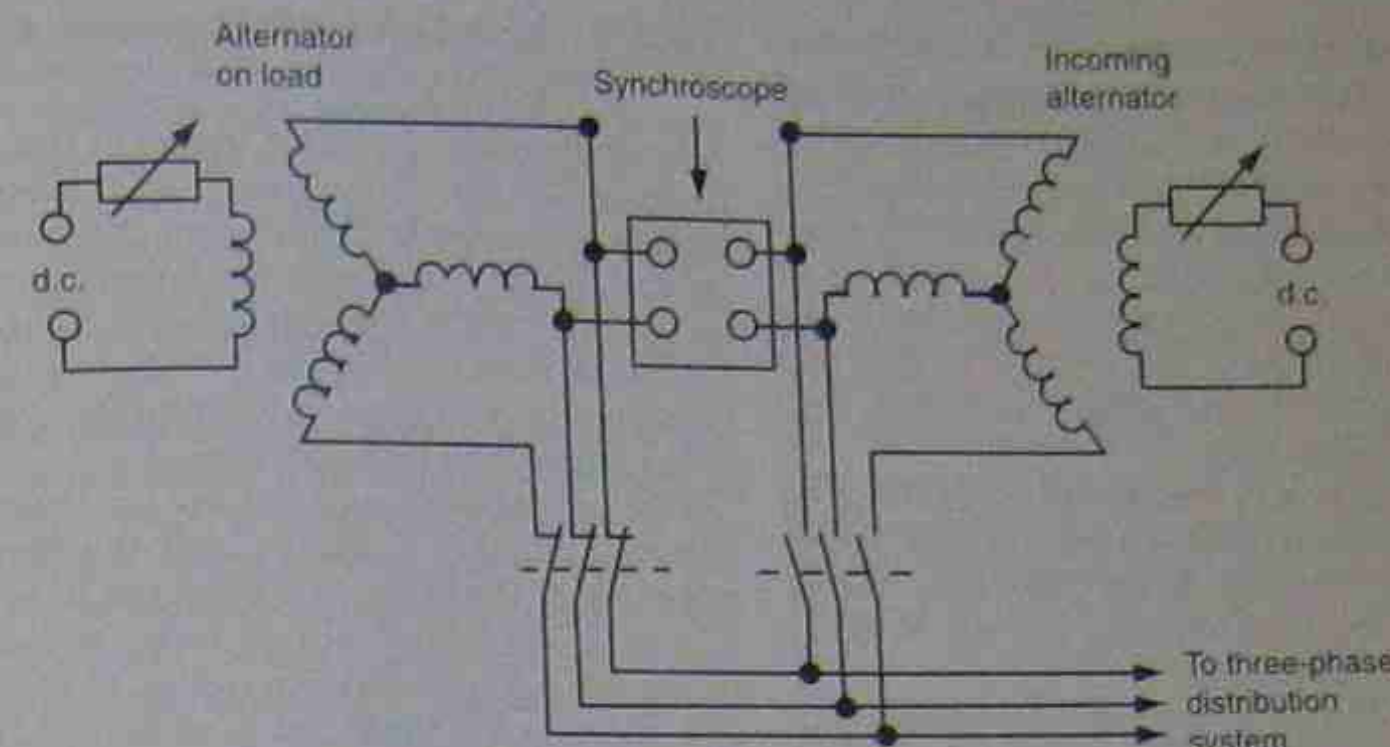


Figure 11.11 • Synchroscope connections for synchronising alternators

nators. Excitation for the main generator is provided by a small alternator and rotating rectifiers. (Refer to section 11.2.5.) The prime mover of the generating plant is designed to be started automatically when fault conditions exist. The processor monitors a number of conditions before the alternator is connected to the load and makes decisions accordingly. Some of these are:

- Start the prime mover and check for correct operating conditions.
- If after several tries—usually three—the prime mover cannot be started an alarm is sounded and a second machine is tried.
- Monitor engine oil pressure and temperature.
- Test output voltage and frequency of the alternator and adjust if necessary.
- Check engine and alternator speed and adjust if necessary to correct frequency differences.
- Monitor phase relationships between mains and alternator voltages.
- Make speed adjustments to correct phase sequences and phase angles to conform with the existing supply.
- When phases and frequencies are synchronised to close main circuit switch for connection to supply.
- Monitor the load on a machine and connect extra machines if required.
- Monitor external mains voltages and decide when to shut the standby supply down.
- Transmit audible and visual alarm signals to signal fault conditions have occurred.
- Operate analogue and digital indicators at the generator installation.
- Record the engine operating hours.

The actual connection of the alternator to the mains may be done directly by solid state circuitry or a main contactor operated in turn by a relay. In high-rise buildings, several units may be installed and each would be given a predetermined starting order. If conditions are given a predetermined starting order. If conditions are such that one or more phases of the mains are lost, alternator number one would start up. If the load is excessive for that machine a second machine would automatically

start and be synchronised with the first, with the possibility that even more machines might be needed. The mains supply coming into the building is continually monitored and when full mains power is restored and maintained for a period of time, the alternators progressively shut down after a prime mover cooling down period. First the load is removed and the prime mover runs for several minutes to allow cooling down time. It is bad policy for an alternator to have its load removed and the engine shut down immediately. Three or four minutes are needed on no load to remove the bulk of the heat from the engine by way of its individual cooling system.

### 11.3.4 Effects of a change in excitation

The primary purpose of connecting two alternators in parallel is either to share any given load between them, or to shift the load to the incoming machine without causing an interruption to the supply.

The incoming machine, when first synchronised, should have no load on it and might even be drawing power from the supply lines. It is then necessary to adjust the incoming machine's excitation until it is delivering its appropriate share of the load to the supply lines. Increasing the excitation of the incoming machine causes it to attempt to increase its generated voltage. For all practical purposes it cannot increase its voltage above that of the line voltage and the original machine, but it does deliver more current and hence takes a greater share of the load. At the same time, losses cause a small drop in output voltage. Simultaneously the original machine sheds part of its load. If the excitation of the incoming machine is increased sufficiently, the original machine sheds all of its load and can then be shut down if desired.

For two alternators in parallel with a fixed load and power factor, any increase in excitation causes the machine with the greater excitation to take more of the load, but at a lower power factor. This machine also increases its kvar output. The machine losing part of its load delivers less power to the line but at a higher power factor—its kvar becomes less. If the first machine is shut down, the incoming machine takes over all the original load and power factor at the original values.



### 11.3.5 Hunting in alternators

The driving torque and speed of a piston engine is not absolutely constant during a complete revolution but varies according to the position and speed of the pistons. This causes minute variations in the speed of the alternator shaft. The speed variations are small but cause momentary increases and decreases above and below the average rotational speed. The effect is called *hunting* and leads to small voltage variations, which can include harmonics distorting the waveform.

It is partially neutralised by the inertia of the rotating parts. Remedies for hunting involve the use of quite heavy flywheels and special windings in the pole faces. Called *amortisseur* windings, they are discussed in more detail in section 11.5.5 later in this chapter.

The voltage pulses created by hunting can cause circulating currents to flow between alternators connected in parallel, resulting in an increase in the mechanical oscillations of the rotating parts. Electrical losses are also increased.

High-speed turbines are not affected to the same extent by hunting. Their major cause of oscillation about a fixed point is the minor adjustments of the governors as load changes on the machine occur.

## 11.4 STANDBY POWER SUPPLIES

Standby power supplies are generally intended to provide mains power at a specified voltage and frequency. There are two main forms of standby power-supply units.

The first type of unit is meant for use where no interruption to a power supply can be tolerated, for example, to computer, hospital, and aircraft navigation equipment. Losing power at a crucial moment in an operation could mean loss of life, or in the middle of a computer operation could mean the loss of valuable data. There is also an increasing use of this type of power supply for portable work because it can often be run from a 12 V vehicle battery. It is quick, convenient and quiet. Built into the vehicle, it is always ready for use.

The second type of standby unit is where momentary losses of power can be tolerated. Such uses would include emergency lighting, theatres, and industrial uses such as fully environmental meat-bird sheds. Delays of several seconds in restoring power can be acceptable in some circumstances. This type of standby power supply would also be suitable for lifts and high-rise buildings.

A subsection of this latter category includes portable power supplies such as small generating plants that can be carried from job to job in a vehicle.

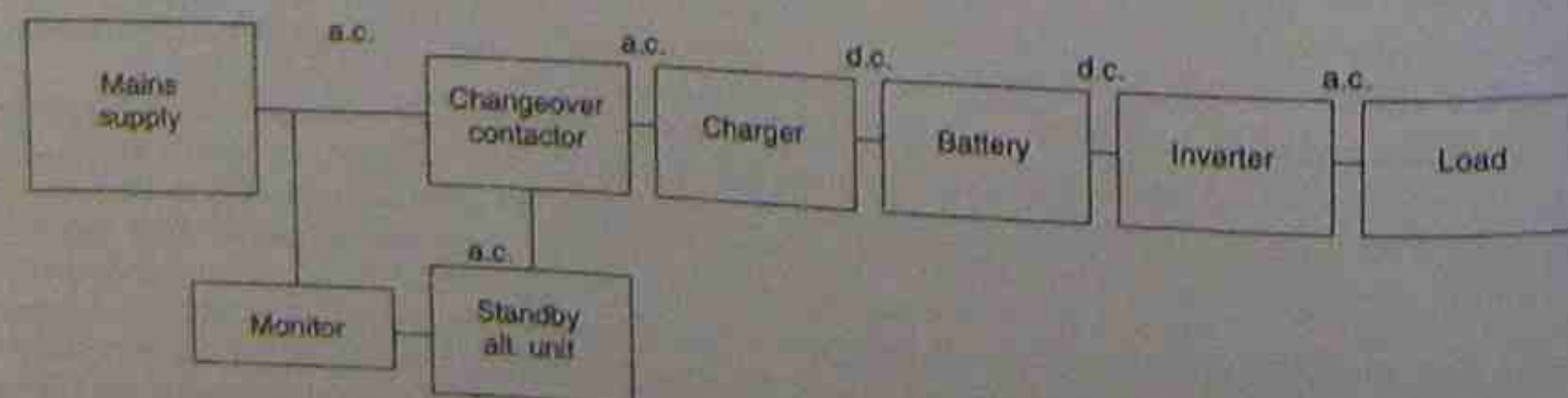


Figure 11.12 • Block diagram for an uninterruptible power supply with backup

### 11.4.1 Uninterruptible power supplies (UPS)

A block diagram of a UPS is shown in Figure 11.12. It can be seen that the unit runs off the mains supply with a battery permanently 'floating' on charge from an inbuilt battery charger. Effectively the battery bank is supplying an inverter, which converts direct current to alternating current at mains voltage and frequency. In the event of losing mains power, the unit continues to operate as long as the battery has sufficient charge.

More critical loads usually have an engine-driven alternator on standby to ensure that the battery charge is maintained. The battery capacity has to be great enough to supply the circuit power while the alternator and engine are being started and run up to speed. Allowances also have to be made for non-starting incidents and provide greater flexibility as a backup in an emergency.

Direct current values are high, so when using a vehicle battery, care must be taken to ensure that the battery does not go flat. For example, a 500 W television set draws about 20 A on 32 V d.c. The current drain would easily exceed 50 A on 12 V.

More modern inverter units are smaller and may draw less current, but they usually have a time rating of about 15 minutes or so and must then be switched off to cool down. A 500 VA modern unit probably has a full-time rating of about 150 VA.

### 11.4.2 Engine-driven alternators

A large range of engine-driven alternators is available, so a choice has to be made on the basis of several factors. They range from buying a small portable unit at the best possible price, to careful planning for the most suitable unit for a particular purpose. It is not enough to select an alternator with respect to the load it has to supply; the choice should take into account many other considerations. Some of these factors are listed below and their order of importance is governed by the actual intended use for the alternator.

#### Purchase price

The overall cost of smaller units may be lower, but in terms of cost per kVA they are more expensive and operate at lower efficiencies. As the size of the unit increases, the cost per kVA reduces, while the operating efficiency increases.

#### Type of prime mover

The economy of the prime mover in terms of efficiency has a bearing on its selection. This in turn is affected by the

type of service it will encounter. For example, a steam turbine has good economy throughout its entire load range. However, it is expensive, large, and needs a long time to get the unit on load from cold. An internal combustion engine has poor efficiency at light loads but is much cheaper to buy initially. For some loads it is cheaper to buy several smaller alternators than one large unit. Problems of paralleling the units then have to be considered (see section 11.3).

The cost and availability of fuel must always be a consideration. While distillate is more expensive initially, as is the diesel engine itself, the fuel cost per hour is less, while maintenance costs are far higher than those for a petrol engine. The petrol engine is cheaper to buy, the fuel is readily available, and the unit is suited to smaller units used purely for portable power supplies on intermittent duties. In the long term the diesel engine runs better on full loads than the petrol engine. The petrol engine is more tolerant of dirty fuel than the diesel engine and does not need specialised skills for maintenance purposes. Figure 11.13 shows a portable generating unit driven by a single-cylinder petrol engine. Two 15 A outlets are available for appliances.

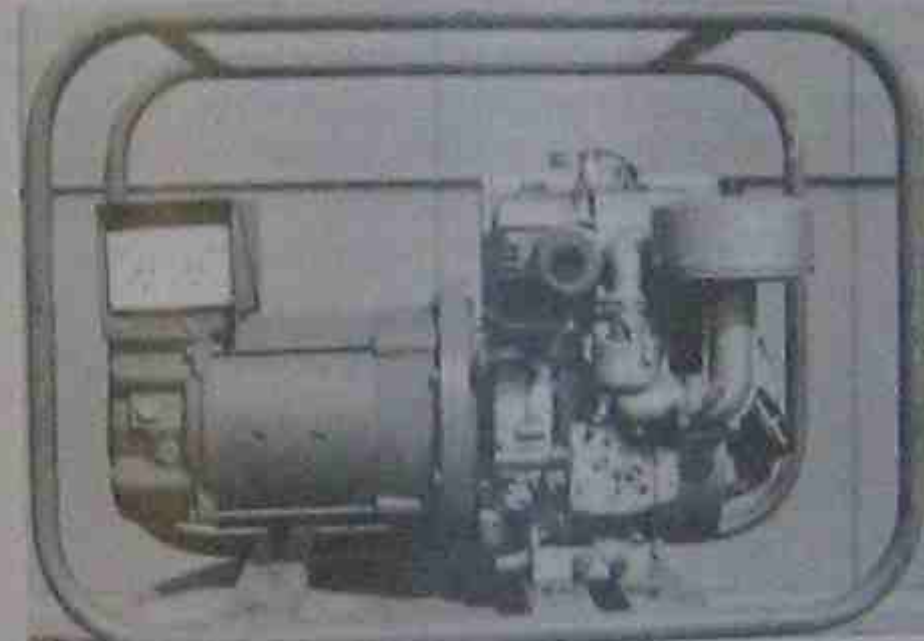


Figure 11.13 • Self-contained portable power supply. The alternator, rated at 6 kVA is driven by a petrol engine. The size and weight of the unit is such that it can be carried to any site where power is required

#### Starting methods

Starting methods are governed by the intended use of the generating unit. The quicker the changeover to auxiliary power, the more expensive is the starting method. The cheapest method involves merely starting the unit manu-

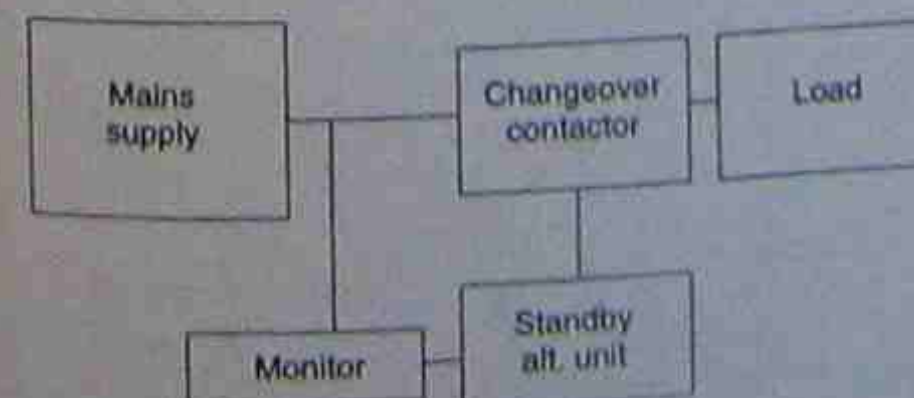


Figure 11.14 • Block diagram for an engine-driven standby alternator

ally when it is realised that the main power supply has failed. A more expensive method involves the use of a changeover contactor that drops out when the main supply fails. In turn this connects a starting motor to the engine and when the alternator is up to speed, connects it to the load.

#### Load sizes and alternator capacities

Smaller generating plant is usually intended for standby purposes for short periods. It usually has only one load connected to it at a time, such as a portable tool or a small lighting load. With middle- and larger-size alternators, consideration has to be given to the possible connection of intermittent larger loads, such as the starting currents of motors. The unit then has to have the electrical capacity and engine power to maintain both the output voltage and the frequency during these current surges to avoid interruptions to other equipment connected to the same supply.

#### Operation of alternators

With the exception of some manually operated equipment, most operations are now beyond the control of the operator. Where some degree of manipulation is available there are two important factors that should always be considered—voltage and frequency. In most cases the voltage is governed by automatic voltage regulators, while the frequency is controlled by the engine governor. The order of operation is to set the speed first, which in turn sets the frequency, and then adjust the voltage of the unit. To do this in the reverse order is to alter the voltage each time the speed is altered.

## 11.5 THREE-PHASE SYNCHRONOUS MOTORS

A three-phase synchronous motor has no starting torque. It has to be manipulated up to speed or as close to it as possible so that it can pull itself into synchronism.

Once up to speed, the rotor field can be excited with direct current and the rotor is in effect then dragged around at the same speed as the three-phase stator field. Its speed is synchronised with that of the stator field. This is markedly different in principle to the induction motor, where the rotating field of the stator is pushing against the induced rotor field. That causes the rotor to rotate, but with some slip, whereas in the synchronous motor there cannot be slip, merely a 'hanging back' due to the load imposed on the machine. This is illustrated in Figure 11.15 and shows as a torque angle. If the load becomes too great for a synchronous motor it immediately pulls out of synchronism.

### 11.5.1 Construction

#### Stator

The stator has a three-phase winding and is of the same type as that in an alternator or induction motor.

When this winding is energised with a.c. it produces a magnetic flux that rotates at a speed called the synchronous speed. It is the same speed at which the synchronous motor would have to be driven to generate an a.c. voltage at line frequency.



The speed can be derived from the same formula used for alternators in section 11.2.3.

### Rotor

Although of similar construction to the alternator rotor, it is usually made with salient poles. When excited with d.c. it produces alternate north and south magnetic poles, which are attracted to those produced in the stator.

### 11.5.2 Operating principle

A synchronous motor works on the principle of magnetic attraction between two magnetic fields of opposite polarity; one field is that of the rotating stator and the other that of the rotor.

A synchronous motor has torque only at synchronous speed, so special steps have to be taken to get the motor up to speed and synchronised with the supply. The two magnetic fields are then rotating at the same speed and lock in with each other.

### 11.5.3 Effect of load on a synchronous motor

When a synchronous motor runs on no load, the relative positions of stator and rotor poles coincide as shown in Figure 11.15(a).

When a load is applied, the rotor must still continue to rotate at synchronous speed but owing to the retarding action of the load, the rotor pole lags behind the stator

pole. Their relative positions are displaced by the angle  $\alpha$  (called the 'torque' or 'load' angle), as shown in Figure 11.15(b). The greater the load applied, the greater is the torque angle.

The magnetic coupling between each stator and rotor pole distorts according to the load applied. If the load on the motor becomes excessive, the magnetic coupling breaks and the rotor slows down until it stops.

When the motor is rotating at synchronous speed, with a fixed d.c. excitation in the rotor windings, the rotor flux cuts the stator windings, inducing a voltage in each phase winding and opposing the applied voltage (Lenz's law). The phase relationship between this induced voltage and the applied voltage depends on the relative positions of each stator and rotor pole, which in turn depend on the load applied to the motor.

Neglecting motor losses, on no load the torque angle is zero, and so the induced voltage  $V_g$  and the applied voltage  $V$  are equal and opposite. The resultant voltage  $V_R$  across the windings is zero, and so the current drawn from the supply is also zero. This is illustrated by the phasors in Figure 11.16(a).

When a light load is applied to the motor, the torque angle  $\alpha$  increases, and the induced voltage  $V_g$  in the stator windings is now  $(180 - \alpha)^\circ$  out of phase with the applied voltage  $V$ , as shown in Figure 11.16(b). These two voltages combine to produce an effective voltage  $V_R$  across the stator windings, which is sufficient to draw a current  $I$  from the supply. Because of the relatively high

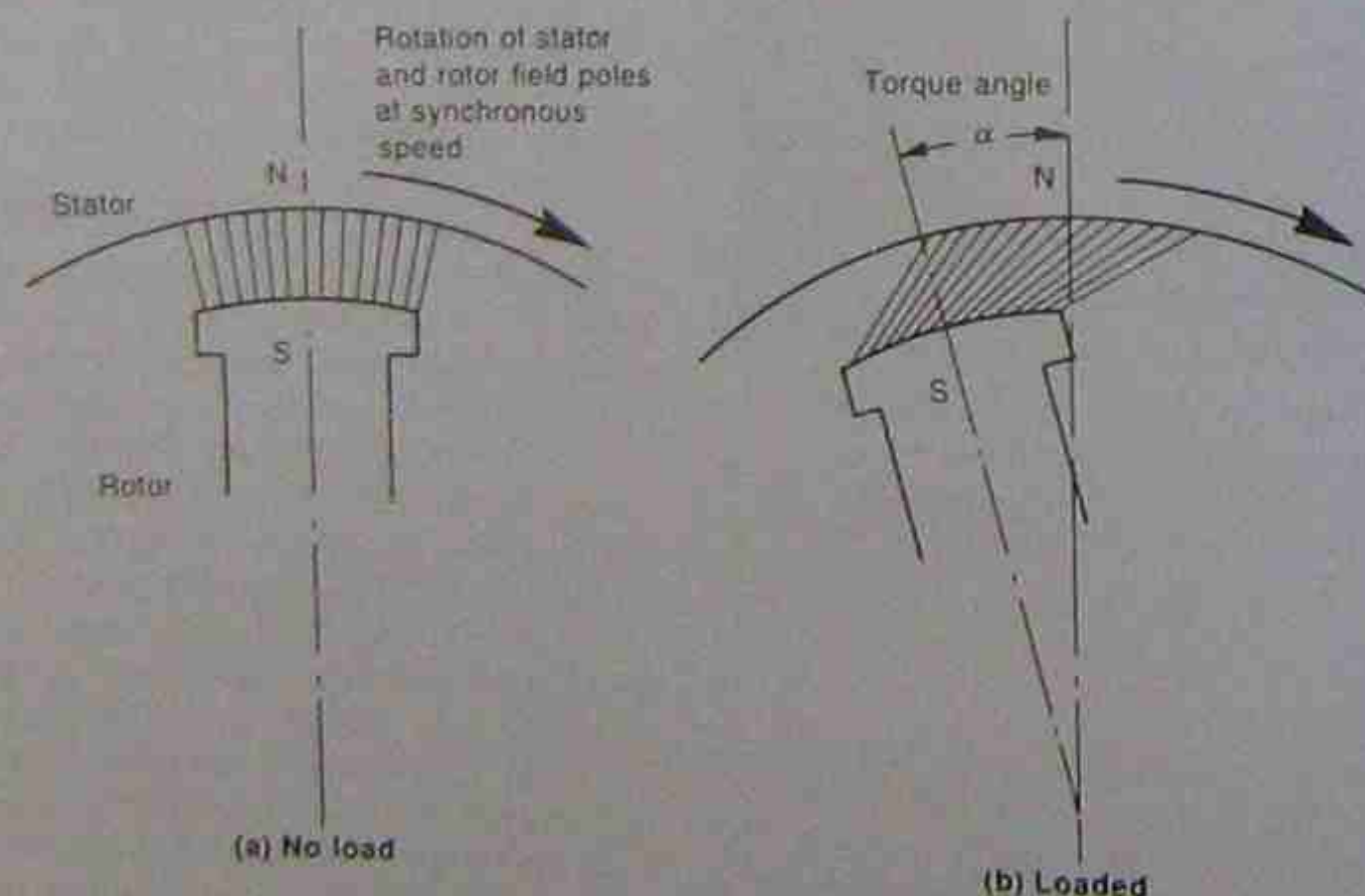


Figure 11.15 • Relative positions of stator and rotor magnetic fields in a synchronous motor.

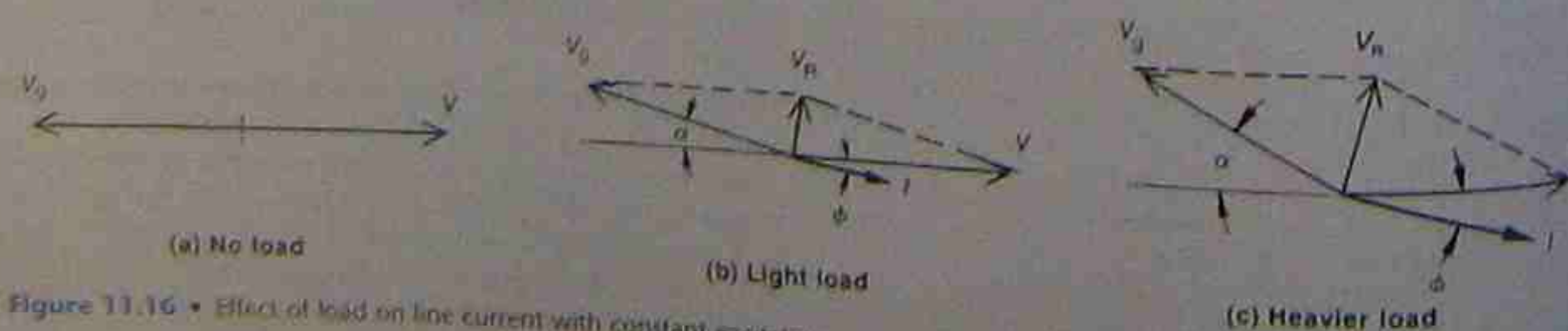


Figure 11.16 • Effect of load on line current with constant excitation

inductance of the stator windings, the line current  $I$  in each winding lags each resultant voltage  $V_R$  by nearly  $90^\circ$ . This causes the line current  $I$  to lag the applied voltage by  $\phi$ .

As the load is increased, so the torque angle is increased. This causes an increase in the resultant voltage  $V_R$  across each stator winding, as seen in Figure 11.16(c). Because of the increase in the value of  $V_R$ , the line current  $I$  increases, and the phase angle  $\phi$  between the applied voltage  $V$  and the line current  $I$  also increases.

For fixed excitation, any increase in load on a synchronous motor will cause an increase in current drawn, at a lower power factor.

### 11.5.4 Effect of varying field excitation

If the load applied to a synchronous motor is constant, the power input to the motor is also constant.

When the rotor field excitation is varied, the induced voltage in each stator winding is also altered.

The phasor diagram in Figure 11.17(a) represents the conditions for a given load at unity power factor. The power input per phase is  $VI_1$ . If the rotor field excitation is decreased, the induced voltage  $V_g$  decreases, as shown in Figure 11.17(b). This causes the line current  $I_2$  to lag the applied voltage  $V$  by  $\phi_2$ . Since the load, and so the power input, is constant, the power component of  $I_2$  must remain the same as  $I_1$  in Figure 11.17(a). The line current  $I_2$  must increase to accommodate the lagging power factor. A reduction in the d.c. field excitation therefore causes an increase in line current, and a lagging power factor.

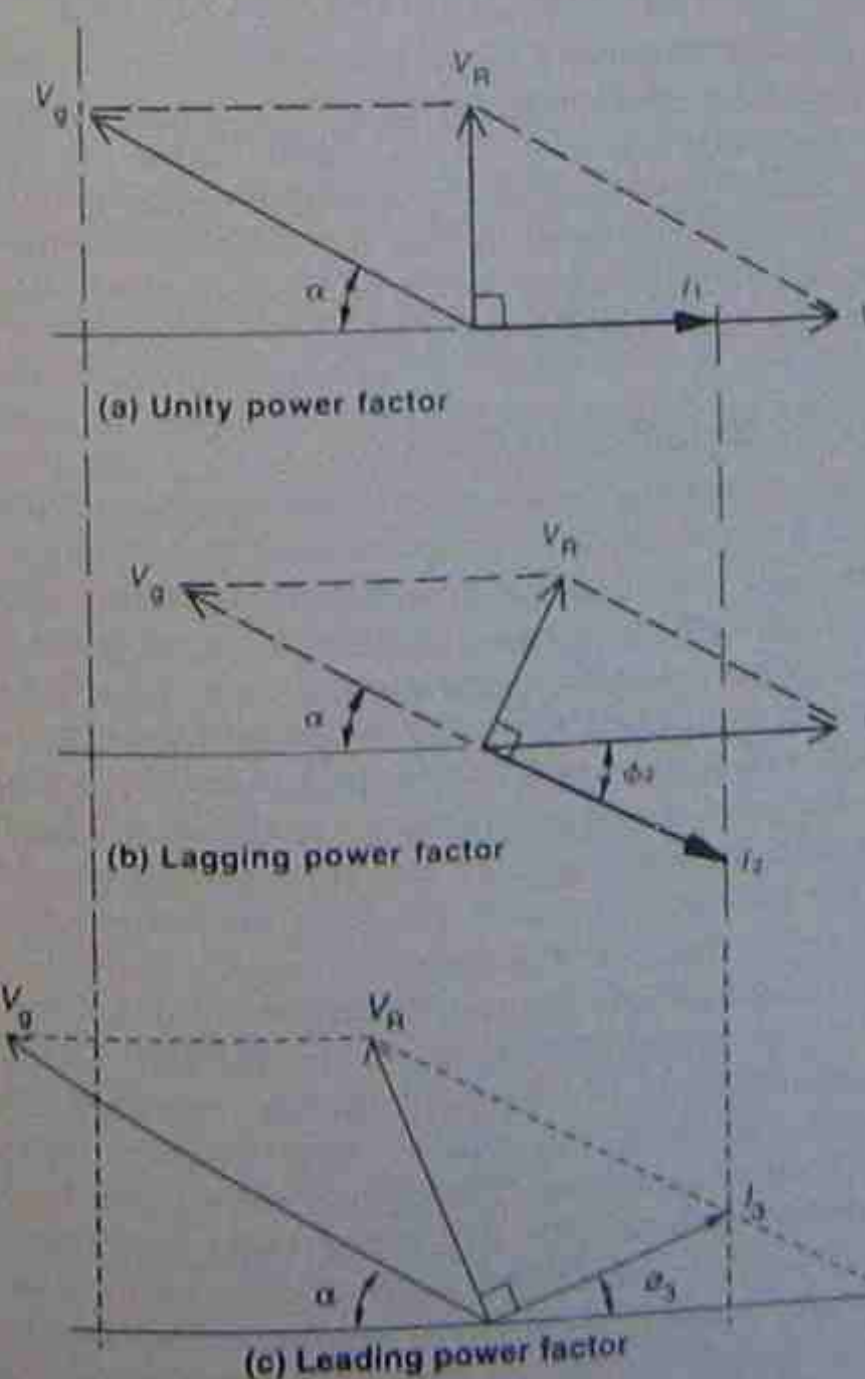


Figure 11.17 • Effect of varying the d.c. excitation

If the d.c. excitation is increased, the induced voltage  $V_g$  increases, as shown in Figure 11.17(c). The line current  $I_3$  will therefore lead the applied voltage  $V$  by  $\phi_3$ , and will also be greater than  $I_1$  in Figure 11.17(a) because the power component is the same, owing to the load remaining constant. An increase in d.c. excitation therefore causes an increase in line current, and a leading power factor.

It can be seen that if the excitation of a synchronous motor on a constant load is varied from a low to a higher value then:

1. stator current gradually decreases, reaches a minimum, and then increases again
2. the power factor, at first lagging, gradually increases, becomes unity when the stator current is a minimum, and then decreases again, but becomes leading.

Care should be taken when adjusting the excitation of a synchronous motor. There are limits to which it can be taken with safety. Over-excitation and under-excitation can cause the synchronous motor to become unstable. Once these limits have been exceeded, the power produced by the motor decreases and the danger of overloading becomes imminent as the machine exceeds its design limits. The most obvious situation is one of under-excitation where the magnetic bond between the rotating field and the rotor is so weakened that the load exceeds the pull-out torque of the motor and it drops out of synchronism. Over-excitation creates a situation where the line current and mechanical load exceed the full-load rating of the machine and the magnetic bond becomes so stiff that changes in load place undue mechanical stresses on the motor shaft.

### 11.5.5 Hunting in synchronous motors

A change in load on a synchronous motor causes a change in the value of the torque angle (Fig. 11.15). In general, the inertia of the rotor prevents an instant change to the new conditions, with the result that the rotor shifts past the point of equilibrium and then has to correct itself. While the rotor and the rotating field in the stator are still rotating at a synchronous average speed, the change in load on the rotor causes this periodic swing around the point of equilibrium. This surging or hunting causes an undesirable fluctuation in line current to the motor.

The usual method for damping these surges is to use a damper winding, called an *amortisseur* winding. It consists of copper bars imbedded in the pole faces of the rotor and shorted out at each end (Fig. 11.18). Any surging causes an induced voltage in the copper bars. This results in a magnetic field being created and opposing the surging effect.

Often the shorting-out bars are extended around the rotor, resulting in a squirrel-cage-type rotor winding about the salient poles. While damping any tendency of the rotor to hunt, they can also assist the motor in starting by acting as sections of a squirrel-cage winding. In effect this winding enables the motor to be started as an induction motor.



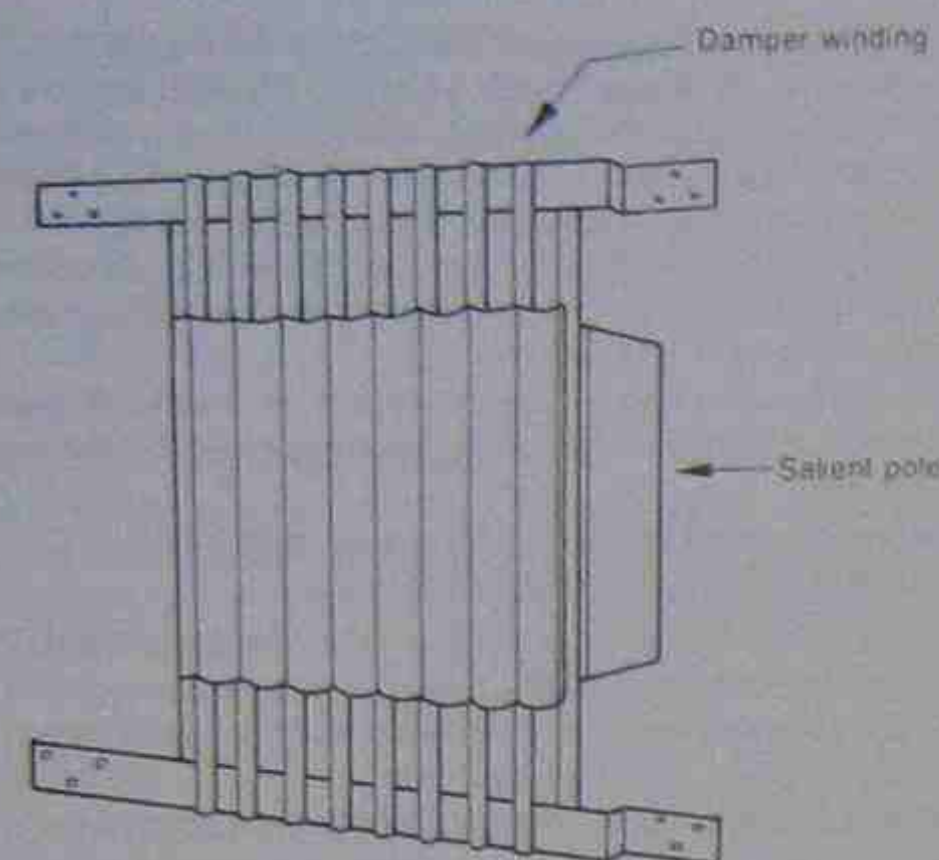


Figure 11.18 • Salient pole with amortisseur winding

### 11.5.6 Applications of synchronous motors

#### Power factor correction

The characteristic of being able to adjust the power factor of a synchronous motor while it is running can be used to advantage in industry as a means of advancing the power factor of a series of loads fed from the plant's mains.

The synchronous motor can be run unloaded, but more often it is used to drive some item of equipment necessary to the full operation of the plant; for example, air or hydraulic compressors, high-frequency alternators, large fans and blowers, or high-pressure water supplies.

An added advantage can be an economic incentive offered by supply authorities for ensuring a certain minimum value power factor in an installation. For example, the charge per kWh may be reduced if the power factor does not drop below 0.75 or some similar figure.

Where large amounts of power are being distributed and power factor correction is needed, specially designed synchronous motors are run without any load connected. Under these circumstances the over-excited synchronous motor is called a synchronous capacitor or condenser.

#### Voltage control

An important application is in the control of voltage for transmission lines. Synchronous motors are installed at suitable positions along the line and their excitation adjusted as desired, to cause them to draw lagging or leading currents in order to raise or lower the voltage. When synchronous motors are installed under these conditions there is a tendency to greater stability of voltage on the transmission line.

#### Low-speed drives

A synchronous motor has good efficiency and at low speeds its high initial cost is adequately compensated by the comparatively lower running cost. At low speeds the induction motor has a decreasing efficiency, while the synchronous motor retains its high efficiency.

#### Rock and ore crushing heads

This application requires a crushing head that moves very slowly and has a very heavy rotating flywheel to provide kinetic energy as sudden shock loads are placed upon the crushing head.

### 11.5.7 Starting methods for synchronous motors

#### Auxiliary motors

Some synchronous motors are equipped with a special motor designed for use only during the starting period. The auxiliary motor runs the synchronous motor up to speed, at which stage it is first synchronised and then connected to the supply. It is an expensive method, particularly if high starting torques are required.

#### Induction motor starting

A reduced line voltage is applied to the stator windings and the d.c. winding on the rotor is short-circuited. With the aid of the amortisseur winding, the complete machine behaves as an induction motor as it accelerates up to a speed slightly below synchronism. At an appropriate time, the short is removed from the rotor winding, d.c. is applied and the full line voltage applied to the stator winding. Because the speed is only slightly less than synchronous speed, the rotor field can lock in with the stator field and accelerate to synchronism.

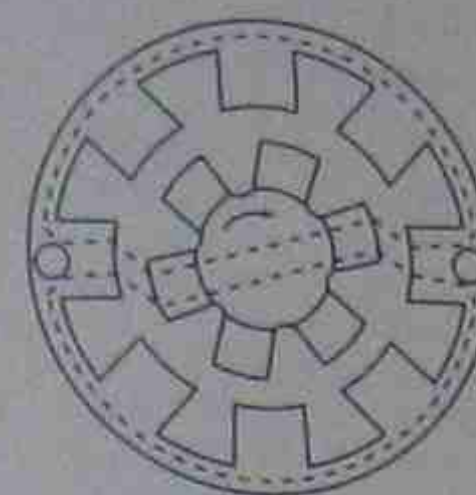
## 11.6 SINGLE-PHASE SYNCHRONOUS MOTORS

The primary purpose of single-phase synchronous motors is for constant speed requirements, even though they have very low efficiency. Their use is usually limited to operations where speed is critical and torque requirements are low. Small synchronous motors are built in a variety of types and constructional details but are almost invariably one of the two types described below.

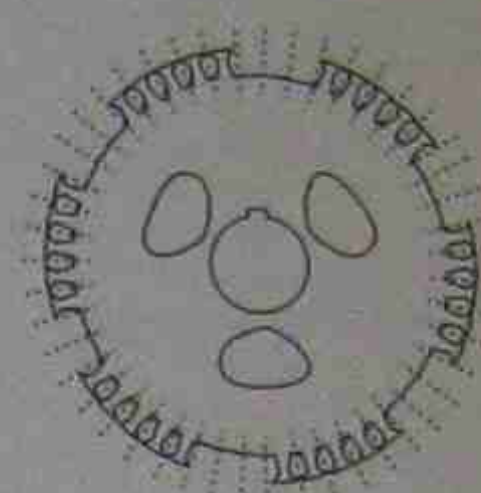
### 11.6.1 Reluctance motors

The stator winding of the reluctance motor is similar to that of the split-phase or capacitor-start motor. The rotor, however, is assembled from laminations from which a number of teeth are cut to form definite salient poles, and the windings are of the usual squirrel-cage type. This can be seen in Figure 11.19(b) where the slots in the rotor lamination will still contain the normal parts of a squirrel-cage winding. The gaps or slots cut in the rotor will often be of unequal sizes to assist the starting function. Note that the number of poles in the stator are not necessarily equal to the number of poles on the rotor.

The motor starts as an induction motor, and the starting winding is open-circuited by the centrifugal switch at approximately 75 per cent synchronous speed. Because the load applied to this type of motor is comparatively light, there is small slip. The salient rotor poles tend to become magnetised by the stator poles and become 'locked' together. The stator poles are changing at twice the supply frequency. The rotor is attracted by the stator poles during the periods of the cycle when they are fully magnetised. During the period when the stator flux is low,



(a) Cross-section of a reluctance motor showing stator and rotor



(b) Cross-section of the rotor of a reluctance motor showing both the gaps and the holes for the squirrel cage bars

Figure 11.19 • Internal configuration of a reluctance motor

the inertia of the rotor carries it past the position of one stator pole and it is then attracted by the next stator pole during the build up of the stator flux. Each rotor pole therefore travels through the space of two stator poles per cycle of supply frequency.

The reluctance motor starts as an induction motor, locks into synchronism, and continues to run at a constant synchronous speed. If the number of salient poles on the rotor is some multiple of the stator poles, the motor will operate at a constant speed which is a submultiple of the synchronous speed. This is called a sub-synchronous reluctance motor.

### 11.6.2 Hysteresis motors

In the hysteresis motor, the rotor is constructed from a specially hardened steel cylinder instead of the normal thin laminations. It is supported on a non-magnetic form called an arbor and has substantial hysteresis losses. The effect of hysteresis is thereby increased and opposes any change in magnetic polarities of the rotor once they are established. The rotor poles 'lock into' the stator poles of the opposite polarities. The details of the rotor are shown in Figure 11.20.

Normally a synchronous motor has no starting torque and is therefore not self-starting without additional means. One method of providing movement for the rotor is to use the shaded-pole principle. The movement of the stator flux across the pole face pulls the rotor along with it. Because the stator and rotor fluxes are magnetically 'locked' together, the rotor runs at a synchronous speed

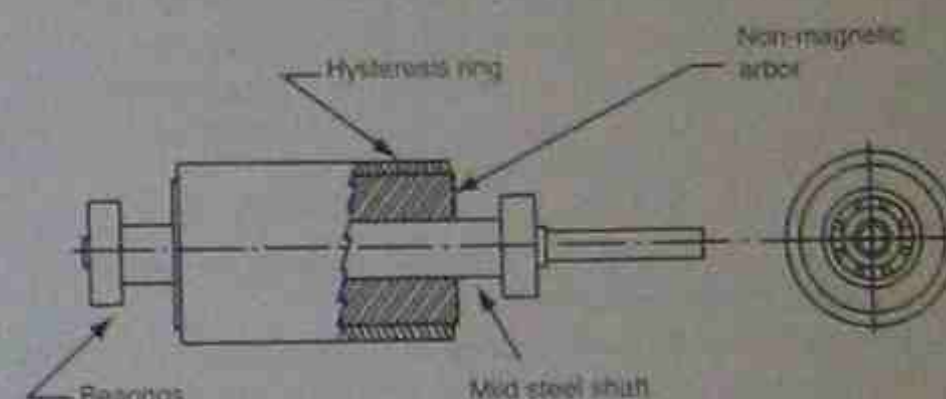


Figure 11.20 • Rotor arrangements for a hysteresis motor

determined by the number of stator poles and the supply frequency.

### 11.6.3 Applications for single-phase synchronous motors

Typical uses of single-phase synchronous motors are in wireless and radio communication installations, recording devices, electric clocks, and synchronous servo-systems.

A further use is in the aircraft industry where a.c. frequencies are normally around 400 Hz, although they can be much higher. As a rule of thumb, the size of a.c. equipment operating at 400 Hz is reduced  $(400/50)^2$  times when compared with the usual power-line frequencies; that is, the amount of iron in the core is reduced approximately 64 times. This results in a major reduction in size and weight. Typical applications are in gyro-compasses and other aircraft instrumentation.



## SUMMARY

- A synchronous machine rotates at a speed depending on the line frequency and the number of poles.
- Larger machines have a three-phase winding in the stator, while the rotor is excited with direct current.
- An alternator is driven mechanically at a suitable speed to enable it to produce alternating current at line frequency.
- Low-speed machines have short rotors with many salient poles, while high-speed machines have long cylindrical rotors and few poles.
- Cylindrical rotors are more common for high-speed work because of the mechanical forces created by high speed.
- Prime movers are often engine driven for low-speed machines.
- Hydroelectric alternators are commonly low-speed machines with the shaft mounted in the vertical plane.
- High-speed machines have high-pressure turbines, either steam or gas driven.
- Air cooling is used for low-speed synchronous machines. It may be natural flow or forced air cooling with fans.
- Cooling of high-speed machines is more complicated because of the long rotors. Forced air cooling is rarely used with very large alternators.
- Hydrogen blown through a sealed machine is one method. The hydrogen gas is cooled by passing it through a heat exchanger.
- Alternators often have a direct-current generator coupled on the same shaft to provide d.c. for the rotor excitation. In some cases the exciter is so large that it also has its own exciter to provide d.c. for the larger exciter field.
- An alternator is rated according to its output voltage and the maximum current flow permitted in its windings. It is a volt-ampere (VA) rating because there is no real control over the power factor of the load.
- Alternators have series resistance and reactance that lead to a voltage drop on load. This also leads to a problem when being paralleled with another alternator.
- Alternators have to satisfy several conditions when being placed in parallel:
  1. identical voltage
  2. identical frequency
  3. same phase rotation
  4. being in phase with each other when finally connected.
- Smaller alternators can be synchronised with each other by using lamps connected in series. These can only be used where some degree of error can be tolerated.
- There are two types of connection:
  1. three dark lamps
  2. two dark and one bright lamp.
- A more exact method is by using a synchroscope. The instrument can be portable or built into a control panel. Larger alternators are brought onto load gradually after being synchronised.
- By increasing the excitation after synchronisation, the load on a machine can be gradually increased to take some or all of the load.
- Bringing an alternator onto load after synchronisation has some side effects:
  1. The power factor of the incoming machine drops.
  2. The power factor of the existing machine increases.
- 3. The reactive volt-amperes alter accordingly.
- 4. The line voltage may drop slightly and has to be adjusted.
- 5. The total load current and power factor remain as before.
- Alternators have minor speed variations during rotation. Called *hunting*, the amount depends on the driving engine and causes ripple or harmonics superimposed on the output voltage.
- Compensation for hunting in low-speed engine-driven machines is achieved with heavier than normal flywheels and other rotating parts.
- In high-speed machines, hunting is usually caused by variations in load and efforts by the governor to compensate for them.
- There are two main purposes of standby power supplies:
  1. *Power supplies where a break-in supply cannot be tolerated.* Uninterruptible power supplies (UPS) are used. They are usually based on a battery-operated inverter circuit that converts d.c. to a.c. The battery supplies electrical energy until alternative power supplies are operated.
  2. *Power supplies where a break of short duration can be tolerated.* They are basically engine-driven alternators of various sizes and capacities. The units may be of the portable type or fixed in a suitable position, depending on intended use. This category also includes battery-operated inverters that are intended for portable use. Current drain can be heavy for larger units.
- A synchronous motor has no starting torque and, if used as a motor, it has to be brought up to synchronous speed mechanically, or by adjusting the connections to, and in, the motor to bring it up to speed as an induction motor.
- A synchronous motor is magnetically locked to the rotating field in the stator and is effectively 'pulled' around.
- Excessive loads cause the magnetic link to be broken and the motor will cease rotating.
- Varying the rotor field excitation will affect the power factor of the motor.
- Decreasing excitation will cause a lagging power factor.
- Increasing excitation will cause a leading power factor.
- Excitation has to be kept within specified limits for stability of operation.
- Setting excitation values outside this range leads to the possibility of stalling the machine or creating uncontrolled hunting.
- Hunting also occurs in synchronous motors. It is mostly caused by fluctuating loads such as reciprocating pumps.
- Hunting in both motors and alternators can be reduced by imbedding special windings in the pole faces of the rotor.
- A synchronous motor is usually started by one of two methods:
  1. Using another motor or an engine to get the synchronous motor up to speed. This is seldom used because of cost.
  2. Reconnecting the synchronous motor as an induction motor until it gets up to speed and then reconnecting it to provide d.c. to the rotor. This is the most common method.

■ Single-phase synchronous motors are generally one of the following two types:

1. The *reluctance motor*—like the three-phase types, it is not self-starting. It can be started manually or be provided with a starting winding. The rotor has salient poles machined in it to induce synchronism.

2. The *hysteresis motor* also has no starting torque. The rotor is made of a magnetically harder material than a normal induction motor.

- Single-phase synchronous motors are inefficient and have low torque. Consequently they are made only in small sizes where a specific use calls for an exact or constant speed.

## EXERCISES

- |   |   |
|---|---|
| 11.1 What advantages are there in using the rotating d.c. field-type construction for synchronous machines?         | 11.9 Why is a synchronous motor not self-starting?  |
| 11.2 What are the constructional differences between low-speed and high-speed alternators?                          | 11.10 State two characteristics that are applicable only to a synchronous motor.                                    |
| 11.3 Explain why a low-speed synchronous machine has a large salient pole-type rotor.                               | 11.11 Explain how an increase in the load applied to a synchronous motor affects the line current and power factor. |
| 11.4 What is the purpose of the 'exciter'?  | 11.12 How can the power factor of a synchronous motor be changed?   |
| 11.5 How does the power factor of the load affect the output voltage of an alternator?                              | 11.13 What are some applications for three-phase synchronous motors?  |
| 11.6 State five conditions that must be satisfied before an alternator can be synchronised with an existing supply. | 11.14 Describe the basic principles of operation of one type of single-phase synchronous motor.                     |
| 11.7 What is meant by the term <i>phase sequence</i> when applied to three-phase synchronous alternators?           | 11.15 List the major characteristics of a synchronous motor.  |
| 11.8 In what way does the principle of operation of a synchronous motor differ from that of an induction motor?     |   |

## SELF-TESTING PROBLEMS

- |   |  |
|---|--|
| 11.16 How many poles must a synchronous machine have to operate at 250 r/min and a frequency of 50 Hz?  | 11.21 Calculate the generated phase voltage of a 25 kVA, 50 Hz alternator with 350 conductors per phase, flux = 0.0038 Wb, distribution constant = 0.91, and coil pitch constant = 0.95. What is the voltage regulation if the output voltage on full load is 240 V? |
| 11.17 What supply frequency would be required to run a four-pole synchronous motor at 3300 r/min?   | 11.22 Find the power rating of a three-phase 3300 V, 100 kVA alternator at power factors of 1.0, 0.8, and 0.65. What is the maximum current of the alternator in each instance?  |
| 11.18 What step-up gear ratio would be required to drive a 60 Hz four-pole alternator with a 50 Hz four-pole synchronous motor?   | 11.23 A three-phase 415 V, 125 kVA alternator supplies its rated load at a power factor of 0.8 lagging. Given that the efficiency of the alternator is 89 per cent, what power is the prime mover required to deliver?   |
| 11.19 A diesel-driven alternator is governed to 720 r/min. If the alternator has ten poles, what is the frequency of the alternator output?   |  |
| 11.20 Find the generated voltage of an alternator with six poles rotating at 1000 r/min if it has 60 active conductors all connected in series. The flux is 0.0083 Wb. Neglect the effects of distribution and chord factors. |  |



# Chapter 12

## Direct current machines

### 12.1 INTRODUCTION

A direct current machine is one that either produces or consumes d.c. In either case it acts as an energy converter. It is possible in practice to use the one d.c. machine as either a motor or a generator. When an electrical input is supplied to the machine it can function as a motor and convert electrical energy to mechanical energy. When driven by a source of mechanical energy, the process of conversion generates electrical power.

Before discussing characteristic details of individual types of machines, it is necessary to have an understanding of some other factors such as construction, internal connections, and reaction to load of a d.c. machine.

### 12.2 MACHINE CONSTRUCTION

Because the d.c. machine can be used as either a motor or a generator, the construction of each is virtually identical other than for specialised exceptions for specific purposes. Descriptions of the main components are given in the sections indicated below, applying equally well to a motor and a generator.

The main components (Fig. 12.1) are:

- field frame or yoke (section 12.2.1)
- end-shields and bearings (section 12.2.2)
- field poles (section 12.2.3)
- field coils (section 12.2.4)
- armature and commutator (section 12.2.5)
- brush gear and brushes (section 12.2.6).

(A dismantled machine is shown in Fig. 12.3.)

#### 12.2.1 Field frame or yoke

The field frame, or yoke, carries the field poles and also provides a magnetic path between them. Since a material of high magnetic permeability is required, cast steel is

often used. It has high mechanical strength and the added advantage of retaining residual magnetism, a factor convenient for certain d.c. generator internal connections. A more modern practice is to roll the yoke from appropriate grades of steel sheet, weld the join, then machine to size. Suitable 'feet' or mounting brackets for holding-down purposes can then be attached, together with the addition of an eyebolt for ease of handling.

The yoke also provides facilities for mounting the end frames or end-shields.

#### 12.2.2 End-shields and bearings

The purpose of end-shields is to support the bearings in which the armature rotates. Additionally, one of the end-shields usually has provision for mounting the brush gear for electrical connection to the rotating armature. Both the end-shields and the bearings vary according to the designed use of the machine. The end-shields might be waterproof for one situation or completely open for another. The bearings might be bronze bushes, or roller or ball bearings.

#### 12.2.3 Field poles

The field poles, once made of special classes of cast steel, are now often fabricated from sheet-steel stampings riveted together. Their high permeability provides a high concentration of magnetic flux at a particular position in the d.c. machine. For the sake of clarity a field pole has been shown separated from its field coil in Figure 12.1. The inner surface of the pole has been curved to follow the shape of the armature and the pole tips have been extended. This shaping permits a greater area in the flux path close to the armature and reduces the magnetic reluctance of the air gap. An incidental advantage is that the tips can be used to hold the field coils in position when the pole piece is bolted into place in the yoke.

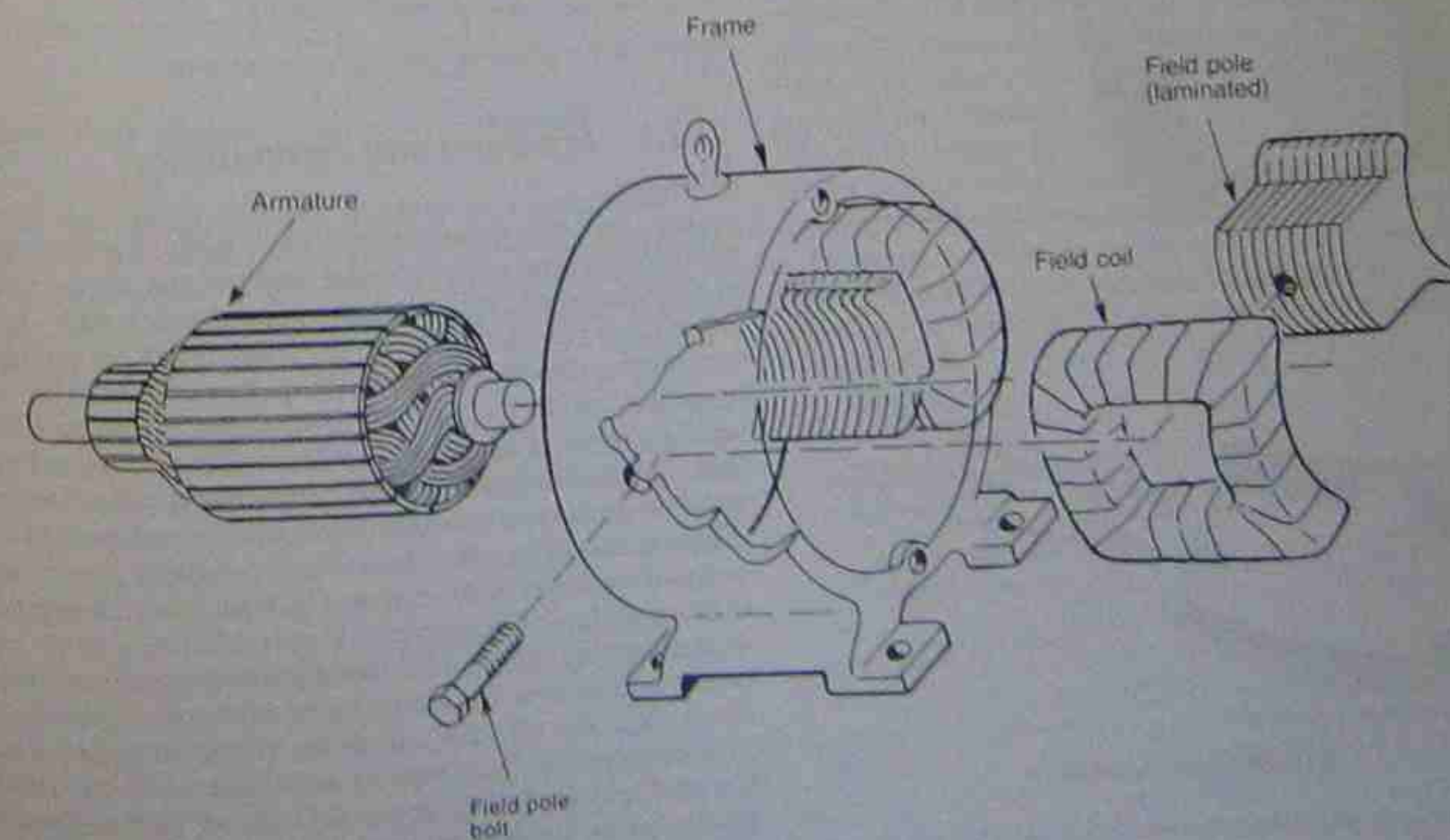


Figure 12.1 • Component parts of a d.c. machine



### 12.2.4 Field coils

Field coils are constructed and named according to the connections relative to the armature with which they are used. If connected in series with the armature, they are called series coils; if connected in parallel with the armature (or 'shunted' across it), they are called shunt coils. The actual construction of the coil will vary accordingly. Because series coils must carry armature current, they are wound with heavier conductors than shunt coils.

The conductor sizes and comparative number of turns on the field coils can be seen in Figure 12.2. In either case the magnetomotive force created must be great enough to force the required magnetic flux through the yoke field poles, air gaps and armature in a series-parallel magnetic circuit (see Fig. 12.4). Some fields are 'excited' magnetically by a field coil consisting of two windings; one a series winding, the other a shunt winding, as shown in Figure 12.2(c). These are called compound (combined) windings.

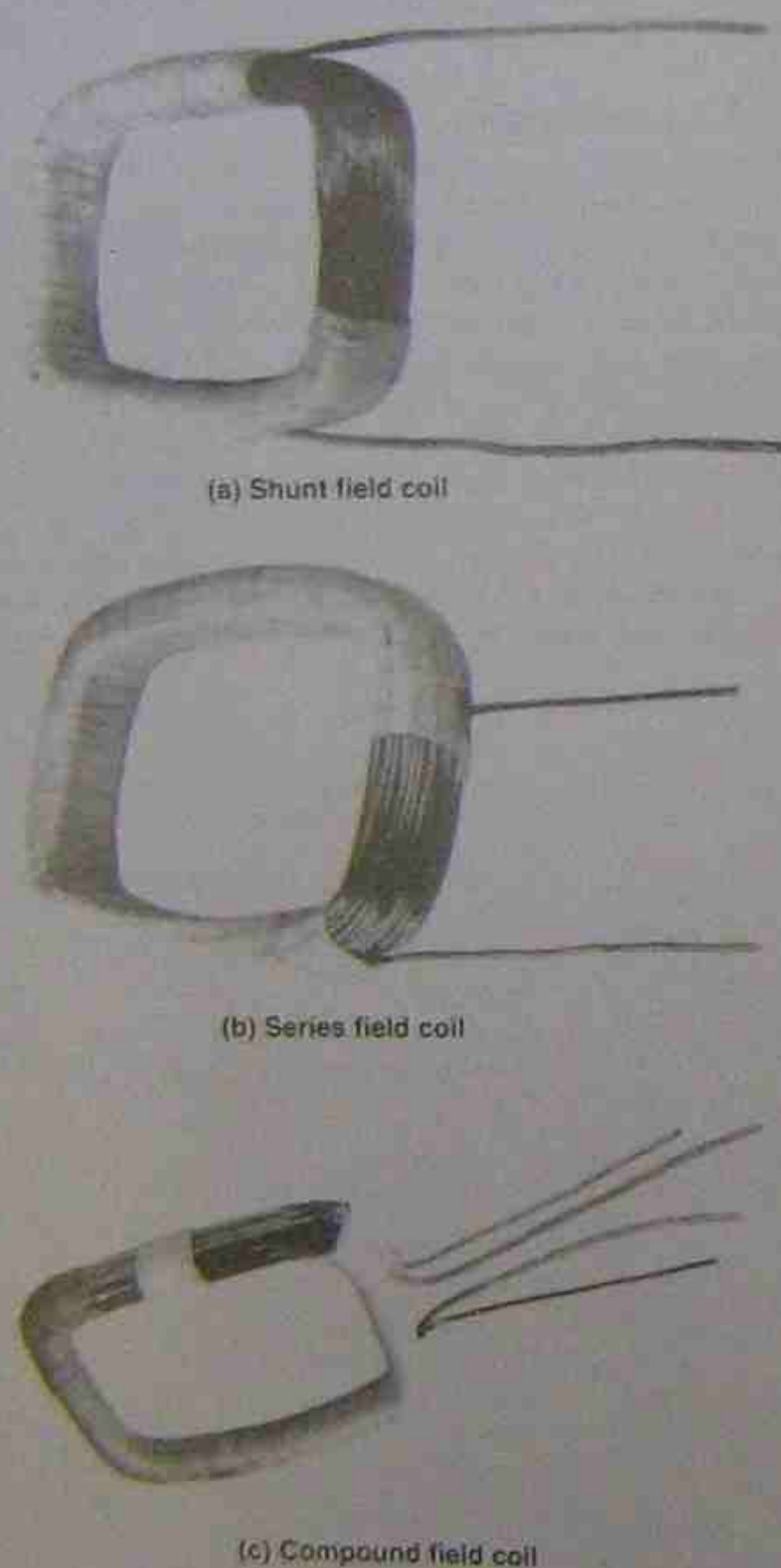


Figure 12.2 • Field coil construction



Figure 12.3 • Dismantled d.c. machine

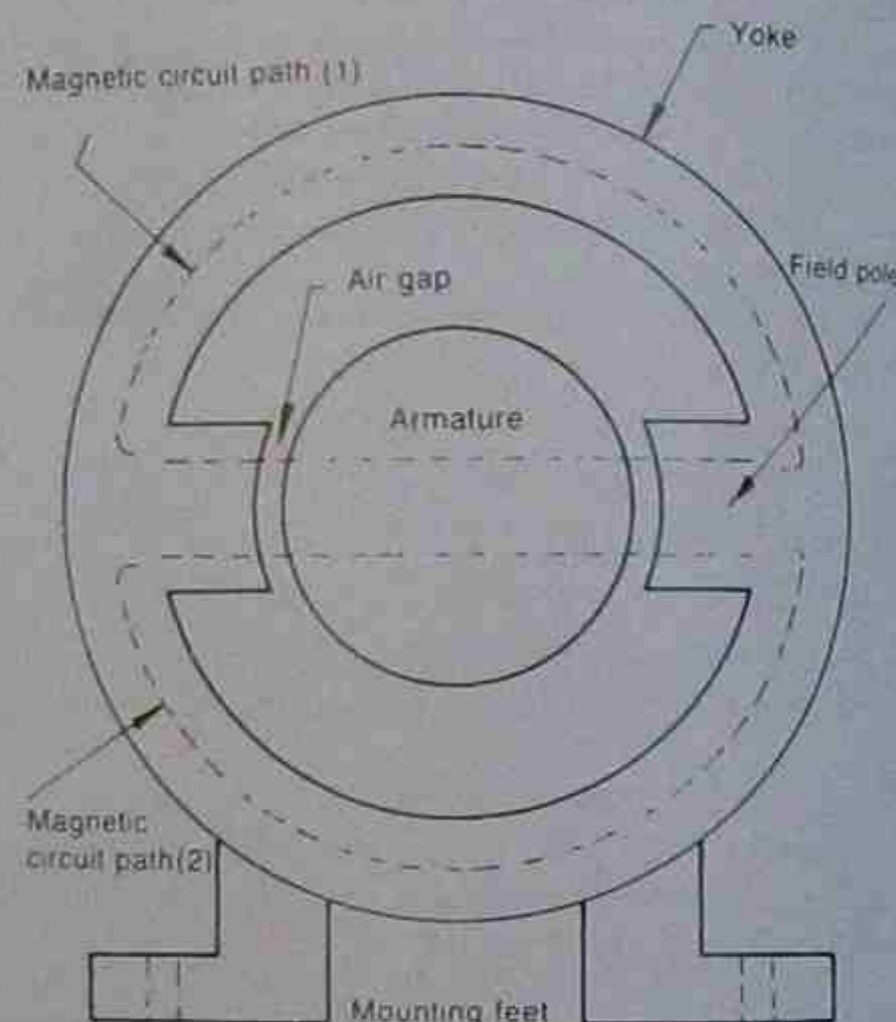


Figure 12.4 • Magnetic circuit in a d.c. machine

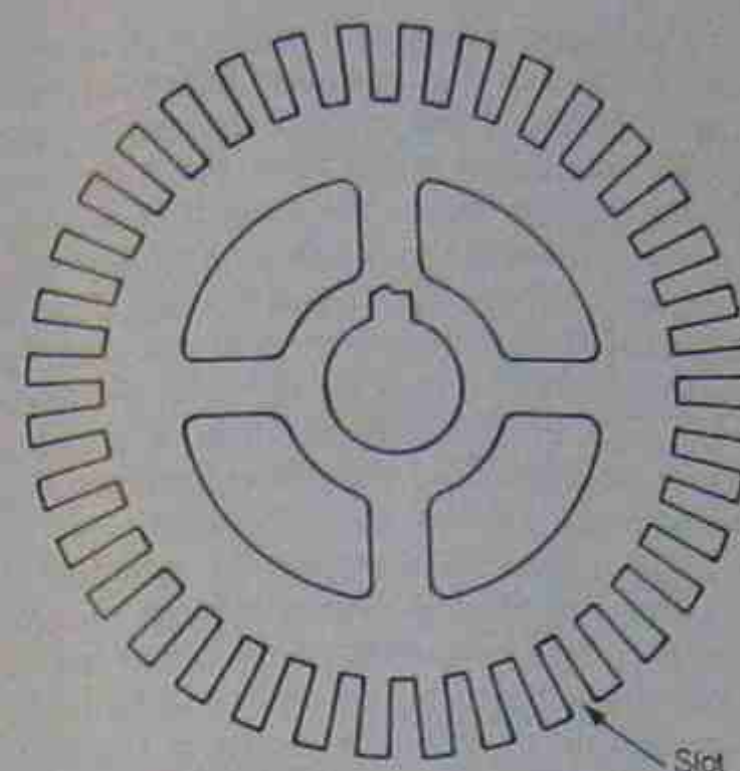
### 12.2.5 Armature and commutator

#### Armature

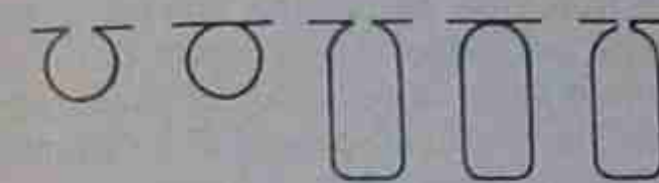
An armature core is assembled from a number of electrical steel laminations, usually keyed direct to the shaft. Figure 12.5(a) illustrates a typically shaped lamination with ventilating holes punched in it. Equally spaced slots are stamped around the circumference for the purpose of holding the armature conductors, while their shape influences the winding method used for any particular armature. Coils that are wound and insulated before being placed in the slots can be used only in armatures with open-type slots.

If semi-closed or fully closed slots are used, it becomes necessary to wind in the coil one turn at a time. Some slot shape variations are shown in Figure 12.5(b).

On larger machines the central portion of the armature core is removed and the remaining laminated cylinder is attached to the armature shaft by means of radial arms (called a spider). This type of construction is shown in Figure 12.6. In practice the outer ring of laminations is made up of a large number of segments stamped directly from smaller sheets of steel.



(a) Armature lamination with 'open' slots



(b) Other slot shapes

Figure 12.5 • Armature laminations and slot shapes

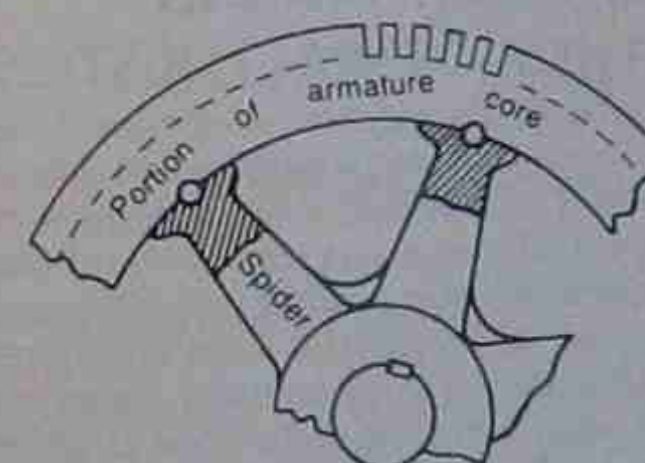


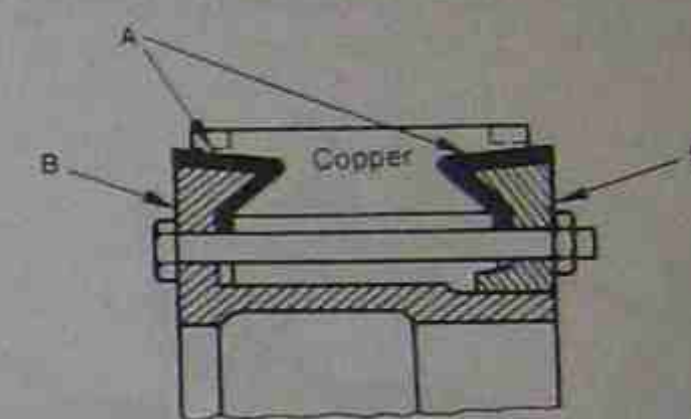
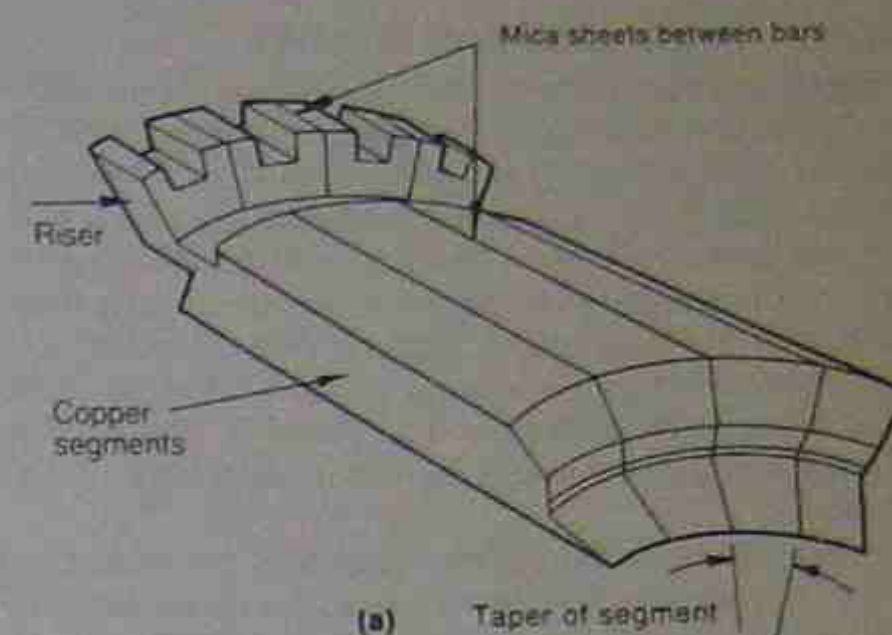
Figure 12.6 • Larger-size armature-core construction

The advantage of this method of construction is a saving in the amount of material used and a consequent saving in weight. In addition, a flow of air through the holes left around the spider gives greatly increased cooling.

#### Commutator

A commutator consists of a set of copper or copper-alloy segments that are wedge-shaped in cross-section and insulated from one another and the armature shaft by mica insulation, as shown in Figure 12.7(a). When assembled, the segments lie parallel to one another and form a cylinder. Grooves in the end of the segments are designed to accommodate specially formed micanite vee rings, which are used in conjunction with mild steel end rings to clamp the segments securely into position.

A sectional view of a commutator is illustrated in Figure 12.7(b). In very small commutators the fixing of segments is achieved by clamping under pressure and rolling over the edges of the clamping rings.



(b)

Figure 12.7 • Commutator construction

The clamping rings in an intermediate-size commutator are designed to be screwed together, while in larger sizes the two clamping rings are pulled together by several equally spaced bolts. In all cases the inside of the steel rings helps locate the commutator on the armature shaft. The commutator may be pressed directly onto the shaft or bolted to the armature spider.

To make suitable provision for connection of coil leads to the commutator segments, slots are cut into the segment adjacent to the armature winding. This method is adequate for smaller commutators. For larger sizes a riser is fitted into the slot and the leads to the windings are connected to them. Both types of connections are shown in Figure 12.8.

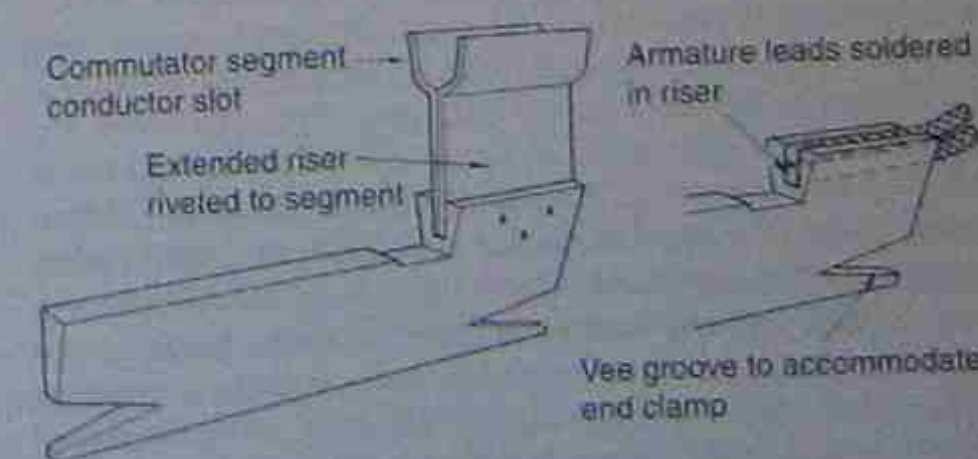


Figure 12.8 • Commutator connection methods



### 12.2.6 Brush gear and brushes

Graphite or carbon brushes are used to provide an electrical connection between the armature windings and the external circuit through a sliding contact with the commutator. Figure 12.9 illustrates the brush gear for a four-pole machine. The carbon brushes must be able to move freely within the brush holder to accommodate any irregularities in the commutator surface, and adjust for any wear. Because of this it is usual to connect the brush to the brush holder with a flexible lead called a 'pigtail'. The same connection terminal is used for joining to the external circuit.

The brushes must maintain contact with the commutator at a constant loading. By adjusting the spring tension, correct brush pressure can be obtained. The brush gear must be suitably insulated from the frame and in many cases its position must also be adjustable. The illustration showing the brush mounting includes the split ring, which permits adjustment of the brush gear.

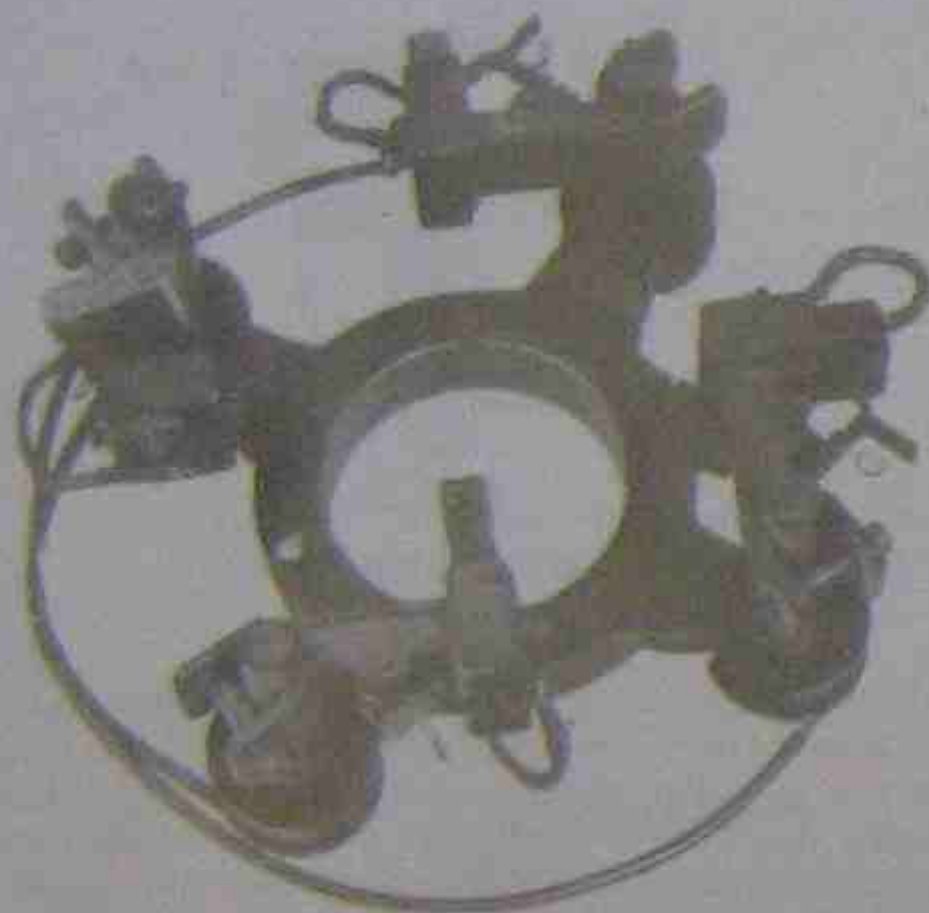


Figure 12.9 • Brush gear assembly of a d.c. machine

### 12.2.7 Action of the commutator

In section 8.3.2 it was shown that a loop rotating within a magnetic field produced an alternating voltage, which was connected to an external circuit via slip-rings and brushes. Special arrangements were made (section 8.6) to ensure that the alternating voltage was sinusoidal. With a d.c. generator reduced to its simplest terms (i.e. a loop rotating within a magnetic field) an alternating voltage is produced as before with the a.c. generator. However, the ends of the loop, instead of being connected to slip-rings, are connected to a two-segment commutator, then through the brushes to the external circuit. The brushes remain stationary and make contact with the segments of the commutator in turn as it and the loop rotate as one unit. Because of this the commutator acts as an automatic reversing switch by exchanging the connections between the loop and the external circuit each time the voltage generated within the loop reverses.

Figure 12.10 shows a loop rotating in a magnetic field in a similar fashion to that in Figure 8.2, where rotation through  $360^\circ$  produces one cycle of alternating voltage. With slip-rings connected to the loop, the same alternating waveform appears across the load. If a two-segment commutator is connected in place of the slip-rings, as shown in Figure 12.10(a), the output voltage is mechanically rectified by the switching action of the commutator and a pulsating form of d.c. appears across the load. The output from such an elementary form of generator is unsatisfactory and practical machines produce a more uniform value of d.c. without the pulsations.

In order to get a more constant output, practical armatures use a number of coils evenly spaced around the armature so that their outputs overlap. When the output from one coil is low, that from another can be high. The output from such an armature is shown in Figure 12.11, with the resultant output shown as a thicker line.

In general, the greater the number of coils, the more constant the output, up to the stage where the output is a steady d.c. value.

With a generator, an alternating voltage is produced within the armature coil, and the purpose of the commutator is to convert this voltage to d.c. for loads external to the armature. The switching action of a commutator is discussed further in section 12.6.

## 12.3 DIRECT CURRENT GENERATORS AND THEIR CHARACTERISTICS

The effectiveness of any machine is measured according to its performance when a load is applied. Generators are used in different ways and one factor that governs performance is the method of field excitation employed. The name given to a d.c. machine, whether motor or generator, usually indicates the type of field connection used with respect to the armature. For example, *series generator* means the field is connected in series with the armature. The characteristics of a machine are to some extent also governed by the field connections, so the same machine may have different tendencies if the field is excited with a different connection.

Characteristics are usually expressed in the form of graphs, the main one being terminal voltage plotted against load current, with the machine running at a constant speed. Over a wide range of machines the same types of curve all have a fairly common shape and are called typical characteristics and the graph axes are not given values, just a name.

The main types of field connections generally used that give a name to the machine are:

1. separately-excited—permanent magnet—wound-field coils
2. shunt-excited—self-exciting field
3. series excited—self-exciting field
4. compound-excited—self-excited with a compound field comprising shunt and series components.

The method of naming by field excitation applies equally well to motors and generators, although the word 'excited' is usually omitted in this context—for example, shunt generator, compound generator or series motor.

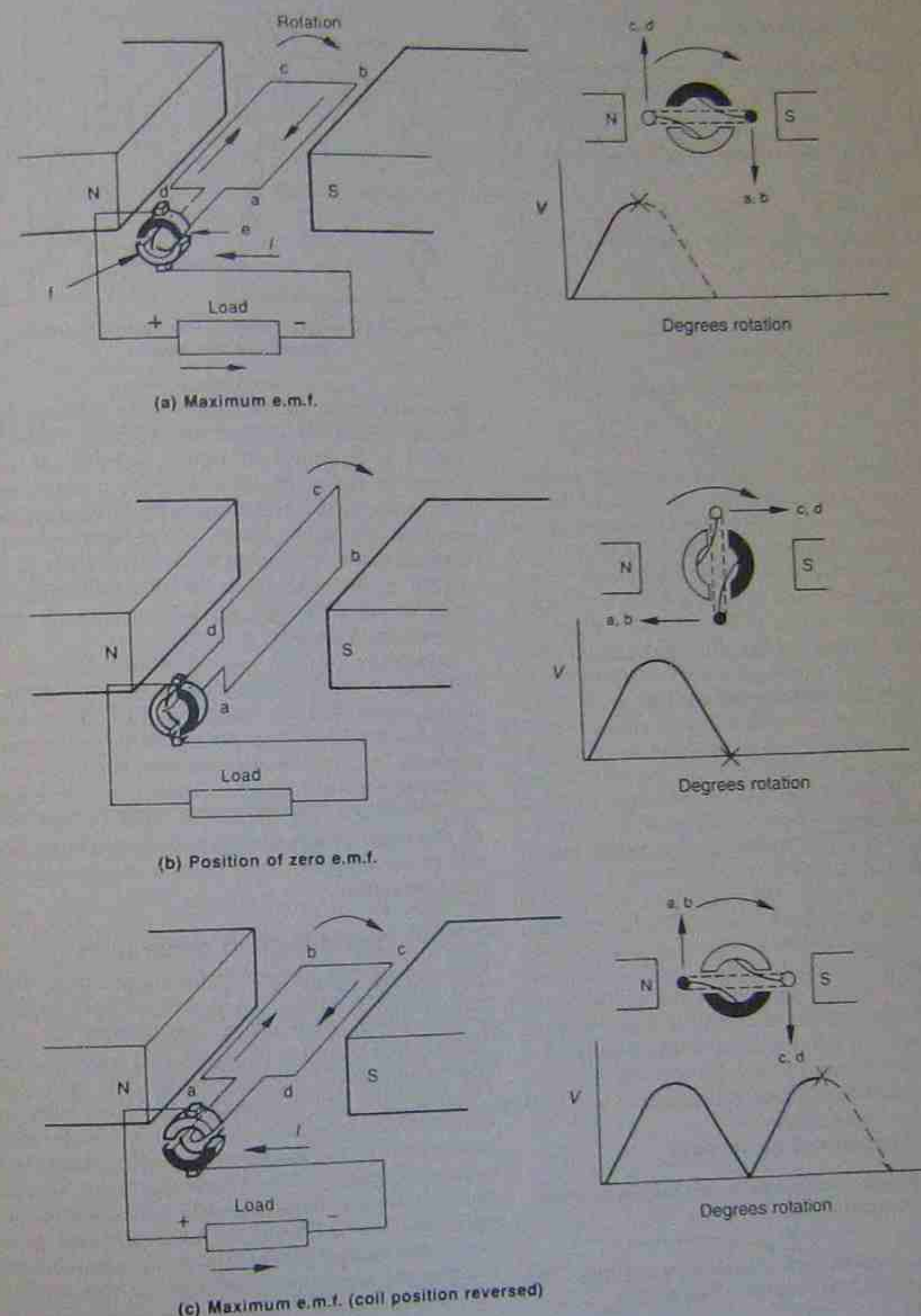


Figure 12.10 • Rectifying action of a commutator

### 12.3.1 Separately-excited generators

The name *separately-excited generator* indicates that the field is supplied from a separate source from that of the generator and it can come from one or two sources as follows.

#### Permanent-magnet field

The field has no winding but consists of a permanent magnet. Once reserved for smaller machines, the latest

developments in magnet construction have allowed the construction of machines up to at least 150 kW output for specialised work. The most common use is still as a tachogenerator, where the linearity of output voltage to speed on light load is an advantage (see Fig. 12.12(a)).

Figure 12.12(b) shows the output voltage/load curve dropping steadily as the load is increased. The drop in



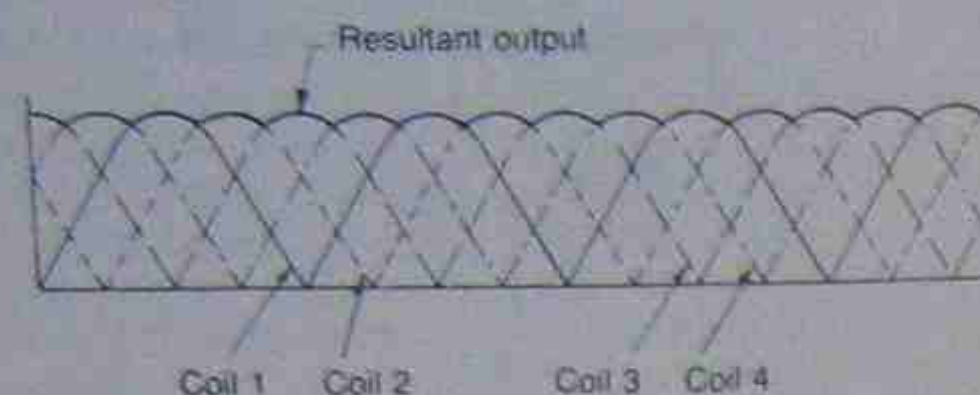
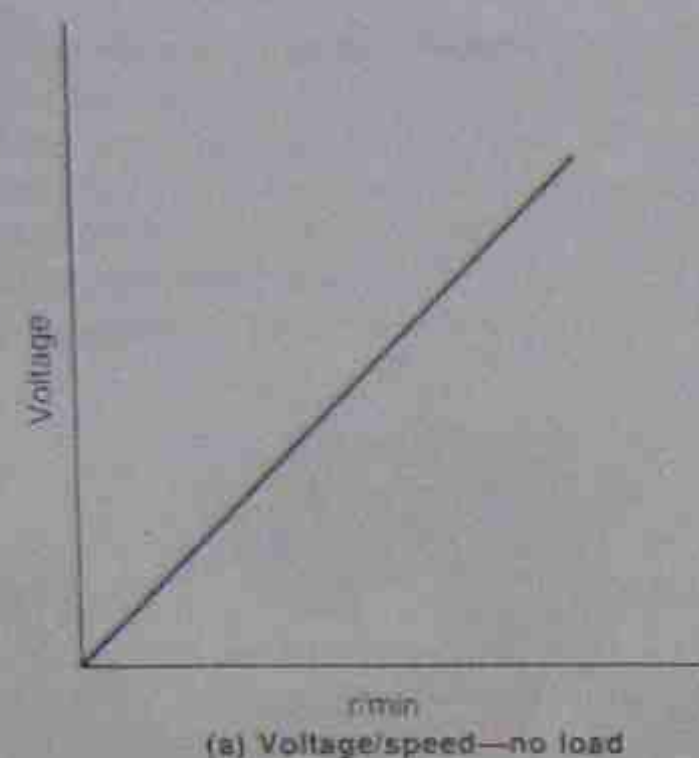
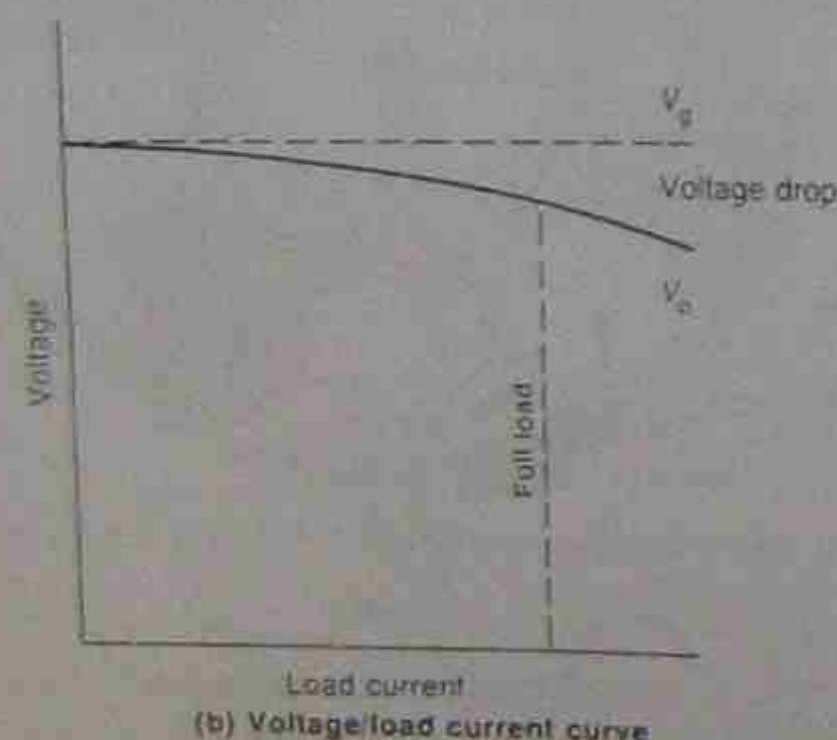


Figure 12.11 • Resultant output from a multi-coiled d.c. armature



(a) Voltage/speed—no load



(b) Voltage/load current curve

Figure 12.12 • Separately-excited permanent-magnet generator characteristics

voltage is due to such factors as armature resistance (see section 12.5) and armature reaction (see section 12.7).

#### Wound fields

With this connection the field windings have current passing through them from an external source. Depending on the use of the machine, the field windings can have few turns with a comparatively high current flowing, or many turns with a much lower value of current. The connection is shown in Figure 12.13.

The usual method of voltage control is by series resistance to regulate the current flowing through the field. A stronger field gives a higher voltage output at the same

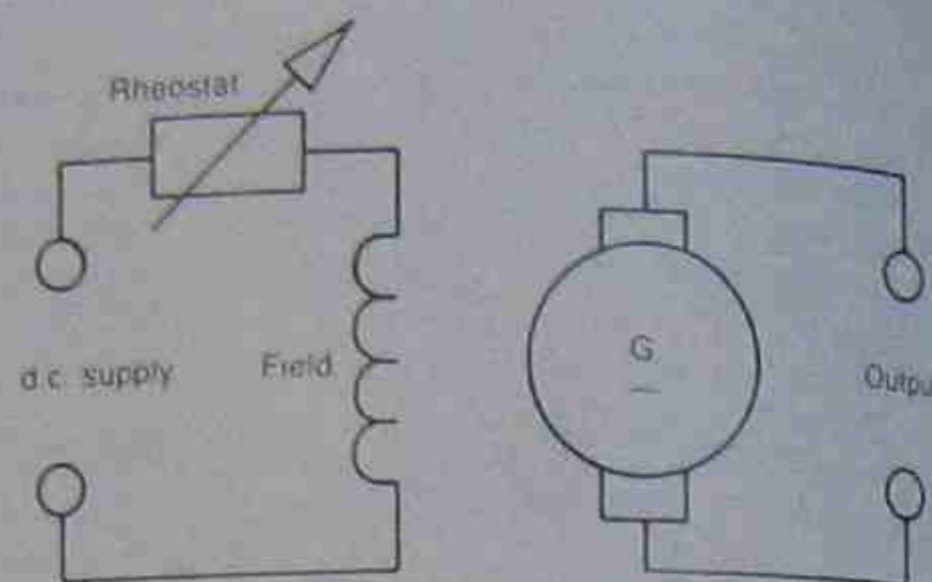


Figure 12.13 • Circuit diagram of a separately-excited, wound-field generator

generator speed. An excitation curve showing the variation in generated voltage for different values of field current is illustrated in Figure 12.14(a). At zero field current in region (i), there may be a small generated voltage due to residual magnetism in the field pole. The graph in the region marked (ii) is usually fairly linear, showing a steady increase in output voltage as the field current is increased. Once the saturation region (iii) is reached, large changes in field current are needed to produce small changes in voltage.

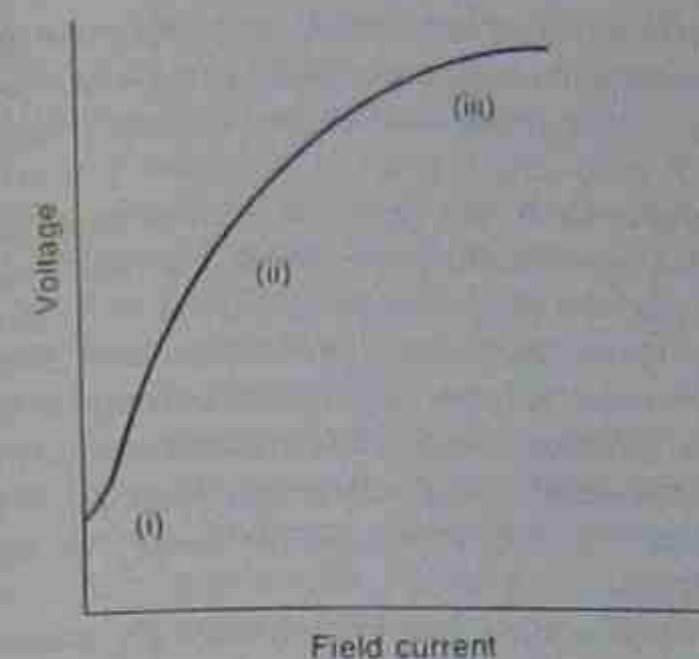
Depending on the use for which the machine is intended, it may be designed to work in either region (ii) or region (iii). In Figure 12.14(b), the voltage/load curve has the same characteristic shape as the permanent magnetic field, for the same reasons. The main use for the separately-excited field connection is in control technology, where a small change in field current in region (ii) can cause a large change in output voltage. That is, it acts as an amplifier, and is used in process work and machine control.

### 12.3.2 Shunt-excited generators

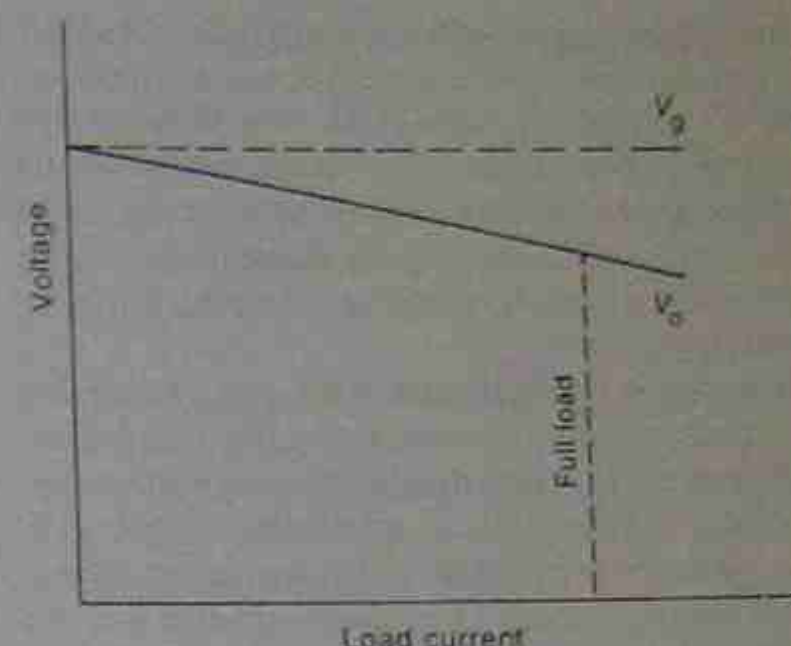
With this type of connection the output from the armature, as well as supplying a load, is fed back to supply the generator field connected in parallel with the armature. The machine is said to be self-excited because it does not rely on an external power source for field excitation.

Because the shunt-connected machine relies on self-excitation for its voltage to build up, certain conditions must be met for the machine to be self-exciting. An examination of Figure 12.15 will show that there is no external source of power to ensure the field is magnetised for initial operation. The first condition is that the field poles must have some residual magnetism. At the commencement of rotation the armature conductors cut this residual flux and generate a small voltage. The generated voltage in turn causes a small current to flow in the field windings, which either increases the amount of magnetism or opposes the residual magnetism already there. If the two magnetic components oppose each other, the machine cannot build up a voltage. The second factor is that the field connection has to be such that the two magnetic components assist each other. Other factors are direction of rotation, correct connections and machine windings in good order.

If all other factors are correct, the small current circulating in the field provides a strengthening of the



(a) Excitation curve



(b) Voltage/load curve

Figure 12.14 • Separately-excited, wound-field generator characteristics

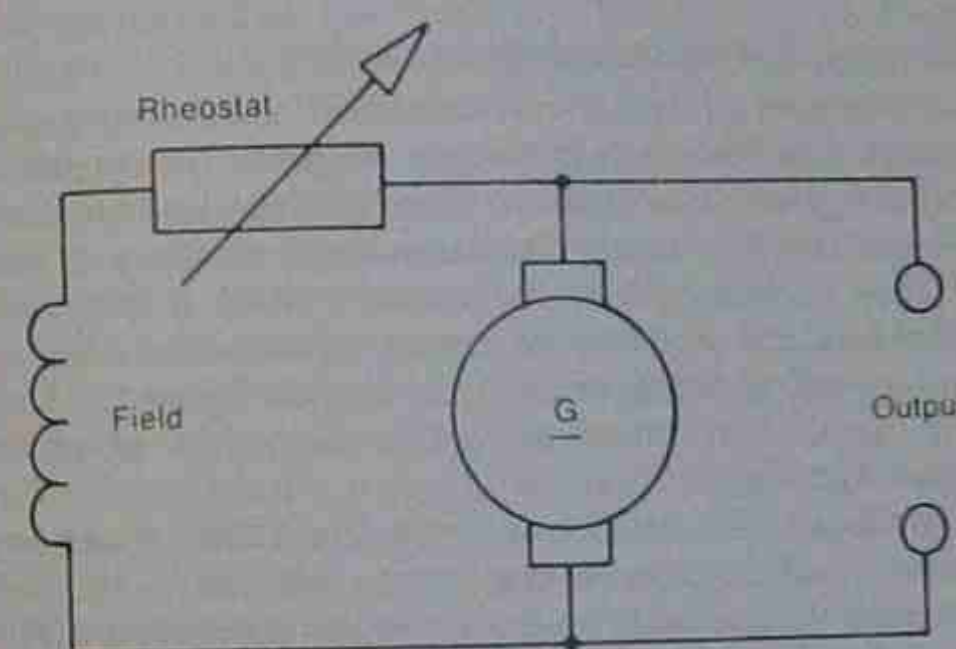


Figure 12.15 • Shunt generator connections

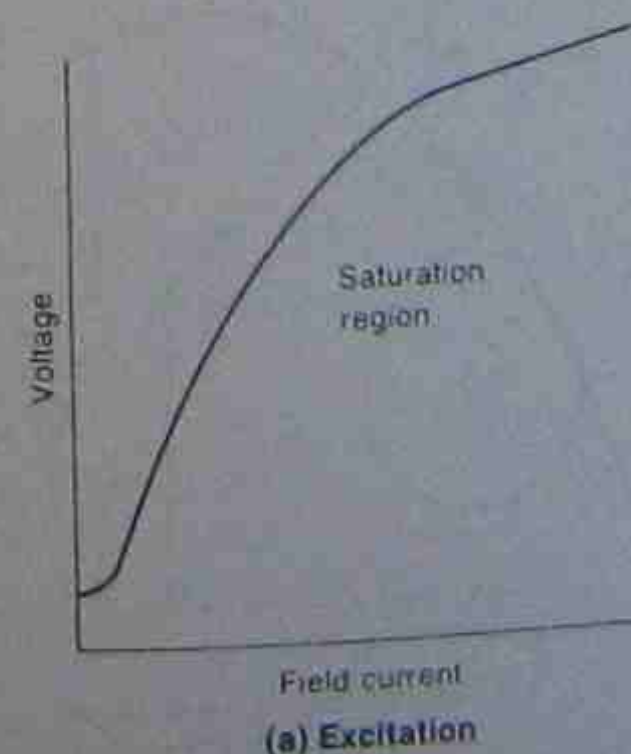
magnetic flux. This leads to an increased generated voltage, more field current, more magnetic flux and so on until the field current is high enough to provide a magnetic flux great enough to send the field poles into saturation. When this is achieved, the generated voltage stabilises at some value. Control of output voltage is achieved by a 'field' resistance, as with the separately-excited machine. If a d.c. generator fails to excite, the conditions above have to be checked out one by one to get the

machine operating correctly again. Probably the most common cause is loss of residual magnetism. The fault is usually remedied by applying a d.c. voltage of the correct value and polarity to the field terminals, such that it causes a current flow in the field in the same direction as would occur when the generator is operating normally.

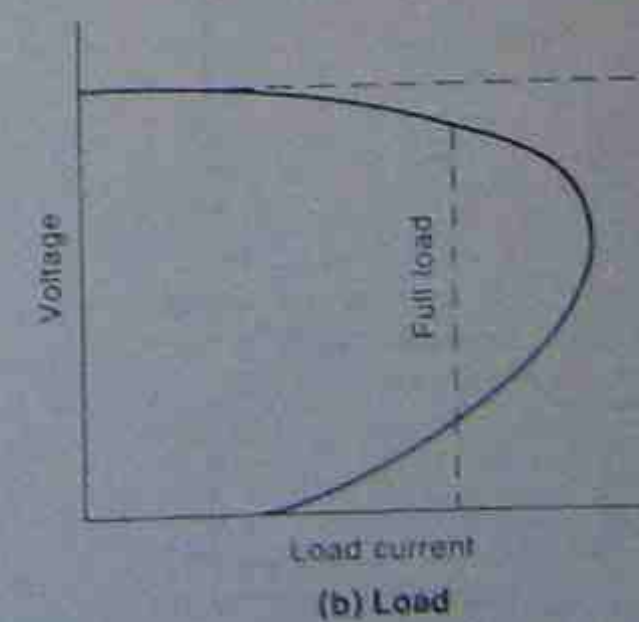
A quick, easy method is to use vehicle batteries and apply this voltage to the field terminals while the generator is stationary. Then remove the batteries from the generator circuit and run it up again to check the result. For higher voltage machines, several batteries in series may be required or, alternatively, an isolation transformer connected to the a.c. mains and a full-wave rectifier might be necessary to obtain the required voltage.

Figure 12.16(a) shows the relationship between field current and generated voltage for a self-excited shunt generator. In the curve shown in Figure 12.16(b), the decreasing voltage characteristic of the separately-excited machine can still be seen, although in the shunt machine the voltage drop is more pronounced at full load. This is because the load is also in parallel with the field and a decreasing output voltage means a decreasing field current, which further decreases the output voltage.

If the generator is loaded to the point where the armature is short-circuited, then, because the field is in parallel with the armature, it also is short-circuited. The only



(a) Excitation



(b) Load

Figure 12.16 • Characteristic curves for a shunt generator



magnetic flux left in the machine is that due to residual magnetism and the result is a small generated voltage, which causes a circulating current to flow between the armature and the short-circuit. This is shown in Figure 12.16(b) as a value of current when there is no apparent voltage being generated. The shunt generator can be safely run under short-circuit conditions, but it is the only type of generator that can.

Under the usual operating conditions, voltage control is by means of a series-connected rheostat in the field circuit, as shown in Figure 12.15. For practical purposes the range of control is held within certain limits, the upper one usually being governed by field pole saturation. Some voltage control can be achieved by speed control but the method also has such limitations as maximum design speed, physical size, and the need for a variable-speed drive source.

The uses for a shunt generator are generally limited to smaller, less costly machines, or cases where the load and speed are practically constant. The shunt generator is very seldom used for larger-size machines.

### 12.3.3 Series-excited generators

In the series-excited generator a field winding connected in series with the armature is also connected in series with the load. See Figure 12.17(a) for the series-connected generator circuit.

In the series generator the load current also flows through the field winding. Consequently a series field winding must have a low resistance so as not to restrict the load current. In the no-load condition, no current flows through the field and the only generated voltage is that due to the existence of residual magnetism. As load is applied to the series generator, the field current and the magnetism in the field poles gradually increase. The increasing field strength gives rise to a generator voltage/load current characteristic that is also an excitation characteristic for the field magnetic circuit, as shown in Figure 12.17(b). It has the same typical shape as the excitation curves for separately-excited and shunt machines, as shown in Figures 12.14(a) and 12.16(a).

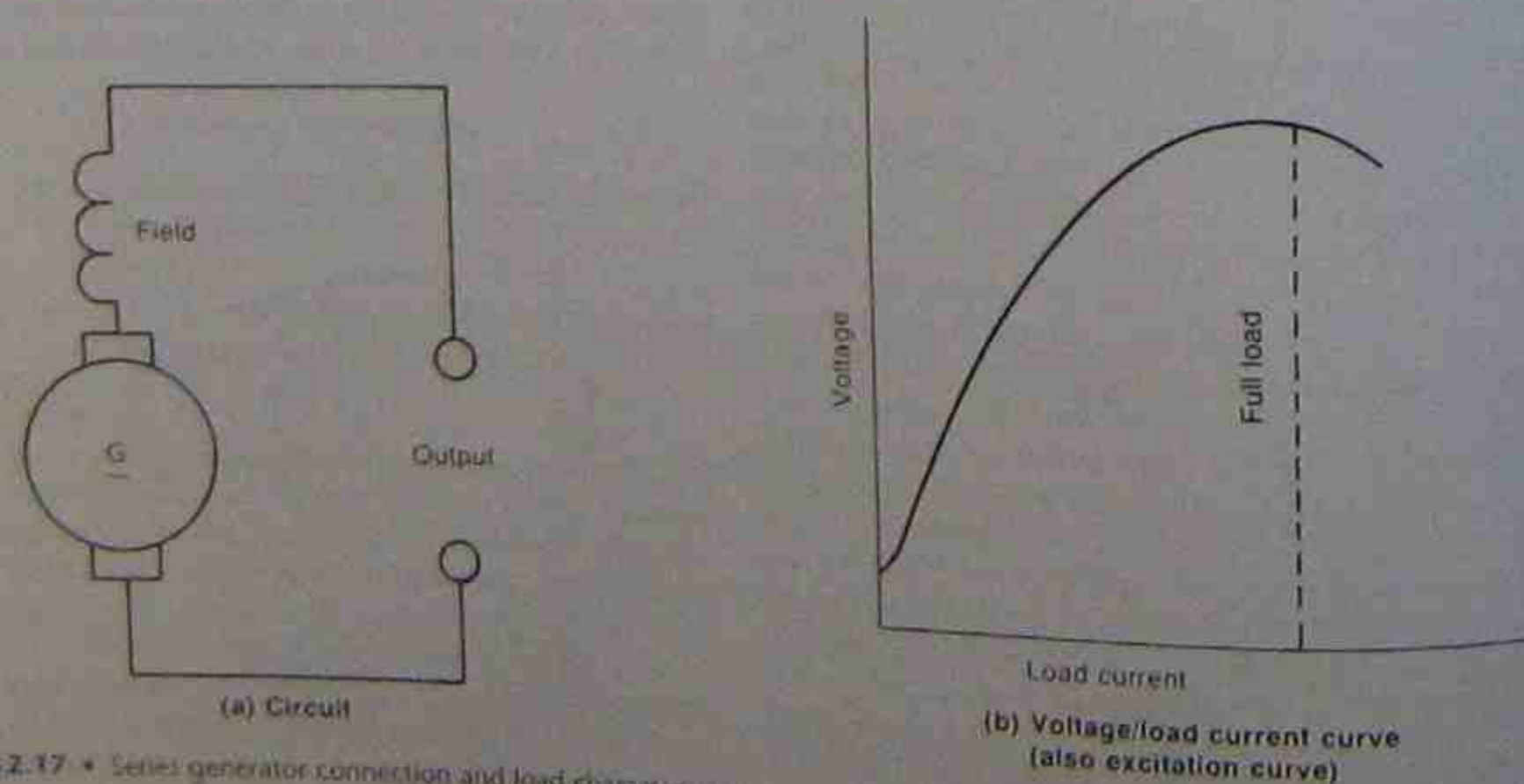


Figure 12.17 • Series generator connection and load characteristics

Once the fields have saturated, any increase in load results in decreasing output voltage because the field flux remains almost constant, while losses in the machine continue to increase.

The series generator, being a self-excited machine, also requires certain conditions to be fulfilled before it can generate a satisfactory output voltage. These conditions are identical to those of the shunt generator in that there must be residual magnetism present and the magnetism produced by the fields must assist the residual magnetism.

Any loss of residual magnetism can be rectified by the application of a direct current to the fields, as with the shunt machine.

Output voltage control can be achieved by speed variations within certain limits, but the most usual method is by connecting a resistor in parallel with the field to divert current around the field. The resistor when used in this manner is called a diverter resistor.

### 12.3.4 Compound generators

A compound generator is a combined shunt- and series-excited generator; that is, it has a magnetic field comprising that created by a shunt field winding and the load current flowing through a series field winding. At the no-load condition the only operative field is the shunt field, and the machine excitation curve is the same as that for any shunt machine, as shown in Figure 12.16(a). The circuit for the compound generator is shown in Figure 12.18(a).

The shunt field can be connected across the armature as shown and is then called a short-shunt compound machine. If connected as shown by the dotted line across the output terminals, it is called a long-shunt compound connection. From a theoretical viewpoint there are minor differences in losses and voltages but in practice there is almost no difference in performance, whether as a motor or a generator, and either connection can be used.

The intention underlying the use of the compound field is to use the rising voltage characteristic of the series generator to compensate for the falling voltage characteristic of the shunt generator. The degree to which the voltage

compensation is intended governs further subdivisions into which the compound generator can be placed.

When the series field overcompensates for the falling voltage characteristic of the shunt generator, the terminal voltage rises as load is applied and the generator is said to be over-compounded, as shown by the appropriate curve in Figure 12.18(b). The level of compounding is governed to some extent by the intended use of the generator and in some makes of larger machines the machine is deliberately over-compounded. The final adjustment is by means of a diverter resistance adjusted to the level required on the actual installation. As with the shunt machine, initial voltage adjustment is with a series field resistor. It is sometimes combined with a measure of speed control.

The under-compounded generator is seldom used because the prime function of a generator is to supply varying loads at a constant voltage. This connection and compounding is more applicable to a d.c. motor. The level-compounded generator is often used as a power source for installations where the machines it supplies are close to the generator, thereby eliminating voltage-drop problems, for example, shipboard installations, machinery where a high degree of control is necessary (as with rolling mills), large automated planers and multiple-lift installations where a converter is needed.

The over-compounded generator can be used to supply d.c. over greater distances where line voltage loss occurs, the rising voltage cancelling out the line loss.

The characteristic of the differentially compounded generator is included in Figure 12.18(b) only for comparison purposes. When the connections are such that the series field magnetism opposes the shunt field magnetism, the effect is to produce a voltage characteristic that falls to zero very rapidly. The uses for differentially compounded generators are virtually nil, although the connection is used as a d.c. generator designed for electric welding with varying degrees of success.

The self-excitation factors of the generator are similar to those of the normal shunt generator in that there must be residual magnetism and the magnetism produced by the field winding must assist this.

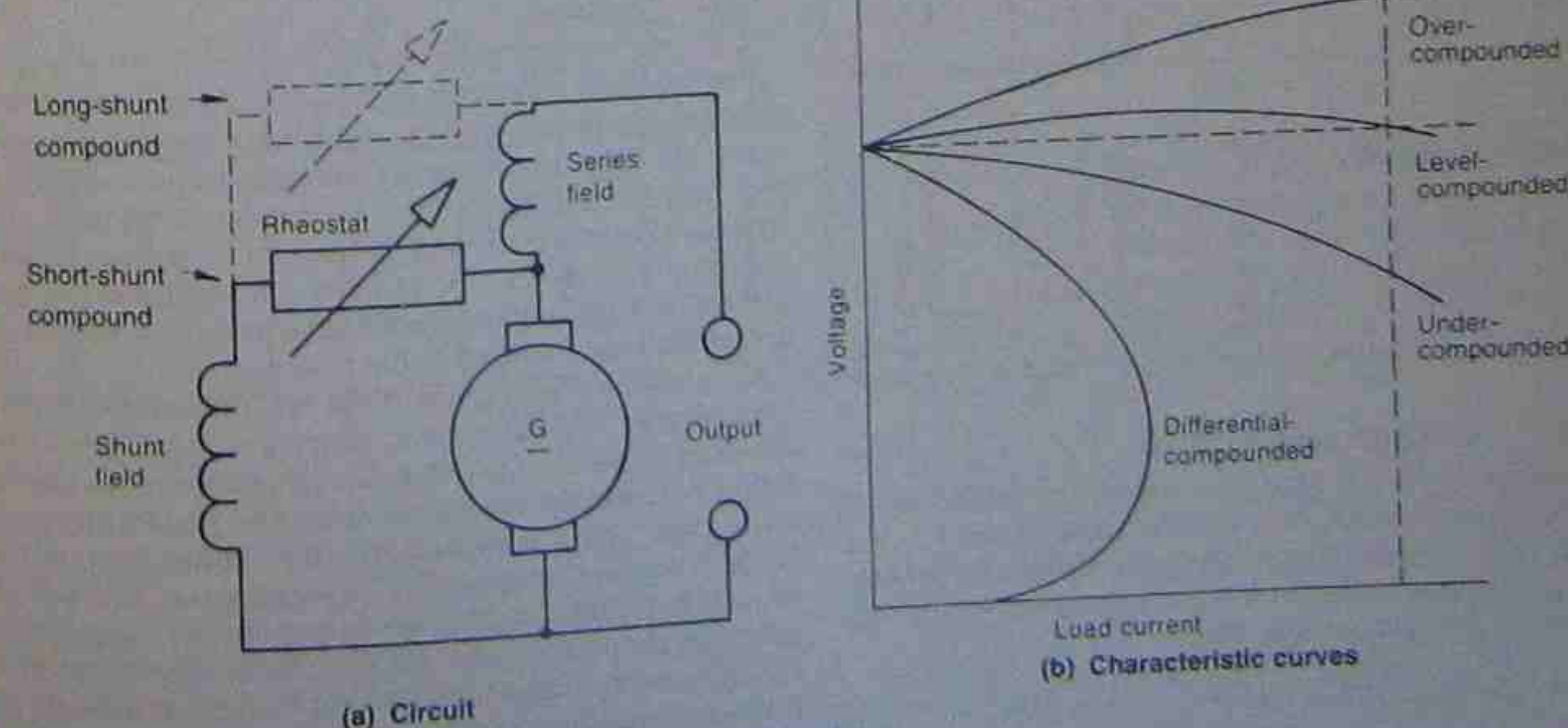


Figure 12.18 • Compound generator connection and load characteristics

### 12.3.5 Generator types compared

#### Voltage control

There are two main methods:

1. **Field flux control.** General concept of resistance in series or parallel with field:
  - (a) Permanent magnet: shunt of soft iron to bypass flux.
  - (b) Separately-excited: resistance in series with field to limit current.
  - (c) Shunt-excited: resistance in series with field to limit current.
  - (d) Series-excited: resistance in parallel with field to bypass field.
  - (e) Compound-excited: resistance in shunt field to limit current.
2. **Speed control.** Use is limited mostly to special cases. Adjust speed of the prime mover.

#### Uses

1. Separately-excited:
  - (a) Permanent magnet: instruments.
  - (b) Wound field: process control, rotary amplifiers.
2. Shunt-excited: small, cheap generators.
3. Series-excited: almost nil.
4. Compound-excited: all general-purpose work.

#### Excitation

1. Separately-excited: permanent magnet or power from outside source.
2. Shunt, series and compound: builds up own field; self-excited.

#### Factors affecting self-excitation of shunt, series and compound generators

1. Residual magnetism is needed.
2. Resultant field flux to assist residual magnetism.
3. Machine connected correctly.



- Machine electrically in good order.
- Direction of rotation.

### 12.3.6 Generated voltages

The value of the voltage generated in an armature winding depends on the following three factors:

- strength of magnetic field
- number of effective armature conductors connected in series
- relative speed between conductors and magnetic field.

The generated voltage for a d.c. machine is found from:

$$V_g = \frac{p\Phi nZ}{a}$$

where  $V_g$  = generated voltage

$p$  = number of poles in the machine

$\Phi$  = magnetic flux per pole in webers

$n$  = revolutions per second (r/s)

$Z$  = number of effective armature conductors

$a$  = number of parallel paths in the armature.

Note: A lap-wound armature has as many parallel paths as there are poles. A wave-wound armature always has two parallel paths.

The above formula is often expressed with the speed given in revolutions per minute:

$$\text{that is, } V_g = \frac{p\Phi nZ}{60a}$$

where  $n = \text{r/min}$

#### Example 12.1

The armature of a four-pole lap-wound armature contains a total of 300 effective conductors. Given the magnetic flux as 0.02 Wb per pole and the speed of rotation as 1000 r/min, find the value of the generated voltage.

$$V_g = \frac{p\Phi nZ}{60a} = \frac{4 \times 0.02 \times 1000 \times 300}{60 \times 4} = 100 \text{ V}$$

#### Example 12.2

Calculate the voltage generated if the armature in Example 12.1 were wave connected.

$$V_g = \frac{p\Phi nZ}{60a} = \frac{4 \times 0.02 \times 1000 \times 300}{60 \times 2} = 200 \text{ V}$$

### 12.3.7 Voltage regulation

Regulation for a d.c. machine covers two areas—speed regulation for a motor and voltage regulation for a generator. As a standard, regulation is the difference between the no-load and full-load values, compared to the full-load value as a percentage, that is:

$$\text{voltage regulation} = \left[ \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \right] \%$$

where  $V_{NL}$  = voltage at no load  
 $V_{FL}$  = voltage at full load

Low values of regulation indicate steadier output voltages. For example, 5 per cent regulation for a generator giving 200 V at no load means that at full load the voltage has dropped to 190 V. For speed regulation, refer to section 12.4.7.

## 12.4 DIRECT CURRENT MOTORS AND THEIR CHARACTERISTICS

Both motors and generators have the same basic construction, as mentioned in section 12.1, and the usual machine can be used in both capacities. In section 12.3, d.c. generators were discussed in some detail and in this section the motor is discussed similarly, since the motor is also grouped or named according to its field connections. For the motor to be useful it must develop torque, or a turning effect. When electrical energy is applied to a d.c. machine, current flows in the armature conductors and produces a magnetic field that affects the main magnetic field (Fig. 12.20). The two magnetic fields tend to neutralise each other on one side of the conductor, giving a weakened field, while the main field is strengthened on the other side. The resulting magnetic field produces a force that acts on the conductors as indicated.

The direction in which the force acts can be found by using the left hand in a similar manner to that of the right hand for obtaining the direction of an induced voltage (see Fig. 12.21).

#### Fleming's left-hand rule (use for motors)

Arrange the thumb, first, and centre fingers of the left hand at right angles ( $90^\circ$ ) to each other.

1. Point the first finger in the direction in which the lines of force are acting.
2. Point the centre finger in the direction in which the current is flowing.
3. The thumb will then point in the direction in which the force is acting on the conductor.

The left-hand conductor in Figure 12.20 has a tendency to be forced upwards and the right-hand conductor downwards. As these are normally imbedded in an armature core at a fixed distance from the centre of rotation, the effect is to create a turning movement, or torque. In the practical d.c. motor the number of conductors is far greater and the torque produced is usually sufficient to drive the load connected to the motor.

As mentioned previously there are similar circuits for both motors and generators. There are more motors in use than generators because one generator in an installation can supply several motors. The generator more often than not is compounded, the motors themselves having varying connections depending on the job in hand. The suitability of a motor connection for any specific purpose will depend on the torque developed and the difference in speed as the load is altered. Because of these factors, the characteristic curves of a motor are concerned with speed and torque as a load is applied.

Type	Field winding	Circuit diagram	Voltage/speed	Voltage/load	Characteristics	Voltage control
Permanent magnet	—				1. Volts directly proportional to speed 2. Output drops slightly on load	Use magnetic shunts on field system
Separately excited	Many turns fine wire				1. Volts directly proportional to speed 2. Output drops slightly on load	d.c. supply Control field current
Shunt generator	Many turns fine wire				1. Voltage is not linear with speed 2. Voltage drops more than permanent magnet on load	Control field current
Series generator	Few turns heavy wire				Rising voltage characteristics	Diverter
Cumulative compounding	Series assists shunt				Voltage characteristic can be made flat or increase with load, depending on compounding	Control shunt field
Differential compounding	Series demagnetises shunt				Voltage drops quickly on load	Control shunt field

Figure 12.19 • Summary of the main points for all types of d.c. generators.



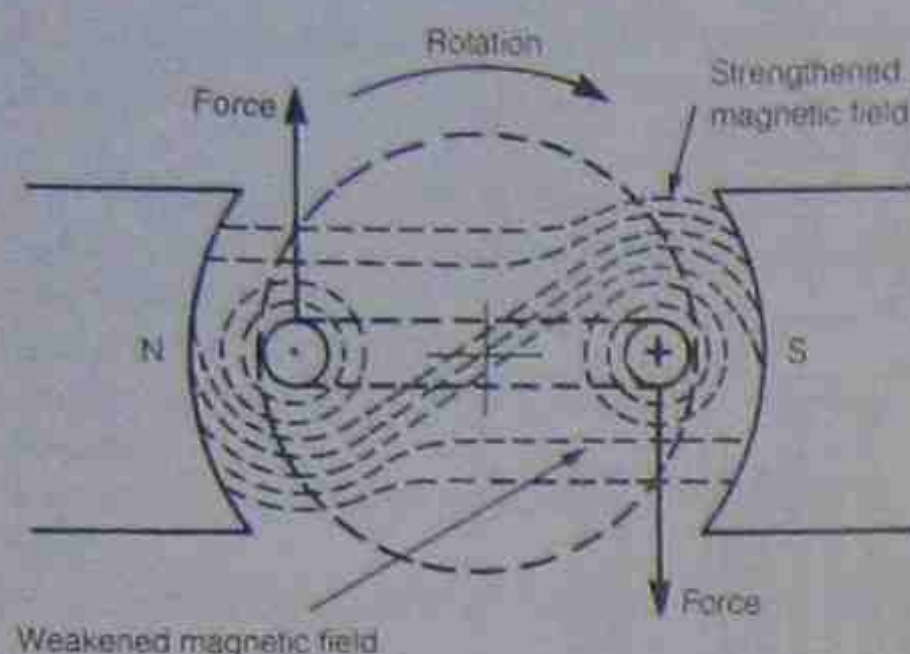


Figure 12.20 • 'Motor effect' produced by an electric current

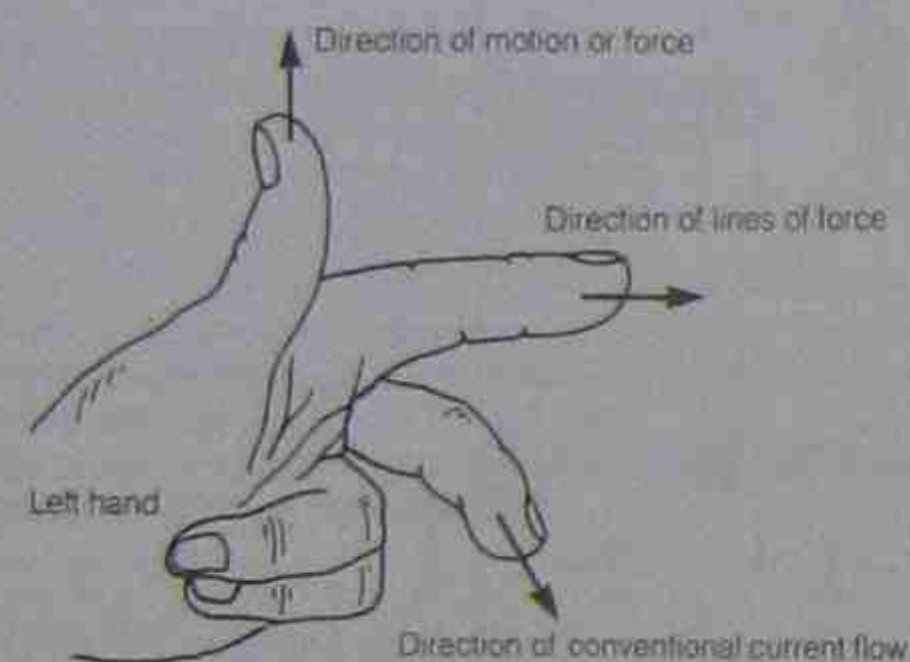


Figure 12.21 • Illustrating Fleming's left-hand rule

whereas generator curves show output voltage plotted against load.

Commutation and armature reaction (discussed in sections 12.6 and 12.7) are applicable in their entirety to motors as well as generators, with the possible exception of the direction of magnetic neutral plane shift, as explained in section 12.7.3.

### 12.4.1 Torque

The magnitude of the thrust exerted on a conductor carrying a current when located in a magnetic field is given by the equation:

$$F = BIl$$

where  $F$  = force on conductor in newtons

$B$  = flux density of main field in teslas ( $\text{Wb/m}^2$ )

$l$  = length of conductor in the field in metres

$I$  = current flowing in conductor in amperes

In the practical case, where an armature has many conductors and also may have several paths, the equation becomes:

$$F = \frac{BIlZ}{a}$$

where  $a$  = number of parallel paths in the armature

$Z$  = number of armature conductors

$I$  = total armature current

Since  $T = Fr$  where  $r$  is the radius of rotation of the armature conductors, the equation becomes:

$$T = \frac{BIlZr}{a}$$

where  $T$  = torque in newton-metres

The formula can be further developed to:

$$T = \frac{p\Phi lZ}{2\pi a}$$

where  $T$  = torque in newton-metres

$p$  = number of poles

$\Phi$  = flux per pole in webers

$l$  = total armature current

$Z$  = number of armature conductors

$a$  = number of parallel paths in the armature

### Example 12.3

A four-pole d.c. motor has a lap-wound armature of 30 coils, each with 20 conductors. If the flux per pole is 0.02 Wb and the armature current is 19 A, calculate the torque produced.

$$T = \frac{p\Phi lZ}{2\pi a} = \frac{4 \times 0.02 \times 19 \times 20 \times 30}{2 \times \pi \times 4} = 36.3 \text{ N m}$$

Points to note when considering a motor in these terms are:

1. In example 12.3 where each coil has 20 conductors, the coil has only ten turns because each coil side acts separately.
2. The output power  $P = \omega T$  (section 1.4) can also be related to the above formula for calculation of torque, provided the speed is known.
3. This in turn can be related to input power from the supply source. A measurement of input power ( $P = VI$ ) can be used to determine efficiency.

### Example 12.4

If the motor in example 12.3 above is rotating at 1100 r/min, find the output power.

$$P = \omega T = \frac{2\pi nT}{60} = \frac{2\pi \times 1100 \times 36.3}{60} = 4.18 \text{ kW}$$

### 12.4.2 Separately-excited motors

Separately-excited motors are of two types: permanent-magnet and wound-field.

#### Permanent-magnet field

The field has no winding but consists of a permanent magnet. This category of both motors and generators was once reserved for smaller machines but the present stage of development in permanent magnets allows the construction of motors up to 150 kW at 230 V with permanent-magnet fields. A common everyday use for the permanent-magnet motor is in small sizes for battery operation in toys, radio-controlled aeroplanes and boats.

Because they have no wound field, there is a growing tendency to a reduced unit cost and an increase in efficiency. Motors up to approximately 7.5 kW use ceramic magnets. While highly resistant to demagnetising, they have a relatively low flux level and are therefore limited in application and size. Normally the magnet is moulded and set in the motor frame and used for low-speed applications (e.g. machine tools).

For larger motors, Alnico magnets are used and the motor is easily adaptable to extreme applications such as steel-mill service (e.g. furnace electrode drives, live table drives). Speed control is usually achieved by varying the voltage applied to the armature. Torque is comparatively linear throughout the normal load range. Figure 12.22 shows characteristic curves of a separately-excited motor.

Printed circuit motors are a variation in construction of the separately-excited motor. The armature itself has no iron in its construction and is consequently an air-cored armature. Figure 12.23 shows the construction of the motor in its simplest form. Several circular magnets are fastened to a casting that forms the basis of field support and motor end-shield in one piece.

The motor end has provision to mount a bearing so that the armature can be maintained in its correct position within the air gap. The second end-shield consists of magnetic material to concentrate the magnetic paths within the motor and provides brush and bearing mounting facilities. For increased torque, motors may have a set of magnets each side of the armature and the material then used in end-shield construction may be non-magnetic.

The armature coils are created by an etching process on a non-conducting substrate. Often of bakelite or fibre-

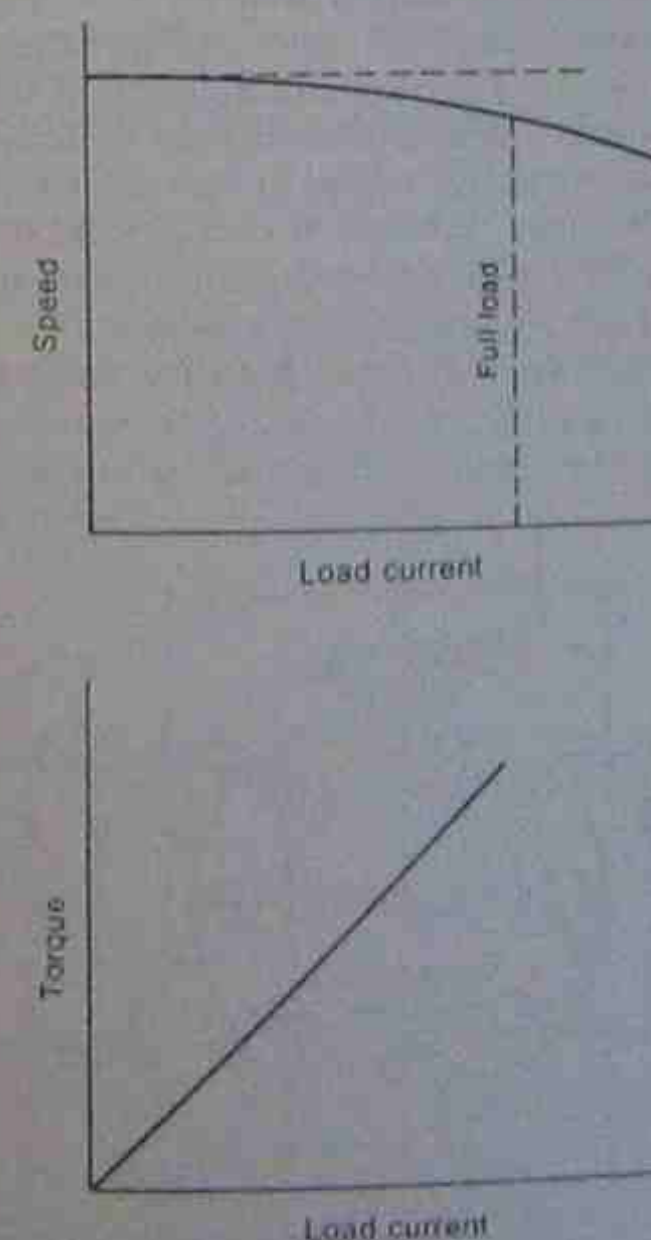


Figure 12.22 • Characteristic curves for a separately-excited motor

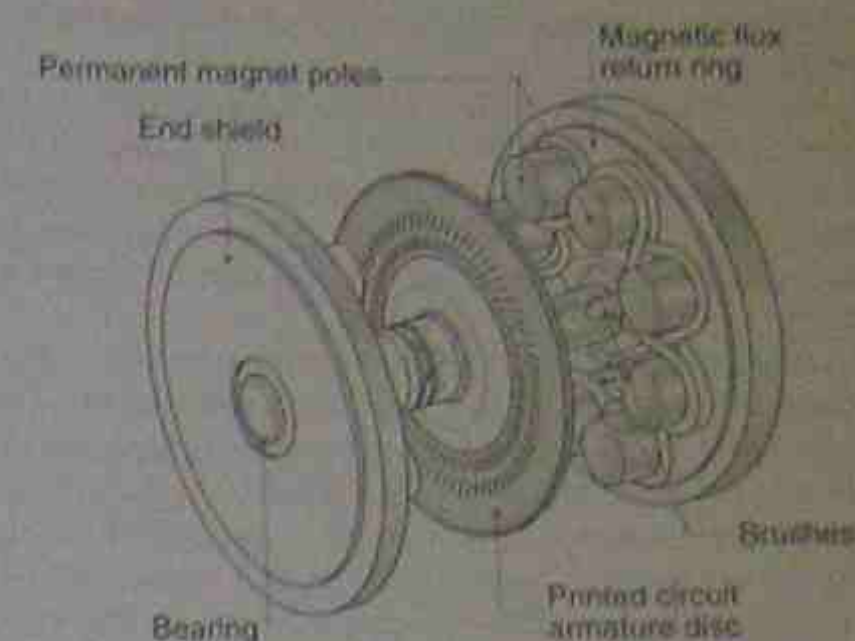


Figure 12.23 • General constructional features of a printed circuit motor

Wernick E. H. (ed.) (1978), *Electric Motor Handbook*, McGraw-Hill Book Co.

glass, the base material is initially coated with a film of pure copper deposited on it by an electroplating process and may be single- or double-sided. Where an armature coil might have to consist of more than one turn, double-sided material may be used. The conductor shapes are outlined on the copper and the material in between is removed by photo-etching.

Of low speed and voltage, printed circuit motors are of light weight, with a short shaft length. Output torque is limited because of armature construction, and efficiency is low. Commutation is never encountered because of low coil inductance.

#### Wound fields

The wound-field version of the separately-excited motor has no limitations in size, as did the earlier versions of the permanent-magnet variety. Like the separately-excited generator, the motor is used mainly in process control work. This type of field connection is adaptable to a wide range of speed control and the torque is also linear with respect to the applied load. See Figure 12.24 for the circuit of the wound-field type and compare it with the generator circuit in Figure 12.13.

Because the machine has similar characteristics to the permanent-magnet motor, its uses are also similar. It has the advantage of being used in other circuits, such as Ward-Leonard control systems, gun-platform levelling, and rotary amplifiers, where a small change in field current can be made to cause a large change in speed. A special construction of the separately-excited wound-field motor makes it suitable for positioning work, as in

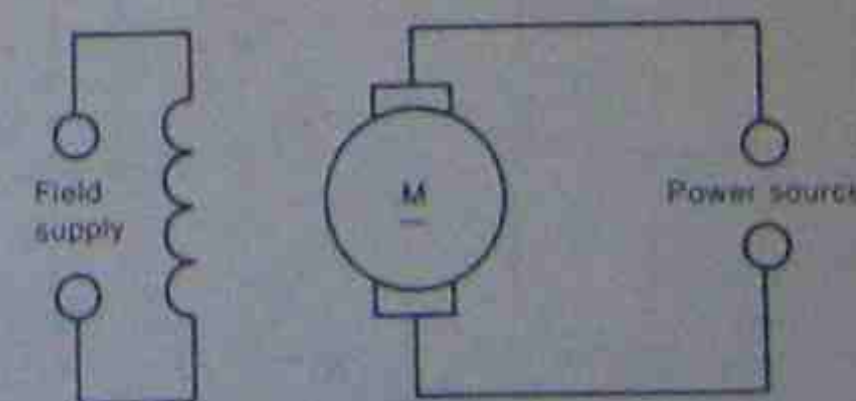


Figure 12.24 • Circuit for a separately-excited wound-field motor



long-distance readings of anemometers and engine speed governors.

Speed control is usually by means of control of field current, although the same effect can be produced by a variation in armature voltage. Under normal circumstances the field-current control method is preferred, owing to lower currents in the control device, giving less electrical power wastage.

It is a characteristic that an increasing armature voltage produces a higher speed, but increasing field current gives a lower speed, while the armature current varies according to the applied load. The rotation of a motor armature in its magnetic field means that there is a generated voltage trying to oppose the applied voltage (see section 12.4.6). The armature current flowing is a function of the difference in these two voltages and the armature resistance.

With a rheostat connected in series with the field, a reduction in resistance means an increase in field current and in turn an increased field strength. At a constant armature speed, an increase in field strength leads to an increased generated voltage (back e.m.f.), which tends to reduce the armature current, and the motor therefore produces less torque. As a consequence the motor slows down, the armature current increases, and the motor stabilises at a lower speed. A decrease in field current leads to an increase in speed.

Precautions must be taken to ensure that the field current does not decrease below a certain level that permits excess armature currents and dangerous speeds to result. Motor reversal is achieved by altering the polarity of the supply to either the field or the armature. Reversing the polarity of both supplies results in no change in rotation, as the direction of current flow in both the armature and field windings is reversed. The basic principle of reversal of rotation for a d.c. motor requires that the direction of current flow through either the field or the armature windings be reversed, but not both.

Figure 12.25 illustrates this method of reversed rotation. In both cases the field polarity is unchanged, while the direction of current flow through the armature is changed (in Fig. 12.25(b)). The torque created is equal in both cases, but the resultant direction of rotation is changed.

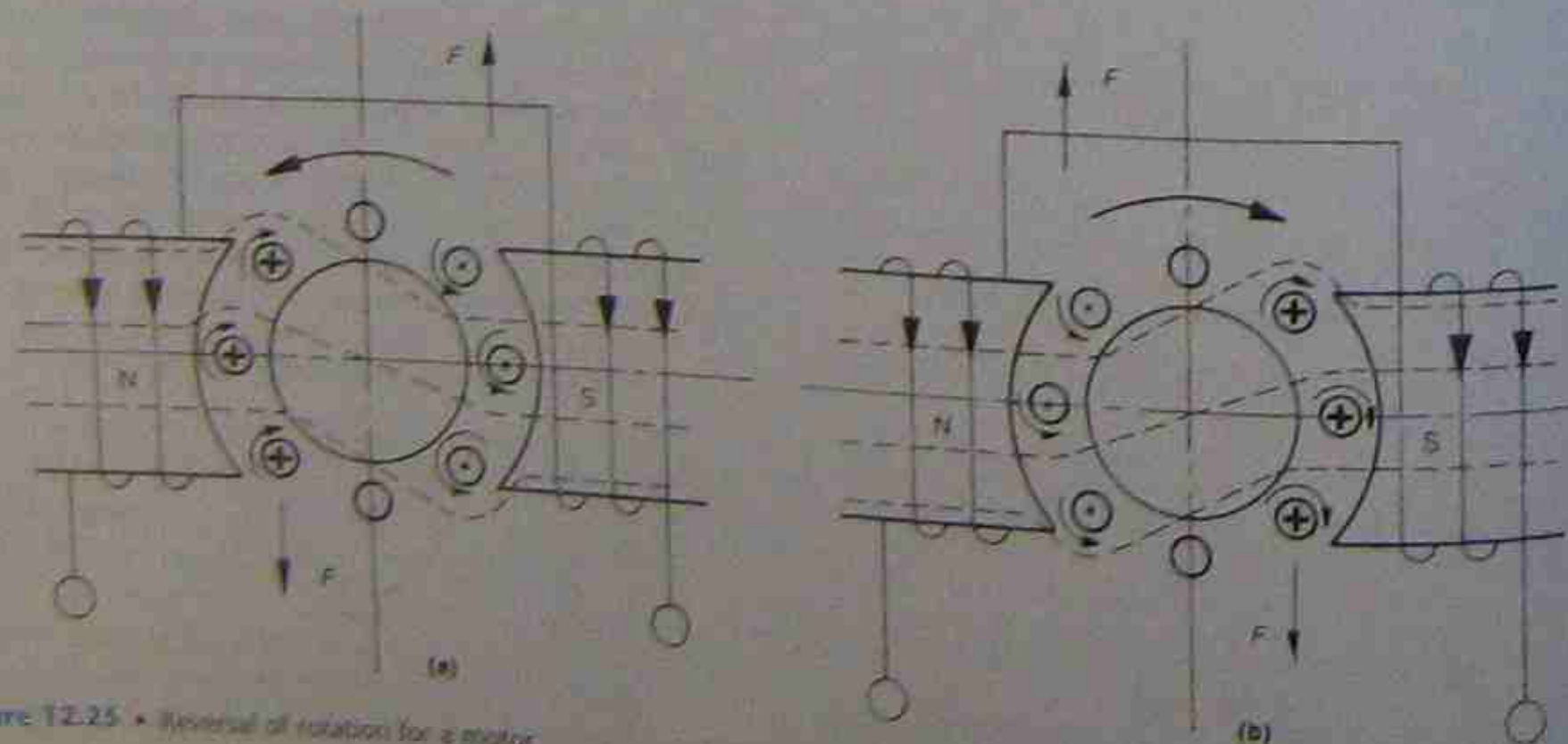


Figure 12.25 • Reversal of rotation for a motor

### 12.4.3 Shunt-excited motors

The shunt-field connection is commonly used in the smaller size range. In larger-size motors the shunt connection is found less frequently, but is still used because of its fairly constant speed characteristic. Of the several types of motor connections, the shunt-excited motor has the best speed regulation throughout the normal speed range. Like the shunt generator, the shunt motor field is connected in parallel with the armature and the motor speed can be controlled by a resistor regulating the current flow through the field. The basic motor circuit is shown in Figure 12.26, together with the characteristic curves for speed and torque.

Under normal operating conditions the speed of the motor is set with the field rheostat. Decreasing the resistance value increases the field current, and causes the same sequence of events with speed adjustment as described in section 12.4.2 for the separately-excited machine. Below normal speed operating ranges, the voltage to the armature is varied with a series armature resistor to give speed variations. In a similar fashion to the separately-excited motor, precautions must be taken to ensure that the field current is never reduced below a certain value in order to prevent excessive armature speeds and current.

Reversal of rotation follows the same pattern as the separately-excited machine in that either the armature or the field current flow is reversed, but not both. Where interpoles or compensating windings are used (see section 12.7) the connections joining the interpoles to one side of the armature must not be disturbed.

### 12.4.4 Series-excited motors

In series-excited motors the field and armature are in series with the supply in a circuit similar to the series generator. The circuit and characteristics are shown in Figure 12.27. The series motor is subject to wide changes in speed as its load is varied, because of changing field current. With a series motor on full load, both the armature and field current are at comparatively high values. Section 12.4.2 discussed in some detail how increasing the field

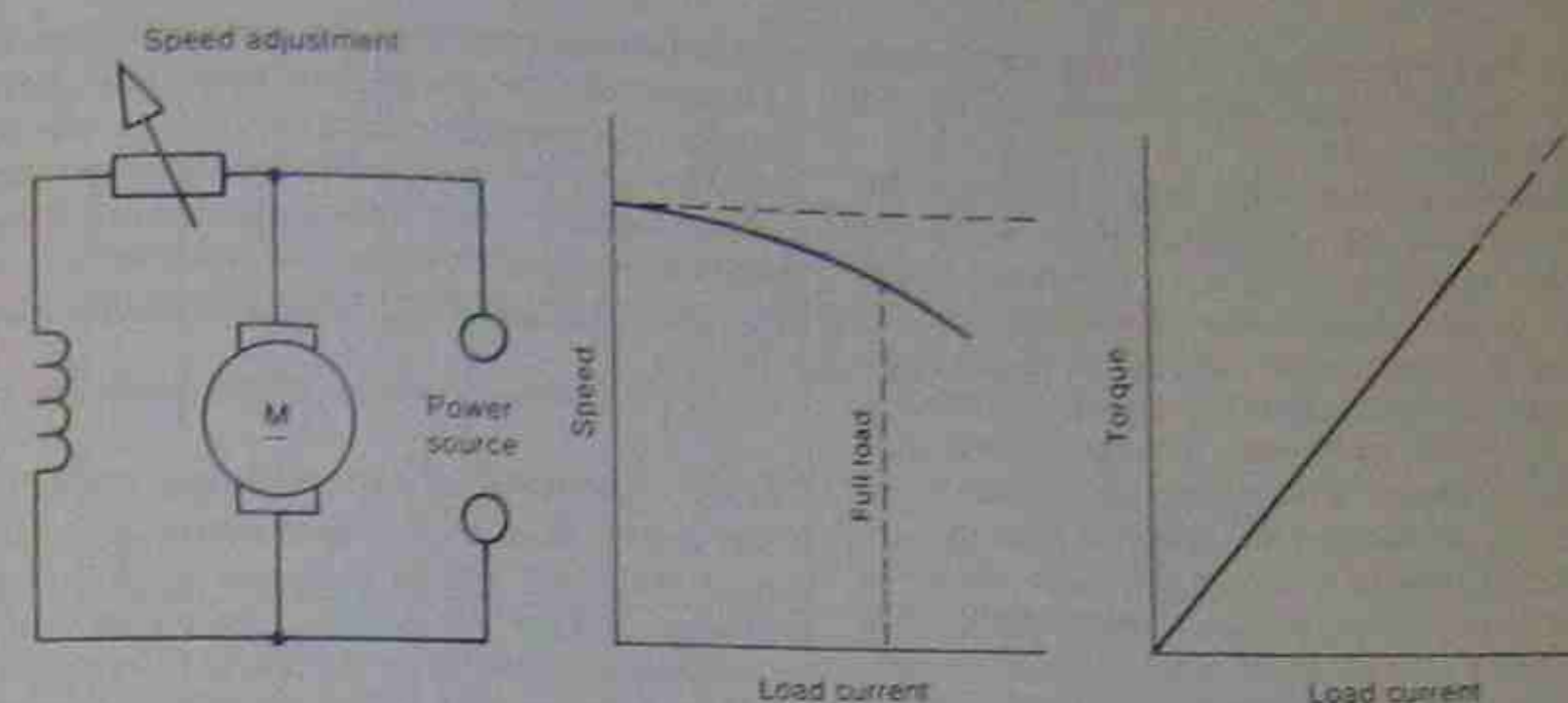


Figure 12.26 • Shunt motor characteristics

current of a motor reduced the speed and, conversely, decreasing the field current increased its speed. Thus with full load (and field) current, the speed of a series motor is low—and, as the mechanical load is removed from the motor, the armature current (also the field current) is reduced. Because the magnetic field becomes weaker, the motor speeds up.

With larger-size series motors, speeds can be attained under no-load conditions that are sufficiently high to cause damage to the motor. A normal precaution is to have a minimum load permanently connected by direct coupling or similar means to prevent the possibility of removing all the mechanical load.

The torque characteristic of a series motor is non-linear because as the load applied to the motor increases and the motor slows down, both armature and field current increase together.

In section 12.4.1 torque was stated to be:

$$T = \frac{p\Phi IZ}{2\pi a}$$

For any one machine, the number of poles  $p$ , the number of conductors  $Z$ , the number of parallel paths  $a$  and the value of  $2\pi$  will remain constant, so the formula can be written in the form  $T \propto \Phi I$ . Since  $\Phi$ , the field flux, is proportional to the armature (field) current,  $T \propto I^2$ , for a series motor.

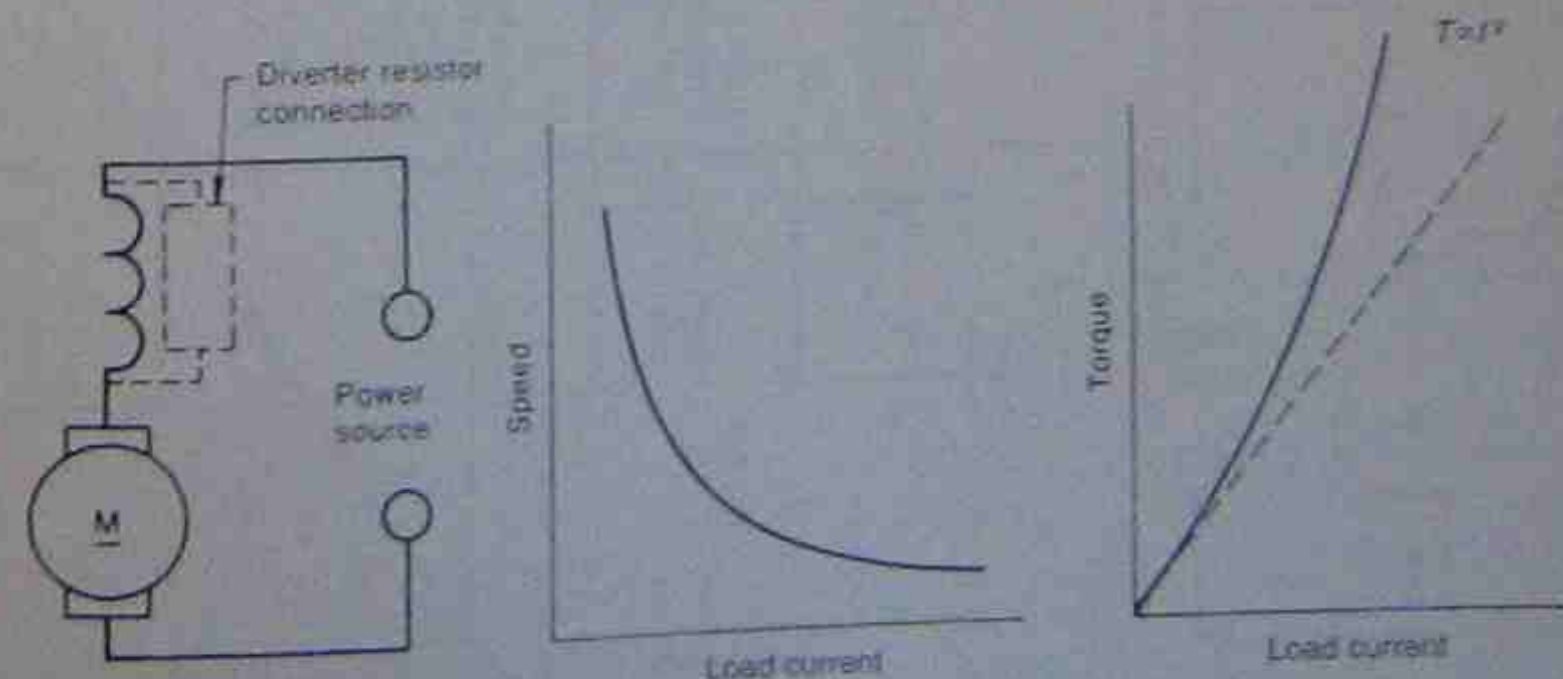


Figure 12.27 • Series motor characteristics

Inspection of the characteristic curves shows that an armature current increase is associated with a decrease in speed and an increase in torque. These factors show the big advantage and common use of the series motor: starting against heavy loads.

Typical uses are traction motors in trams, electric trains, cranes, anchor winches, and elevators, and starter motors for motor cars.

To reverse the direction of rotation, reverse either the field or armature leads (but not both).

Speed control methods are not really applicable to series motors because of their inherent wide range of speeds, but at any one load and voltage the speed can be increased with the use of a diverter resistance to bypass some of the armature current around the field.

### 12.4.5 Compound motors

When providing a motor with two field windings on one set of field poles, provision exists for the two circuits to assist or oppose each other. With the series and shunt windings assisting one another the magnetic field strength is increased and is called the cumulatively compounded connection. This is the connection normally used. Differential compounding is possible but has little practical use. If a differentially compounded motor is loaded beyond a certain point its current increases rapidly.



and the motor abruptly changes its direction of rotation. Depending on size and torque of the motor, this reversal can twist a motor shaft off.

The cumulatively compounded motor combines the characteristics of both the series and shunt motors. Its speed regulation is not as good as in the shunt motor, but is superior to the series motor. While the torque of the shunt motor is approximately linear, the torque of the compound motor increases more rapidly—but at the cost of some loss in speed. Its torque, however, is less than that of the series motor. The compound motor is the general workhorse among motors and is especially suitable to loads that require a reasonably high degree of starting torque, but do not require a series motor. The shunt winding allows the motor to run at very light loads, a factor that gives it an advantage over the series motor. Applications include punches, shears, and rolling mills, and drive motors for machines subject to sudden or shock loads and reversals, such as large metal planing machines. Characteristics of the compound motor are shown in Figure 12.28.

It should be noted that with large traction loads, such as diesel electric drives in ships and particularly diesel electric locomotives with multiple bogie drives, the basic drive motor is referred to as a series motor. In fact it is probably a compound motor with the shunt field open-circuited during starting. Several series motors may also be connected in series with one another. As the load becomes mobile, it is normal practice to reconnect the series motors in parallel and still later to convert the series motor connection to a shunt or a cumulative compound type.

While it can be said that a series motor (or a shunt motor) is applicable to some particular job of work, it should be appreciated that the one motor can be electrically reconnected while still rotating, to suit conditions that have changed since the motor started. Similarly a d.c. motor in motion can be reconnected to behave as a generator supplying a resistive load and to form part of a braking sequence to reduce wear on brake shoes (e.g. in an electric train travelling downhill).

One form of emergency braking for electric trains is to reverse the electric motors and apply full voltage. With regard to reversing the cumulatively compounded motor,

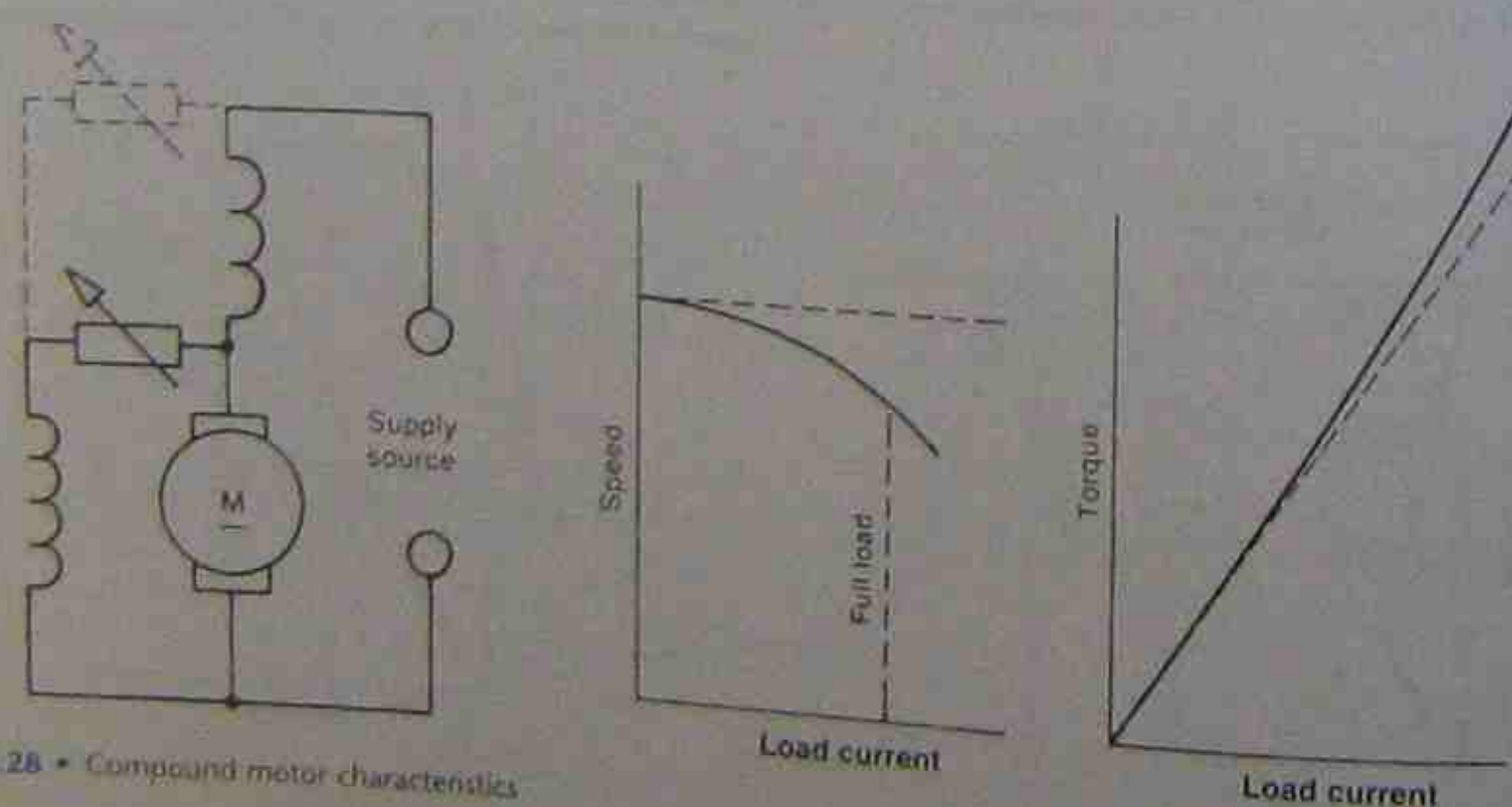


Figure 12.28 • Compound motor characteristics

it must be remembered that there are two field windings. As is often the case the machine might have interpoles as well and the reversing situation has to be handled more carefully. Both the shunt and series windings have to be reversed together, but not the armature or the interpoles. Reversing the shunt or series windings merely changes the machine connection from cumulative to differential compounding.

Figure 12.29 summarises the characteristics of d.c. motors.

#### 12.4.6 Generated voltage in a motor

When a voltage is applied to a motor at standstill, the current that flows will be governed by the resistance of the motor, and the initial or starting current can be quite large unless steps are taken to prevent it. Typically a 200 V compound motor of 3.5 kW could have an armature resistance of approximately 0.5  $\Omega$ .

$$I = \frac{V}{R} = \frac{200}{0.5} = 400 \text{ A (plus field current)}$$

Under everyday operating conditions this figure is far in excess of the usual current a motor of this size would draw, so other factors must be involved. In section 5.9 it was stated that the three factors necessary to produce an e.m.f. were a conductor, a magnetic field and relative motion between the first two. With an electric motor at standstill, the third factor does not exist.

The relative motion component does exist; however, the instant the motor starts rotating an e.m.f. is generated. From Lenz's law the induced e.m.f. opposes the applied voltage and the effective voltage causing current to flow in the motor is the difference between these two voltages (see Fig. 12.30).

The generated voltage, usually called *back e.m.f.* or *counter e.m.f.*, is always assumed to occur only in the armature.

For a motor field:

$$I_f = \frac{V}{R_f}$$

where  $I_f$  = field current  
 $R_f$  = field current resistance  
 $V$  = applied voltage

Type	Field winding	Circuit diagram	Speed/load	Torque/load	Characteristics	Speeds below normal	Speed above normal	Methods for reversing
Permanent magnet	—				Speed drops slightly on load Torque proportional to load			Change supply polarity 
Shunt	Many turns fine wire				Speed drops slightly on load Torque approx. proportional to load			Change armature or field 
Series	Few turns heavy wire				Speed decreases and torque increases with increase of load			Change armature or field 
Cumulative compound	Series assists shunt				1. Speed drops more than shunt 2. Torque increases more than shunt			Change armature or field 
d.c. motors with interpoles	Few turns heavy wire				Gives better commutation under all loads			Interpoles and armature must always be reversed together 

Figure 12.29 • Summary of the main points for all types of d.c. motors



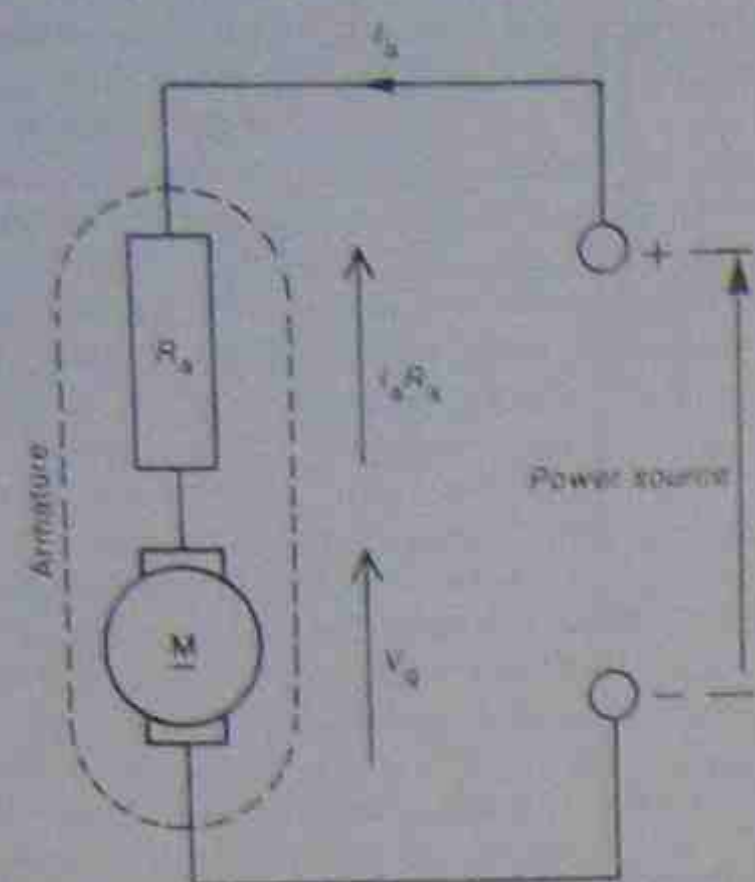


Figure 12.30 • Generated voltage in a d.c. armature

For the armature:

$$V = V_g + I_a R_a \quad (\text{motor})$$

Transposing:

$$I_a = \frac{V - V_g}{R_a} \quad (\text{motor})$$

where  $I_a$  = armature current  
 $V$  = applied voltage  
 $V_g$  = back e.m.f.  
 $R_a$  = armature resistance

### Example 12.5

A 500 V d.c. motor draws an armature current of 540 A on full load. Find the value of the back e.m.f. if the armature resistance is 0.002 Ω.

$$\begin{aligned} I_a R_a &= V - V_g \\ \therefore V_g &= V - I_a R_a \\ &= 500 - (540 \times 0.002) \\ &= 495.92 \text{ V} \end{aligned}$$

### 12.4.7 Speed regulation

Speed regulation for a motor expressed as a percentage is found from:

$$\text{speed regulation} = \left[ \frac{n_{NL} - n_{FL}}{n_{FL}} \times 100 \right] \%$$

where  $n_{NL}$  = speed at no load  
 $n_{FL}$  = speed at full load

The smaller the value of percentage regulation, the less speed the motor loses on load.

Regulation values of 5.6 per cent indicate good speed regulation, where there is little speed loss from no load to full load; 100 per cent regulation is very poor and means the motor stops altogether when placed on load.

### Example 12.6

A d.c. shunt-connected motor runs at 1050 r/min on no load and slows to 990 r/min on full load. Find the speed regulation.

$$\begin{aligned} \text{regulation} &= \left[ \frac{n_{NL} - n_{FL}}{n_{FL}} \times 100 \right] \% \\ &= \left( \frac{1050 - 990}{990} \right) \% \\ &= 6\% \text{ (i.e. small speed loss on load)} \end{aligned}$$

## 12.5 EFFICIENCY OF D.C. MACHINES

In section 1.4.2, mention was made of losses in machines and these were listed as friction, windage and other losses. Friction is present in all rotating machinery; windage is present because of air circulation due to rotating components, and in fans added to ensure forced circulation of air for cooling purposes. In electrical machines the term 'other losses' comprises copper losses, iron losses, magnetic leakage and other lesser factors.

### 12.5.1 Losses

Copper power losses are due to the resistance of electrical windings, while iron power losses are due to hysteresis and eddy currents in the iron core of the armature. While the iron loss is almost constant from no load to full load, the copper loss varies considerably. These two are the main electrical losses in a motor and the two are added to obtain the total power loss. The power loss in copper conductors varies as the square of the current flowing ( $P = I^2 R$ ). At light loads, the small current flow means the copper loss is at a minimum. If the armature current is doubled, the copper loss becomes four times as great and four times as much heat is generated, which has to be removed, usually by air circulation.

### 12.5.2 Generator efficiency

For analysis purposes it is usual to assume that all the armature resistance is concentrated into one component and not distributed throughout the windings.

Figure 12.31 shows a shunt-connected generator separated into its component parts, while the broken lines indicate the whole unit.

If the designed generated voltage of the generator in Figure 12.31 is 200 V, and the armature has a resistance of 0.5 Ω, then for every ampere of current being supplied by the armature there is an internal voltage drop of 0.5 V due to the armature resistance. For every 2 A of load current, 1 V will be lost internally, and if 200 V is required at the generator terminals, then the generating section will have to generate a higher voltage in the windings. That is, for a 10 A load the generated voltage will have to

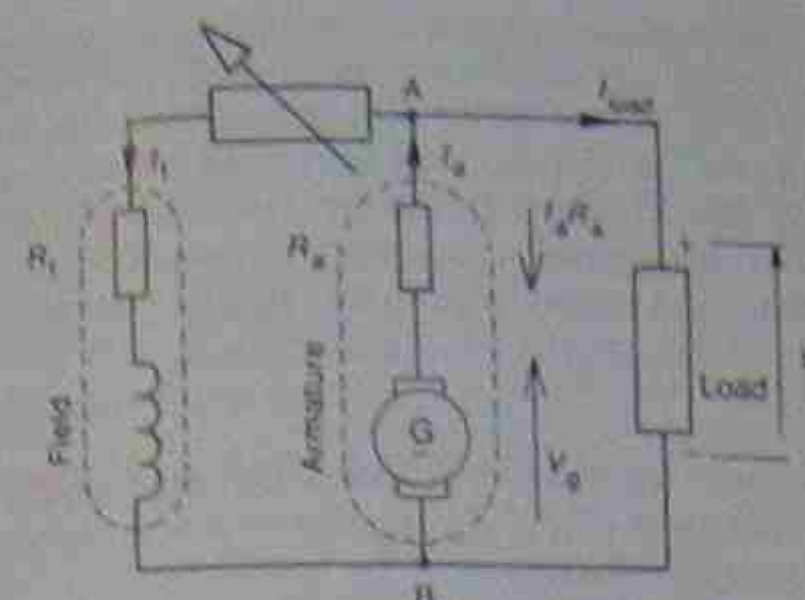


Figure 12.31 • Equivalent circuit of a shunt generator

be 205 V to give a terminal voltage of 200 V between points A and B.

The armature current  $I_a$  will also include the field current  $I_f$  as well as the load current  $I_{load}$ :

$$\text{that is, } I_a = I_f + I_{load}$$

The voltage drop due to internal resistance is equal to  $I_a R_a$  ( $V = IR$ ) and the generated voltage  $V_g$  is equal to the terminal voltage  $V$  plus the  $I_a R_a$  voltage drop, that is:

$$\text{for a generator, } V = V_g - I_a R_a$$

With a series field winding the resistance of the field must be added to the armature resistance.

### Example 12.7

Find the value of the e.m.f. generated in a d.c. generator if the terminal voltage is 204 V, the armature resistance is 0.3 Ω, and the armature current is 12 A.

$$\begin{aligned} V &= V_g - I_a R_a \\ \therefore V_g &= V + I_a R_a \\ &= 204 + (12 \times 0.3) \\ &= 204 + 3.6 \\ &= 207.6 \text{ V} \end{aligned}$$

### Example 12.8

Find the terminal voltage of a compound generator given the following facts:

load current = 18 A  
 series field resistance = 0.2 Ω  
 armature resistance = 0.35 Ω  
 shunt field current = 0.85 A  
 generated voltage = 230 V

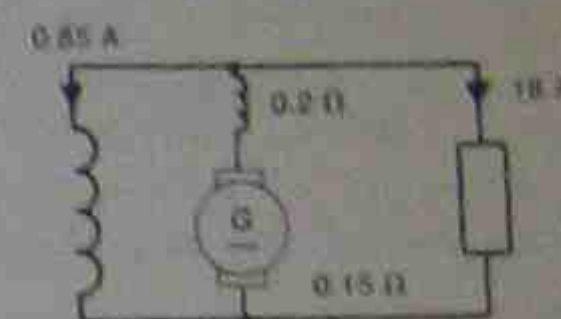


Figure 12.32 • Circuit for example 12.8

From the circuit shown in Figure 12.32:

$$\text{total armature current} = I_a = I_f = 18.85 \text{ A}$$

Total armature circuit resistance equals:

$$0.35 + 0.2 = 0.55 \Omega$$

$$I_a R_a = 18.85 \times 0.55 = 10.36 \text{ V}$$

$$\text{terminal voltage} = 230 - 10.36 = 219.64 \text{ V}$$

The overall efficiency of a generator can be found by adding all the losses to the output power and comparing this with the input power.

Figure 12.33 shows the losses generally found in a machine. While appearing to be a considerable number, several are relatively small, and an efficiency of 80 per cent or better is quite common. For practical purposes figures 12.33 and 1.3 are identical and the formulae in section 1.4.2 are still applicable.

that is, power input = power output + losses

$$\text{and efficiency} = \left[ \frac{\text{power output}}{\text{power input}} \times 100 \right] \%$$



Figure 12.33 • Losses in a generator



**Example 12.9**

Find the input power and efficiency of a d.c. generator supplying a load of 35 A at an output voltage of 200 V if the losses are as follows: friction 250 W, iron 125 W, field 200 W, armature copper losses 490 W, other stray losses 85 W.

$$\begin{aligned}\text{total losses} &= 250 + 125 + 200 + 490 + 85 \\ &= 1150 \text{ W}\end{aligned}$$

$$\begin{aligned}\text{efficiency } (\eta) &= \frac{\text{power output}}{\text{power output} + \text{losses}} \\ &= \frac{200 \times 35}{(200 \times 35) + 1150} \times 100 \% \\ &= 86 \%\end{aligned}$$

**12.5.3 Motor efficiency**

The theoretical approach to the efficiency of a motor is similar to the generator method. Armature resistance is considered as one component and the winding as another. This is shown in Figure 12.34, and the similarity to Figure 12.31 can easily be seen.

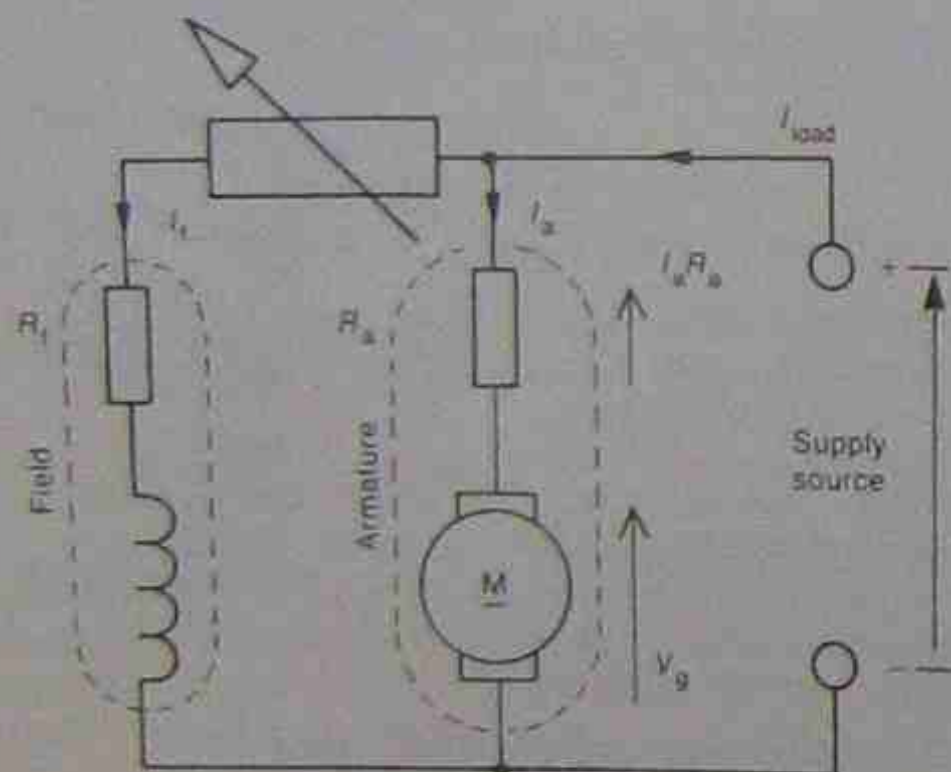


Figure 12.34 • Equivalent circuit of a shunt motor

The back e.m.f. generated is subject to the armature voltage drop ( $I_a R_a$ ) and is equal to the difference between the supply voltage and the  $I_a R_a$  voltage drop:

that is, for a motor,  $V = V_g + I_a R_a$

The only variation from the formula for generator is the polarity of the armature voltage drop ( $I_a R_a$ ). This is illustrated in Figure 12.34 with arrows indicating the directions of the applied and generated voltages, and showing them opposing each other. The result is that the effective voltage causing a current to flow through the armature circuit is smaller than the applied voltage.

$$\text{that is, } I_a = \frac{V - V_g}{R_a}$$

The overall efficiency of a motor can be found in a similar manner to that of a generator; that is, power input = power output + losses.

Whereas the input to a generator was mechanical power and the output electrical power, the input to a motor is electrical power and the output mechanical power. The losses are shown in Figure 12.35.

**Example 12.10**

A shunt-connected motor draws 25 A on a 200 V d.c. supply. If the motor field has a current of 1 A flowing through it and the armature resistance is 0.25  $\Omega$ , find the value of the back e.m.f.

$$\begin{aligned}I_a &= 25 - 1 = 24 \text{ A} \\ V &= V_g + I_a R_a \\ \text{that is, } V_g &= V - I_a R_a \\ &= 200 - (24 \times 0.25) \\ &= 200 - 6 \\ &= 194 \text{ V}\end{aligned}$$

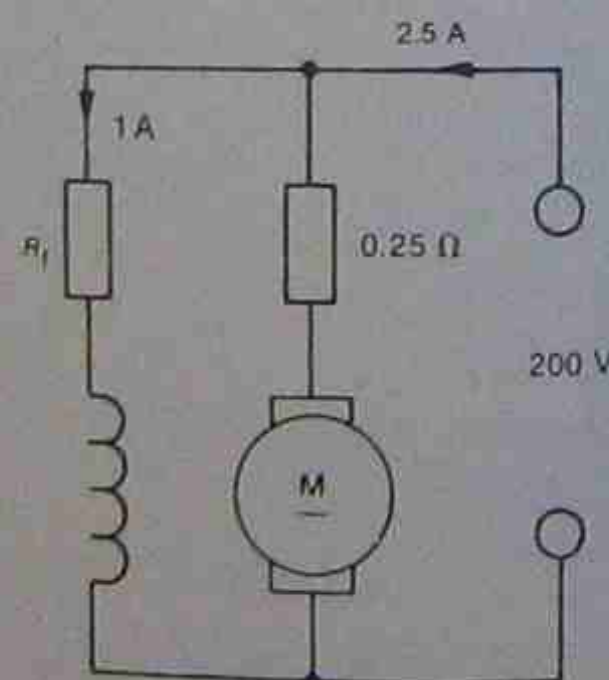


Figure 12.36 • Circuit for example 12.10

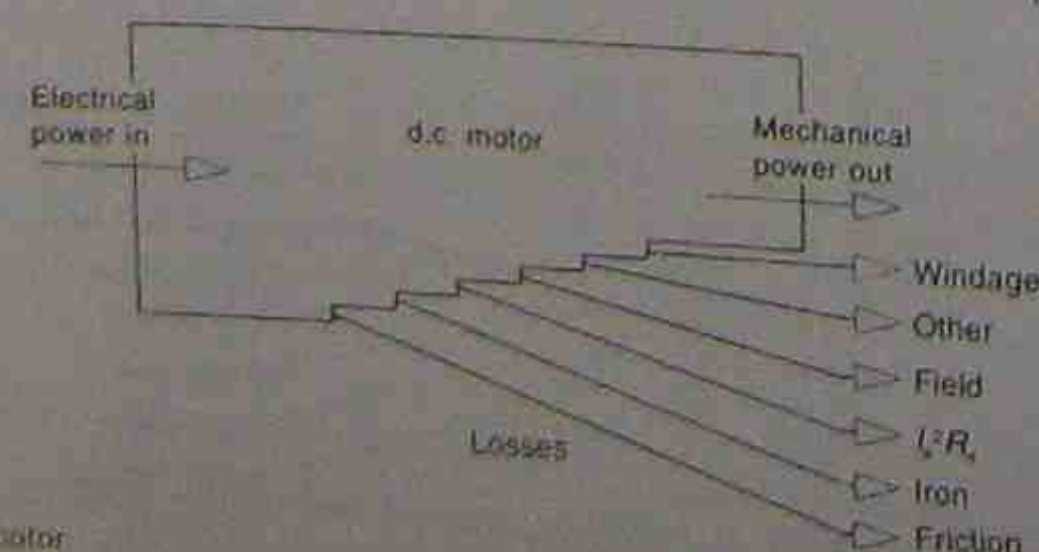


Figure 12.35 • Losses in a motor

**Example 12.11**

A 250 V d.c. compound motor connected long shunt takes a current of 82 A at full load. Calculate the output power and the efficiency, given the following details:

$$\begin{aligned}\text{armature resistance} &= 0.09 \Omega \\ \text{shunt field resistance} &= 125 \Omega \\ \text{series field resistance} &= 0.04 \Omega \\ \text{all other losses total} &= 750 \text{ W}\end{aligned}$$

The circuit is shown in Figure 12.37:

$$\begin{aligned}I_f &= \frac{V}{R_f} = \frac{250}{125} = 2 \text{ A} \\ \text{armature current} &= 82 - 2 = 80 \text{ A} \\ \text{input power} &= VI = 82 \times 250 = 20\,500 \text{ W} \\ \text{losses: shunt field } (I^2 R) &= 2^2 \times 125 = 500 \text{ W} \\ \text{series field } (I^2 R) &= 80^2 \times 0.04 = 256 \text{ W} \\ \text{armature } (I^2 R) &= 80^2 \times 0.09 = 576 \text{ W} \\ \text{other} &= 750 \text{ W} \\ \text{total losses} &= 2082 \text{ W} \\ \text{output power} &= 20\,500 - 2082 = 18\,418 \text{ W} \\ \text{efficiency } \eta &= \frac{18\,418}{20\,500} \times 100 = 89.8 \%\end{aligned}$$

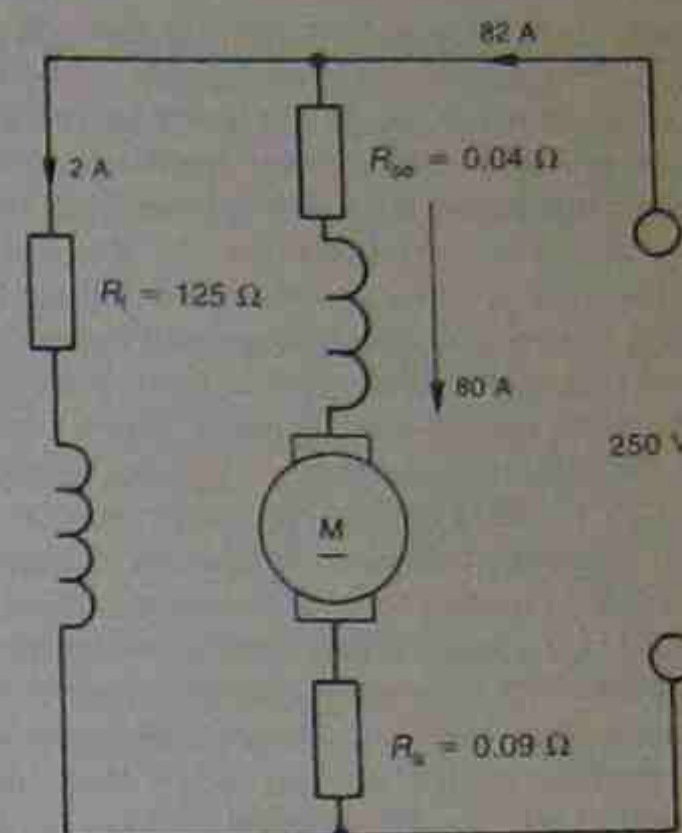


Figure 12.37 • Circuit for example 12.11

Speed of rotation has some influence because speed reduces the time available for the commutator switching action, apart from any irregularities in the commutator surface.

**12.6.1 Coil current reversal**

Figure 12.38(a) shows a coil X about to undergo commutation. The generator is shown as supplying a current of  $2I_a$  amperes to the load, half of which is passing through this coil. A short period of time later the brush has made contact with segments 2 and 3 (Fig. 12.38(b)) and coil X has been short-circuited. The load current stops flowing through coil X and flows direct to the load through the adjacent coils and segments 2 and 3. When the coil is short-circuited and the current stops flowing, the magnetic field about the coil collapses, producing a self-induced voltage in the coil. Because of the short-circuit, this self-induced voltage sets up a comparatively high circulating current through the coil and the short-circuit.

After another short time interval the brush breaks its contact with segment 2 and also open-circuits the high circulating current in coil X, causing sparking between the brush and the commutator. At the same instant the

**12.6 COMMUTATION**

It has been shown that the voltage induced in a single coil of a d.c. generator is alternating. A commutator is necessary to ensure that the current in the external circuit always flows in the one direction. During the brief interval when a coil is short-circuited by a brush, the current in the coil must reverse its direction. This reversal of armature current in a coil as it passes beneath the brush is called *commutation*. In a wider sense the same word is used in referring to sparking between the brush and the commutator, whatever the reason for this might be. In either of these cases good commutation occurs when there is little or no sparking between the commutator and the brushes.

The two major factors opposing ideal commutation are:

1. self-inductance of the coil undergoing the current reversal process (section 12.6.1)
2. armature reaction (section 12.7).

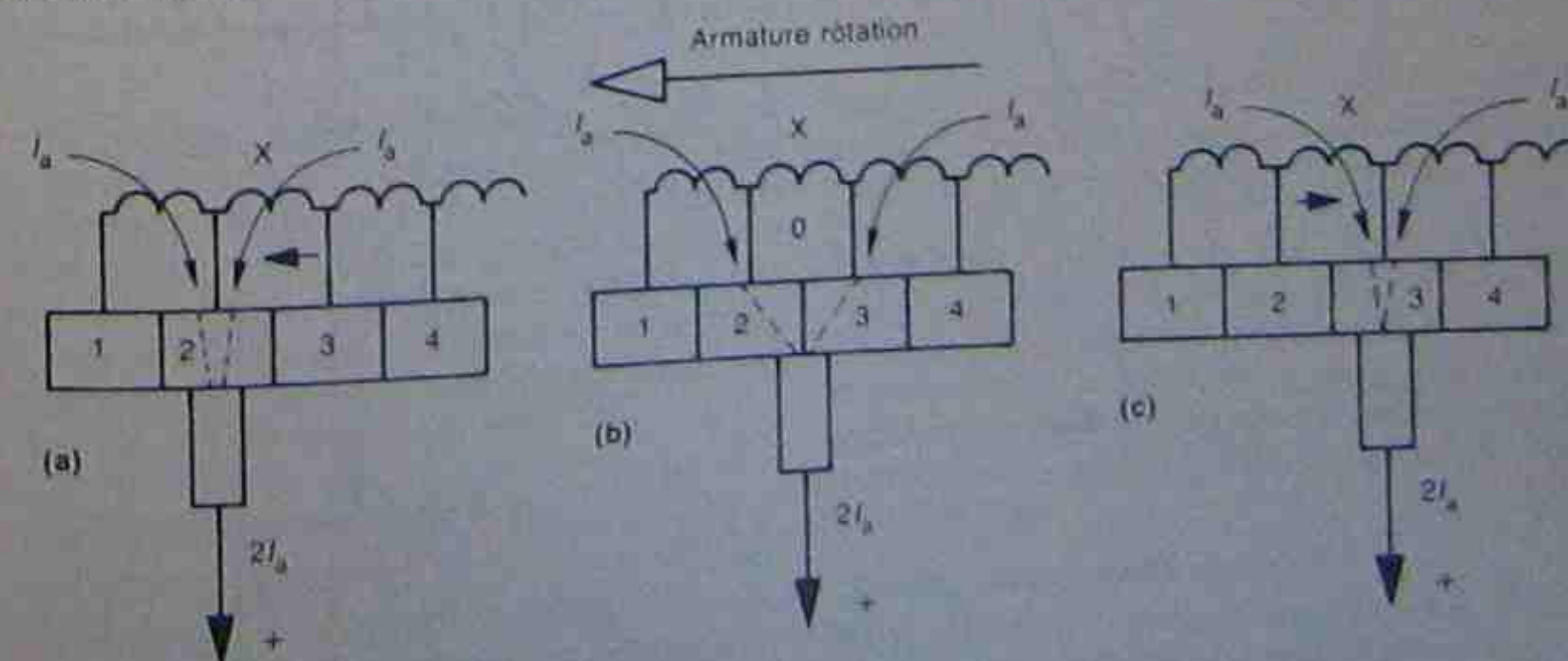


Figure 12.38 • Reversal of current flow during commutation



current to the load commences flowing through coil X again, but in the opposite direction (see Fig. 12.38(c)).

There are two direct methods to correct for this type of commutation problem. One is to use brushes that have a higher contact resistance; the other is to shift the brushes slightly out of their correct position in the magnetic neutral plane. This produces a generated voltage in the coil, opposing the self-induced voltage and partially cancelling it. The first method leads to the production of heat at the commutator surface and increased losses, while the second has the disadvantage of needing to be adjusted each time there is a load change. Because armature reaction leads to somewhat similar commutation problems, there are self-adjusting methods, discussed in section 12.7, that are suitable for counteracting both self-induction and armature reaction. As a general principle, commutation problems due to armature inductance are countered by altering the position of the brushes, while those due to armature reaction are countered by the addition of special windings.

## 12.7 ARMATURE REACTION

An armature, when rotating in its magnetic field, can have varying values of armature current flowing in its coils. The current can vary from zero at no load to the designed maximum, the actual value depending on the size of the machine. The armature, in carrying the current, sets up a magnetic field of its own. This field combines with the main field, producing a resultant field, and the process is called armature reaction. The resultant field is twisted in either the direction of rotation, or against it, depending on whether the machine is being used as a generator or a motor.

### 12.7.1 Main field distortion

A generator that has no load on the armature has no current flowing in the armature conductors and conse-

quently there is only one magnetic field—that intentionally provided for the armature conductors to cut and generate a voltage. This is shown in Figure 12.39(a), with the magnetic field leaving the north pole, crossing the air gap to the armature core, and eventually entering the south pole on the opposite side.

Its direction is parallel to the centre line or axis through the field pole. At 90°E to the polar axis is the geometric neutral position. Under no-load conditions the geometric neutral plane is also accepted as the magnetic neutral position or plane. Unlike the geometric neutral, which is in a fixed position, the magnetic neutral position can be varied by a shift in the magnetic field. The relative positions of the planes are shown in Figure 12.39(b).

Figure 12.39(b) also shows the field created in a two-pole armature by load current flowing through the armature conductors. This field is set up at right angles to that of the main field and parallel to the magnetic neutral position. Taking each field in isolation, the relative directions are in either the horizontal or the vertical planes.

In a practical case the armature field can only be present if the main field is also present, so there are actually at least two magnetic fields present when the machine is on load. The end result is a combination of these fields into one resultant field, whose direction will depend on the relative strengths of each field.

The shift in the main field axis is illustrated in Figure 12.40(a). It has shifted ahead in the direction of rotation, and has become more concentrated in the trailing pole tips, with a consequent weakening of the field strength in the leading pole tips. Figure 12.40(b) shows the vector approach for determining the direction of the resultant field, while Figure 12.40(c) shows the angle of shift for the magnetic neutral plane.

Figure 12.41 shows the shift in the main field for a d.c. motor. For the same direction of rotation, the shift is in the opposite direction to that of the generator (i.e. against the rotation of the armature).

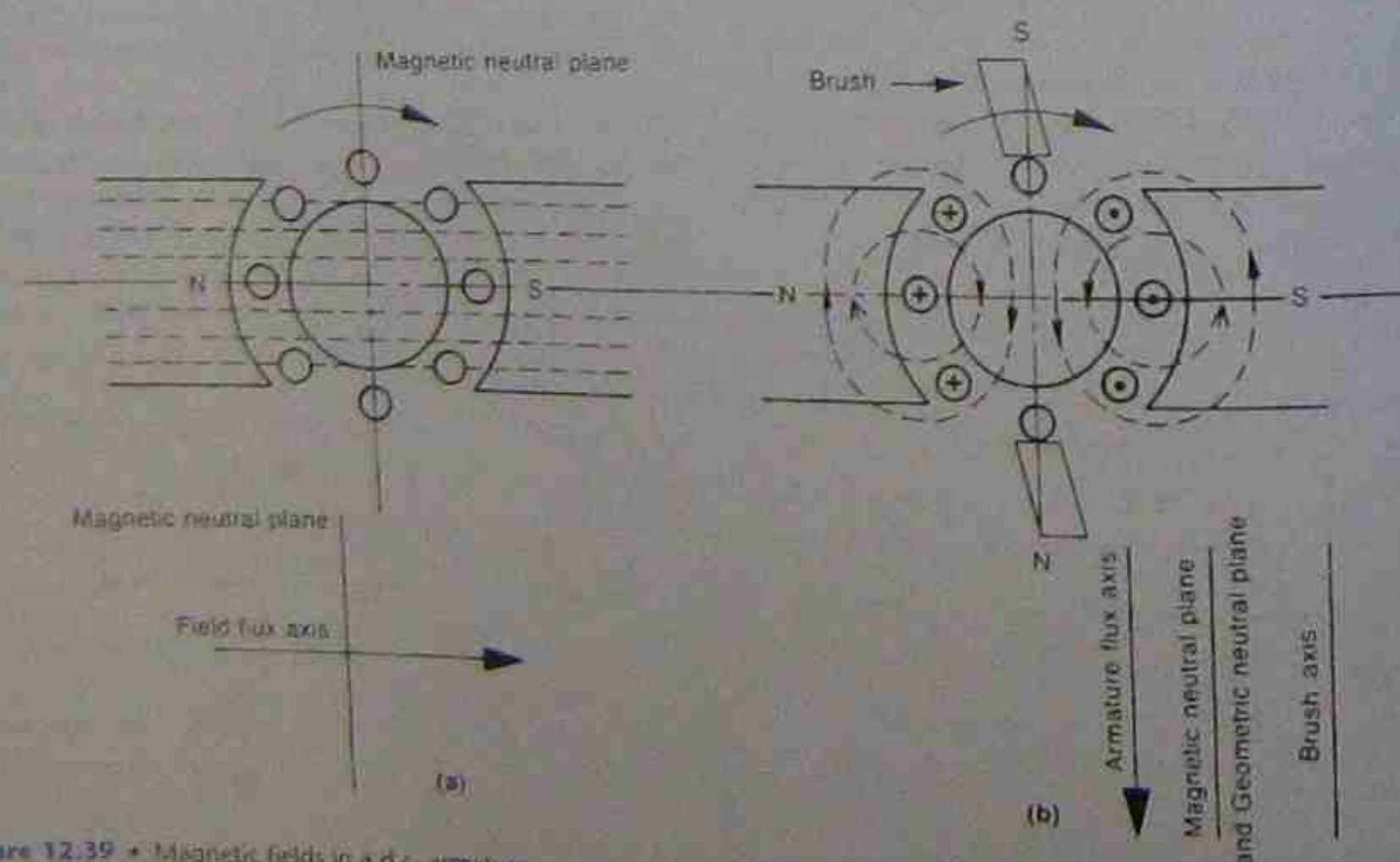


Figure 12.39 • Magnetic fields in a d.c. armature

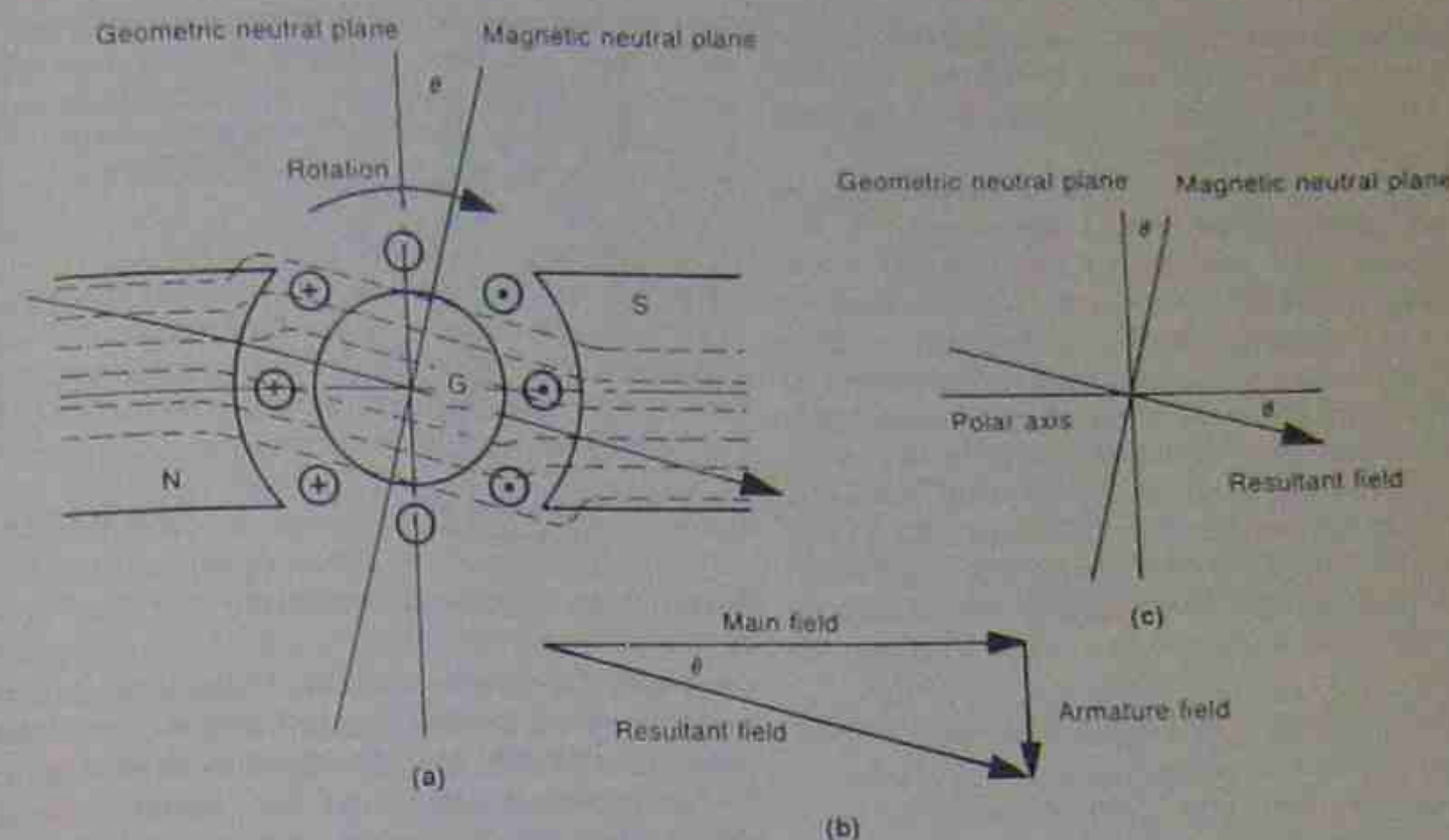


Figure 12.40 • Field shift in a d.c. generator

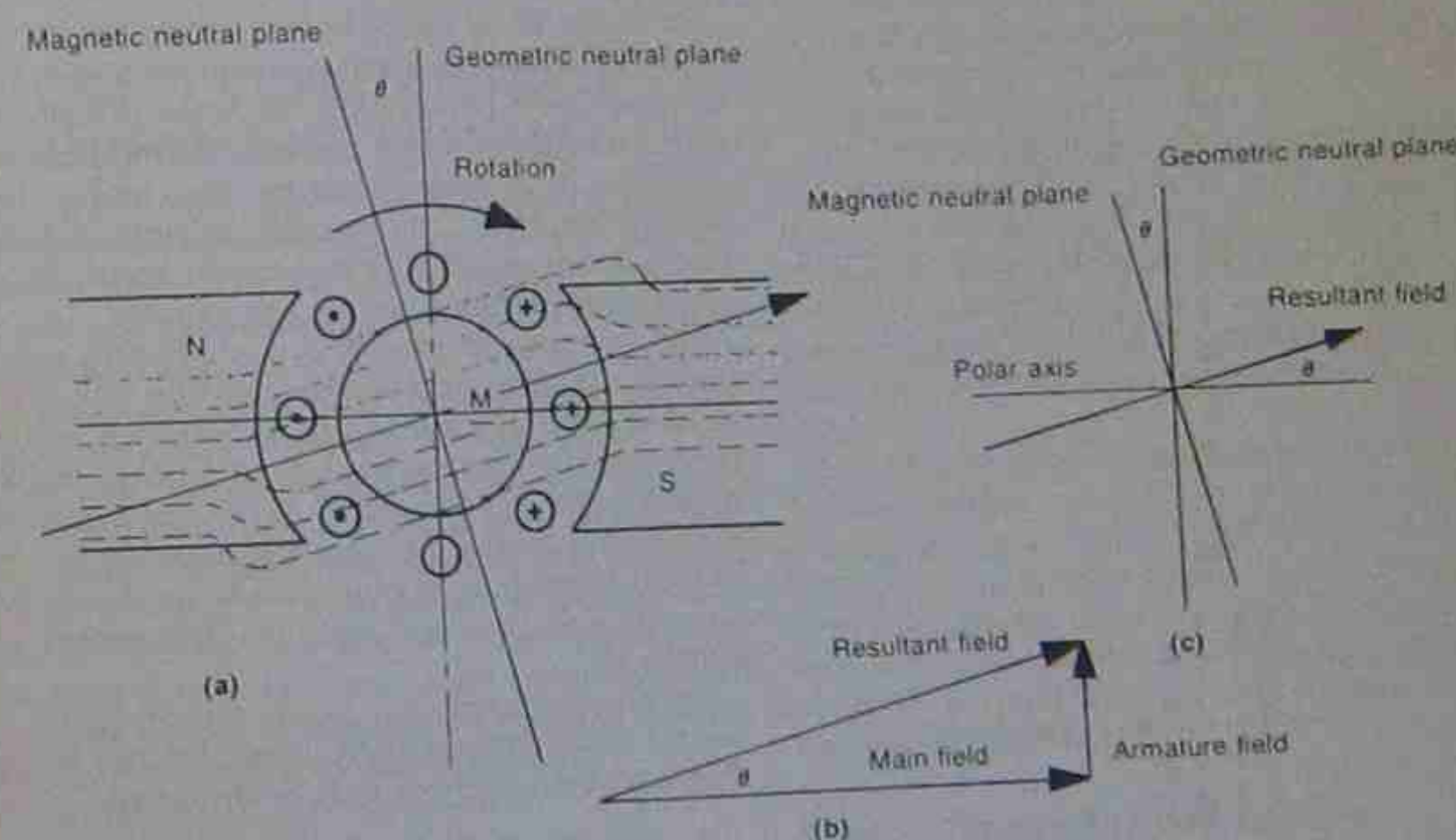


Figure 12.41 • Field shift in a d.c. motor

Whether the machine is being operated as a generator or a motor, the result of loading the machine is to shift the field flux to a new position. The amount of shift depends on the size of the load applied. The brushes are placed nominally in the magnetic neutral plane at full load to obtain the best commutation performance. While they are not in the magnetic neutral plane at light loads, less current is flowing and the sparking is less.

### 12.7.2 Correction methods for armature reaction

For reliability, a d.c. machine must have good commutation to extend the working life of both the commutator and the brushes. Since the effect of placing a load on the

armature is to cause sparking at the commutator, so reducing intervals between overhauls, steps have to be taken to counteract armature reaction.

#### Brush shift

The simplest method is to shift the brushes into the new position of the magnetic neutral plane each time the load is altered. It is a satisfactory method for loads that are relatively constant or change only occasionally. Where loads are subject to sudden or rapid change, the method is unsatisfactory.

#### Compensating windings

When correctly designed and installed, compensating windings are probably the most successful in minimising



armature reaction—and the most expensive. They consist of coils let into the face of the main field poles, as shown in Figure 12.42(a), producing a magnetic field opposing the field set up by the armature.

The coils are connected in series with the armature so that the load current in the coils is always equal to the armature current. The number of turns has to equal the number of effective armature turns to ensure that the ampere-turns in the compensating windings are equal to the ampere-turns in the armature. They are connected so that the field produced by the compensating windings is always equal and opposite to that produced by the armature current. Effectively, then, there are three magnetic fields produced in the machine, two of which cancel each other out, leaving the third (the main field) unaffected. The magnetic neutral plane remains undisturbed and the brushes can remain in it, irrespective of any load applied to the machine.

Figure 12.42(b) shows the vectors for the magnetic forces.

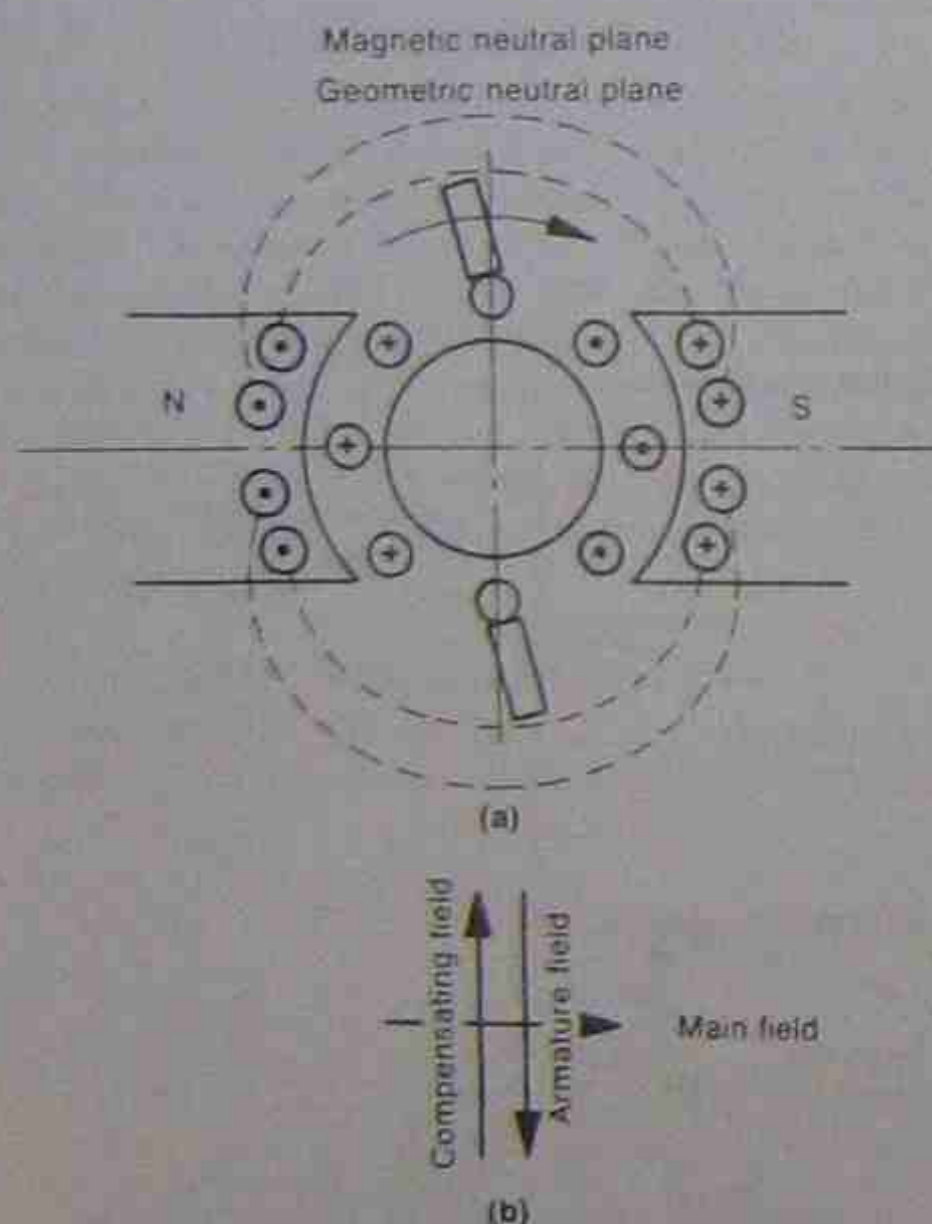


Figure 12.42 • Compensating windings

### Interpoles

Probably the most common method for compensating for armature reaction is the use of interpoles. These are smaller than the main field poles and are connected in series with the armature. The number of turns, multiplied by the armature current, gives the necessary ampere-turns to produce a magnetic field equal in strength to that of the armature cross-field. The poles are shown in Figure 12.43(a), and illustrate the difference in size of the two types.

To cancel out the effects of armature reaction and achieve good commutation, the field produced by the interpoles must be equal and opposite to the armature

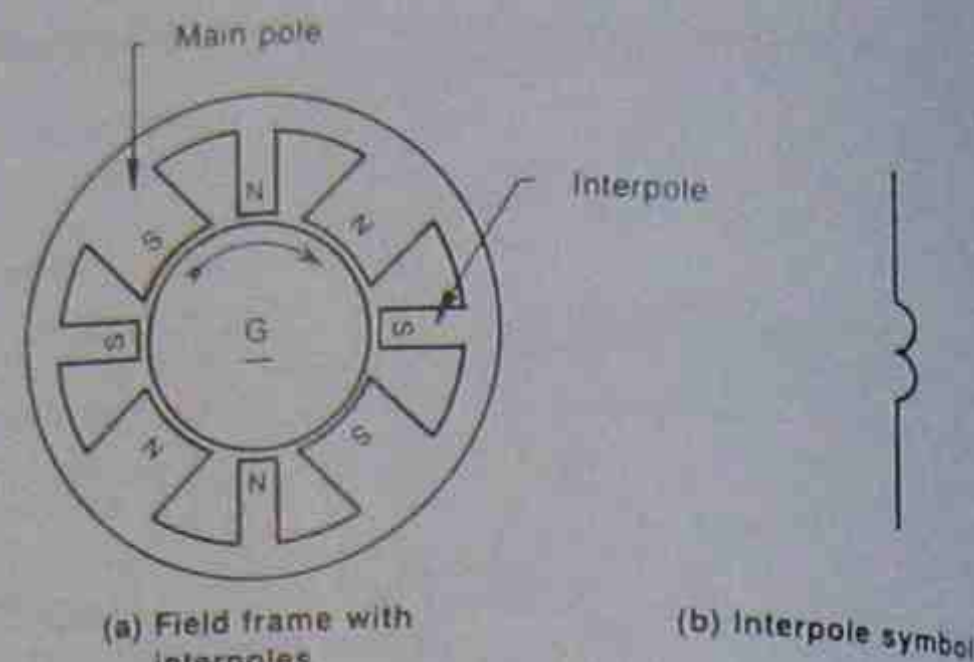


Figure 12.43 • Location of interpoles

cross-field. To achieve this, the interpoles must be connected to give a specific polarity with respect to the main poles on either side. Once the correct connection has been found, that one connection will remain constant no matter what use the machine is put to, motor or generator. The connection is also unaffected by the direction of rotation.

In Figure 12.44 the polarities shown for the interpoles apply for a generator being driven clockwise. Given that the main field poles retain the same polarity as shown, with a d.c. power supply applied, the machine would run clockwise as a motor. Because the current flow would become reversed, the interpole polarity would also be reversed, but would still be correctly connected for good commutation while operating as a motor.

The interpole method is a very effective one for minimising the effects of armature reaction. While it is not as good as the use of compensating windings, it is much the cheaper of the two methods. Most modern machines can operate between no load and 25 per cent overload without appreciable sparking at the commutator. For any given output an interpole machine can be made smaller than a non-interpole machine because of increased operating efficiencies.

For rapidly fluctuating loads, compensating windings are far more effective than interpoles, but in very large machines both methods may be employed.

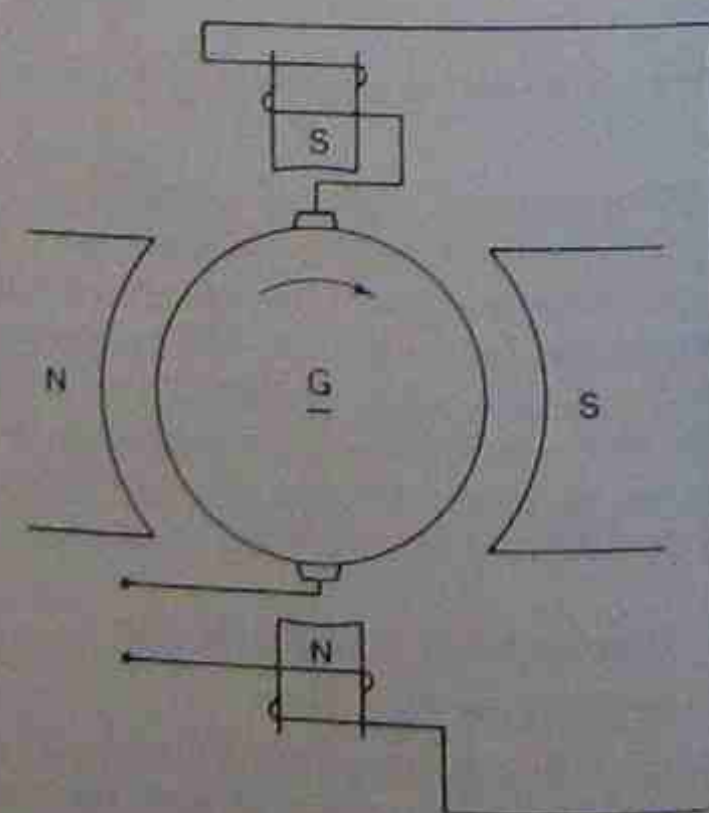


Figure 12.44 • Interpole connections

While the primary purpose of interpoles is to cancel out the effects of armature reaction, causing a field to be created at right angles to the main field, an increase in the number of turns can correct for commutation problems caused by self-inductance and current reversal in the armature coil.

Shifting the brushes out of the magnetic neutral plane in an attempt to neutralise this latter effect causes the armature cross-field to be split into two components. One of these components causes direct demagnetising of the main field and this can be corrected with additional excitation.

If an interpole has more turns than is necessary to correct solely for armature reaction, the pole is then able to produce a field that can induce a voltage in the armature to oppose that voltage produced by self-inductance during current reversal. At the same time, more excitation is created, leading to a higher operating efficiency. That is, an interpole can be designed to correct for both self-inductance and current reversal in the armature coil, as well as to counter the field produced by the armature cross-field.

It should be noted that the two terms *interpoles* (intermediate poles) and *commutating poles* are synonymous and can be freely interchanged. In this chapter the word *interpoles* has been used.

## 12.8 DIRECT CURRENT SERVO- AND STEPPER MOTORS

Direct current servo-mechanisms offer many advantages over alternating current versions. A servo-motor is usually defined as any motor that can be remotely controlled. It is essential that the response characteristics be identical in both directions of rotation. It must be able to stop, start, change direction, run at constant speed, or be able to take up accurately any desired position throughout 360°.

To do this there are two distinct types of servo-motors. One is a rotating machine free to rotate in either direction, the other a semi-stationary machine that only rotates to take up a particular position or angle when required by the system. In this there are also two distinct types. One moves in discrete steps of fixed angles (stepper motors) while the other is able to take up any angle of rotation and maintain that angle (positional control).

The advantages of d.c. servo-motors are:

1. higher output torque for the same-size motor
2. control with smaller input currents
3. easy to stabilise
4. high efficiency.

### 12.8.1 Servo-motors and mechanisms

Servo-mechanisms are a class of control systems with the following properties:

1. They are error actuated.
2. They have some means of power amplification.
3. They contain moving parts.
4. They are automatic in operation.
5. They generate an error signal that can be fed back to the input of the system.

Figure 12.45 shows just such a system. It has a potentiometer that can be manually adjusted to any desired

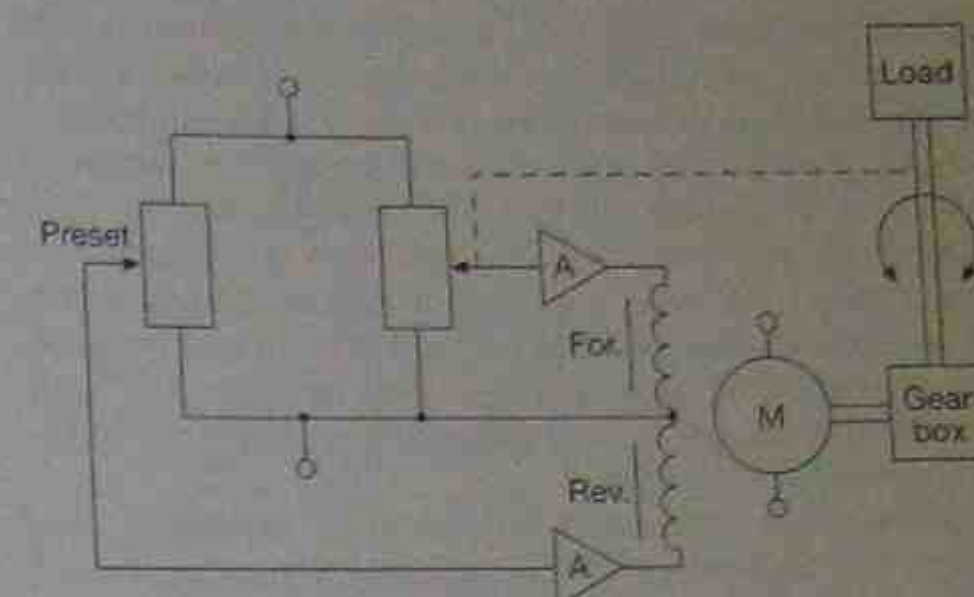


Figure 12.45 • Basic servo-mechanism arrangement using a bridge circuit for obtaining an error voltage

position. A second potentiometer is connected in parallel with the first so that the supply voltage is across the outer terminals of the potentiometers. The two adjustable taps then form the other half of a bridge circuit. Any voltage difference between them is an indication of the difference in their positions. If both taps are in identical positions then the voltage between them is zero. The two potentiometers can be some distance apart connected only by their common power source and a third conductor supplying the error signal.

The error is amplified and connected to the field of a d.c. motor connected in turn to a gearbox and the load. By manually shifting the position of the first potentiometer, a voltage difference is created between the two taps. This, on being amplified, supplies field current to the motor, which then drives the load and the position of its potentiometer until the two voltages are again equal and the motor stops.

This type of servo-mechanism belongs to a class called 'remote position control'. Applications include profile cutting, mill motor drives, tape control of machine tools, remote control of ships' engine governors, and they once were the basis for gun control on warships. The modern version is a.c. operated and generally provides a more accurate position control over longer distances with quicker response times.

### 12.8.2 Printed circuit motors

The separately-excited d.c. motor can compete on equal terms with hydraulic systems because of the development of printed circuit motors and advances in solid-state electronics. These advances have enabled armatures to be made without iron cores, so leading to the production of armatures with low inductance and near-perfect commutation. Torque was increased markedly with the introduction of new and improved permanent magnets.

Iron-cored armatures operating in conjunction with permanent magnets have set positions in which the iron core is attracted to the magnetic poles. These spots can be felt by rotating the armature with the fingers. Removal of the iron core removes these spots, which have to be overcome by extra torque, only obtainable from the motor.

Without the iron core, the armature windings can often be more evenly distributed around the armature, so giving a more even torque. Having no iron in the armature al-



means elimination of iron losses in the armature. The mass of the armature is also reduced, making it more responsive to load alterations, owing to a lower inertia.

For higher-quality printed circuit motors, the technique discussed in section 12.4.2 has been superseded by a process for stamping out the armature and conductors. The method provides many more active armature conductors, a number that can be further increased by stacking several stampings on top of one another. The basic principles of assembly and construction of the rest of the motor remain the same.

The method of construction is more expensive, and motor bearings have to be accurately machined and placed for precision assembly of the motor, in order to maintain a high operating efficiency.

Printed circuit motors of this construction can maintain a fairly constant speed. They are also able to operate at very low speeds, down to as low as one revolution per minute.

### 12.8.3 Stepper motors

A stepper motor can rotate in either direction, subject to a voltage of either polarity being applied to the windings. The category name *stepper motor* is usually applied to a motor that can rotate in fixed increments of rotation, say, in steps of 30° or 45°.

This is illustrated in Figure 12.46, which shows an elementary motor with three windings surrounding a two-pole permanent magnet able to rotate freely in either direction within the winding. Table 12.1 shows the connections and polarities available to produce steps or increments of 30° intervals, giving a total of twelve different positions. The stepper motor can skip over increments and take up a position according to any given electrical connections.

The following assumptions are made with regard to windings A, B, and C in Figure 12.46:

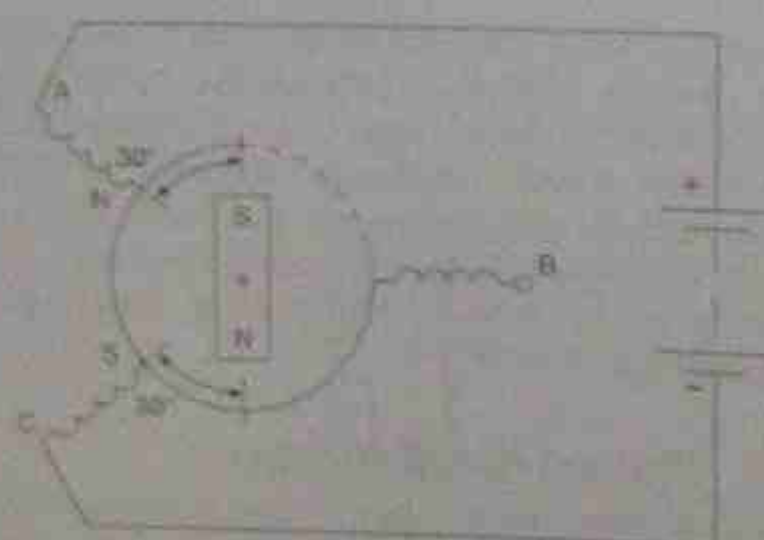


Figure 12.46 • Incremental control with a stepper motor (see Table 12.1, Position 7)

1. When the outside end of each winding is connected to the positive terminal of the supply, the inner end of the winding exhibits the characteristics of a north pole.
2. When connected to the negative terminal, the end adjacent to the magnet behaves as a south pole.
3. The inside ends of the windings are joined at a common junction.
4. The three windings are identical and distributed evenly around the circumference of the stator.

For the connections shown in Figure 12.46, the outer end of the A winding is connected to the positive terminal and

Table 12.1 • Polarities for the stepper motor in Figure 12.46

Position	A	B	C
1	-	0	+
2	-	-	+
3	0	-	+
4	+	-	+
5	+	-	0
6	+	0	-
7	+	+	-
8	+	+	0
9	0	+	-
10	-	+	-
11	-	+	0
12	-	+	+

gives a north polarity at the end closest to the permanent magnet. This attracts the south pole end of the magnet. The B winding is not connected. The C winding, being connected to the negative terminal of the supply, behaves as a south pole and attracts the north pole end of the magnet.

Because the A and C windings are at an angle of 120° to each other, the magnet cannot align itself with either winding and settles into a position 30° out of alignment with both windings. Both windings are exerting equal and opposite forces on the magnet, trying to get the magnet to rotate in opposite directions. As a result the magnet stabilises in the position shown.

When moving the magnet from one position to another at fast stepping rates, inertia often causes the magnet to overshoot the correct position. It then has to rotate backwards in the opposite direction hunting for the correct position. Without some damping effect this can cause undesired oscillation about any desired point. Some inherent natural damping is created by the generation of eddy currents, but additional damping might be required.

The uses of stepper motors include machine tool systems such as numerically controlled machines, remote positioning systems such as space applications, and computer peripherals such as printers and business machines.

Table 12.1 shows the polarities required for each connection of the windings to rotate the magnet to any of the twelve possible positions. A zero indicates no connection.

### 12.8.4 Positional control

If the circuit of Figure 12.46 is modified to that shown in Figure 12.47, the incremental steps can now be adjusted and true positional control achieved. The circuit modifications include a potentiometer connected across the supply and connected to winding B. Since the two windings A and C are effectively connected in series, the common junction of the three windings is at a potential half that of the supply. The centre tap of the potentiometer can be adjusted to this value and no current will flow in winding B. By adjusting the centre tap in either direction, a positive or negative voltage can be applied to this winding. The magnetic field produced will cause the magnet to move in one direction or the other as required.

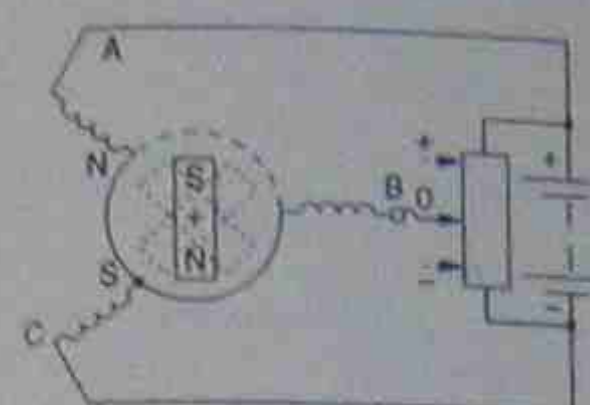


Figure 12.47 • Principle of positional control. Note Position 1 is for the rotating magnet's north pole to point to the top of the page

The uses of positional control are remote indication of anemometers to record wind speed and direction, slave machines following set patterns as in machine control, and remote control of engine governors.

### 12.8.5 Brushless d.c. motors

A computer disk drive assembly has two motors. One is a stepper motor as described in section 12.8.3. Its function is to shift the reading head across the magnetic tracks on the disk. It usually has more poles than described in the above section.

The second motor in the assembly is a hybrid type of brushless d.c. motor. Its function is to drive the disk at a constant speed of (usually) 300 revolutions per minute. Because the motor has no commutator, the coils have to be electronically switched. See Figure 12.48 for a simplified circuit. The stationary central section of the assembly often comprises two sets of iron-cored poles in series, although some models use three sets of windings.

Speed and position sensing is provided by a central printed circuit giving control over the transistor-switched circuitry supplying power to the main windings. Motor rotation and speed is monitored by sensors, often comprising small light-emitting diodes that may be switched on and off rapidly. Other methods are the use of magnetic sensors or Hall-effect semi-conductors. For each method used, the primary function is to control the speed of the motor as accurately as possible and to sense the position of the rotating magnet in relation to the fixed wound poles for correct switching or commutation of the coils.

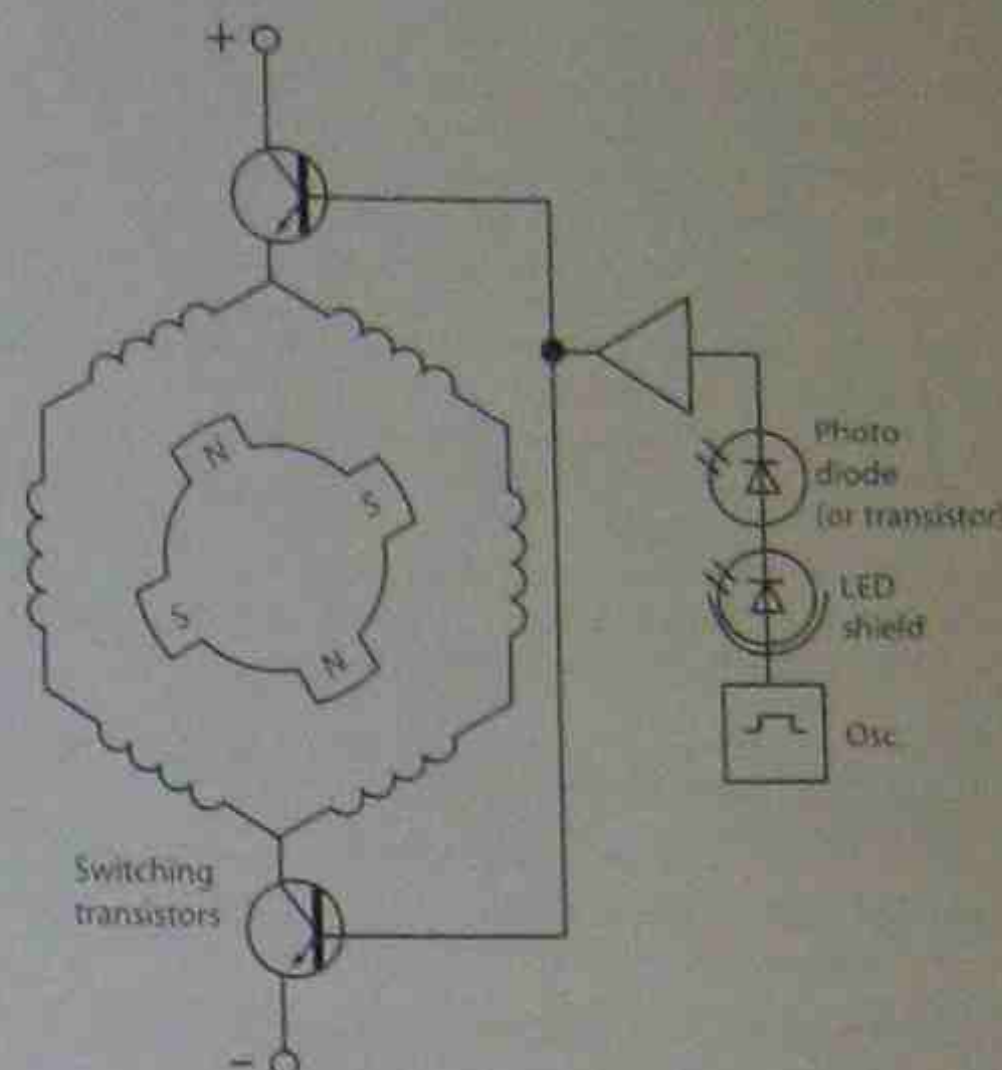


Figure 12.48 • Basic principles of the operation of a brushless d.c. motor

Minor variations in speed are further compensated for by a phase-locked loop system incorporated in the drive circuitry for the stepping motor.

The outer rotating part is a circular ring of magnets that may match the number of fixed wound poles. The outer ring because of its greater weight also tends to act as a flywheel to stabilise against minor speed fluctuations. It is not recommended that dismantling one of these motors be undertaken lightly. For disk drives in particular, the positions of both motors in the drive have to be synchronised with each other and with the standards for disk drives. A lack of synchronism with the standards usually means the drive is useless for any other machine and disks cannot be interchanged with those used in other machines.

## SUMMARY

- Physical construction for both motors and generators is identical for all practical purposes.
- Internal connections for the various types of field connections are also identical.
- Alternating current is actually generated in the armature but is changed to direct current by the commutator.
- To improve the performance the single loop is replaced by a number of coils with many turns and distributed around the windings.
- Generators are d.c. machines driven to provide a voltage.
- Motors are d.c. machines supplied with d.c. to provide a torque.
- There are several types of connections for direct current machines. They are classified by their field excitation and connections as follows:

1. separately-excited—permanent magnet or wound fields
  2. shunt-excited
  3. series-excited
  4. compound-excited—cumulative or differentially compounded.
- Losses in a d.c. machine may be mechanical or electrical and are reflected in its efficiency.
  - A d.c. motor has low armature resistance and might need additional series resistance on being started, to limit the high inrush of a starting current.
  - The extra resistance that might consist of an electrical conductor or a conducting liquid is progressively switched out of circuit. As the motor speeds up it generates a back e.m.f. that opposes the applied e.m.f., so reducing the input current.



- Starters for electric motors may be manual or automatic.
- Commutation is the action of switching or exchanging armature conductors as the armature rotates. It can produce sparking at the brushes as the current flow is continually reversed through the armature conductors.
- Armature reaction is the result of the armature current creating a magnetic field of its own as a load is placed on the machine. It can distort the main field and effectively shift its neutral position.
- The effects of commutation and armature reaction can be reduced by the introduction of either compensating windings in the pole faces, or interpoles (commutating poles) placed between the main poles.
- Servo-motors are specialised versions of d.c. motors and may be rotating or positional in action.
- Stepper motors are d.c. motors that take up a rotational position, depending on which connections to the windings are used and the polarity of the supply. Stepper motors can be connected to give intermediate positional control.
- Computer disk-drive motors are almost always d.c. motors without commutators. The switching is done outside the motor, electronically, and the speed is controlled by external means, which may be magnetic, electronic, or by light pulses.
- The type of motor for the previous point is called a brushless d.c. motor. Its rotating component is a permanent magnet shaped like a ring. It is external to the field windings and acts as a flywheel. The field windings are internal and stationary.

## EXERCISES

- 12.1 Explain the function of the commutator in a d.c. machine.
- 12.2 Describe how an alternating voltage waveform is generated in a d.c. armature and how d.c. is provided to the external circuit.
- 12.3 List the physical differences in construction between series and shunt field windings.
- 12.4 Explain how armature reaction affects the performance of a d.c. machine and list the methods used to minimise armature reaction.
- 12.5 Discuss the difficulties of commutation in a d.c. generator.
- 12.6 Sketch the voltage/current characteristic of an over-compounded d.c. generator and explain its shape.
- 12.7 Why is a shunt generator the only type of connection that can be run on a short-circuit?
- 12.8 Sketch the speed/torque characteristic for a series motor and explain its shape.
- 12.9 A shunt generator is not building up an output voltage. Describe steps to be taken to determine the cause of the problem.

## SELF-TESTING PROBLEMS

- 12.10 What is the current rating of a 25 kW 400 V d.c. generator at full load? What current will flow at half-load?
- 12.11 The terminal voltage of a 15 kW shunt-connected generator is 600 V on full load. If the field resistance is 200  $\Omega$  and the armature resistance is 0.1  $\Omega$ , what is the actual value of generated voltage?
- 12.12 The following values of resistance were measured when checking a d.c. shunt motor:
- armature resistance 2  $\Omega$
  - shunt field resistance 100  $\Omega$ .
- Calculate:
- (a) the initial current flow when connected direct-on-line to 200 V
  - (b) the current flow when the motor runs at full load, if a back e.m.f. of 180 V is generated.
- 12.13 A 20 kW 600 V motor has an armature resistance of 0.07  $\Omega$ , a series field resistance of 0.05  $\Omega$  and an interpole resistance of 0.08  $\Omega$ .
- (a) What is the total resistance of the armature circuit?
  - (b) Find the value of additional resistance required in the starter to limit the starting current to 400 per cent of normal full-load current. (Neglect shunt field current.)
- 12.14 A motor rated at 750 W consumes 940 W of power. Calculate the efficiency of the motor.
- 12.15 The back e.m.f. of a 200 V shunt motor is 180 V when drawing an armature current of 40 A. Find the armature resistance.
- 12.16 A six-pole lap-wound shunt motor draws 360 A on load. If the flux per pole is 0.06 Wb and the armature has 864 turns, calculate the torque of the motor if the losses are equivalent to 4 per cent of the total torque. (Ignore the shunt field current.)
- 12.17 A 220 V d.c. motor draws 40 A on load and runs at 800 r/min. Find the torque developed by the motor if its losses are 0.5 kW.

- 12.18 A long-shunt generator supplies a current of 100 A at 220 V. If the resistance of the shunt field is 50  $\Omega$ , the series field is 0.025  $\Omega$ , the armature is 0.05  $\Omega$ , the total brush drop is 2 V, and the iron and friction losses amount to 1 kW, find:

- (a) the generated e.m.f.
- (b) the power losses due to resistance
- (c) the power output of the driving motor
- (d) the generator efficiency.

- 12.19 A generator of 15 kW output has the following losses:

- excitation 450 W
- windage and friction 725 W
- coupling losses 565 W.

Calculate the generator efficiency on full load.

- 12.20 A 25 kW shunt-connected generator operates with a terminal voltage of 250 V. The armature has an effective resistance of 0.18  $\Omega$  and the shunt field has a resistance of 110  $\Omega$ . Calculate:

- (a) the full load current
- (b) the field current
- (c) the total armature current
- (d) the induced armature voltage
- (e) the voltage regulation.

- 12.21 A d.c. generator produces an induced voltage of 620 V. If the terminal voltage is 600 V when the armature current is 100 A, calculate the armature resistance.

- 12.22 The output voltage of a separately-excited generator delivers 15 kW to a 250 V load. Given that the resistance of the armature is 0.2  $\Omega$ , calculate:

- (a) the induced voltage
- (b) the voltage regulation.

- 12.23 Find the efficiency of a 660 V 50 kW generator, given the following details:

- armature resistance, 0.04  $\Omega$
- field resistance, 60  $\Omega$
- stray losses, 2250 W.

- 12.24 Find the power output of a d.c. motor that develops a torque of 98 N m when rotating at 1440 r/min.

- 12.25 What power is produced by a d.c. motor rotating at 1700 r/min if it produces 27 N m of torque?

- 12.26 The combined losses in a d.c. motor total 727 W. What torque must be produced just to overcome the losses at a speed of 730 r/min?

- 12.27 A 240 V d.c. motor has an armature resistance of 0.3  $\Omega$ .

- (a) What is the armature starting current?
- (b) Calculate the extra resistance required to limit the starting current to three times a full load current of 20 A.

- 12.28 A 200 V d.c. motor draws a current of 15 A. Given an armature resistance of 0.4  $\Omega$ , calculate the value of the generated back e.m.f.

- 12.29 Calculate the generated back e.m.f. of a 600 V d.c. motor if it has an armature resistance of 0.37  $\Omega$  and is drawing an armature current of 12 A.



# Chapter 13

## Electric motor control and protection

### 13.1 INTRODUCTION

The full advantages of an electric motor drive can be achieved only when there is compatibility between the following three major components:

- the drive motor
- the driven machine
- the control equipment.

There are many forms of motor starting methods and at least as many forms of speed control. A motor might have to meet starting current requirements, as well as running a machine up to operating speed without imposing severe mechanical shocks on the system. This is particularly applicable to larger motors.

### 13.2 REQUIREMENTS OF MOTOR CONTROL EQUIPMENT

The prime function of a motor starter is to connect the motor and its coupled machine to the supply mains without disturbance to other machines and users. It must do this with due consideration to the mechanical inertia of the driven machine, its permitted acceleration, and to the allowable time taken to get it up to operating speed. It must do this repeatedly and with minimal maintenance problems. Under these conditions the selection of a motor starter must take into due consideration the following factors:

1. The limitation of starting current to values acceptable to the supply authorities, thus causing minimal disturbance to other local users as regards line voltages.
2. Control of starting and accelerating torque from the viewpoint of mechanical shocks to the machine system and the motor driving shaft.
3. Protection of the motor against overloads and overheating.
4. Isolation of the motor in the event of a fault.
5. Provision for interlocking the motor's operation with that of other motors and machines.
6. Motor reversal.
7. Speed control.
8. Motor braking.

### 13.3 LIMITATION OF STARTING CURRENTS

AS/NZS 3000 states that supply authorities might require the starting currents of motors to be contained within certain limits, depending on the power of the motor. Supply authorities in turn have varying requirements and enquiries might have to be made to them in specific cases.

Since there are so many different circumstances and so many types of installations, it is almost impossible for a supply authority to lay down firm rules and hope to cover all cases for all installations.

It is worth noting that any information booklets issued by a supply authority use the phrase: 'Notwithstanding any of the above the authority's engineer may decide ...'

The regulations governing the starting and running currents drawn by electric motors and the maximum demands of an installation are long and involved. There is the further complication that the local rules might vary from one supply authority to another. The intent of these regulations is to prevent the creation of large transient currents that could cause voltage surges on consumers' mains to the detriment of other users.

### 13.4 THREE-PHASE MOTOR STARTERS

The following methods of motor starting are commonly used:

1. direct-on-line (DOL)
2. star-delta
3. primary resistance
4. autotransformer
5. electronic
6. secondary resistance
7. part-winding starting.

Each method of starting has advantages and disadvantages. With the exception of DOL starting, each method limits the starting current in varying degrees.

The second, third, fourth and fifth methods reduce the voltage applied to the phase windings. Electronic starting often has provision for controlling motor current independently of the motor voltage.

The effect of reducing motor voltage is to reduce the starting torque of the motor. In approximate terms, and ignoring minor losses, the torque developed by an induction motor is directly proportional to both the stator current and the air gap flux:

$$\text{that is, } T \propto I_{\text{stator}} \times \Phi_{\text{stator}}$$

Because  $\Phi \propto I_{\text{stator}}$  the expression can be written as:

$$T \propto I_{\text{stator}} \times I_{\text{stator}} \text{ or } T \propto I_s^2$$

$$\text{but } I_s = \frac{V_{\text{stator}}}{Z_{\text{stator}}}$$

Since the stator impedance is constant,  $I_s \propto V_s$ .

Substituting this in the expression  $T \propto I_s^2$ ,

$$T \propto V^2$$

In practical terms this means that if the voltage is reduced by some percentage then the torque is reduced to the square of that percentage, for example:

- 100 per cent line voltage means 100 per cent starting torque
- 80 per cent line voltage means  $(80\%)^2$  or 64 per cent starting torque.

If a reduction in voltage causes a motor to reduce its starting torque below that of its load requirements, then that motor is unable to start. The usual result is that excessive current is drawn and the motor overheats.

The problems associated with starting and accelerating squirrel-cage motors are mainly due to the relationship



#### 1.4.4.2. *Stimuli della scrittura*



metallic positive temperature coefficient resistor while the second method uses a liquid negative temperature coefficient element. It is this fact that enables the liquid-type primary resistance starter to have an advantage over the metallic resistor type.

### Applications

Because of the lowered starting torque, the primary resistance method of starting induction motors is limited to loads where initial starting torque requirements are comparatively low, that is, loads where the running torque only comes into play at full speed. Such uses as fans, blowers, and water pumps are the usual applications.

### 13.4.4 Autotransformer starting

Autotransformer starters generally use two autotransformers connected in an open-delta configuration to provide reduced-voltage starting. Taps are usually provided on the transformers to enable selection of the required starting torque. The principle is illustrated in Figure 13.3.

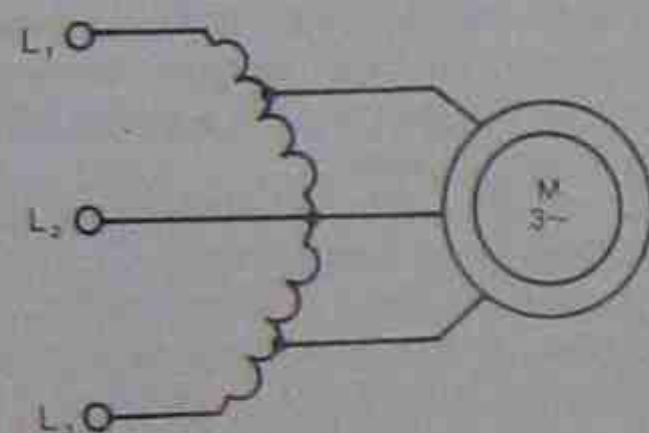


Figure 13.3 • Starting connections for an induction motor using an open-delta autotransformer

Points to note are:

1. The motor starting current varies directly with the applied motor voltage.
2. The line current varies as the square of the motor voltage.
3. The torque varies as the square of the motor voltage.

The second point means that the starting current with an autotransformer starter is less than that obtained with a primary resistance starter. This is its major advantage—for the same starting current the motor torque is increased.

The third point means that if a 50 per cent voltage tapping is chosen, then the resultant starting torque is 25 per cent of full-load torque. A tapping has to be selected that will be the minimum that enables the motor to start against its load.

The major characteristics of this type of starter are:

1. low line current
2. low line power
3. low power factor
4. open-circuit transition periods
5. acceleration is in a series of steps. It is not continuous or smooth.

The provision of tappings on the transformers makes it possible for a choice of voltages (and hence currents) to be available for starting purposes.

The use of a transformer makes it possible to reduce the line input current at a greater rate than that at which the torque is reduced. Transformers are discussed in greater detail in Chapter 14, but briefly:

$$\text{input voltage} \times \text{input current} = \text{output voltage} \times \text{output current}$$

that is,  $V_1 \times I_1 = V_2 \times I_2$  (neglecting all losses)

During starting, a reduced voltage  $V_2$  is applied to the motor, thereby reducing the starting current  $I_2$ . Because of transformer action, however, the input current  $I_1$  is reduced still further. It can be illustrated by the following example.

#### Example 13.1

A 415 V, three-phase induction motor draws 160 A when connected DOL. If an autotransformer starter, with the motor connected to the 70 per cent tapping, is used to start the motor, determine:

- (a) the voltage applied to the motor during starting
- (b) the starting current taken by the motor
- (c) the starting current drawn from the supply.

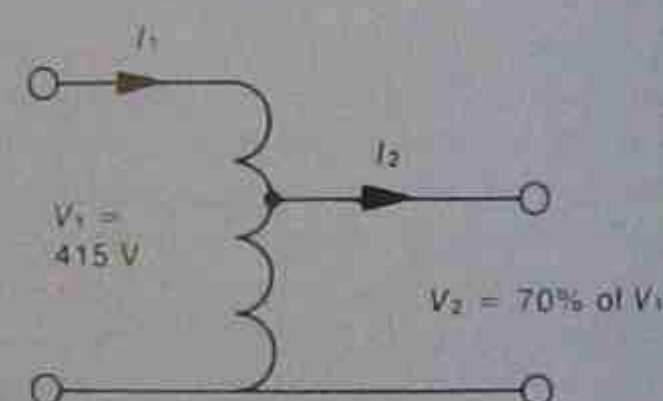


Figure 13.4 • Circuit diagram for example 13.1

- (a) For 70 per cent tapping:

$$\begin{aligned} \text{motor voltage} &= 70\% \text{ of input voltage} \\ &= 70\% \text{ of } 415 \text{ V} \\ &= 0.7 \times 415 \\ &= 290.5 \text{ V} \end{aligned}$$

- (b) For 70 per cent tapping:

$$\begin{aligned} \text{motor current} &= 70\% \text{ of DOL starting current} \\ &= 70\% \text{ of } 160 \text{ A} \\ &= 0.7 \times 160 \\ &= 112 \text{ A} \end{aligned}$$

- (c)  $V_1 I_1 = V_2 I_2$

$$\begin{aligned} I_1 &= \frac{V_2 I_2}{V_1} = \frac{290.5 \times 112}{415} \\ &= 78.4 \text{ A} \end{aligned}$$

Note that the motor voltage has been reduced by 70 per cent to 290.5 V. Because  $T \propto V^2$ , the torque will have been reduced to  $(0.7)^2 = 0.49$  of the DOL value. While the motor current has been reduced to 70 per cent of the DOL value, the line input current has been reduced to 0.49 or 49 per cent of the DOL value. For a primary resistance starter to give the same

reduction in line input current, the voltage applied to the motor would need to be reduced to 49 per cent of the DOL value further reducing the starting torque. For comparison purposes, see Table 13.1.

Table 13.1 • Comparisons between primary resistance and autotransformer starting

Starter type	Voltage applied to motor	Starting current	Starting torque
Primary resistance	49%	49%	$(49\%)^2 = 24\%$
Auto-transformer	70%	49%	$(70\%)^2 = 49\%$

A more expensive form of autotransformer starter designed to alleviate the problem of open-circuit transients is the Korndorfer starter. It uses three autotransformers and an extra contactor. Its use is limited to applications where there is no reasonable alternative. It maintains a continuous torque during the transition periods of reconnection. (See Fig. 13.5.)

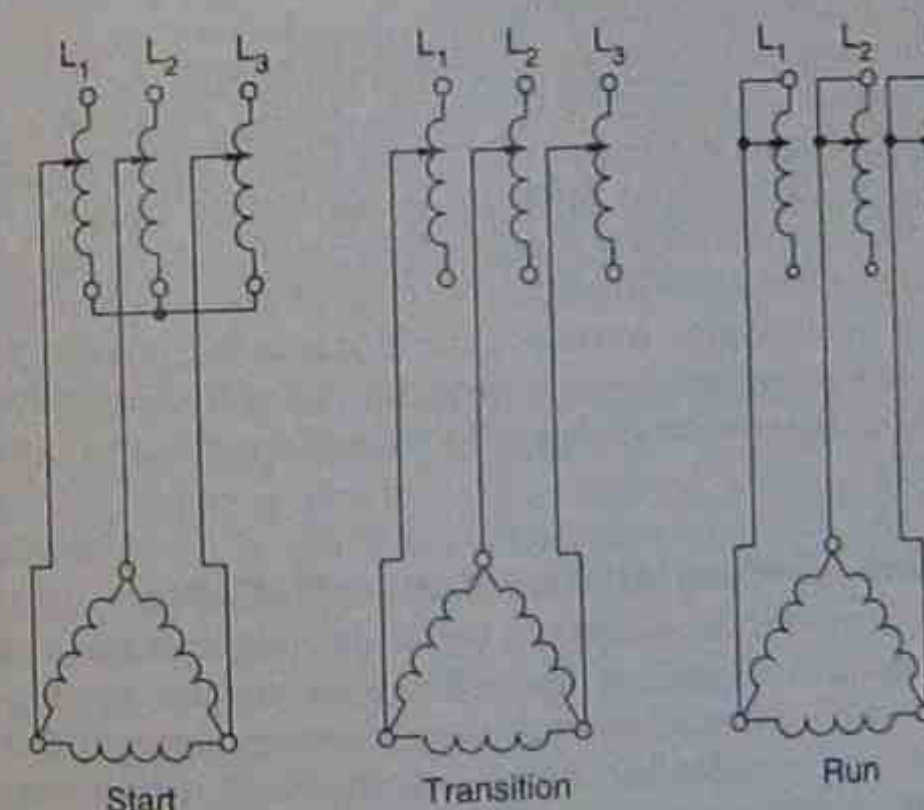


Figure 13.5 • Autotransformer Korndorfer switching

### Applications

Owing to the high cost of autotransformer starters, their use is restricted to heavy loads that have to be started from rest. Such applications are larger-type refrigeration units and air-compressors where the motor might have to start against a substantial head pressure. In some cases electrically operated relief valves might also have to be fitted to release the head pressure to enable the motors to start.

The open-delta connection for transformers is also referred to in Chapter 14, section 14.9.5.

### 13.4.5 Electronically controlled starting

Three-phase induction motors are designed to operate at standard line voltages and frequencies. In Australia, standard line voltages are intended to run on a three-phase line-to-line voltage of (usually) 415 V and a frequency of

50 Hz. This results in the flux density in the air gap of the motor being within defined limits.

Any motor starter designed to reduce the line voltage to a motor also has a tendency to reduce the current flowing to the motor, thereby reducing starting torque.

The autotransformer method of starting goes part way to solving the problem of maintaining starting torque and current at a reduced voltage, but the method also has disadvantages.

It was reasoned that if the motor starting current could be manipulated to satisfy the above requirements, then the voltage and frequency might also be controlled. This line of reasoning gave rise to the electronically controlled starter. It was developed to include such refinements as control over the following:

1. starting currents
2. overload currents
3. over- and under-voltage monitoring
4. motor protection
5. frequency
6. motor isolation
7. sequencing other motors
8. dynamic braking
9. low-speed operation
10. slip compensation (better speed regulation)
11. remote computer control.

In an electronically controlled starter, the controlling circuits are more involved than in a normal relay-operated starter. The general principle is to convert the alternating current supply to direct current, which is then fed through a filter to remove most of the transients. The d.c. is then supplied to an inverter to convert d.c. back to a.c. using a high-speed switching sequence. This is shown in block diagram form in Figure 13.6.

The units can be programmed to monitor and control motor currents during starting and stopping sequences. This gave rise to the term *ramping*. It is simply a term for the control of motor current during the starting and stopping sequences. If a graph is drawn for motor current against time, the curve is a straight line. In those terms the motor can be ramped up or down. See Figure 13.7. These linear curves are highly variable and depend on the information programmed into the unit.

The motor current is controlled to remain within two values by the starter programming.

1. The starter is programmed to ensure that the current never exceeds a predetermined maximum value.
2. The starter is programmed to provide a sufficient minimum value of current to ensure that the motor has sufficient torque to enable starting.

During the starting sequence, as the motor accelerates up to speed and the motor current tends to decrease the starter increases the available current and hence the available torque is kept constant to keep the motor accelerating up to a speed governed by the frequency of the supply.

During the stopping sequence the motor is disconnected from the supply and brought to a rapid and controlled stop by the starter; that is, it is *ramped* down. See section 13.7 for



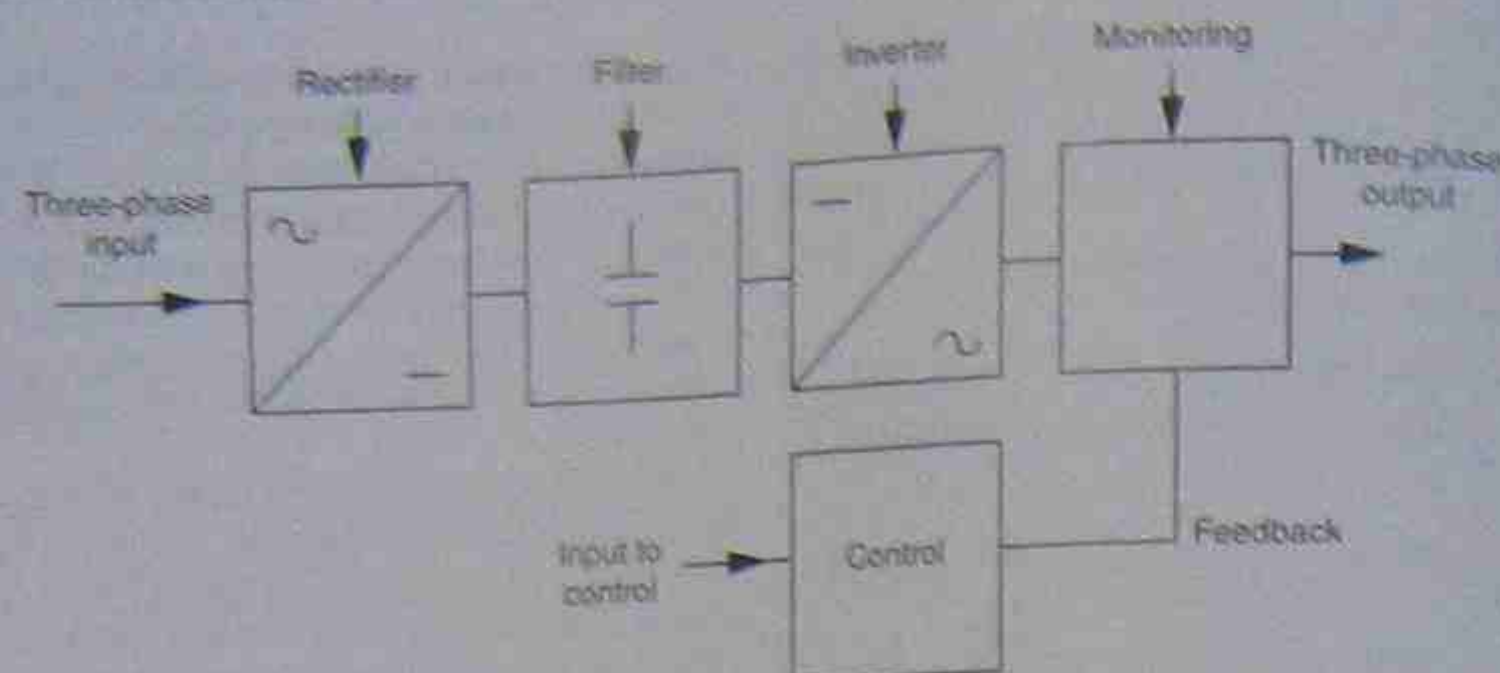


Figure 13.6 • Block diagram for electronic motor control

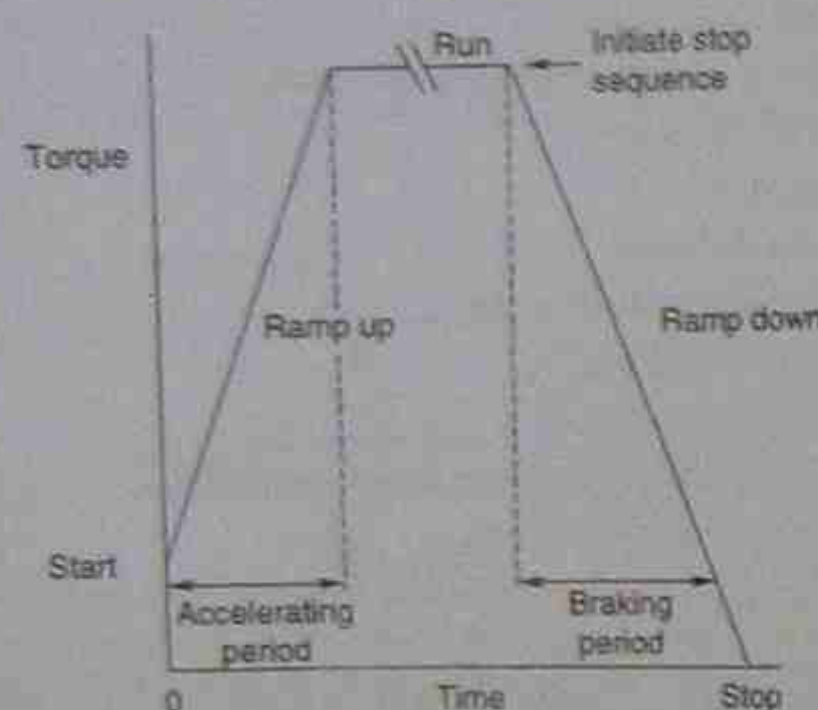


Figure 13.7 • Ramping control

various methods of braking a.c. motors. On a production line, time spent waiting for a machine to coast down to a stop is waste time and is usually not tolerated.

In a starter of this type there is considerable interaction between the applied voltage, the motor current and the starter-generated frequency. Electronically all three are monitored within the starter and the result is a voltage and a frequency supplied to the motor that meet the prevailing motor conditions.

For example, an increased voltage will increase the starting current (say 10%), while an increased frequency will decrease starting current (approx. 5%). These are two opposing effects. Similarly, increasing the applied voltage will increase the starting torque, but an increase in frequency will decrease the starting torque.

The inverter and the d.c. being supplied to the inverter have to be continually monitored. The inverter also has the task of converting d.c. to a.c. It does this by breaking the d.c. up into small units of either polarity. The resulting alternating voltage wave is only vaguely similar to a sine wave and as a result generates harmonics at a ratio many times higher than the fundamental frequency. The current waveform is filtered to some extent by the inductance of the motor windings and is closer to a sinusoidal shape.

#### Applications

This method can be a more expensive way for starting squirrel-cage motors, although initial costs are being

reduced constantly and for smaller-size motor starters the initial cost is now approaching a comparable value. Care should be taken in selecting motors to be used in conjunction with these types of starters. The starters are capable of running squirrel-cage motors at speeds well above and below their designed levels. In circumstances where there is a need to start them regularly or run them at slow speeds for extended periods, consideration must be given to cooling requirements.

The units can be made at ratings in excess of 300 kW. Since costs for the units are high, careful consideration must be given to their possible use. Centrifugal fans are one possible use and their use is more than justified in printing workshops where a printing press must be run up to speed slowly and smoothly because of the rolls of paper being fed through. Another typical use is on production lines where several motors must be controlled and their speeds integrated to ensure smooth and co-ordinated processing.

### 13.4.6 Secondary resistance starting

Despite the predominant use of squirrel-cage motors and their improved starting methods, there are still applications where the wound-rotor motor has advantages that more than compensate for their initial cost. Apart from the high starting torque characteristics, there are still current surge limitations that cannot be met by a squirrel-cage motor combined with any of the above starters.

The speed/torque characteristic of any induction motor depends to a large extent on the relative proportions of resistance and reactance in the rotor circuit. When rotor resistance is equal to the rotor inductive reactance, maximum torque is produced. At the instant of starting, while the rotor is still stationary, the frequency of the currents in the rotor will equal the line frequency. This causes increased inductive reactance in the rotor circuit. With the introduction of external resistance into the wound-rotor circuit, the rotor and impedance values can be adjusted to produce maximum torque at starting and at the same time minimise starting currents. (See Fig. 13.8.)

#### Metallic resistor starters

For a wound-rotor motor, the rotor windings are connected internally in either star or delta configuration and the connecting leads are brought out to slip-rings. With secondary resistance starting it is possible to control motor

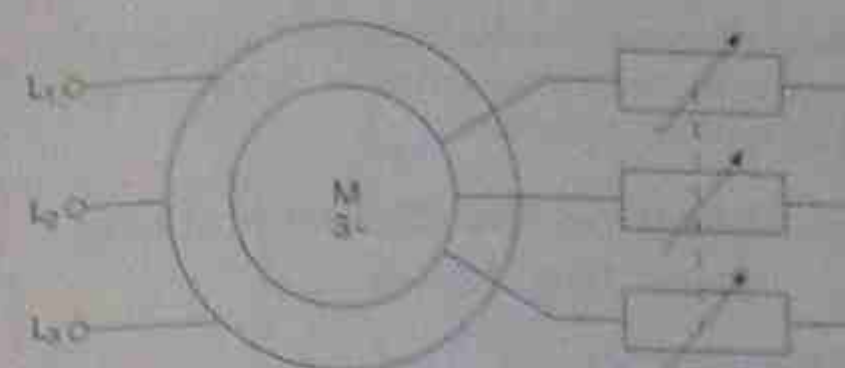


Figure 13.8 • Basic power circuit for secondary resistance motor starting

performance and still satisfy the starting current requirements of a local supply authority.

The speed/torque characteristics of a wound-rotor motor have already been discussed in Chapter 10. It was shown that the incidence of maximum torque could be made to occur at different speeds by adjusting the external resistance placed in the rotor circuit.

While external resistance is connected in the rotor circuit the starting torque is almost proportional to the starting current. It cannot be truly proportional because of the inductive reactance of the rotor windings.

Full line voltage is applied to the stator windings for starting and the external rotor resistance is progressively reduced as the motor accelerates. Equal values of resistance in the circuit of each phase is the norm but on occasion these resistances can be made unequal, resulting in unbalanced rotor currents. As the resistance is reduced either manually or by contactors, the motor accelerates in a series of stages. The greater the number of resistance stages the smoother is the acceleration.

#### Liquid resistor starters

The introduction of liquids in chambers was an attempt to replace metallic resistors and eliminate the steps or stages in the starting process. This method makes starting smooth with a gradual acceleration in speed until the final step where the liquid resistor is finally shorted out. As a consequence, transient effects are minimal.

The passage of current through the liquid causes partial vaporisation of the electrolyte in the chamber. This affects the value of the resistance between electrodes. The greater the current flow the greater is the vaporisation. As the liquid heats up, the resistance between the electrodes is progressively reduced and the motor can accelerate smoothly up to working speed, since the current flow controls the relative proportions of liquid and vapour in each of the liquid chambers. The final stage of the starting sequence occurs when a timed contactor shorts out the liquid chambers.

#### Applications

The wound-rotor motor is ideal for driving machines designed to handle impact loads. Such machines are presses, drop-forging hammers and guillotines. Heavy loads are applied suddenly and reliance is placed on the inertia of the heavy rotating parts to complete the action of the machine. It means also that the drive motors can be of lesser power since, apart from starting the machine, their sole purpose is to make up the losses of the rotating parts.

It follows that heavy rotating parts of machines, including large flywheels, might take considerable energy to get

them rotating at the required speed. For an electric motor to get the machine rotating at this speed, a lengthy starting sequence is usually required.

Overhead cranes use wound-rotor motors on occasion since the resistance in the rotor circuit forms part of a variable speed process. Variable speed characteristics are discussed in section 13.8.

### 13.4.7 Part-winding starting

An alternative method of motor starting is the part-winding method. As with other methods, the primary intention is to reduce starting currents.

The phase windings of the stator are divided into parallel sections, each of the requisite number of poles and each capable of withstanding full line voltage. Parts of the stator winding are energised and, as the motor gains speed, more sections of the stator winding are energised. Normal control and power components are used to provide the necessary switching. Since most of the motor's windings remain connected to the line in a closed transition sequence, current surges are kept to a minimum.

Figure 13.9 shows each phase winding divided into two sections, each section being connected sequentially to the line voltage. Starting torque is down to approximately 45 per cent and the starting current is about 65 per cent of normal DOL starting. Because of current imbalance during the starting sequence, the motors tend to be noisy at this time, which restricts application of the method to

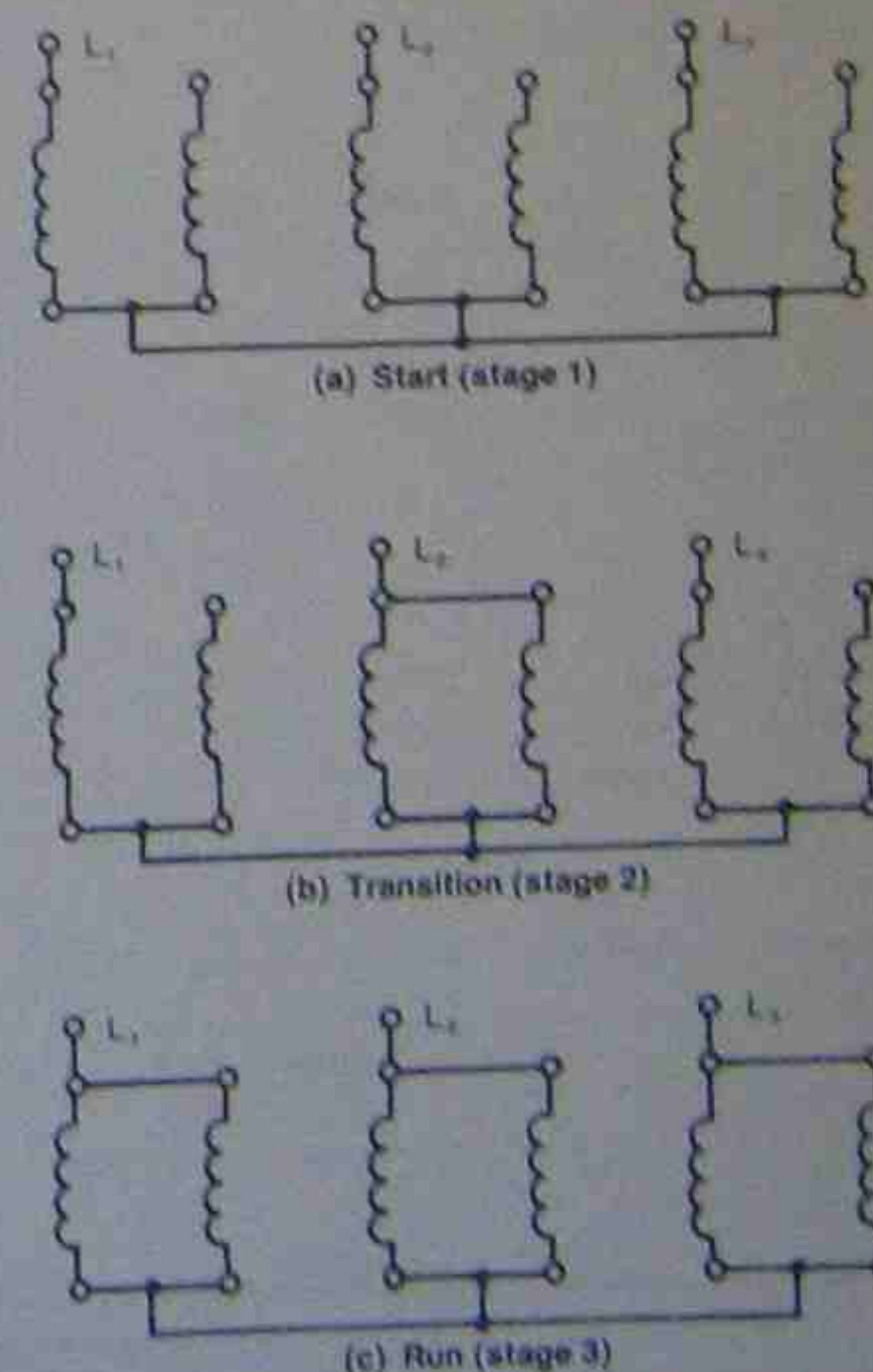


Figure 13.9 • Part-winding starting



cases in which a motor requires occasional starting before running for long periods.

### 13.4.8 Comparison of starting methods

Table 13.2 shows the relative characteristics of starting methods.

## 13.5 ALTERNATING CURRENT MOTOR-STARTER CIRCUITS

The following are push-button motor starter circuits for the more common types of starters. It must be emphasised that the circuits presented are only representative. There are many variations for each type and further variations from one manufacturer to another.

Table 13.2 • Relative characteristics of various starting methods

Starting method	Stator voltage at start	Starting current %I <sub>FL</sub>	Starting torque %T <sub>FL</sub>	No. of starting steps	Current surge during transition stages	Types of loads suited	Example loads	General comments
Direct on line	Line voltage 100%	700%	150%	1	n.a.	Light inertia loads	Centrifugal pumps, lathes	Starting torque greater than full-load torque
Primary resistance	Reduced to 63%	300%	40%	2+	none	Almost no load	Fans, small bores	Poor starting torque ( $T \propto V^2$ )
Star-delta	Reduced to 58%	200%	33%	2	yes	Light loads	Motor-generator units	Starting torque 1/3 full-load torque
Auto-transformer	90%	300%	80%	2	yes	Substantial proportion of full load	Hydraulic pumps, conveyors	Starting torque slightly less than full-load torque
Secondary resistance	Line voltage 100%	100%	100%	2+	no	High inertia loads	Shock loads such as presses, shears	Rotor resistance adjusted to give starting $T_s = FLT$
Electronic controlled starters	100%	See note below	•	•	n.a.	Variable speed drives	Machine planers, to suit printing presses, high speed tools	Starter programmed application

Note: The figures quoted in this table must be considered as only a general guide. Many variables can be encountered, the types and design of motor and motor, applications, loads and starters being only some of the factors.  
 \* Due to the possible number of variations in settings for this type of starter, any figures placed in these positions would be meaningless.

These circuits present the principles of operation only and it is to be expected that other starters encountered might have different circuits.

### 13.5.1 Direct-on-line contactor starter circuit (Fig. 13.10)

#### Circuit operation

1. Pressing the start button completes a circuit from  $L_2$  through the normally closed stop button to coil K1/4, and the overload to  $L_2$ .
2. Main contactor coil K1/4 then closes and applies full line voltage directly to the motor via contactor contacts K1.1, K1.2 and K1.3.
3. Contact K1.4 bridges out the start button contacts so

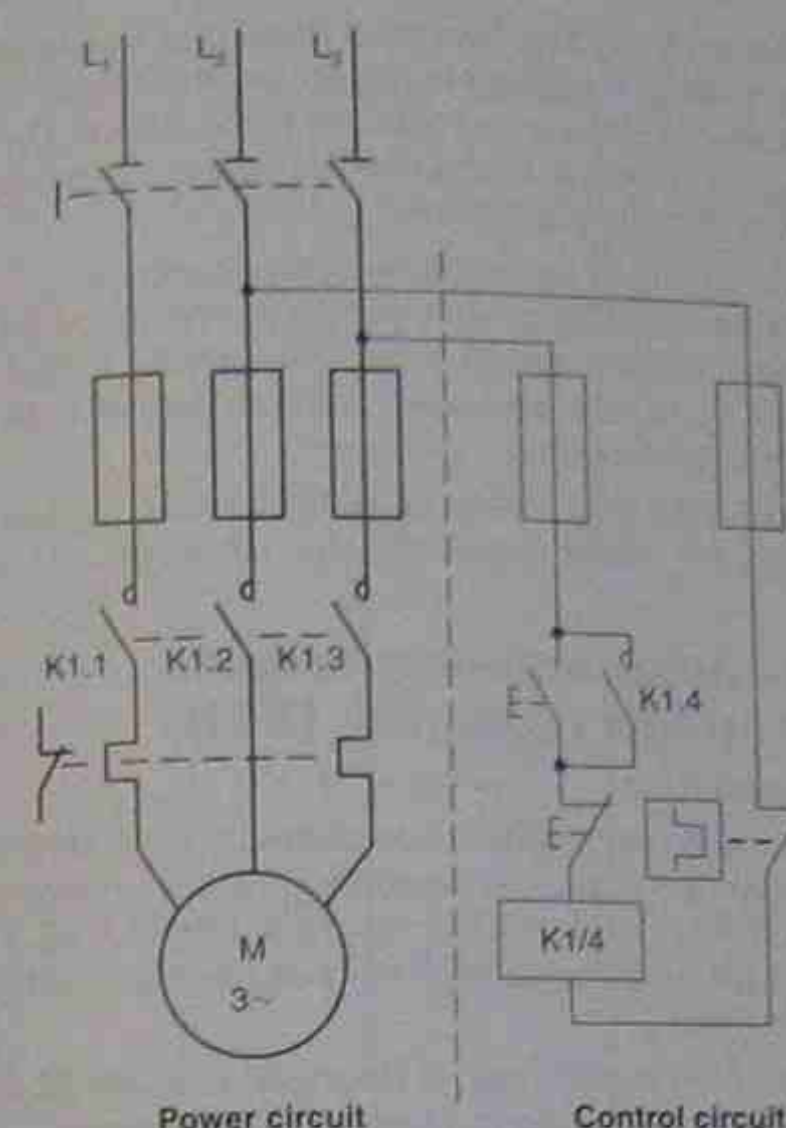


Figure 13.10 • Contactor circuit for DOL starting

that, on the release of the start button, the contactor remains in the operational state—that is, the control circuit is latched in the 'on' position. Pressing the stop button disables the latching circuit and allows the main contactor to revert to the 'off' state.

### 13.5.2 Star-delta contactor starter circuit (Fig. 13.11)

#### Circuit operation

1. Pressing the start button completes a circuit from  $L_2$  through the normally closed stop button and two normally closed contactor contacts (K4.1 and K3.4) to coil K2/5, and the overload contact to  $L_2$ .
2. When K2/5 operates, it causes the 'ends' of the three windings to be joined in star configuration via contacts K2.1, K2.2 and K2.3.
3. Simultaneously, coil K3 is open-circuited by K2.5. This is the delta connecting coil and it must be isolated when the star connection is in operation. Similarly, when the delta connection is in operation, the star connection must be isolated, a method called *electrical interlocking*. As a precaution, the star and delta connecting contactors are often mechanically interlocked, in addition to the electrical interlocking provided by contacts K2.5 and K3.4.

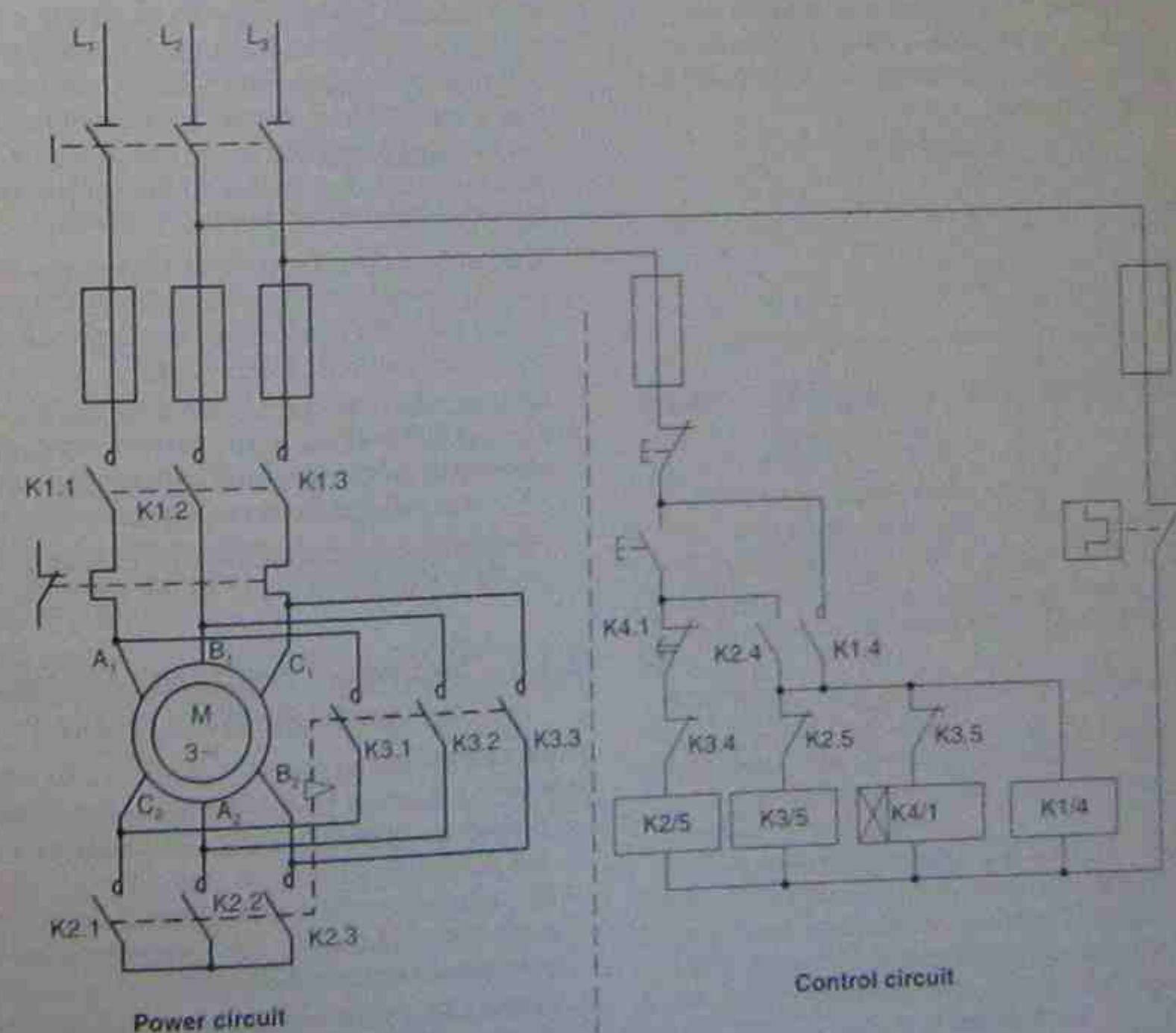


Figure 13.11 • Contactor circuit for star-delta starting



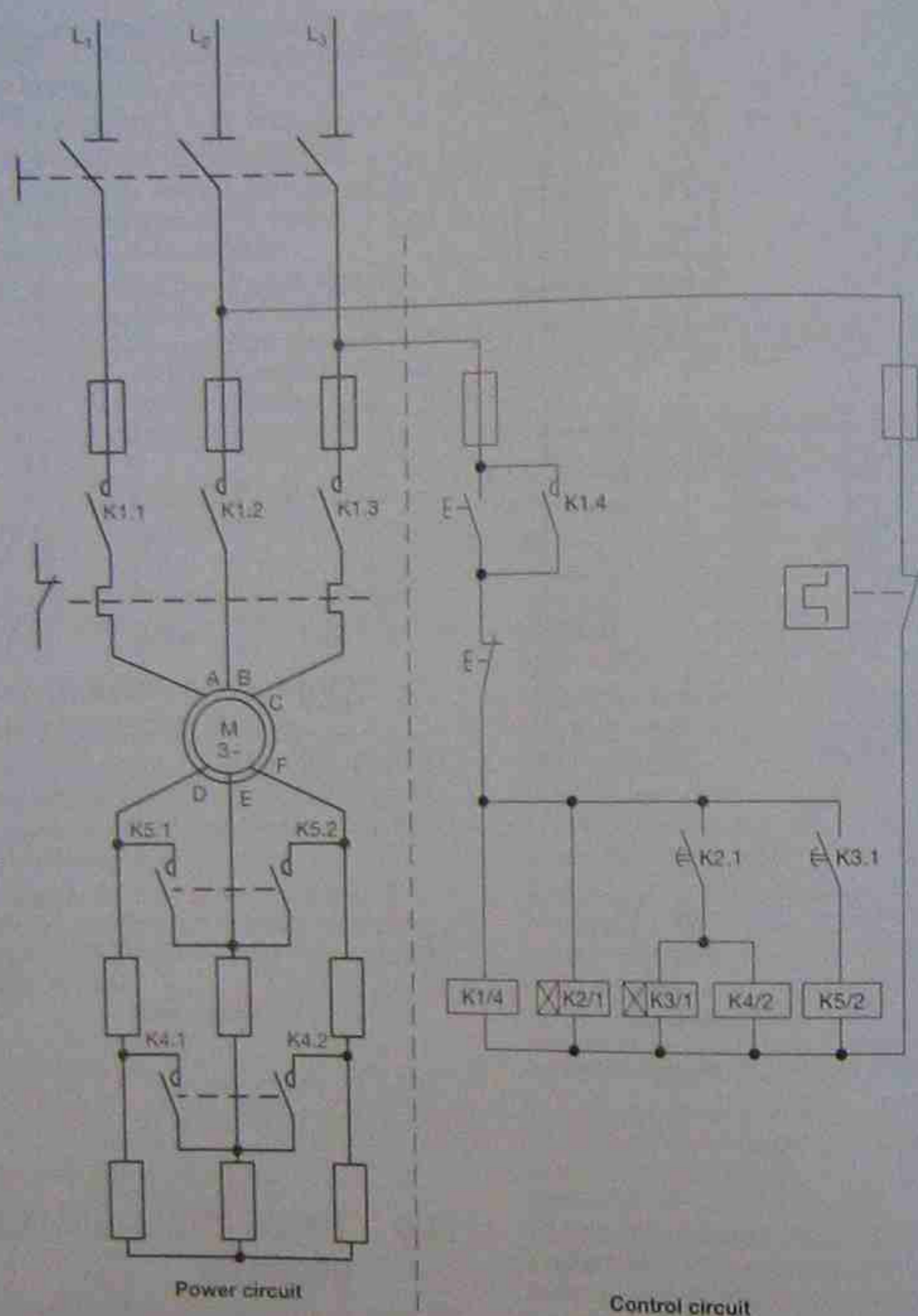


Figure 13.14 • Contactor circuit for secondary resistance starting

### 13.7 THREE-PHASE MOTOR BRAKING

In many installations it is quite satisfactory to allow a machine to coast to a halt as its inertia is dissipated in friction losses within the machine. This inertia, which can be quite considerable in larger machines, can be dissipated more quickly by some form of braking. The braking system used must be of a type to suit the machine and its requirements.

The major types of braking in use are:

1. mechanical
2. eddy-current discs
3. dynamic

4. regenerative
5. plug braking

#### 13.7.1 Mechanical braking

The principle of mechanical braking is to bring equipment to a complete halt and act as a parking mechanism. As a general rule, mechanical braking consists of creating deliberate friction between rotating and stationary components. Machine braking systems might use more than one braking method. For example, an overhead crane might use the dynamic method for slowing down a load, and a solenoid-operated mechanical brake for holding the load stationary. In the case of a machine working, the

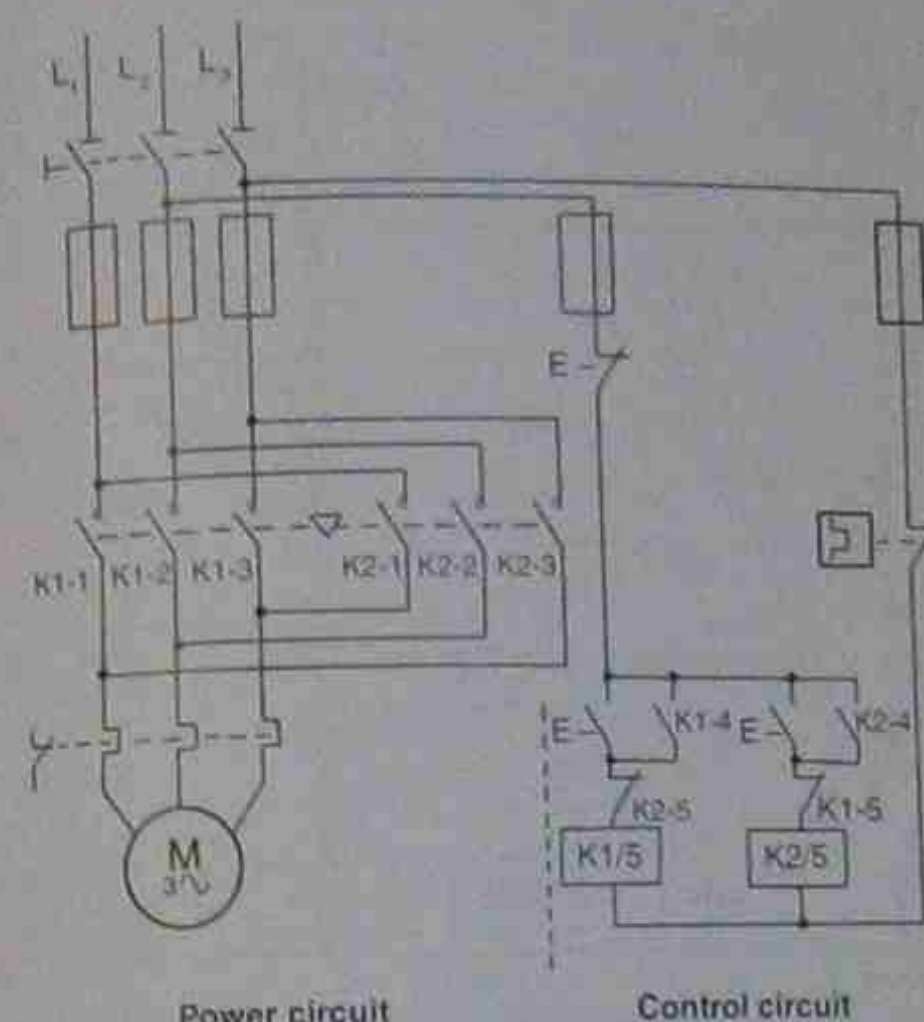


Figure 13.15 • Two-contactor DOL reversing circuit

automatically when power is removed. This is a protection in the event of a power failure. As a general guide, travelling cranes use this form of solenoid braking on all directional movements. See Figure 13.16.

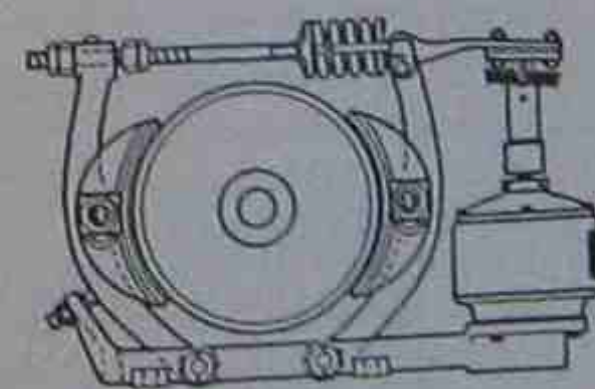


Figure 13.16 • Mechanical braking with brake shoes and solenoid

It can be seen that the brake shoes are held in the 'on' position against a flat pulley by a substantial spring. An application of power to the motor also releases the brake and allows the pulley to rotate.

Another system of mechanical braking uses a flat disc rotating in a mixture of finely powdered iron dust. The dust may be in a dry form or as a paste immersed in a liquid. A coil surrounds the container and on the application of a direct current voltage the iron powder grips the disc and holds it firmly against the container. If two discs free to rotate are used, the device can be used as a clutch mechanism.

It is worth noting that the mechanical system of braking usually brings the machine to a complete halt and can be used as a holding brake as well.

#### 13.7.2 Eddy-current disc braking

An eddy-current disc consists of a sturdy disc connected to the machine shaft and free to rotate with the machine between a set of coils held firmly in a stationary position. As the disc rotates, eddy currents are induced in the stationary coils, eddy

currents are set up in the rotating disc and form a load on the machine. As the machine slows down, the induced voltages and currents become less and the rate of deceleration becomes less.

Eddy-current discs are not capable of bringing a machine to a complete stop, nor are they capable of being used as a holding brake. They simply increase the rate of slowing down of the machine.

#### 13.7.3 Dynamic braking

Dynamic braking works on the principle of using the motor as a generator and dissipating the machine's inertia as electrical energy.

In alternating current motors this is often achieved by disconnecting the rotating motor from the power supply and applying direct current to the windings. Because the rotor is still moving, circulating currents are generated within the rotor. These form a load on the machine and slow the motor rather more quickly than just coasting to a halt. Like the eddy-current disc method, it only hastens the slowing process and cannot bring the motor to a complete stop. A mechanical braking system is still needed as a holding brake.

The principle is shown in Figure 13.17. The main contactor and the contactor applying direct current to the stator windings are electrically interlocked, and on pressing the start button, the main contactor K1/5 is energised and isolates contactors K2/4 and K3/1.

When the stop button is pressed, K1/5 drops out and the normally open section of the switch completes the circuit to contactor K2/4. When it is activated it isolates the main contactor and simultaneously applies direct current to the stator windings. At the same time as K2/4 is energised, the time delay contactor K3/1 is also energised. After a preset time lapse it operates and switches off the direct current.

During the stopping process the stop button must be held in the 'stop' position for a short period to activate the braking system. The direct current is usually obtained from a rectified alternating supply.

A typical use for dynamic braking is in electric trains where the driving motors are used as generators and the energy generated is dissipated in banks of resistors. Some large cranes also use this system but, as with other applications, a system of mechanical braking is also required for bringing all movement completely to rest.

Another form of dynamic braking is by using what is known as an *induction generator*. Capacitors are connected across the input terminals of a three-phase motor. When it is necessary to stop the motor, the power supply source is removed and resistors are connected across the motor terminals.

The motor, while it still rotates, generates alternating currents, which are dissipated within the resistors. The system involves extra contactors, resistors and fairly large capacitors, but is an excellent method for controlling the speed of motors and equipment connected to overhauling loads.

#### 13.7.4 Regenerative braking

Regenerative braking uses the inertia of a moving load to convert mechanical energy into electrical energy and feed it back into the power supply source. Not used very often



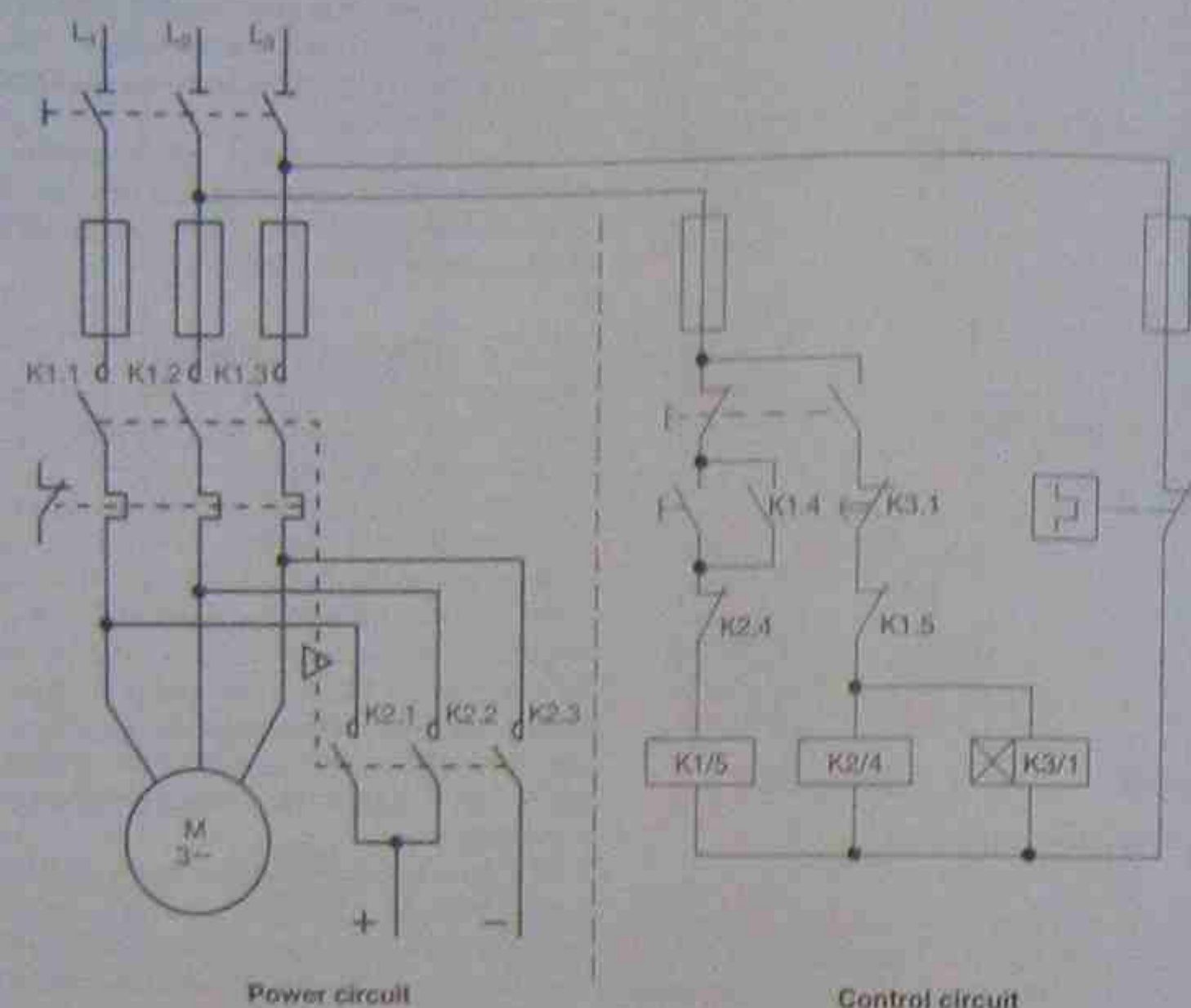


Figure 13.17 • Braking an a.c. motor by d.c. injection (dynamic braking)

with alternating current sources, it is a more involved method than those described above and involves the use of extra equipment.

The electrical energy fed back into the supply source has to be considerable to justify the additional expense. It follows that the mechanical energy available to supply it also has to be considerable.

A typical application of regenerative braking is its use in electric traction systems such as trains or trams. There are often thousands of tonnes on the move and this constitutes considerable inertia. If this energy can be transformed into electrical energy and slow down the train or tram, a large saving in electricity costs can be achieved. There will also be a saving in wear and tear on the brake shoes used in a mechanical system.

The system becomes less effective as the vehicle slows, and mechanical braking is also required. At some point the electrical energy being generated will be insufficient to be fed back into the supply line and the system has to be disconnected from the supply. On occasion the system may then use dynamic braking as a further slowing process.

Because of the expense of fitting extra equipment to machines, plus the fact that the method cannot completely stop and hold machinery in a stationary position, the applications of regenerative braking are limited, for alternating current working, its main use is in controlling overhauling loads, for example, cranes lowering heavy loads.

### 13.7.5 Plug braking

Plug braking with three-phase motors is the system of reconnecting a motor to rotate in the reverse direction,

while still rotating in the forward direction. It is a sudden and almost violent method for bringing a motor to a complete stop. The actual time taken depends on the amount of inertia in the accompanying machine.

In order to use plugging as a stopping mechanism, some means must be provided to remove all power from the motor at the instant of change in direction. This can be done with a friction-operated single-pole changeover switch mounted on the motor driving shaft. Another method uses an eddy-current disc rotating between magnets to activate contacts, which in turn control the main contactors.

The starter circuit has push-buttons to activate rotation in the required direction and the movement of the shaft closes the appropriate contact and allows the main contactor for that direction to latch in. A stop button allows the contactor in use to drop out and also activates the contactor for the opposite direction. This is latched in until the first amount of reverse movement occurs. This movement opens the holding-in contact of the starter and removes all power from the motor.

A control circuit for a three-phase motor using the plugging method of braking is shown in Figure 13.18. The power circuit has been omitted since it is identical to that of a normal three-phase reversing contactor (see Fig. 13.15.)

Motors generally have to be specially designed for this application by having stronger driving shafts. The drive shaft has to withstand the forces created by the driven machine's inertia in bringing the machine to a halt. The motor bars also have extra mechanical forces exerted on them. Again, if it is necessary, some mechanical brake

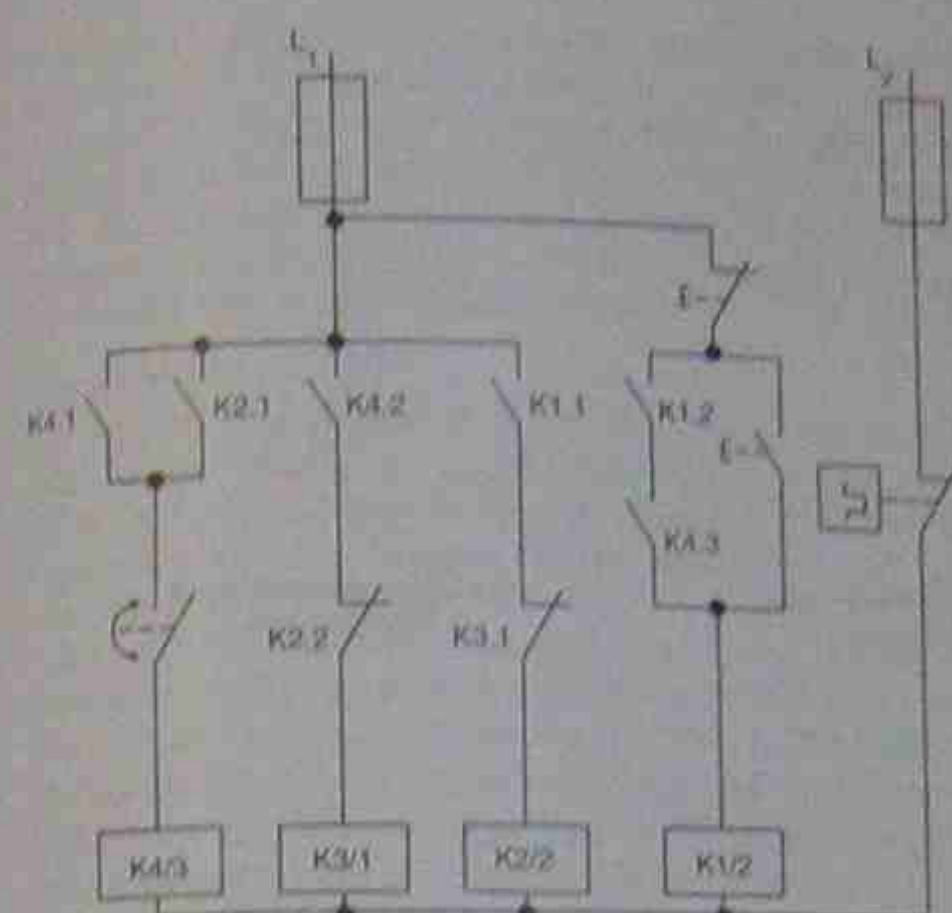


Figure 13.18 • Control circuit for plug braking

may have to be applied to hold the machine in position. One plugging stop is generally recognised as being equivalent to about three repetitive normal starts.

The motor windings might also have to be specially designed if the application calls for repeated starting and stopping. It is characteristic of a three-phase motor that the amount of current flowing when plugging is applied is almost equal to normal starting current. Also the starting current flow is applied for almost the same length of time as normal starting.

Probably the most common application is in larger production lathes doing repetition process work. In such an application a mechanical holding brake might not be needed.

Electronic starters equipped with current limiting or ramping circuits can use this system of braking with some success. The inverter circuits can sometimes be reversed in action and the excess generated energy converted to direct current and dissipated by dynamic braking. Normally it cannot be fed back into the supply source as can be done with a normal regenerative braking system.

## 13.8 SPEED CONTROL OF A.C. INDUCTION MOTORS

Torque is produced in an induction motor by the interaction of two magnetic fields. One magnetic field is created by currents flowing in the stator windings. This rotating field cuts the conductors in the rotor and induces a voltage in them. The rotor voltage causes currents to flow in the rotor and produce a second magnetic field.

The two magnetic fields interact with each other and cause the rotor to rotate in the direction of the stator field. It accelerates to approximately 96 per cent of the speed of the rotating stator field. This 4 per cent difference in speed on full load is the slip speed. Without slip an induction motor cannot develop torque.

The speed of an induction motor is always governed by the rotating magnetic field in the stator. This stator field

always rotates at a synchronous speed governed by two factors:

1. the number of pairs of poles
2. the frequency of the applied voltage.

In section 8.7.1 it was stated that the synchronous speed could be found from:

$$n = \frac{120f}{p}$$

where  $n$  = synchronous speed  
 $f$  = line frequency.

The number 120 is derived from the product of the number of seconds in a minute and the fact that magnetic poles always come in pairs. The other two quantities are called variables.

It is important to note that there are only two variables. If the frequency increases, the speed increases:

$$(n \propto f)$$

If the number of poles increases, the speed decreases:

$$(n \propto \frac{1}{p})$$

These two basic principles are the only factors that can affect the change in speed of an induction motor, although the methods adopted to achieve this are many.

### 13.8.1 Speed control by changing the number of poles

Changing the number of poles in a stator winding always involves an abrupt step change from one speed to another. On a 50 Hz supply a two-pole motor will rotate at 3000 r/min (ignoring slip speed). If a change is made to a four-pole stator the speed will quickly change to 1500 r/min. The change in speed can transmit minor transients into the supply lines. With larger motors a short time delay should be introduced when changing from one winding to the other.

The most common method is to design windings that can be interconnected to change the number of poles. It is invariably a 4:2 ratio, that is, a two-pole winding converts to a four-pole winding, or a four-pole to an eight-pole winding, and so on.

Figure 13.19(a) illustrates the principle and connections involved for a four- to eight-pole speed conversion. Only one phase is drawn; small rectangles are used to represent pole-phase groups and the arrows indicate the sense of winding direction. It is necessary that the pole windings be connected in pairs opposite each other as shown.

Note that the centre-tap ( $T_A$ ) of the winding has been brought out so that it can be accessed externally. In Figure 13.19(b), the four pole-phase windings have been redrawn in a vertical line. If  $A_1$  and  $A_2$  are bridged and connected to line  $L_2$  and the centre-tap  $T_A$  connected to line  $L_1$ , the motor will have four conventional poles as indicated by the arrows.

In Figure 13.19(c) the bridge has been removed,  $A_1$  is reconnected to line  $L_1$  and  $A_2$  left connected to line  $L_2$ . As indicated by the arrows, the current flows through all four pole groups in series and all give the same polarity, for example, as shown, there would be four north poles.

The magnetic flux is diverted in the stator and exits



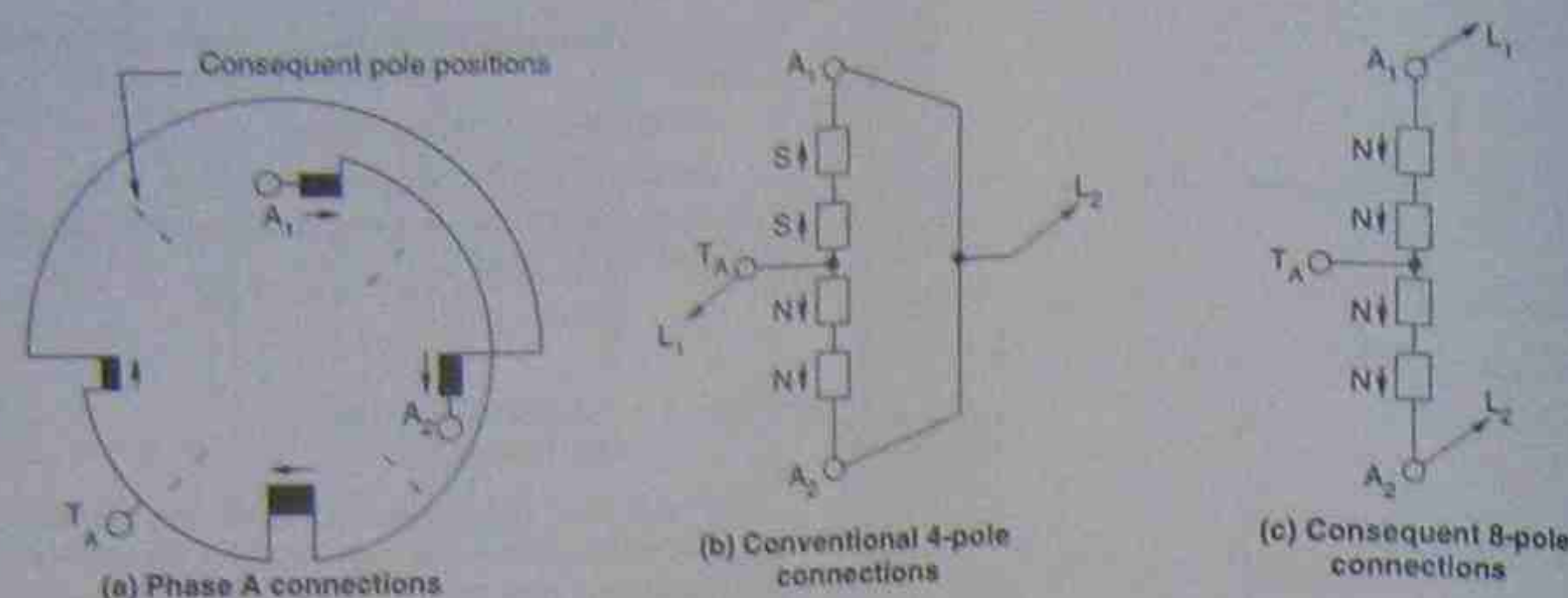


Figure 13.19 • Series-parallel connections for a two-speed motor

between the north poles as indicated by the broken lines. The resulting magnetic circuit of the motor is that of an eight-pole machine.

To get around this 1:2 ratio limitation, some stators have been designed to accommodate two electrically separate windings. Only one winding is used at a time. These windings need not be in the ratio of 1:2 but can be any reasonable relationship. For example, one winding could be a two-pole winding, the other a six-pole winding.

Activating the two-pole winding would cause the motor to rotate at 3000 r/min. During this period the other winding, if not connected in star configuration, must have the delta bridges open-circuited to prevent induced currents flowing in the unused winding. When provided with a suitable switch, the windings could be exchanged without stopping the motor or its coupled machine. The motor would then change speed to 1000 r/min.

Step speed control with pole amplitude modulation (PAM) is a rather lesser known system. It was developed for close speed ratios such as four to six pole and eight to ten pole. It relies on the principle of unequal coil groupings within the motor when manufactured. Connections are made with special contactors to control speed steps. PAM windings are covered by copyright but can be manufactured under licence. PAM motors are made as small as 0.5 kW but have been made in sizes of 7 MW.

### 13.8.2 Speed control by changing frequency

One important aspect of this method of speed control is that, at higher frequencies, the standard induction motor runs at speeds well above the base design value. At increased speeds, air circulation is improved, resulting in improved cooling.

Better cooling permits higher current densities to be used, even though there is increased friction and windage losses due to higher speeds. There are also increased iron losses due to the higher frequencies. At higher frequencies the impedance of the windings is also increased and to ensure a constant flux density in the air gap, a higher supply voltage is required.

At constant flux density in the air gap, torque is proportional to current flow. Since power is dependent on both torque and speed, it can be seen that the power output of the motor increases at a faster rate than the speed increase.

Increasing the frequency of a complete plant would ensure all motors ran at a faster speed and this might not always be desirable. Decreasing the frequency would ensure that all motors ran more slowly, and produce the same undesirable result. In general then, frequency changing as a method of speed control is limited to specific machines or groups of machines, as in a series of transport rollers in a steel mill.

There are two main methods for frequency changing. The first uses rotating machinery to achieve the desired result. It is expensive, although less efficient than some other methods, but experience has shown it to be extremely reliable, with minimal maintenance problems. As a consequence it is still in extensive use.

The second method uses electronic switching to synthesise an irregular-shaped alternating current wave from direct current. It is a comparatively new procedure and has become very popular.

#### Rotating machinery for frequency control

One common motor control system is the Schrage motor where the speed is altered by adjusting the brush positions for each phase.

Figure 13.20 illustrates another method for speed control. In this instance it is the Kramer method for controlling the speed of a wound-rotor motor. It can be seen

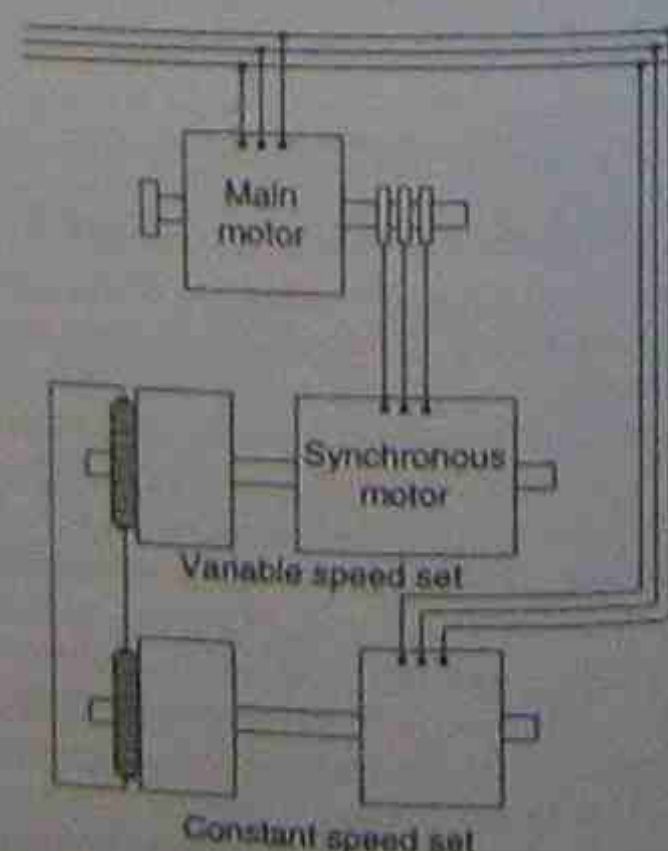


Figure 13.20 • Kramer drive using rotating machines

that four rotating machines are used to control the speed of one motor. The system can only be justified economically for extremely large motors or integrated groups of motors in heavy industry. Where Schrage motors have practical limitations, the Kramer system can be built in megawatt ranges. Reliability and minimal maintenance have been well established in both systems.

#### Wound-rotor motors

The slip in any induction motor is proportional to the rotor copper losses. In a wound-rotor motor the rotor resistance can be varied with the addition of external resistance, so rotor copper losses and speed can be adjusted with a controller.

Because rotor current is proportional to the developed torque, it would follow that rotor losses would vary with the applied load, thereby affecting the speed. This method of speed control has the characteristic of a variation in speed for a variation in load; that is, increasing the load causes the speed to decrease, while decreasing the load results in a speed increase.

For this reason speed control of a wound-rotor motor by varying the rotor resistance is satisfactory only for a steady load. Speeds lower than half full-load speed are not practical, and increased losses at lower speeds lead to high operating temperatures, which might exceed the ratings of the motor. Motor efficiency is poor, speed regulation is poor, and the external resistances consume wasteful power.

Various methods have been tried for speed control. The two most common are:

1. unequal voltages applied to stator windings
2. unequal resistances inserted in rotor windings.

Unlike the rotating machinery systems described above, these speed changes are step changes. Probably the most common application is in the hoist and lowering mechanism of overhead cranes.

#### Electronic frequency control

The rapid advances made in semiconductor technology have led to much more efficient and effective means of altering mains frequencies. Figure 13.21 is a block diagram of an inverter drive.

The three-phase supply is first converted to a direct current supply. There are at least two possible conversion methods in general use. One is to use a fixed or uncontrolled rectifier circuit and the other is to use a controlled rectifier circuit. Each type of circuit has its advantages and disadvantages.

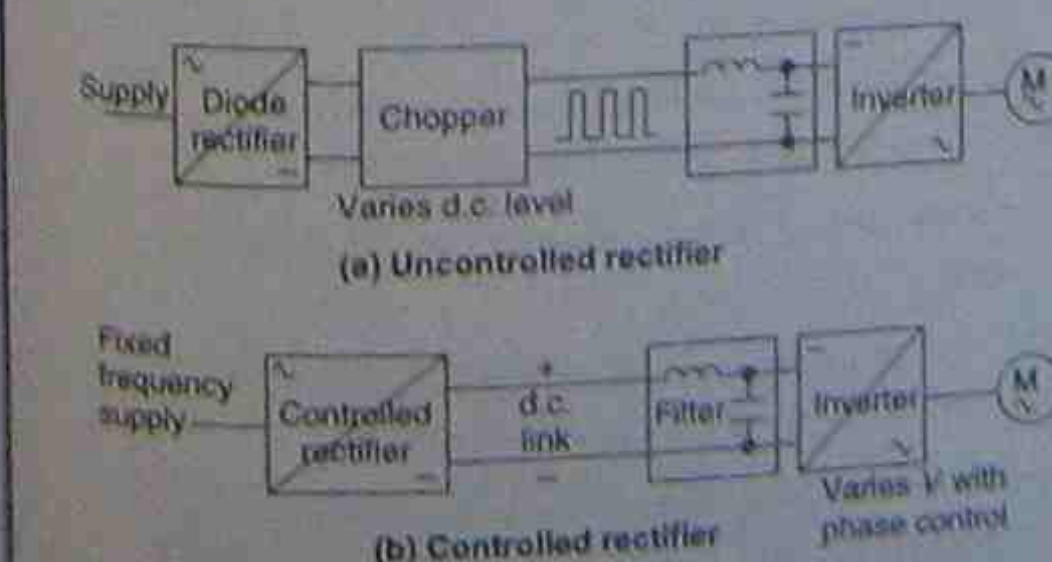


Figure 13.21 • Variable frequency motor drives

#### Uncontrolled rectifiers

The output voltage from an uncontrolled rectifier circuit (e.g. a bridge rectifier) is governed by the a.c. input voltage. The d.c. output is then fed to a 'chopper' circuit. Its function is to switch the d.c. on and off at a rate higher than the fundamental frequency of the supply. The on-off action adjusts the average d.c. voltage level supplied to the inverter.

Figure 13.21(a) shows the approximate square-wave shape of the chopper output. This is then fed through a filter circuit to remove as many transients and spikes as economically reasonable and it then becomes the input to the inverter circuit.

#### Controlled rectifiers

A controlled rectifier circuit such as one using silicon-controlled rectifiers with phase control has the advantages of a fast response, relative cheapness, and the ability to maintain a regenerative action of feeding power back into the mains. It has the disadvantage of operating at a lagging power factor.

Because the d.c. from the controlled rectifier does not have to be fed through a chopper circuit, it tends to be less complicated and possibly a more efficient circuit. The output is generally filtered before being supplied to the inverter section. (See Fig. 13.21(b).)

To maintain optimum performance of an a.c. motor with a varying frequency supply, it is necessary to maintain the designed magnetic flux conditions in the magnetic circuit of the motor. This is generally achieved by ensuring that the ratio of supply voltage to frequency is kept constant. Any change in frequency must then be accompanied by a change in voltage, that is:

$$V/f = k$$

The actual type of circuit and the control method depend to a great extent on the motor application. A balance has to be selected between the desired factors of speed, torque, and power.

Other factors involved are the type of circuits in the unit and whether the final output sends a signal of its own performance to the unit's input for monitoring and self-adjustment of the unit.

Figure 13.22 shows a typical unit for electronic frequency control of an induction motor.

Summarising:

- (a) The inverter controls the output frequency.
- (b) The motor voltage is set by the d.c. link voltage.
- (c) Other parameters such as current, slip, and slip compensation minimum and maximum speeds, can be controlled.
- (d) Acceleration and starting current ramps up and down can be controlled.

Types of speed control are listed in Table 13.3.

## 13.9 ALTERNATING CURRENT MOTOR PROTECTION

In addition to monitoring an electric motor for such functions as controlled acceleration, reversing, braking, or speed control, a starter should also provide the motor with





Figure 13.22 • Typical electronic frequency control unit for an induction motor

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some form of protection. Line voltages and motor currents need to be monitored, and when required, isolate the motor from the supply.

Protective devices take many forms but most are designed to operate within the control circuit of the motor starter. In this way a fault occurring in one phase can be used to isolate all three phases and disconnect a motor from the supply.

One common cause of motor failure is temperature rise above design values. This can occur as a result of an electric fault, or be due to mechanical overloading by the driven machine. The overload might be a relatively small one for a sustained period, or it might be a large and sudden overload such as occurs when a machine locks up because of a mechanical fault.

Table 13.3 • Types of motor speed control

Type of motor	Speed characteristic, no load to full load	Type of speed control
a.c., squirrel-cage, multi-speed	Speed drop up to 5% from two or more initial speeds	Pole changing. Windings of different pole numbers, or reconnect one winding to change the pole number
a.c., squirrel-cage, single-speed	Speed drop up to 15%, depending on design	Primary voltage control. Stator frequency control at constant volts per cycle
a.c., slip-ring	Speed drop up to 50%, depending on rotor resistance	Secondary resistor connected to slip-rings. Machine and solid-state conversion feedback of rotor power
a.c., synchronous	No speed drop. Speed set by stator frequency	Adjustable frequency from motor generator set or solid-state frequency converter

### 13.9.1 Fuses

The fuse is possibly the simplest form of circuit protection. It consists of a fuse element designed to melt and prevent further current flow. The major disadvantage of a blown fuse is that the active component has to be replaced.

The primary purpose of a fuse is to protect a circuit, rather than any load. Under short-circuit conditions the reaction time of a fuse in isolating a circuit is probably the fastest of all protection systems.

A fuse element has to have a current rating high enough to allow a motor to draw starting currents, yet low enough to give some protection against overloads. As a result of these opposing factors a fuse cannot provide complete protection for both circuit and load.

Figure 13.23 shows two types of fuse carriers. Figure 13.23(a) is a porcelain carrier. The fuse element is threaded through a hole in the body of the porcelain. The hole might include an asbestos tube to contain the wire and prevent the scattering of molten metal when the fuse element melts.

The fuse element, being open to the atmosphere, deteriorates over time and causes the current fusing value to decrease. The device is also open to misuse because the fuse element can easily be replaced with another of an incorrect rating.

Figure 13.23(b) shows a high-rupturing capacity (HRC) fuse. It has a plastic carrier and base and is designed to be used in conjunction with replacement fuse units that are non-renewable. HRC fuse elements are enclosed in an insulating tube filled with powdered quartz to quench any arc that might develop. Figure 13.23(c) shows an example of a replacement cartridge. This is a type that has lugs to hold the fuse element in place with machine-threaded screws. HRC fuses of lesser current ratings are often manufactured with plug-in fuse elements.

AS/NZS 3000 has scant reference to rewirable fuses. The modern trend is to use circuit breakers and/or HRC fuses as being more consistent and reliable in terms of tripping values. Equipment manufacturers have no control over the size of fuse wire used in replacing blown fuse elements by third parties, hence the safety element becomes a determining factor in which protective equipment should be installed.

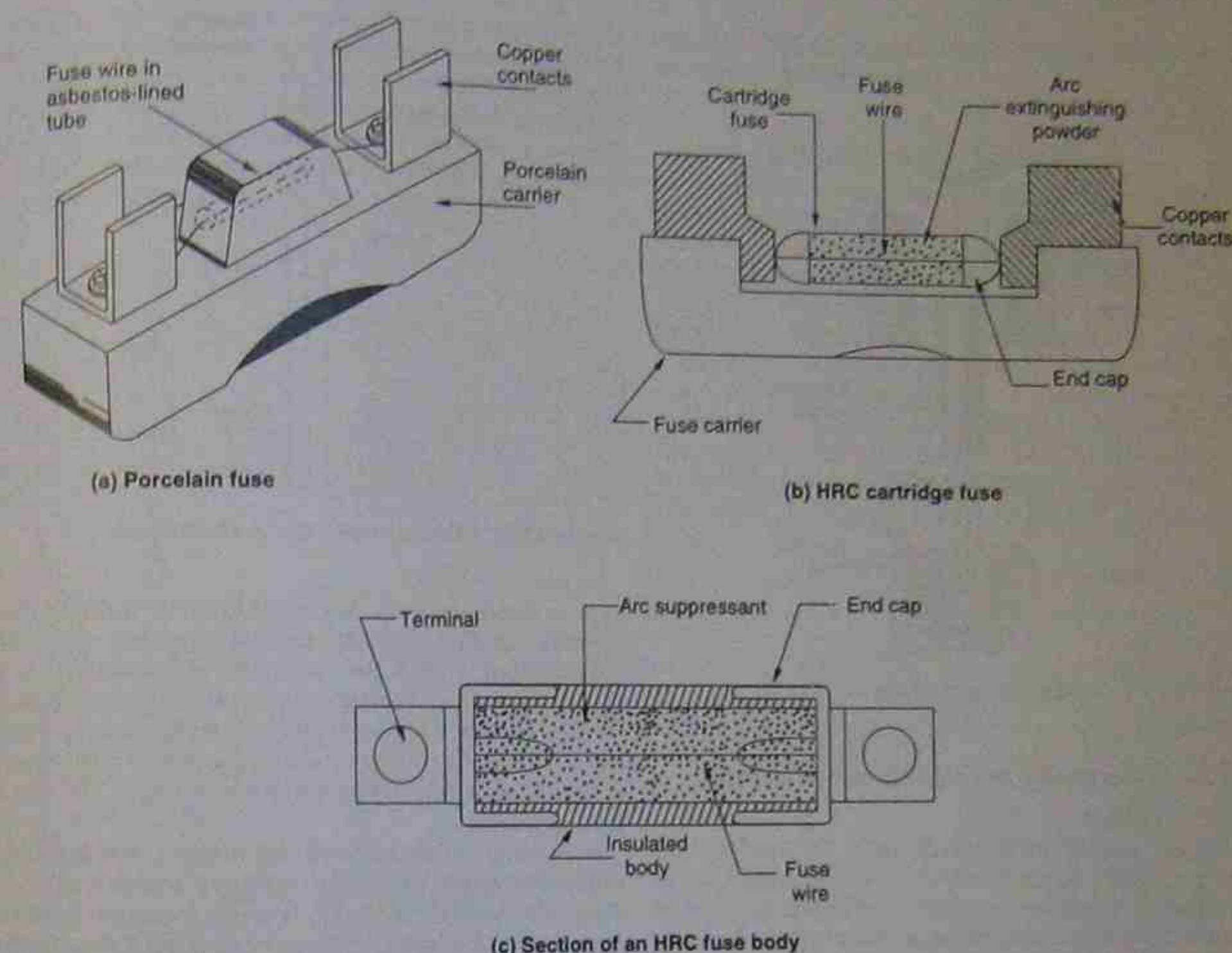
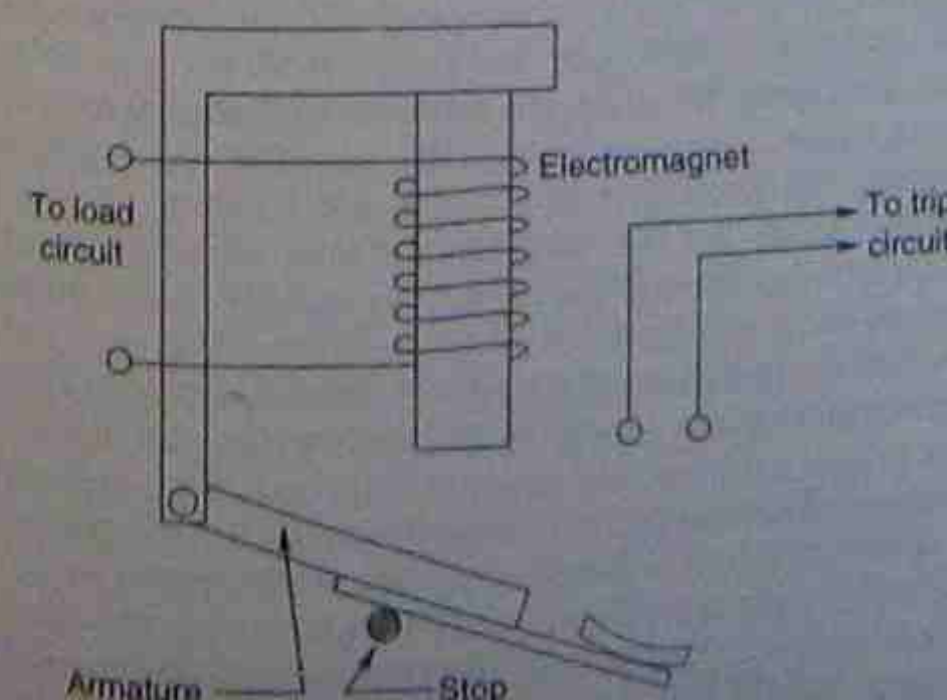


Figure 13.23 • Examples of fuses

### 13.9.2 Magnetically activated over-current relays

#### Instant tripping

Instant tripping relays are operated by the direct action of the motor current on an armature. The principle is illustrated in Figure 13.24. The relay consists of a series coil wound on a magnetic core. The coil is connected in one motor line and the armature is attracted to the main body of the core when the motor current exceeds a predetermined value.



The mechanical movement of the armature can be arranged to either close or open an electrical circuit as desired. The tripping value is varied by altering the position of the armature.

A popular alternative construction for an over-current relay is that of a coil wound on a cylinder. The coil is connected in series with the motor so that motor current flows through it. A plunger positioned so that it can be attracted into the coil activates the tripping process when the motor current exceeds the preset value. The direct-acting over-current relay has one serious disadvantage for protecting electric motors. Starting currents far exceed normal full-load running currents and the relay would trip out each time an attempt was made to start the motor.

#### Delayed tripping

Time-delayed tripping is achieved by attaching a small oil dashpot to the plunger, as illustrated in Figure 13.25. The piston has a small hole drilled in it and when excess currents attempt to pull the plunger into the solenoid, the action of the oil moving through the small hole delays the tripping action sufficiently to allow the starting current to return to normal full-load current.

When correctly adjusted, the relay will not trip on starting current but will trip on even small sustained overloads.



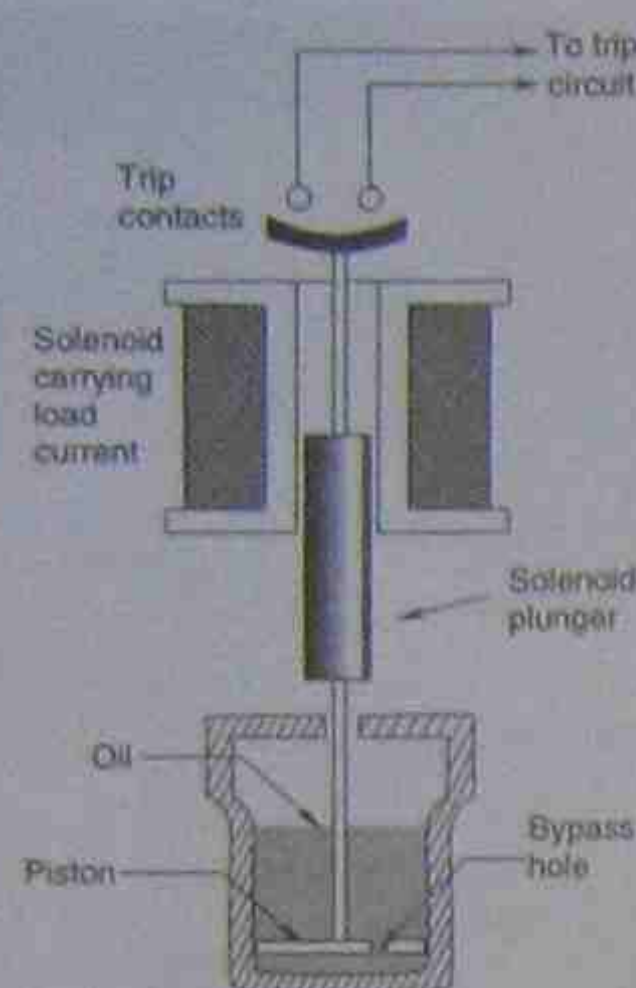


Figure 13.25 • Overload trip with oil dashpot time lag

### 13.9.3 Thermally activated over-current relays

Many types of thermal overload relays are available for motor protection. Some operate on different principles to others but all types are designed to open a contact when a temperature-sensitive element receives sufficient heat to activate it. Because the contact is usually connected in the control circuit of the starter, the contact opening allows the main contactors to drop out and switch off the power to the motor.

Correctly designed thermal elements produce an amount of heat related to the amount of motor current. The quantity of heat stored, and hence the temperature of the bimetal strip, relates to the amount of bending of the strip. After small short-duration overloads, the heat can dissipate, and the temperature of the strip is reduced. If small overloads continue for any length of time, the amount of heat generated will activate the relay.

With starting currents, insufficient heat energy is developed in the strip for it to bend enough in the time taken to run the motor up to speed, and for the current to reduce to normal running values. The operating principle of a bimetal strip is illustrated in Figure 13.26.

Ideally there should be a thermal detecting element in each line of a three-phase motor but the trend is to only two. In economic terms the extra cost involved is small to that involved in replacing a partially burnt-out motor.

Thermal overload elements are placed in the main supply lines leading to the motor, while the associated control contacts are connected in series with the control circuit. This is to ensure that if one overload operates it disconnects the motor from the supply.

### 13.9.4 Combined thermal-magnetic over-current relays

In the thermal-magnetic version of the over-current relay the advantage of the inbuilt delay of the thermal

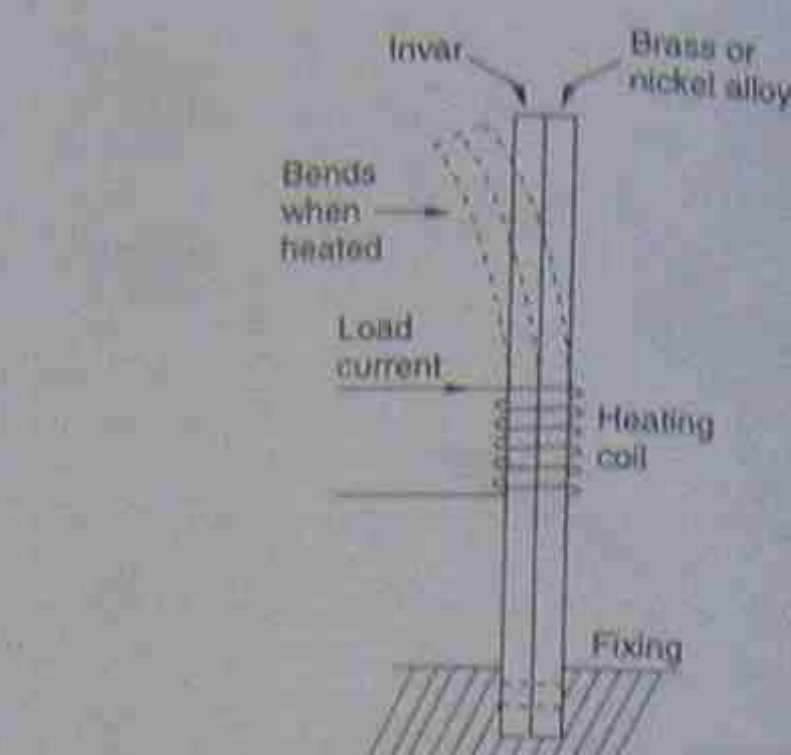


Figure 13.26 • Operating principle of a bimetal strip

type is combined with the instantaneous tripping characteristic of the magnetic current overload relay. The combination of the two methods is considered ideal motor protection. For very high currents the magnetic section of the relay acts almost instantaneously. For small overloads, the heat accumulated in the thermal section causes delayed tripping according to the rate of heat generation.

Depending on design and application, the combined unit might not have oil-filled dashpots to delay the magnetic relay action. Instead it is set at a current rating in excess of motor starting requirements and the thermal element rating is retained at the lower value.

### 13.9.5 Temperature-dependent resistor protection

Temperature-dependent resistors were shown in section 2.13 to have either positive or negative temperature coefficients. A popular trade name for this type of resistor is *thermistor*, although other names do exist.

A resistor with a positive temperature coefficient (PTC) has the characteristic of increasing its resistance only gradually until a critical temperature is reached. Above this point its resistance increases rapidly.

This critical temperature can be varied by altering the composition of the material from which it is made. The determination of a critical temperature for a PTC resistor can also determine its use. See Figure 2.26.

For example, many electric motors are designed to have a maximum operating temperature of 60°C. At this temperature the heat generated by motor losses is approximately equal to the heat being lost by the motor. Effectively this means that the temperature of the motor then remains constant.

A PTC resistor is usually made in the shape of a flat disc, approximately the size of a five-cent piece, but smaller and larger sizes are available. When suitably insulated and placed inside the windings of a motor, the internal temperature of the windings can be monitored.

If the critical temperature is, say, 65°C, then the PTC's resistance would increase rapidly above this temperature and can be an indication that there might be something wrong with either the motor or its load.

Temperature-dependent resistors, under normal conditions, are only capable of handling small values of current and must be used in conjunction with other equipment.

Figure 13.27 illustrates one method for monitoring the temperature of motor windings. A PTC resistor is inserted into each phase winding of the motor and all are connected in series with the coil of a small relay.

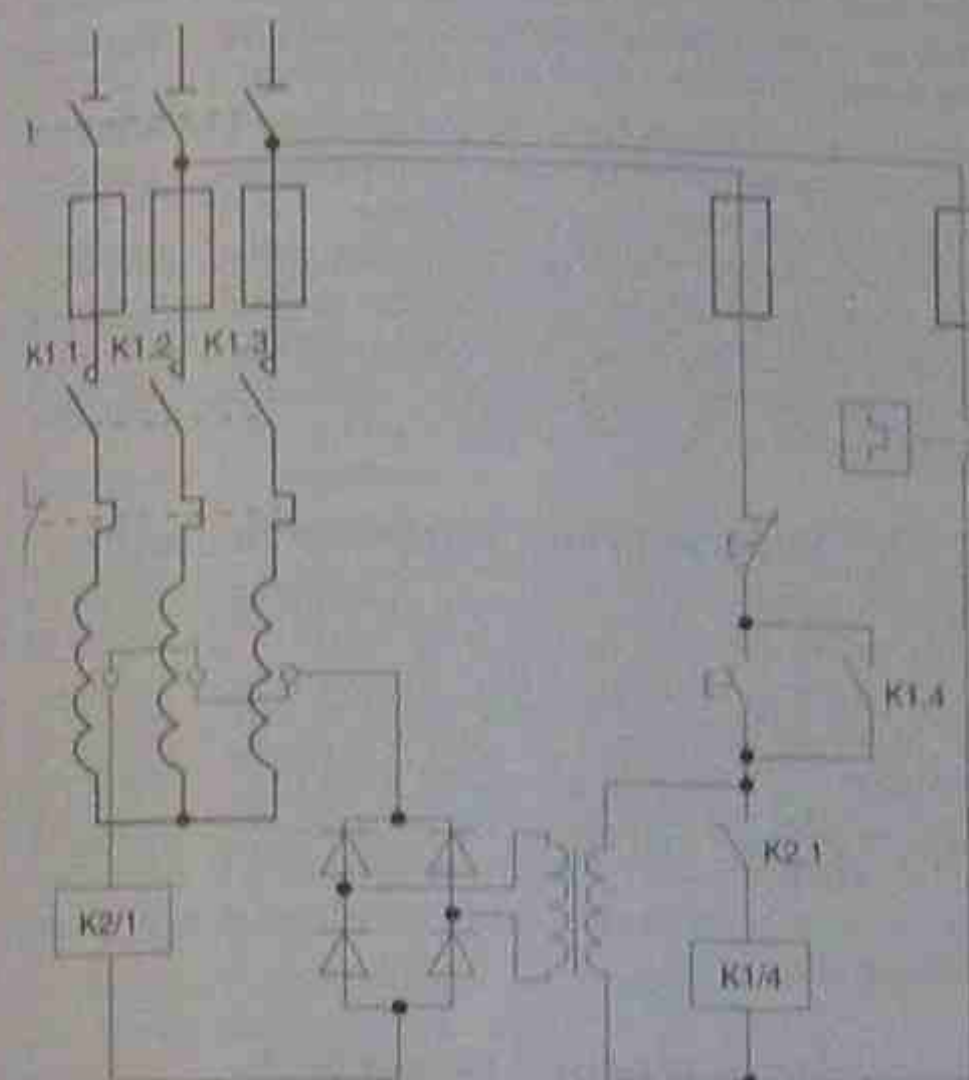


Figure 13.27 • Using PTC resistors to protect motor windings

This relay controls a pair of contacts in the control circuit of the motor starter. An isolating transformer and a bridge rectifier supply this circuit with direct current.

When the starting button is pressed, the transformer supplies power to the PTC resistor circuit and, provided their collective resistance is below the critical temperature value, enough current will flow to activate the relay coil and close the contact connected in series with the main contactor coil.

Normal DOL starting procedure follows, with normal contactor action. If the temperature of any one of the three PTC resistors rises above the critical value, the resistance of the circuit increases, the current flow through the relay coil decreases, and the relay drops out. This then causes the main contactor to drop out and isolate the motor.

In a manner similar to other thermally activated devices there is an inherent delay in a PTC resistor cooling down and resetting itself. A thermal overload normally is made as small as possible to reduce its thermal capacity but this has no effect on the thermistor when it is buried within the windings because they regulate the rate of cooling.

For a locked rotor situation, PTC resistors are an inadequate form of motor protection and external thermal and magnetic overload protection should still be provided. The time taken for motor windings to heat up when the rotor is locked in a standstill position is comparatively long and irreversible damage can be done to the motor windings

before the PTC resistor exceeds its critical temperature and disconnection occurs.

### 13.9.6 Under-voltage protection

Two kinds of under-voltage protection are available to motors controlled by contactors. The first is called no-volt protection because once the voltage is reduced below the holding-in voltage level of the coils, the contactors drop out. When power is restored, the motor has to be taken through the starting sequence again until it is up to speed.

The second type is an additional part of a control circuit and keeps the contactors in a holding position for momentary dips in voltage. If the power is restored before the motor can coast down appreciably in speed, full power is immediately restored to the motor. One such circuit is illustrated in Figure 13.28. The control circuit only is shown.

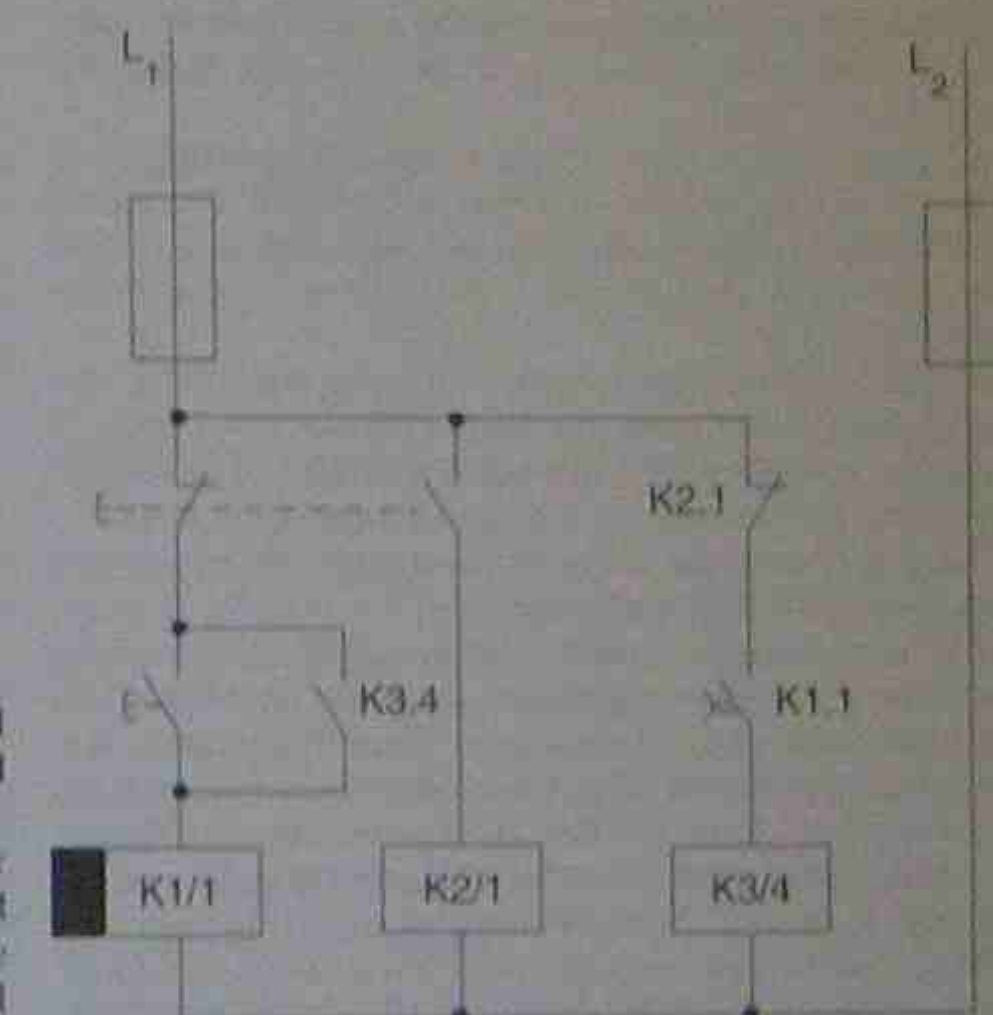


Figure 13.28 • Control circuit for under-voltage protection

When the start button is pressed, relay coil K1.1 closes immediately. This closes contact K1.1. (As the symbol indicates, the relay can close instantly, but delays on opening.) The circuit is completed for relay K3.4 and it closes and connects the motor through contacts K3.1, K3.2, K3.3 to the three supply lines. K3.4 contact latches across the start button so holding the circuit in a completed condition. Note the normally closed contact K2.1 is connected in series with K3.4.

To stop the motor, pressing the stop button releases relay K1.1 and also completes the circuit to relay K2.1 via a mechanically attached switch at the same time. Contact K2.1 opens, releases the main contactor K3.4 and so isolates the motor from the supply.

During a sudden dip in voltage the delaying action of K1.1 and its accompanying contact K1.1 ensures that the circuit to the main contactor remains complete.

If the power dip is short, the motor can restart automatically without an operator being required to initiate a



starting sequence. If the power dip is greater than the delay time of the contactor, the starting sequence has to be initiated.

In the interests of safe working, many machines do not lend themselves to this type of circuitry because an automatic restart might be dangerous to the operator.

### 13.9.7 Over-voltage protection

For alternating current motors connected to a distribution system, over-voltage is a fairly rare occurrence. Over-voltage is more common with long-distance high-voltage transmission lines where lightning strikes are likely to occur. It is a more prevalent problem with variable speed inverter generating plants such as exist in aeroplanes and submarines. They are discussed later in the context of direct current machine protection.

Power factor improvement has been discussed in section 8.16.7. Because capacitors are encouraged to keep loads at high power factors it can lead to the uneconomic practice of connecting capacitors in parallel with individual induction motors.

This can lead to over-voltage transients occurring when a motor is switched off. The size of the capacitors should be sufficient only to correct the power factor of each load and preferably ensure that it still has a lagging power factor.

Capacitors connected across an induction motor can cause self-excitation as the motor continues to spin. In some circumstances this generated voltage can be as high as double line voltage. In normal circumstances this over-voltage lasts only for a short period and most equipment can cope with the voltage surge.

There are occasions when a motor application requires the fitting of surge suppression devices. One example is the submersible bore pump. In its operating location it is a very good weathering point and, since many bores are fed from overhead lines at a distance from a source of supply, the installation is vulnerable to lightning strikes. In an attempt to protect the motor against what may well be a 500 kV surge, over-voltage surge suppression are fitted. Motor protection is rather dubious in such circumstances.

### 13.9.8 Single-phasing protection

A three-phase motor operating under ideal conditions will draw three equal phase currents. This implies that the three line voltages are also equal, a situation that rarely exists in practice. A small variation in voltage of say 2 per cent can cause a current variation of about 10 to 15 per cent.

The function of an overload relay, whether magnetic or thermally activated, is to disconnect the motor from the supply lines under specified conditions of current flow and within a set period of time.

Overload relays are incapable of protecting a motor against internal faults, not is that their intended function. Commutators are intended to handle the starting currents of induction motors. Fault currents may be many times the value so fuses or circuit breakers should be installed ahead of the controller.

The only protection readily available for a three-phase motor is the provision of thermal overload heating elements in each phase. An internal fault in the motor draws

excessively or greatly unbalanced line currents. Thermal or magnetic overloads can then disconnect the motor from the supply.

If an external fault occurs, such as a line to the motor becoming open-circuited when the motor is running, the motor is also said to be 'single-phasing' and the remaining line currents increase by approximately 73 per cent each. One of the phase windings then carries about twice as much current as the other two and motor damage can occur.

For smaller motors the cost of installing phase-sense relays might be prohibitive but for larger motors it can be worth while as additional protection.

Voltage-sensitive relays are connected across each phase with operating contacts connected to the motor's control circuit to ensure the motor is disconnected from the supply in the event of any phase voltage deviating outside specified limits.

### 13.9.9 Reverse phase sequence protection

Some machines can be damaged if inadvertently driven in the wrong direction by the drive motor. This can occur when the phase sequence of the supply has been changed.

A phase-sensitive relay is supplied by voltages from each phase and isolates the motor from the supply if its phase sequence is incorrect. The relay itself may be purely mechanical and operate a valve, which in turn operates contacts in the motor control circuit, or it may be an electronic device.

### 13.9.10 Environmental protection

Induction motors are available in many different enclosures, depending on the task allotted to them. Some of the types of enclosures are:

1. open
2. totally enclosed
3. duct or force-ventilated
4. drip-proof
5. flameproof
6. weatherproof
7. submersible
8. explosion-proof

AS/NZS 1359.21 lists more than a dozen methods for cooling induction motors. Adding to this a variety of different mounting types, such as horizontal or vertical, tends to make the list rather large.

The type of motor enclosure chosen depends on the atmosphere under which it has to function. The requirements listed below are general main groups but under each there can be many subgroups as indicated above.

#### Open motor

The ends of the machine are open, allowing free ventilation through and around the windings. An air enclosure through the motor by a fan attached to the motor shaft. The motor needs to be installed in a clean and dry atmosphere.

#### Protected motor

With the protected motor enclosure, the windings and the parts are protected mechanically but a free flow of air is

all drawn through the motor by a fan attached to the motor shaft. The protection is often obtained by fitting wire mesh or perforated metal over enclosure openings.

#### Drip-proof motor

Drip proofing is an advance on the protected type of enclosure. The openings are further protected by a hood, preventing foreign materials and moisture falling vertically into the motor and entering the motor. The hood may be incorporated into the enclosure during manufacture of the motor.

#### Duct ventilated

When installed, the motor might not be in an atmosphere of suitable composition to be allowed to flow through the motor. Corrosive atmospheres, high temperatures, high humidity and similar conditions are examples. For ventilation, cool and clean air must be drawn in from outside the installation.

There are two major types of ventilation in this case. In one type, air is drawn from outside through a duct and it can be expelled inside the installation, or it may have to be ducted to the outside atmosphere again. In the second type, a blower is installed outside and air is forced through a duct to the motor. It may be expelled directly or it can be ducted outside into the atmosphere again. It is a method of cooling usually adopted for very large motors.

#### Totally enclosed

In the totally enclosed type there is no contact between the air inside the machine and the air outside. The fan attached to the shaft is external to the motor proper and enclosed within its own housing. The motor housing is usually ribbed, and the air driven by the fan flows along the ribs and removes the internal heat by conduction through the housing.

The heat is removed from the motor at a slower rate than by direct cooling but the increased surface area cooled by the finning process assists. Modifications to this method of enclosing a motor enable it to be classified as waterproof, weatherproof or submersible.

#### Flameproof

The flameproof type is a totally enclosed motor with additional precautions to seal the bearings and assembly contact surfaces. Electrical connections are through a special sealed gland. The motor housing is made strong enough to withstand any internal explosion and still prevent sparks escaping to the external atmosphere.

The motor is used when there are flammable gases and the risk of explosion if sparks enter this atmosphere. The enclosure must comply with stringent regulations before being classified as flameproof.

## 13.10 STARTING PRINCIPLES OF D.C. MOTORS

Direct current motors up to 1.5 kW can be started directly on line but as indicated in Chapter 12 this allows excessive armature currents to flow and cause burning of both commutator and brushes. Smaller machines, due to their low inertia, can sometimes be started direct on line but larger ones cannot.

A typical 200 V 5 kW d.c. motor has an armature resistance of about 0.3 Ω. From Ohm's law it can be seen that the starting current is many hundreds of amperes:

$$I = \frac{V}{R} = \frac{200}{0.3} = 666 \text{ A}$$

This high current drain is a direct cause of the armature not rotating and being able to generate a back e.m.f. A general guide is to limit the maximum starting current to about two or three times full-load current. This figure should be noted, is only a general guide and can be affected by such factors as motor size, duty cycle, and type of load.

A motor starting on load needs a different type of starter to a motor starting without a load. It can vary from 1.5 to 7 times full-load current.

The only effective means to prevent damage caused by high starting currents is to limit the current by inserting resistance in series with the armature.

Figure 13.29 illustrates the basic principle for starting a d.c. motor.



Figure 13.29 • Basic starting circuit for a d.c. motor

The method applies to all types of connection for d.c. motors. A resistor capable of being varied is inserted in series with the armature, and full voltage is applied to the start field. As the motor accelerates, the armature resistance is gradually reduced. It is important that start fields be kept at or near full line voltage while the motor is being accelerated up to full speed.

The effects of starting a d.c. motor DOL are the:

1. rapid wear of brushes
2. burning of the commutator surface
3. overheating of commutator connections—leading to open circuits in the armature
4. burning of brush pigtail
5. flexing of armature windings—leading to chafing of armature windings and short circuits
6. shock loads on armature shafts, including bolts, drive bolts, or other transmission components
7. heavy current surges (transients) on supply wires

Desirable elements of d.c. motor starters and starting are:

1. circuit balancing
2. over-current protection
3. all series armature resistance in circuit when starting
4. full line voltage applied to start field when starting

Most starters for d.c. motors reduce the series resistance in a series of steps, as the armature current rises and falls in a series of steps. Figure 13.30 shows how the current rises for a motor with three resistance steps for the series resistance.



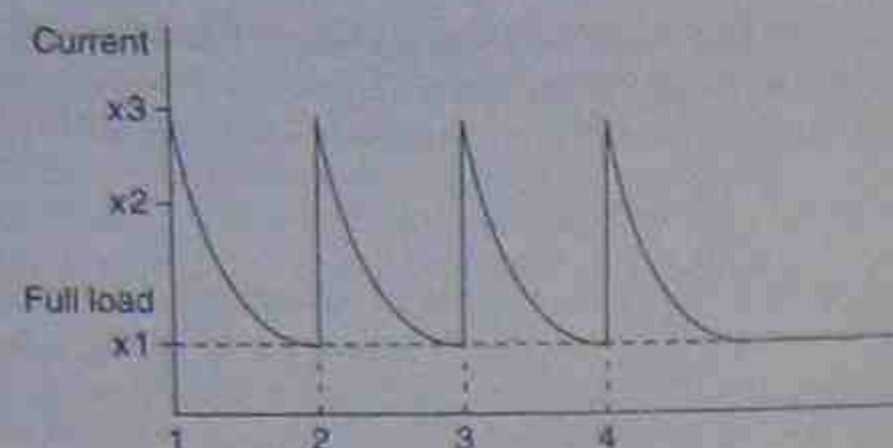


Figure 13.30 • Load current surges during starting sequence

The first current surge occurs when power is applied to the motor. As the motor gradually accelerates, a generated e.m.f. builds up and opposes the applied voltage. Because the difference between generated e.m.f. and applied e.m.f. gradually decreases, the armature current also decreases.

When the line current has reduced to approximately full-load current, the first resistance step is removed from the armature circuit and the current again increases abruptly. This is repeated as the motor has further gains in speed until all the resistance is taken out of the armature circuit.

### 13.10.1 Manual d.c. motor starters

#### Three-terminal faceplate starters

Manual starters are mainly of the three-terminal faceplate type and are designed for use with shunt or compound motors. With minor circuit alterations they can also be used with series motors. A typical circuit is shown in Figure 13.31.

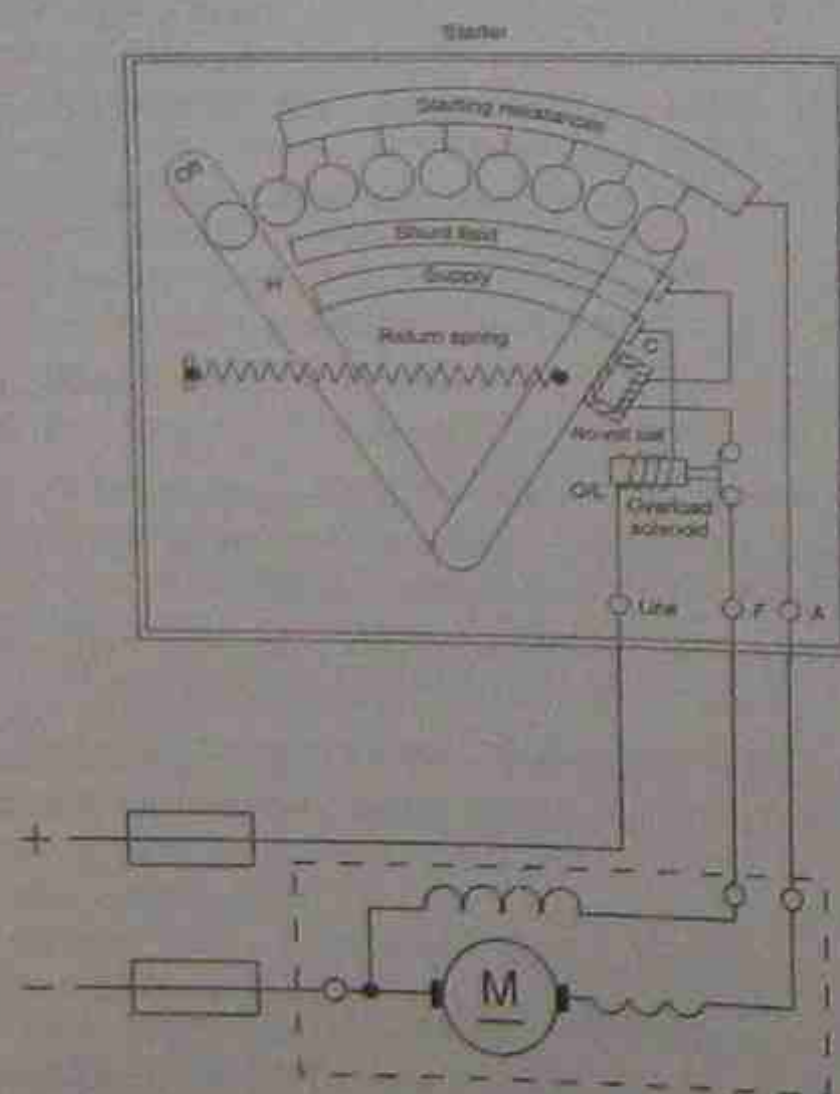


Figure 13.31 • Three-terminal manual d.c. motor starter

When the spring-loaded starting handle H is moved to the first stud, all the resistance in the starter is inserted in the armature circuit and full voltage is applied to the field.

As the motor accelerates, the handle is advanced, removing resistance from the armature circuit. Although this is added to the field circuit, the value of resistance is so low in comparison to the shunt field resistance that its effect can be ignored.

Current flows to the field through a series coil C, which magnetises an iron core situated so that, when handle H completes the magnetic circuit, it is then held against spring tension in the position where all the armature resistance is shorted out. The coil C is placed in the circuit to protect the motor and does this in two ways. If the field develops an open circuit, no current flows in the coil and the magnet releases the handle, allowing the spring to return H to the off position before the motor can accelerate to excessively high speeds. (Increased speed of a shunt motor is achieved by weakening the field.) Additionally, should the supply source fail or through some fault decrease to a low voltage, the magnetic strength of C is reduced and the spring again returns H to the off position. The coil C is often called a no-volt release coil.

Some situations, such as overloads on the motor or a faulty starting sequence, can cause the motor to draw an excessive current. To prevent damage to the motor, an additional means of protection is usually fitted to motor starters. In Figure 13.31 a coil of low resistance (O/L) is connected in series with one of the lines. When the current exceeds a preset value, the core is pulled into the coil and an associated pair of contacts shorts out coil C, releasing H and allowing it to return to the off position. This type of protection is called overload protection and can take many forms.

### 13.10.2 Automatic starters

Although an automatic starter is more expensive than a manual starter, it is electrically superior and has other advantages. A careless or inexperienced operator of a manual system can cause damage to both the starter and the motor if the starter is not used correctly. An automatic starter in good order will, at the press of a button, accelerate the motor up to speed in a starting sequence that can be repeated accurately and consistently.

Other advantages of automatic starters are:

1. Push-button control stations can be located at a distance from the starter.
2. Operation can be left to untrained personnel.
3. The push-button function can be replaced by a process control mechanism (e.g. pressure switches, float valves, moisture detectors).

In any discussion of automatic starters it must be appreciated that there are many variations of the basic design, depending on the equipment used, its location and any desired effects of individual starters. In all automatic starters, however, there are two types of circuits: power and control. The power circuit operates the motor and has the motor current flowing through it. The control circuit works on much smaller currents and operates the switches, contacts, relays and timers necessary for bringing the motor up to speed when required and affording it protection against overloads.

A circuit illustrating the action of an automatic starter for a shunt motor is shown in Figure 13.32. Operation is by push-buttons with the accelerating stages controlled by

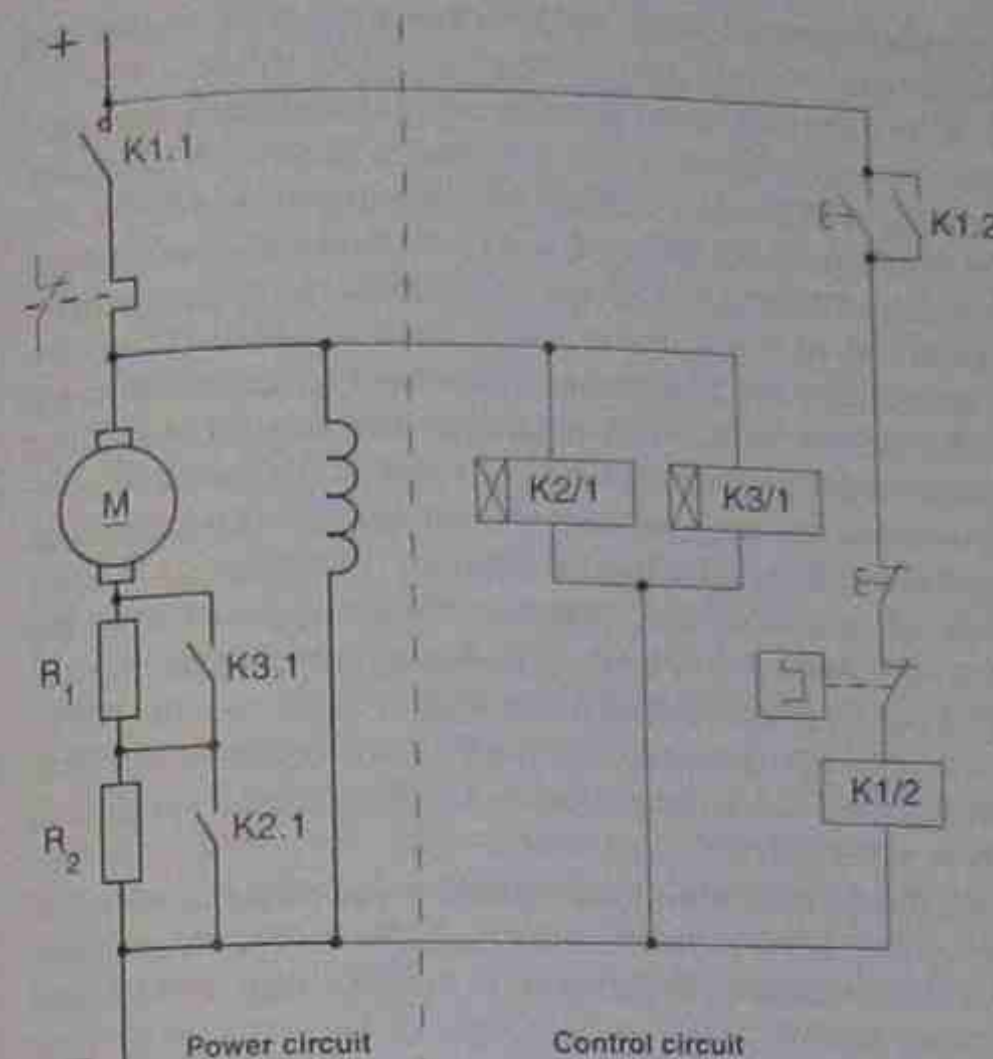


Figure 13.32 • Example of an automatic d.c. motor starter circuit

delayed action relays. The circuit has been divided into two parts with a broken line to distinguish between power and control circuits.

The power circuit is shown to the left of the line, with the motor field, motor armature and the accelerating resistors. The control circuit is below the line, with the push-buttons, main relays, timing relays and their respective contacts.

Two of the relays are of the delayed-action type. Relay K3/1 has a reaction time of approximately twice that of relay K2/1; for example, 5 seconds for K2/1 and 10 seconds for K3/1.

When the starting button is pressed, relay K1/2 is activated. One of its contacts K1.1 closes and applies full power to the field and also to the armature in series with the starting resistors. The armature current creates torque and the motor commences accelerating. The second contact K1.2 latches the starting button and ensures that power continues to be applied to the motor when the start button is released.

Simultaneously, full voltage is applied to both slow-acting relays K2/1 and K3/1. After an elapsed time of, say, 5 seconds, relay K2/1 is activated and contact K2.1 shorts out resistor R2. The reduced resistance in the armature circuit causes an increase in armature current and creates additional torque. This in turn enables further acceleration to a higher speed.

After a longer delay (say 10 s), relay K3/1 is activated and closes contact K3.1. This shorts out the remaining resistor in the armature circuit and allows full voltage to be applied to the armature.

The motor is protected against overloads by a thermal overload and the use of contactor coils ensures that there is protection against low voltages. Motor protection is discussed in section 13.14.

The time taken by a motor to reach operating speed is

dependent on the starting torque and the load imposed on the motor. In the example given above, the stage times are fixed and this may not always be a satisfactory solution to motor starting. More effective means might be required.

### 13.10.3 Automatic acceleration control

The nature of the motor start and the way in which the motor accelerates is governed by the starter itself. When series resistance stages are removed from the armature circuit there are surges in both current and torque. These surges might be unacceptable. For example, if a wrong value of resistor is chosen, a motor might not start on the first stage but will surge violently on a second stage.

The number of resistance stages in the starting procedure also affects the operation of the starter and the motor. A close ratio between maximum and minimum accelerating torques will give a smooth start with minimal surges, but requires many starting stages. A wider ratio, on the other hand, has fewer stages but results in sudden torque and current surges.

To achieve good starting sequences with surges reduced to a minimum, the operation should be taken out of the hands of an operator and made automatic. Then the rates of acceleration will be consistent and reliable.

There are methods for automatic starting control of d.c. motors that have existed for many years and have proved their reliability. Solid state technology and more advanced designs of d.c. motors also make it possible to control the supply of power to the motor over a wide range of operating conditions.

All d.c. motor starting methods are different ways of starting a motor on a reduced voltage and gradually increasing that voltage until it is on full line voltage. All effective methods control the rate of increase of input current and the accompanying acceleration rates.

Some of these methods are described below.

#### Definite time acceleration

Relays are activated in accordance with strict time intervals. The circuit in Figure 13.32 is typical of such a method. The method uses timing relays (electrical or mechanical), oil dashpots, or electronic timers. No allowance is made for load or motor conditions. For example, a motor could be stalled but after a definite time interval the next stage is activated, that is, less resistance and still more armature current.

#### Current-limited acceleration

This method is suitable for motors that have to cope with varying loads where the starting conditions may also vary. The maximum current is predetermined and the starting intervals depend on the magnitude and inertia of the load. Each successive stage is controlled by a contactor that is itself controlled by the previous stage. Auxiliary contacts and coil interlocking methods are used. The relays consist of a set of cylindrical coils designed to carry the armature current. Each will release its iron core at different current levels.

On starting, the first relay will attract its iron core. As the motor accelerates, the armature current will gradually decrease until the relay can no longer hold the core and releases it. Auxiliary contacts are then made. These



activate the next relay in the circuit and at the same time bypass some of the starting resistance in the armature circuit. Acceleration and torque are then increased until the next relay in the sequence goes through the same procedure.

If at any stage the load becomes too much for the motor and the current remains at a high level, the next stage in the starting sequence cannot be initiated.

#### Back e.m.f. starting

With back e.m.f. starting, voltage-dependent relay coils are connected in parallel with the armature. As the back e.m.f. generated by the armature rises, the current flowing in the armature falls.

This causes the armature voltage to increase until it reaches values that progressively activate relays. These relays remove part of the starting resistance from the armature circuit and the current again increases and repeats the sequence.

If for any reason the motor is unable to accelerate to full speed, the current remains high and the relays are unable to reduce the resistance in the armature circuit.

The principle is illustrated in Figure 13.33.

Assume a supply voltage of 200 V, a full-load current of 20 A, a starting current factor of 2 (40 A), and an armature resistance of 1  $\Omega$ . Also assume that the voltage relays activate at 120 V and 160 V.

If two starting resistors each of 2  $\Omega$  were placed in series with the armature, the starting current would be:

$$I = V/R = 200/5 = 40 \text{ A}$$

that is, the current would increase to point A in Figure 13.33(b) when first switched on.

The voltage distribution across the series armature circuit would be  $V = IR = 40 \times 2 = 80 \text{ V}$  across each of the series resistors and  $200 - 160 = 40 \text{ V}$  across the armature.

As the motor accelerates, it generates a back e.m.f. This opposes the applied voltage and produces a lower net

applied voltage and causes the armature current to decrease.

When the current in the armature circuit has dropped to the full-load current of 20 A (point B in Fig. 13.33(b)) the voltage distribution will be  $V = IR = 20 \times 2 = 40 \text{ V}$  across each resistor and  $200 - 80 = 120 \text{ V}$  across the armature.

Relay K2/1 will activate at 120 V and short-circuit resistor  $R_2$ .

Resistor  $R_1$  would suddenly have its voltage increased to  $200 - 120 = 80 \text{ V}$ . As a result the armature current will surge back up to 40 A. For  $R_1$ ,  $I = V/R = 80/2 = 40 \text{ A}$ .

Because the armature is also in series, its current will also increase to 40 A (point C in Fig. 13.33(b)).

Acceleration of the armature will increase and the above procedure will be repeated until the current drops to 20 A again (point D in Fig. 13.33(b)).

The voltage across the armature will now be the line voltage, less the voltage across  $R_1$  ( $20 \times 2 = 40 \text{ V}$ ), that is,  $200 - 40$  or 160 V.

At this point the second voltage relay will be activated and short out the remaining resistance. The motor will continue running on a 200 V supply and a full-load current of 20 A.

#### 13.10.3 Solid state controllers

The disappearance of direct current supplies for industrial applications caused d.c. motors to be used only when their versatility and characteristics greatly exceeded those of a.c. motors for a particular application.

Solid state technology introduced the silicon controlled rectifier (SCR), so direct current became readily available without the need for the installation of expensive and dedicated machinery.

An SCR has the electrical ability to switch alternating current waveforms at precise instants in each cycle. The resulting a.c. waveform is not sinusoidal and the output is not pure d.c. As a consequence, harmonics are introduced into both the a.c. and d.c. circuits. Because of these

harmonics, direct current motors suffer increased electrical losses, which show as heat and higher running temperatures. Performance is reduced and the motors are noisier in operation.

A block diagram for electronic control of a shunt-connected motor is shown in Figure 13.34. An alternating current supply is rectified by a combination of rectifiers and silicon-controlled rectifiers. The current taken by the motor is monitored so that current surges can be controlled by the control circuitry. Separate controlled rectifier units are used in this instance for both field and armature supplies. This enables control of starting currents in the armature and enables speed control by regulating the strength of the field currents. Starting resistors are not usually needed because the d.c. voltage is adjusted according to the torque requirements and speed of the motor. Full voltage is not applied until the motor is up to its operating speed.

Solid state systems for d.c. motors are considerably more efficient than the older motor-generator systems, while still retaining their flexibility. Reliability might be slightly less in the sense that electronic components can fail without warning. This disadvantage is decreasing as more and more progress is made with electronic component reliability.

Solid state drives can be installed in any situation where an alternating current supply is available. In mines, where there might be explosion hazards due to the presence of gases, the solid state motor drive is usually preferred because of inherent safety features. The controllers eliminate the hazards of sparks that might occur with contactors and open contacts. Size is no limitation to their installation since 4000 kW fully reversing d.c. motor drives are already installed in mines and rolling mills.

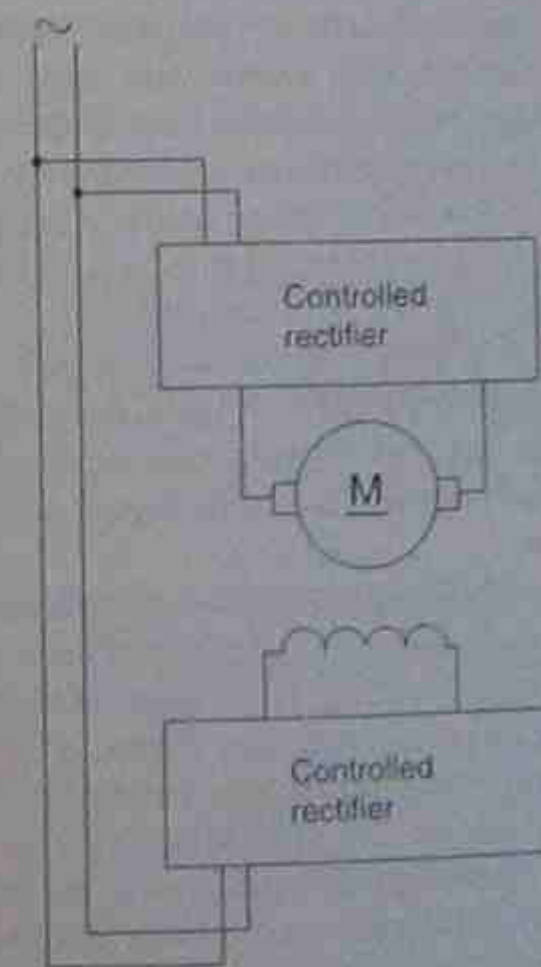


Figure 13.34 • Solid state control of a d.c. motor

### 13.11 DIRECT CURRENT MOTOR REVERSAL

Direct current motors can be reversed in only one of two ways. These are:

1. reversing the current through the shunt and series fields, or
2. reversing the current through the armature.

Note: It is important that precautions be taken to ensure that the connection between the interpole and the armature is never altered. For all practical purposes the interpoles are part of the armature circuit. Reversing the current through one must also reverse the current flow through the other. The sole purpose of interpoles is to minimise the field set up by the armature when it draws current. In an ideal situation the interpoles would neutralise this armature field. It is definitely not part of the normal field circuit and plays no direct part in creating motor torque.

The first method—reversing the currents in shunt fields—involves opening and closing inductive circuits, with the result that induced voltages high enough to cause damage are produced. These then have to be countered in some way. In compound motors there is the added complication of also interrupting the armature current in order to reverse the series field.

The second method is usually adopted for reversing a motor with contactors. All that is required is two contactors for armature current, plus any auxiliary contacts that might be needed. No highly inductive circuits are opened or closed, thus removing any need for precautions against high induced voltages.

Figure 13.35 illustrates a circuit for a reversing controller used in conjunction with a compound-connected motor. The back e.m.f. starting method is used for controlled acceleration. Contactor coils K1/1 and K2/1 operate at voltages of 200 V and 120 V respectively.

This circuit is not complete and some details not relevant to the explanation have been omitted. Indeed, as it stands the circuit is not very practical. It does, however, serve to illustrate the functions required for a starter of this type.

It can be seen from the power circuit that when contacts K4.1 and K4.2 are closed, current will flow from positive downwards through the armature and the interpoles (solidly connected together) and then through the series field and the starting resistors  $R_1$  and  $R_2$  and back to negative.

When contacts K5.2 and K5.1 are closed, the current flow will be upwards through the interpoles and armature but in the same direction as before for the rest of the power circuit. In both instances the direction of current flow through the shunt and series fields is unchanged. Contactors K4/6 and K5/6 are mechanically interlocked to prevent current bypassing the armature. The two contactors are also electrically interlocked by contacts K4.5 and K5.5.

The starting sequence is similar to that in Figure 13.33, although the starting resistors' relays are activated at 160 V and 200 V in that case. Contact K4.3 is the latching contact for the forward direction and contact K5.3 for the reverse direction.

When a starting button is pressed, the circuit is completed through the stop button, the normally closed contact K3.1, and one of the normally closed interlocks. This isolates the main contactor for the reverse direction. Simultaneously either K4.4 or K5.4 is closed and this

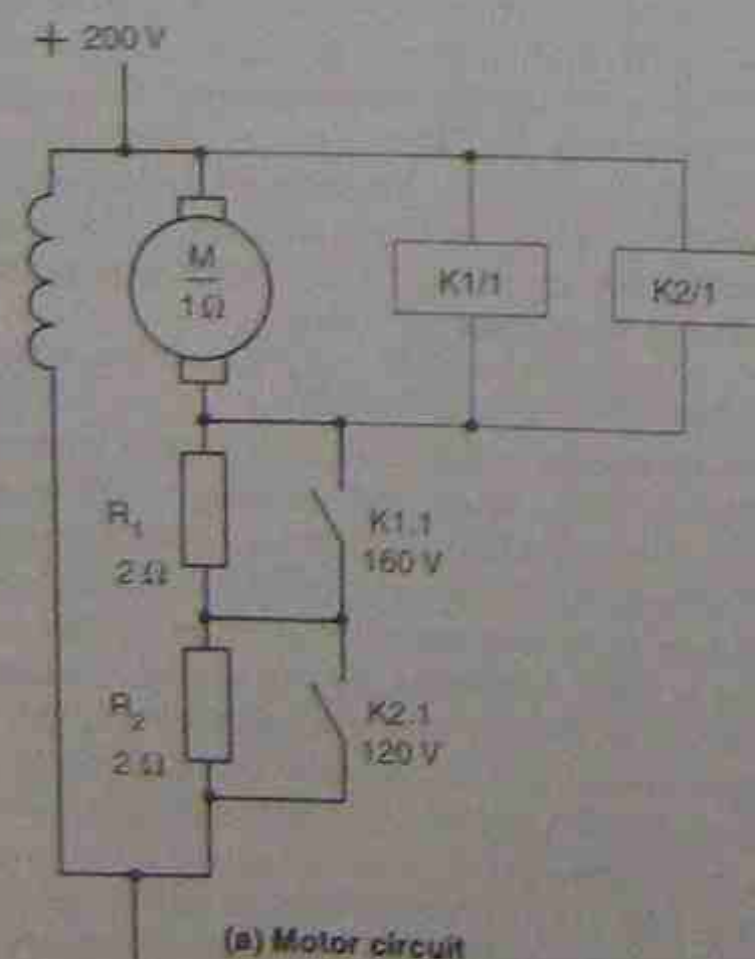


Figure 13.33 • Back e.m.f. d.c. motor starting



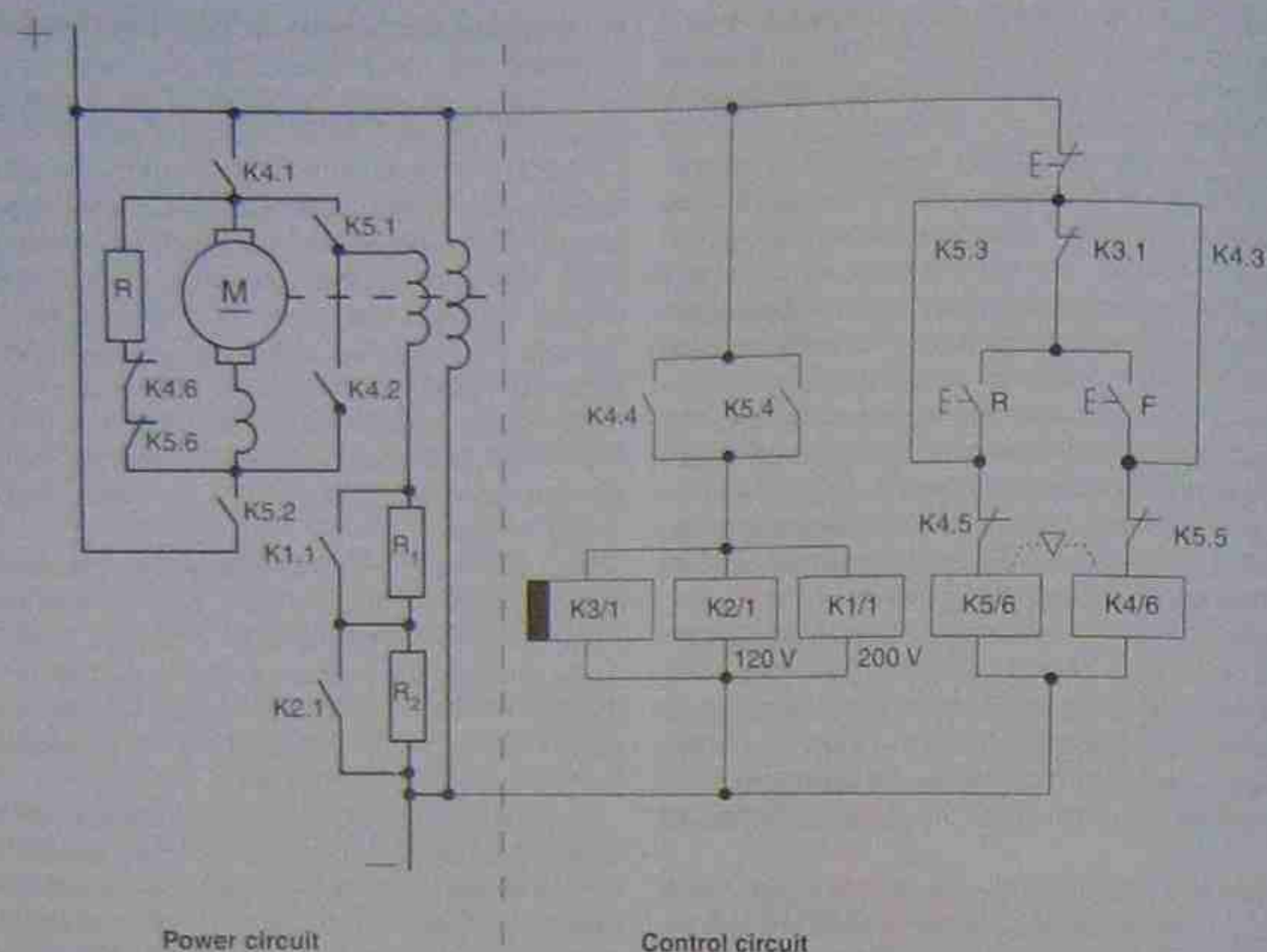


Figure 13.35 • Principles of a reversing contactor for a compound connected d.c. motor

activates relay K3/1, as well as bringing the back e.m.f. relays K1/1 and K2/1 into the circuit.

Relay K3/1 has an important function. As its symbol indicates it acts instantly but its release function is delayed for several seconds. When power is applied to relay K3/1, contact K3.1 opens immediately.

Its immediate function is to isolate both forward and reverse push-buttons until the motor has come to rest after the stop button has been pressed. To prevent high surge currents the motor must come to rest before power is applied to drive it in the reverse direction.

To hasten the process of bringing the motor to rest, a resistor is connected in series with contacts K4.6 and K5.6 and in parallel with the armature. It is there to act as part of a dynamic braking system. At the instant of starting, this resistor is taken out of the circuit by the action of either one of the two main contactors. When power is removed from the motor by pressing the stop button, relay K3/1 keeps the starting circuit isolated until the dynamic braking action has taken effect.

### 13.12 DIRECT CURRENT MOTOR BRAKING

For most situations it is sufficient to allow a machine and motor to coast to rest when switching off. At times, some form of braking is required to bring the machine to rest in a shorter period.

The methods used for d.c. motor braking are almost identical to those used for a.c. motors. Mechanical braking is seldom used as a stand-alone braking method but is often used for bringing motors to a standstill when

electrical methods are having a lesser effect and it is also used as a holding brake.

Eddy-current disc and dynamic braking methods are still as effective as with a.c. methods. They are almost useless to bring a motor to a complete halt and hold it stationary. As motors slow down, the eddy currents and generated voltages also become less and are unable to continue exerting an adequate braking force. Since most d.c. motors are powered by local rectifier supplies, the use of regenerative braking is ruled out as a possible braking method to bring a motor to a standstill.

Plug braking is still effective and probably the quickest method of bringing a motor to a halt. As with a.c. motors, equipment must be installed on the motor to prevent it starting up in the reverse direction. Again a holding brake is also required.

At the instant of applying reverse power to a d.c. motor the back e.m.f. and the d.c. power supply are in series and additive, thereby providing a voltage almost twice line voltage across the armature. The result is that very high currents, and consequently torque, are created. The motor shaft is being driven in one direction by the driven machine while the windings are trying to drive it in the reverse direction. Machine and motor shafts have to be designed for forces many times greater than normal full load.

It might be necessary to introduce resistance in series with the armature to reduce the value of this current and torque, but this leads to a decreased braking effect. A lot of energy has to be converted rapidly to heat, mechanical stresses of the motor and windings are high, and it is advisable to consult motor manufacturers to have specially-built motors installed.

### 13.13 SPEED CONTROL OF D.C. MOTORS

The speed of a d.c. motor is directly proportional to the back e.m.f., and inversely proportional to the strength of the magnetic field. From these two factors it can be seen that the speed of a d.c. motor can be altered by varying the armature voltage and/or the field strength. When a fixed voltage d.c. supply is used, the only remaining means of speed control is by manipulating the strength of the shunt field.

A motor is usually brought up to speed using series armature resistors and maximum field strength. Motor speed is then increased by inserting series resistance in the shunt field. Field control is successful and reasonably economic over a limited speed range. A fine-speed adjustment is possible but because of the high inductance of the field windings the response to speed changes is comparatively slow.

There are practical limits to increasing the speed of any d.c. motor above its normal full speed unless the motor has been specially built for higher speeds. For a standard motor, doubling the speed is usually more than sufficient to approach the designed mechanical limits for the windings. Running a d.c. motor at a speed that causes the windings to lift causes irreparable damage.

The forces exerted on windings and commutator segments increase out of all proportion at higher speeds. Commutation problems become more prominent and lead to increased sparking. In extreme cases brushes tend to float and bounce on the commutator surface, causing more sparking. Rotational effects on bearings also have to be considered.

Once a common form of speed control, resistance was inserted in series with the armature. It was an inefficient method and led to occasional stalling because of the pronounced drooping torque characteristic developed by the

motor. Before solid state technology there were few alternatives available.

Modern electronic voltage control methods have replaced the series resistor system, eliminating the need for large banks of resistors. Precautions often had to be taken to remove the heat being radiated from the resistors. The a.c. supply is rectified with silicon controlled rectifiers enabling a wide range of d.c. voltages to be applied to the armature.

The characteristics of d.c. motors under speed control conditions are summarised below.

#### Field control

Field control is applicable for speeds from just below base speed up to approximately twice base speed. Torque decreases as speed increases, while the power remains constant. (See Fig. 13.36.)

#### Armature voltage control

Armature voltage control is applicable for speeds from zero up to base speed. Torque remains constant. (See Fig. 13.36.)

Motor speed control methods are listed below in Table 13.4.

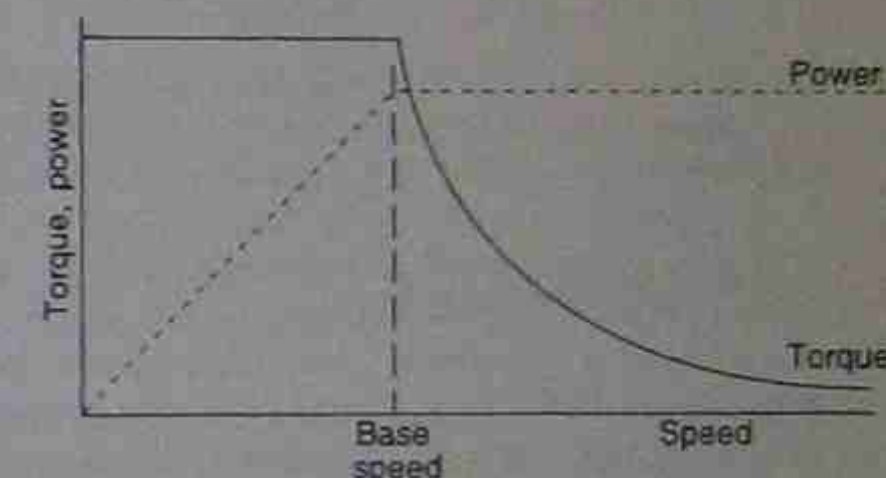


Figure 13.36 • Direct current motor speed characteristics

Table 13.4 • Summary of motor speed control methods

Motor type	Speed characteristic, no load/full load	Type of speed control
a.c. squirrel cage, two-speed	Speed drop 5%	Pole changing, two windings
a.c. squirrel-cage, single-speed	Speed drop up to 15% depending on design	Primary voltage control. Stator frequency control ( $V/f = k$ )
a.c. slip-ring	Speed drop up to 50% depending on resistance step	Secondary resistance connected to slip-rings
a.c. synchronous	Speed drop 0%	Adjustment of stator frequency
d.c. series connected	Speed drop up to 100% depending on control	Series resistance. Solid state chopping of wave
d.c. shunt connected	Speed drop 5% without series resistance, 50% with series resistance	Armature shunt and series resistors
d.c. self-excited	Speed drop up to 5%	Adjustment of armature voltage



### 13.13.1 Other methods of speed control

#### Ward-Leonard system

The principle of operation of the Ward-Leonard system is illustrated in Figure 13.37. A prime mover (engine or another electric motor) drives both a small separately excited generator called an exciter and the main generator. A small additional separately excited generator operating as a tachometer provides a reference voltage proportional to the speed of the generator.

The output from the exciter armature supplies the field windings of the main generator. At the same time the generator armature supplies electric power to drive the motor. In turn the motor speed is indicated by the output from another tachometer.

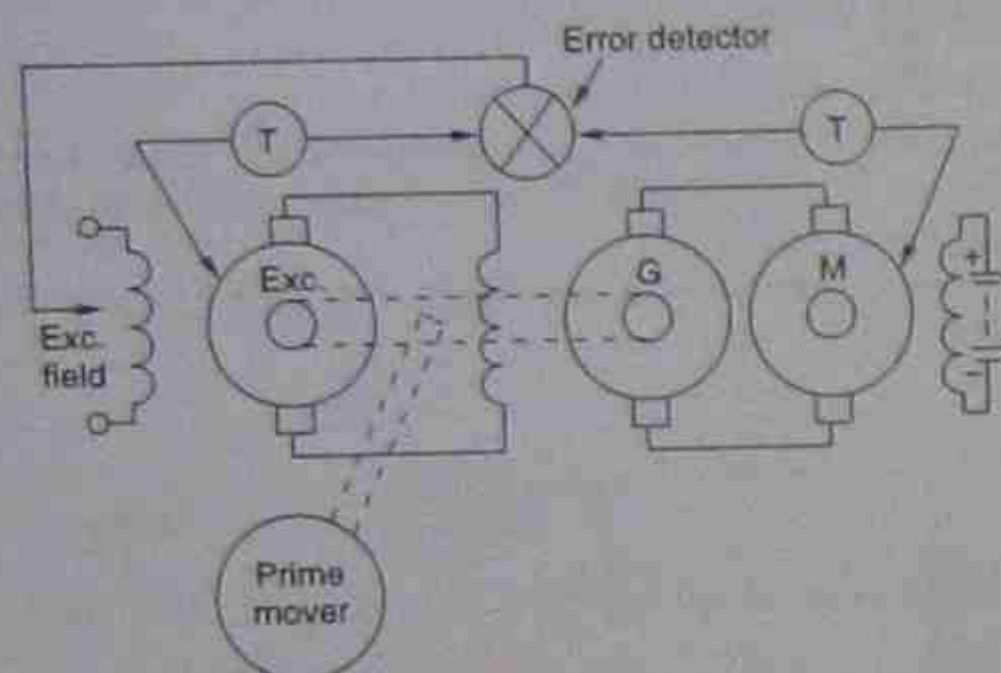


Figure 13.37 • Ward-Leonard system

The two tachometer voltages are connected to an error detector, where the two voltages are compared. The difference in voltage, which may be of either polarity, is amplified and supplies the field of the exciter.

The system enables remote control with only a small exciter field current being manipulated at a remote position. With suitable connection arrangements the final motor drive can be stopped or reversed at will. A wide range of speed adjustment is also attainable.

Once used for gun control on warships, remote control of ship propulsion equipment and machine control in machine shops and rolling mills, its usefulness has been somewhat restricted since the introduction of the amplidyne system.

#### Advantages of the Ward-Leonard system

1. The speed range is much greater than that obtainable with armature voltage and field strength control.
2. Control is generally with a comparatively small rheostat with a small power input.
3. All heavy armature current contactors are eliminated. The motor is stopped, started, or reversed by adjustment of the polarity of the generator voltage.
4. Generators with special characteristics can be made to match specific load requirements.
5. The system lends itself to remote control.

#### Applications

- Excavators and electric shovels.
- Speed control of electric motors—variable voltage.
- Ship propulsion power systems—variable speed and direction.
- Electric train control.
- Industrial machines, for example, large planers.

#### Amplidyne system

The amplidyne system, while more expensive than the Ward-Leonard system, has the advantage of being more sensitive to smaller changes in operating conditions.

An amplidyne can be likened to a separately excited d.c. generator with its normal output brushes short-circuited. When driven by a prime mover this would normally lead to excessive currents flowing in the armature.

In this machine, the main field strength is reduced to the value where the current flowing through the short-circuit is limited to normal full-load current. In turn this produces a field by armature reaction at right angles to the main field. An extra set of brushes is installed to connect to the voltage generated by the armature reaction. The brushes are connected to the load as shown in Figure 13.38. These arrangements allow the amplidyne output current to be controlled by a few milliamps of current in the normal field circuit of the machine. The amplification is so high that special-purpose field windings are often introduced for stability of operation by damping the machine's response.

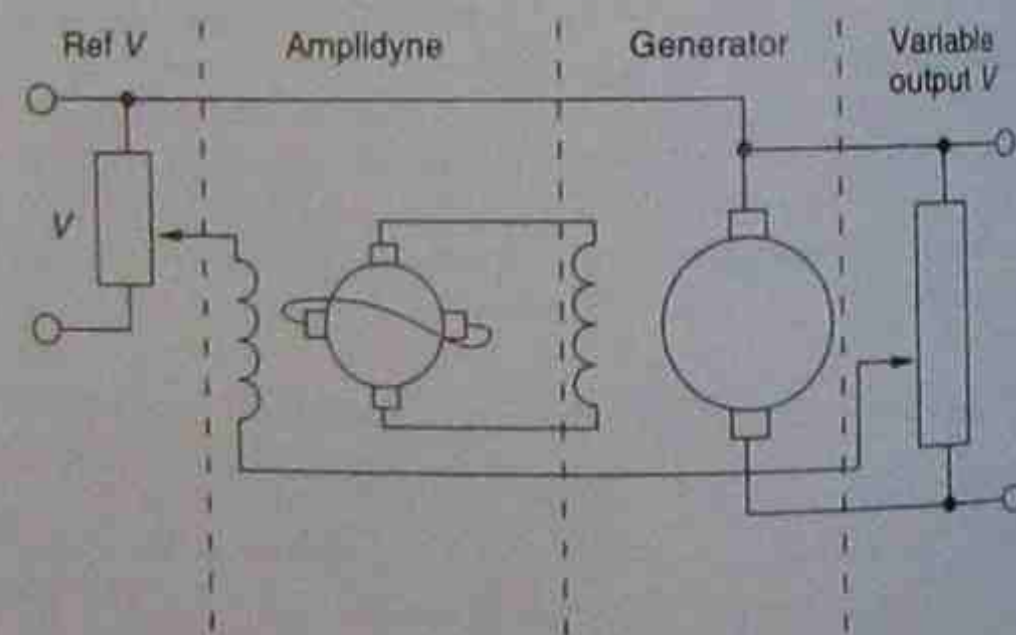


Figure 13.38 • Typical amplidyne application (all non-essential fields omitted)

Practical circuits often have several fields. Their combined effect on the resultant magnetic field determines the output of the machine. Windings and/or separate poles may be provided for stabilising the output as well as monitoring output voltages and currents.

#### Advantages of the amplidyne system

1. Fast response time to an input signal change (typically less than 0.25 s).
2. Inbuilt fields for voltage and current regulation.
3. External circuits can be configured for variable voltage control or speed control.
4. Elimination of contactors in controllers.
5. Readily adapted to remote control.

#### Applications

- Armature current control, for example, strip rolling.
- Excavators and electric shovels.
- Constant voltage control for generators.
- Variable voltage control to give speed control of larger motors.
- Voltage control of alternating current generating plants.

### 13.14 DIRECT CURRENT MOTOR PROTECTION

In general terms, d.c. motors require the same sort of protection as a.c. motors. Thermal and magnetic overload protection is as much applicable to d.c. motors as it is to a.c. motors. Fuses are an essential part of both d.c. and a.c. circuits.

There are, however, some items of protection that apply specifically to d.c. motors.

#### 13.14.1 Field-failure protection

Extreme weakening or complete loss of a shunt field is an unlikely event, but it is a possibility that exists and precautions need to be taken. The complete or partial loss of the shunt field results in a sharp reduction of generated back e.m.f. This causes a big increase in armature current, often without a corresponding rise in torque. When a motor is coupled to a load it might be unable to increase the speed of the load and high currents continue to flow, thus damaging the armature windings.

If the motor can shed the load or is unloaded, high speeds occur. This can result in armature windings being thrown out of the slots by centrifugal force. Commutator segments can also be thrown out of their assembly. Where motors are coupled to loads subject to the forces of gravity, loss of motor control allows the load to fall out of control. Damage and injury can occur.

To prevent these incidents a field-failure relay is used. It consists of a pair of normally open contacts with the activating coil connected in series with the shunt field. The normally open contacts of the field-failure relay are connected in series with the main contactor.

While field current flows, the relay is activated, the contacts are closed, and power can be applied to the armature by the main contactor. In the event of a field failure the relay contacts open, allowing the main contactor to fall out and isolate the motor. Figure 13.39 shows part of a control circuit with a field failure relay in circuit.

#### 13.14.2 Field discharge protection

When disconnecting the shunt fields of many d.c. motors from the supply, the induced voltages created as the magnetic field collapses can be high enough to break down the insulation of the windings. An electric circuit should be connected in parallel with the field to enable this converted energy to be dissipated without damage to the circuit.

In Figure 13.39, two forms of protection are shown, although only one need be used.

Where the polarity of the field supply is constant the

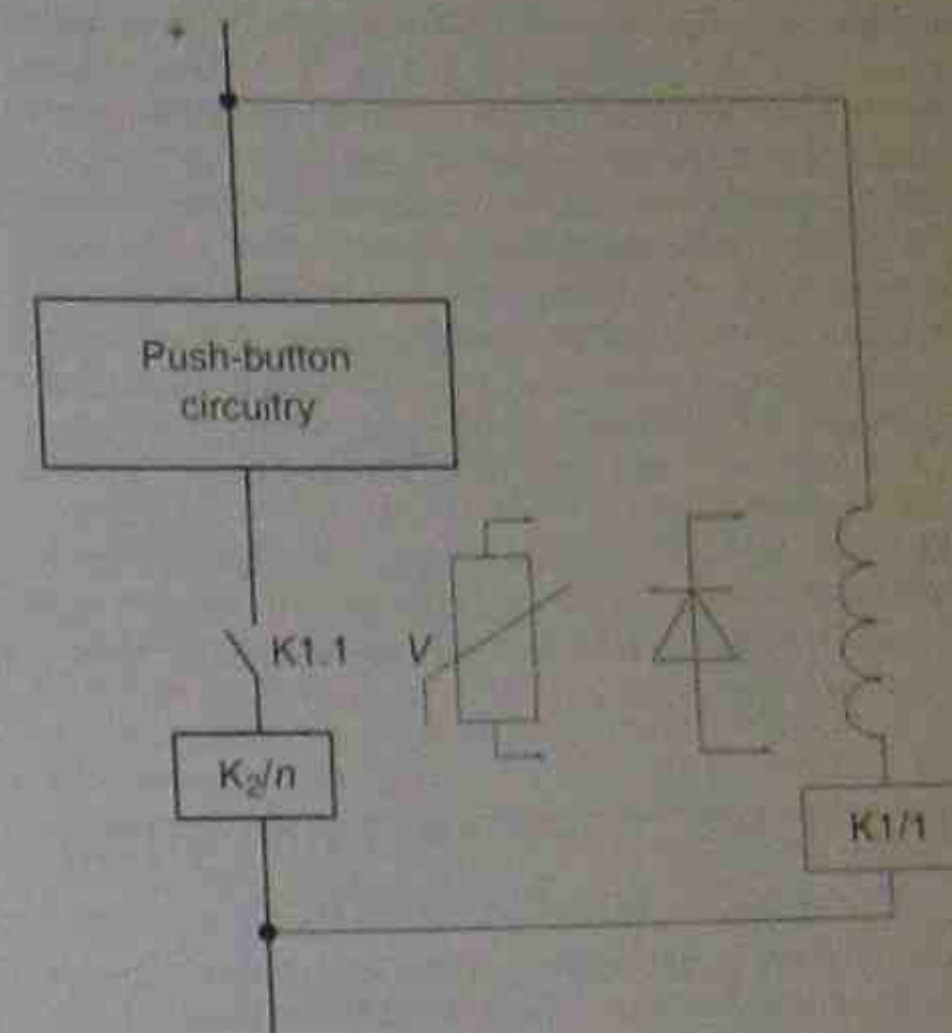


Figure 13.39 • Field failure relay connections

reverse-connected diode is sufficient protection for the field circuit. The diode has to have a voltage rating high enough to withstand line voltage in the non-conducting state and it has to have a current rating high enough to avoid being damaged by the discharge currents.

Where the polarity of the field supply is subject to reversal, the second type of protection is used. It consists of a special compound that has a high resistance at normal voltages. When the rated voltage is exceeded, the resistor reverts to a low resistance and allows the energy to dissipate. When the high voltage is removed, the unit changes back to a high resistance. The components are made under several trade names and are also used for lightning protection.

#### 13.14.3 Over-voltage protection

Although included here as a protection method, over-voltage protection is more applicable to direct current generators. Generators subject to a wide range of speeds when driven by a prime mover are capable of producing high voltages. The output voltage can be three to four times normal voltage while under the influence of full-strength magnetic fields.

Automobiles, aircraft, and similar engine-driven units have generators driven either by belts, or directly driven by solid drives. They are an accessory and quite separate from the primary drive intention. The engines are necessarily subject to a wide range of speeds, so it follows that the generators will also have a wide speed range.

Since the generator is expected to produce a useful output at comparatively low speeds it will need some form of voltage control when driven at high speeds. Many systems for regulating the output voltage have been used but all rely on controlling the field current of the generator to control output voltage.

Probably the most common form of voltage control is a



quick-acting relay sensitive to voltages above a certain level. Older style voltage regulators often had a voltage-controlled relay that inserted resistance in the field circuit when the relay was activated.

In more modern units, voltage sensitive semiconductor components were introduced. These conduct at specific voltages and reduce the current flowing through the field. Depending on circuit configuration, the unit can insert resistance into the circuit or divert the current around the field when voltage levels exceed a set value. The method is accurate and can also be combined with current-controlled sections.

Many mobile units use alternators with rectifier units to produce direct current. A similar control method is used for over-voltage protection since the alternator field is excited with direct current.

### 13.15 BASIC CONCEPTS OF STATIC AND LOGIC CONTROL

In this chapter so far mainly relays and contactors have been discussed. Automatic control had its beginnings with these components. Relays can perform many of the functions required for automatic control. Contacts of relays can be normally open or they can be normally closed or even a combination of both.

The basic relay provided adequate control for automatic control and processing of industrial processing for many years, but as the demand for improvement grew, the limits of the relay became apparent. Mass production industries required improvements that the relay could not compete with in the sense of high speeds, reliability of service and minimum maintenance.

Solid state circuitry was introduced initially because of its ability to operate as on/off devices and to reliably repeat the operation for millions of times more than a relay could and without more than cursory maintenance. The decision for it to be in either an on state or an off state depended on an input signal from an external device called a transducer.

The transducer in general provides an input signal in the solid state device and this in turn operates the required device. For example, a thermostat can be manufactured to close its contacts at a specific temperature. Closure of the contacts acts on an electronic component, which can then start an air-conditioning system. When the temperature in the monitored area drops sufficiently, the contacts of the thermostat open and the air-conditioner stops. Note that the system has only two states—on or off.

In this example the thermostat replaced the start push-button of the relay circuit and a solid state device such as a triac (refer to section 16.5 for more information) replaced the contacts of the relay. For industrial process control, this on/off method does not provide sufficient accuracy for the production of many products. Devices such as the thermostat above cannot operate at the one temperature for both on and off states. This introduces a differential; that is, if the contacts open at 22°C it is extremely unlikely they will also close at the same temperature. Depending on the circuit, the closing temperature may be 18°C giving a differential of 4°C.

This led to the introduction of the programmable controller. Originally intended to be a replacement for the relay panel, initially it did little more than manage the on/off sequencing of motors and solenoids. It gradually evolved into the intelligent item of equipment it is today.

The modern programmable logic controller (PLC) has a relatively low cost and the original programme can easily be reprogrammed to monitor something completely new when the manufacturing requirements change. A logic control programme is stored in its memory and this tells the central processing unit when certain events should take place and the sequence in which they will occur. It makes these decisions based on information it receives from sensors connected to its input terminals combined with user-programmed instructions.

Figure 13.40 shows a block diagram for a solid state reduced-voltage starter for a three-phase motor. It can be seen that the central processor has three inputs to receive information from the starting circuit, the line voltage and the line current. This enables it to start and operate the

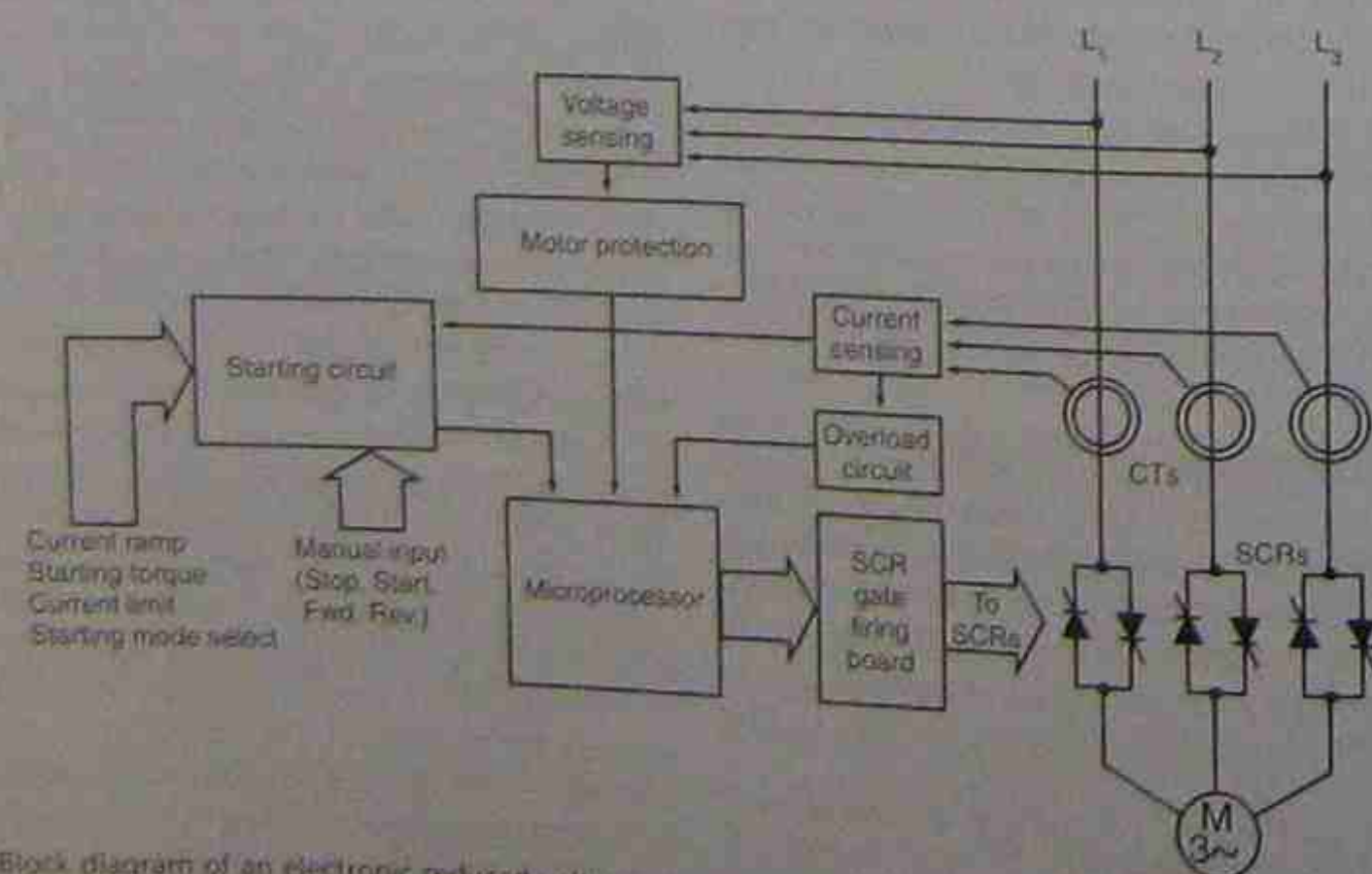


Figure 13.40 • Block diagram of an electronic reduced voltage motor starter

motor efficiently. It monitors the line current at all times, particularly during the start-up sequence, to limit the amount of current that can flow into the motor at that time. This is often set at about 300 per cent of full-load current. If at any time any one phase voltage deviates outside set limits or disappears altogether the motor protection circuit conveys this information to the processor and the processor takes the required action to protect the motor. Similarly, the motor is also protected against overloading and overheating. Note that there has to be an operator on hand to push the necessary buttons for the motor to start and stop.

#### 13.15.1 Programmable logic controllers (PLCs)

Figure 13.41 shows a block diagram for a programmable logic controller. The inputs to the PLC receive information from external sources while the PLC outputs send information to the controlled process whether it be the starting of an electric motor or some other appropriate task.

By introducing a PLC into the starting process for the motor controller shown in Figure 13.41 there is no longer any need for an attendant to be on hand to start or stop the motor.

This is illustrated in the block diagram of Figure 13.42. At the heart of the PLC is a decision-making unit called a microprocessor. The basis of this is shown in the block

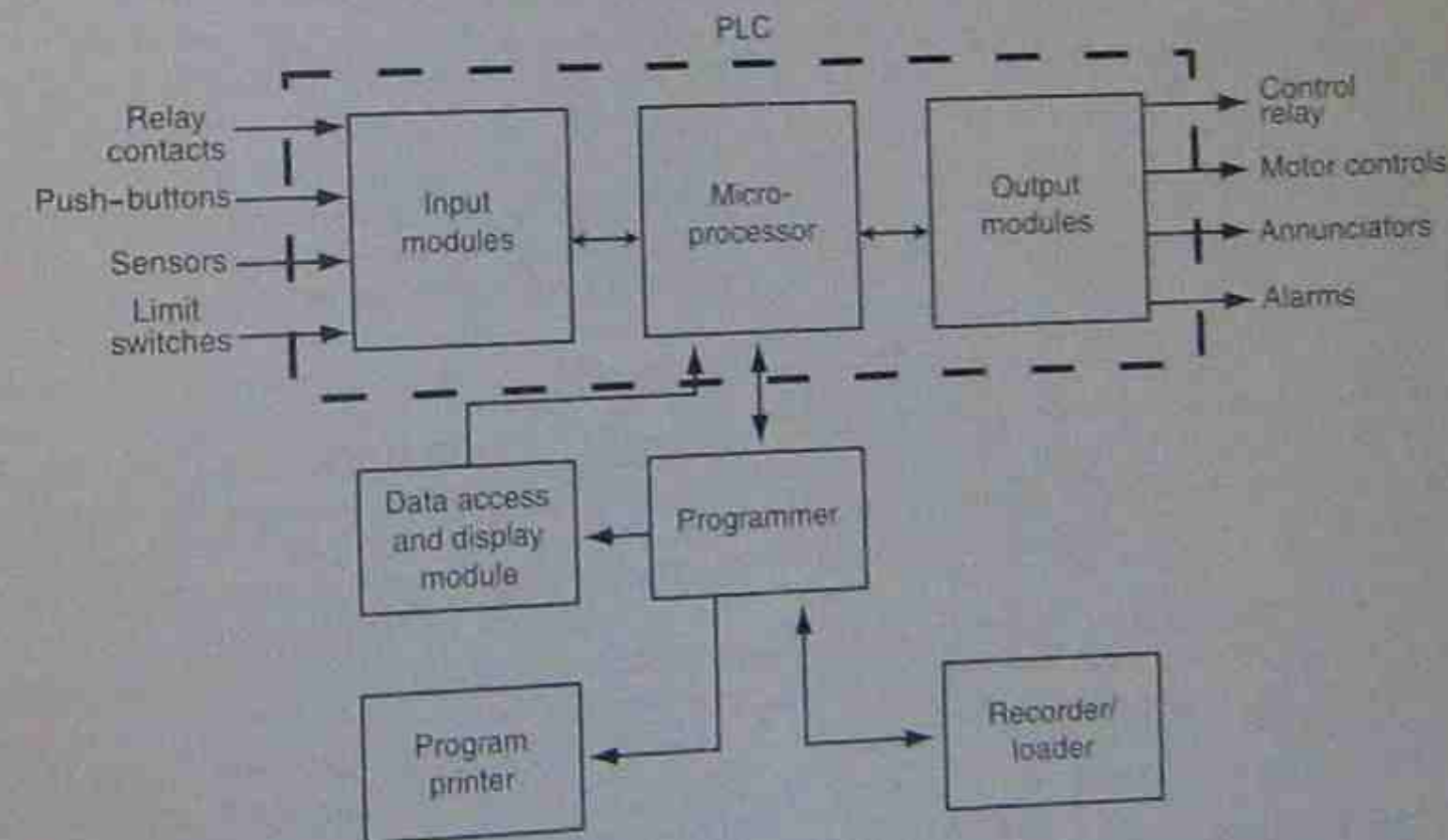


Figure 13.41 • Block diagram for a programmable controller

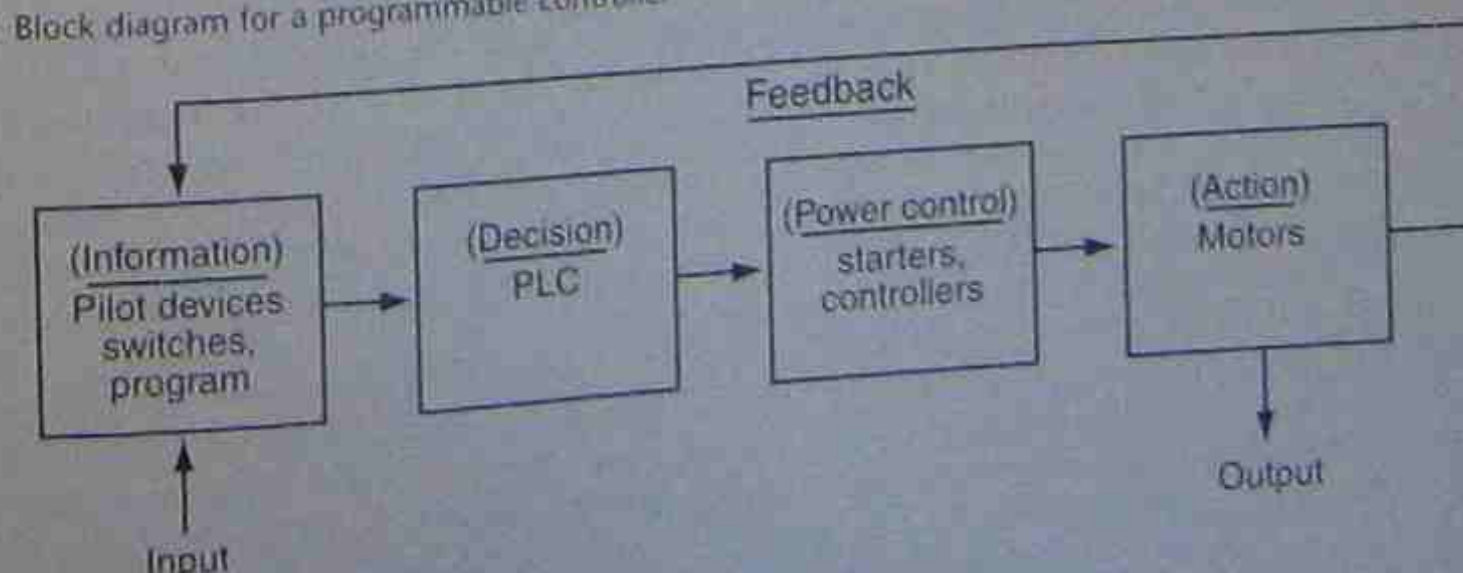


Figure 13.42 • Block diagram of an automatic starter

diagram of Figure 13.43. Note that the microprocessor is part of the PLC.

Technically there is a difference between a microcomputer and a microprocessor. A microcomputer contains a microprocessor and various other circuits to store information, provisions to connect it to the process being automated, and a clock. The clock provides specific electric pulses at specific times to control the internal processes of the unit.

#### Microprocessor programmes

A group of instructions that enable a microprocessor to perform a specific task is called a programme. A programme is a step-by-step procedure to solve a problem, initiate certain actions, or manipulate data that it stores within its memory.

The programme consists principally of numbers that have to be placed in a read-only memory (ROM) within the processor. It is then able to control the process under control repeatedly without variation until it is re-programmed from an external source.

#### 13.15.2 Transducers

By definition a transducer is a device where any variation in energy magnitude of any form is able to reproduce that variation in another measurable form. In this electronic age this is generally accepted to appear as an electrical voltage even though it may be in millivolts.



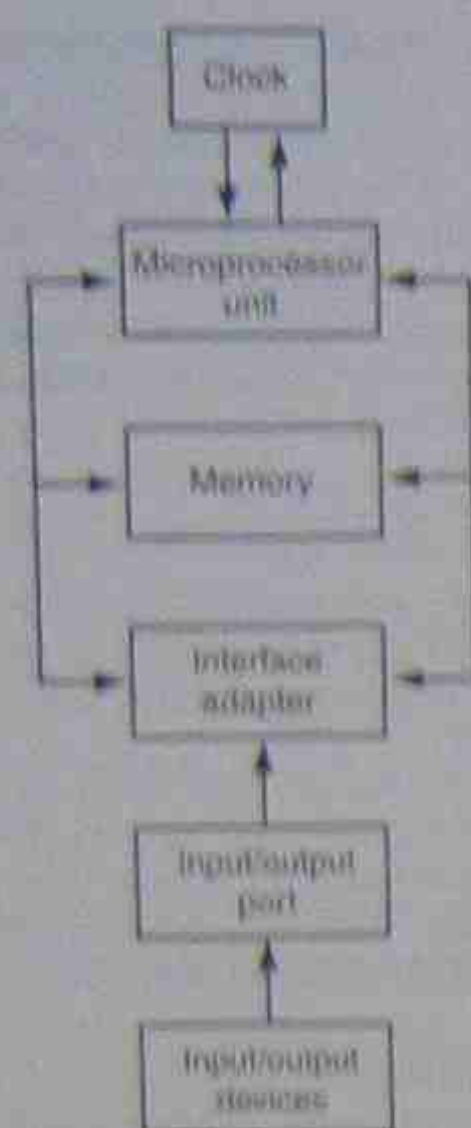


Figure 13.41 • Block diagram of a microcomputer

In Chapter 2 mention was made of thermocouples where two dissimilar metals on being heated at their junction produced a voltage. For example, a copper/constantan thermocouple with the cold end kept at a constant temperature produces 4.3 mV at 100°C and 14.8 mV at 300°C. A graph of a range of these values is approximately linear over a restricted range and can be used to indicate on a voltmeter suitably calibrated as a temperature. Alternatively the thermocouple can be connected to a PLC and be part of the control process.

Mechanical devices can be used as electrical limit switches to indicate to a PLC that some machine has reached the limit of its position. Pressure switches can be fitted with a pair of contacts to indicate an on/off relationship, or if fitted with certain types of reactive material can provide an infinite number of pressure readings to a PLC.

Positive and negative temperature coefficient resistors were also mentioned in Chapter 2 and, provided they are suitably calibrated, they can also be used as temperature indicators.

### 13.15.3 PLCs and safety

Safety in respect of programmable controllers needs to be looked at from the three aspects described below.

#### PLC safety and protection

The PLC in an industrial environment obviously needs a certain minimum of mechanical protection. Additionally it needs some basic electrical protection. The transducer connections radiate out from the controller and are subject to spurious voltages being induced in the connecting cables. This is generally referred to as electrical noise and can be misinterpreted by the microprocessor as a form of input. It can produce erratic equipment operation, incorrect data entry and prove difficult to trace as the source of trouble.

In the industrial situation there are usually many machines and other equipment being switched on and off continually. This causes voltage spikes and surges in the main supply. Since a PLC operates at a low voltage a transformer is employed to reduce the mains voltage to a suitable value and as a consequence these surges in voltages are transferred through the transformer to the processor.

Suppression of this electrical noise becomes quite an essential requirement for satisfactory operation of a PLC. This might mean applying special runs with shielded wiring to the transducers as well as noise suppression actually at the transducer.

#### Controlled equipment safety

Where machinery is controlled by a PLC, precautions have to be taken to ensure that erratic operation by a PLC does not lead to the destruction of that machinery. This usually means that extra equipment has to be installed. For example, a second limit switch might have to be installed as a backup to the first one actually controlled by the PLC. With heating baths, a second temperature sensor might have to be installed as a backup to the main one that sends information to the processor and overrides any function of the PLC and the first sensor.

#### Personnel safety

Operators or maintenance personnel must be protected against any erratic behaviour of the controlled process or task. Unexpected starting or stopping of equipment due to spurious signals getting into the system wiring can cause accidents. Emergency stop buttons should be included as part of the installation to override all other input signals.

AS/NZS 3000 has made it mandatory for provision of isolating switches in equipment not directly under control of a worker. Provision has to be made for isolation switches capable of preventing the PLC from bypassing them. The isolation must be a physical barrier and not just the switching off of electronic equipment.

## SUMMARY

- A motor starter is intended to start and protect the motor it controls.
- A starter limits starting currents, monitors any overloads, and stops or isolates the motor if necessary.
- There are several methods for limiting starting currents.
 

Direct on line	Line voltage starting
Star-delta	Reduced voltage starting
Autotransformers	Reduced voltage starting
Electronic	Reduced voltage starting
Primary resistance	Reduced voltage starting
Secondary resistance	Line voltage starting. Resistor in rotor circuit
- Each starting method has its own advantages.
- Starting torque varies with each starting method.
- Alternating current starters can be either manual, push-button, or automatic.
- Three-phase motors are always reversed by reversing the phase rotation—that is, reversing any two lines.
- Three-phase motor braking methods are:
  - Mechanical: friction with brake shoes; the only holding method.
  - Dynamic: electrical energy dissipated in resistance; includes eddy current discs.
  - Regenerative: converts mechanical energy to electrical energy and returns it to the supply source.
  - Plugging: full reversing power applied; power to be removed when motor stops.
- The speed of a three-phase motor can be controlled by changing the number of poles in the windings or by changing the line frequency.
- The number of poles can be changed by altering winding connections or by having more than one winding.
- Line frequency can be changed by converting the power supply to d.c. and then synthesising an a.c. supply at a different frequency. Non-sinusoidal waveforms generally detract from motor performance.
- Wound rotor motors are only partially adaptable to speed control with external resistors. They have poor performance and efficiency.
- Motor protection using fuses will protect the motor circuit, but not necessarily the motor.
- Magnetically operated relays controlled by motor current give protection to the motor but operate too quickly to prevent tripping on starting currents.
- Delayed tripping of magnetic-type overload relays is achieved with oil-filled dashpots.
- Thermal overloads have a built-in delaying action but will also trip on small overloads after a delay. The delay enables motor starting.
- Some overloads have combined thermal and magnetic protection. On small overloads, the thermal section will trip after a short delay. For excessive currents, the magnetically operated overload will trip more quickly than the thermal type.
- Temperature-dependent resistors embedded in the motor windings allow monitoring of winding temperature. Above a critical temperature, PTCs enable the main contactor to isolate the motor. The motor needs time to cool down before PTCs reset.
- Under-voltage protection has two forms: low voltage and no-voltage. No-voltage protection is inbuilt when using contactors. Low voltages are countered with slow release relays. These do not release immediately for momentary dips in voltage.
- Single-phasing protection can be achieved with three thermal overloads—one in each phase.
- A motor is physically protected by selecting the correct type of housing when choosing a motor for a particular purpose. Sealed types are available for special applications.
- Direct current motors are generally started by inserting resistance in series with the armature. The resistance is gradually reduced as the motor accelerates and current decreases.
- Voltage control as a means of controlling starting currents is usually available only in selected motors. Extra equipment is needed.
- Direct current motor starters can be manually or push-button operated. Full automatic starting and stopping is available with special starters.
- Acceleration, torque and starting currents can be controlled with timed relays, voltage sensitive relays, and electronic control.
- Direct current motor rotation can be changed by reversing the current flow through the fields or the armature—not both.
- Interpole fields must not be altered more correctly connected.
- It is usual to reverse armature current on larger motors to change the direction of rotation, rather than alter field connections.
- Direct current motor braking is usually by dynamic braking backed up by mechanical braking.
- Regenerative braking is an economic proposition only for very large inertial loads—for example, electric trains. It has to be supplemented with other types of braking.
- Diesel-electric trains use dynamic braking because they operate on their own generated supply. It is the most common form of electrical braking for all machinery.
- Plug braking is not recommended for d.c. motors unless special equipment or special motors are used.
- Other methods of speed control are the Ward-Leonard and amplyne systems. Both need expensive rotating machinery. Both give excellent results and control motor currents, voltages, and direction of rotation. They are used only for dedicated purposes and not as a general power supply.
- Direct current motor protection is similar to that of a.c. machines with some additional features. Loads need to be protected against over-voltages from faulty generating supplies or accessories.
- Direct current motor shunt field currents need to be monitored against field failure resulting in excess armature currents and motor runaway.
- Shunt fields on larger motors need some form of discharge protection against the high induced voltages generated when the magnetic field collapses.
- Automatic control of electrical equipment is attained with programmable logic controllers that are pre-programmed to make decisions based on signals conducted to them by transducers.



## EXERCISES

- 13.1 List the most important functions of a motor controller.
- 13.2 Describe the purpose of an over-current relay in a starter circuit.
- 13.3 Why are timing devices used in motor starting circuits?
- 13.4 List several types of relay used to control starting currents in a motor starter.
- 13.5 What is the function of a resistor inserted in an armature circuit for starting purposes?
- 13.6 What is the function of an accelerating resistor?
- 13.7 Why is it considered satisfactory to connect small d.c. motors direct on line?
- 13.8 Why is it considered unsatisfactory to start a large a.c. motor direct on line?
- 13.9 List three types of a.c. motor starter and describe the function of one of them.
- 13.10 Discuss the reasons why a three-phase star-delta starter and motor cannot be started against a heavy load.
- 13.11 Explain why an autotransformer starter can start larger loads than a primary resistance starter. (Consider the same size motor in each case.)
- 13.12 If a three-phase delta-connected motor has a maximum starting current of 100 A, explain why the current is reduced to 33 A when the motor is connected in star configuration.
- 13.13 What important advantage does a compound d.c. motor starter have over a normal faceplate starter?
- 13.14 What important differences exist between primary resistance and autotransformer starting?
- 13.15 Why should the shunt field of a d.c. motor be protected against high voltages?
- 13.16 What effect does an open-circuited shunt field have on a d.c. motor?
- 13.17 What are the disadvantages of a definite time accelerating relay? Are there any advantages?
- 13.18 How does a current-limited accelerating relay operate?
- 13.19 Compare the operations of back e.m.f. and current-limiting relays.
- 13.20 Explain the operation of a dynamic braking system.
- 13.21 Explain how an eddy current disc braking system functions.
- 13.22 What single important function does a mechanical braking system have that cannot be matched by electrical braking systems?
- 13.23 What is the function of plug braking? How is it accomplished?
- 13.24 Describe an overhauling load, where it might occur, and its possible dangers.
- 13.25 What is the major difference between plug braking systems on a.c. motors and d.c. motors?
- 13.26 Discuss the relative merits of dynamic and plug braking.
- 13.27 What is meant by a thermal overload device? Where is it connected into a circuit?
- 13.28 Compare the operations of a thermal operating device with a delayed-action magnetic relay.
- 13.29 Why must a magnetically operated overload have a delaying device fitted when starting an electric motor?
- 13.30 What is a thermistor? Describe its function and discuss its place in a control circuit.
- 13.31 Why are PTC resistors in a motor control circuit considered to be automatically resetting? Why do they have a long time delay before setting and resetting?
- 13.32 What is meant by part-winding starting? Describe its operation.
- 13.33 Compare secondary resistance starting with primary resistance starting.
- 13.34 What precautions should be taken when operating a d.c. motor with a weakened shunt field?
- 13.35 Both a Ward-Leonard machine set and an SCR rectifier unit can provide a variable voltage d.c. supply. List the advantages of each method.
- 13.36 What means are available for controlling the speed of a d.c. motor?
- 13.37 What two methods are available for controlling the speed of an a.c. motor?
- 13.38 Describe the operation of an amplidyne unit.
- 13.39 How does an amplidyne unit reverse the direction of current through its connected load?
- 13.40 What is meant by the base speed of a d.c. motor?
- 13.41 What is meant by the base speed of an a.c. motor?
- 13.42 How is the speed of a d.c. motor increased above its base speed?
- 13.43 Describe two ways in which the speed of an a.c. motor can be increased. Why are there only two ways?
- 13.44 What is the function of electrical interlocks in d.c. and a.c. motor starters?
- 13.45 What is the function of a series resistor in the shunt field of a d.c. motor?

- 13.46 How is torque developed in an a.c. motor?
- 13.47 How is torque developed in a d.c. motor?
- 13.48 What is the purpose of placing two stator windings in a three-phase motor?
- 13.49 What are the dangers of opening the field circuit of a d.c. shunt motor when it is running unloaded?
- 13.50 What is the function of a fuse? Describe its operation.
- 13.51 What is the modern method for obtaining direct current for a motor when only alternating current power is available?
- 13.52 What are the main advantages of solid state drives to the mining industry?
- 13.53 What are the main elements of a PLC?
- 13.54 What are the functions of the input and output modules of a PLC?
- 13.55 How does the electrical installation of a new programmable control system compare with that of an older relay installation?
- 13.56 Why is programmable control becoming the most popular form of control for industrial systems?



# Chapter 14

## Transformers

### 14.1 INTRODUCTION

A simple transformer consists of two separate windings on an iron core. One of the windings (called the *primary*) is connected to a source of electrical energy and the other (the *secondary*) to a load. The voltage of the secondary can be higher, lower, or the same voltage as the primary supply voltage. If higher, it is called a *step-up transformer*, if lower, a *step-down transformer*, and if at the same voltage, it is referred to as a *one-to-one* or an *isolation transformer*. Many transformers are fully reversible in operation, so the winding connected to the source of supply is always referred to as the primary winding.

A transformer has no moving parts, so it needs minimal maintenance. It ranges in size from a few volt-amperes to over 100 MV A with efficiencies over 99 per cent in the larger sizes. Its level of efficiency is far higher than any other electrical apparatus, and its cost of delivered energy is far lower.

### 14.2 OPERATING PRINCIPLE

The operation of a transformer is based on the principle of mutual induction. The primary and secondary windings and the magnetic core are all stationary with respect to each other. Because the primary winding is connected to an a.c. supply, an alternating flux is produced in the magnetic core (i.e. the magnitude of the flux is changing with respect to time). Therefore the three factors required to produce an induced voltage are present: conductors, flux and relative movement. The standard circuit symbol for a single-phase, iron-cored transformer is shown in Figure 14.1(a). A sketch of a small transformer is shown in Figure 14.1(b). Note the two windings are wound separately and placed side by side.

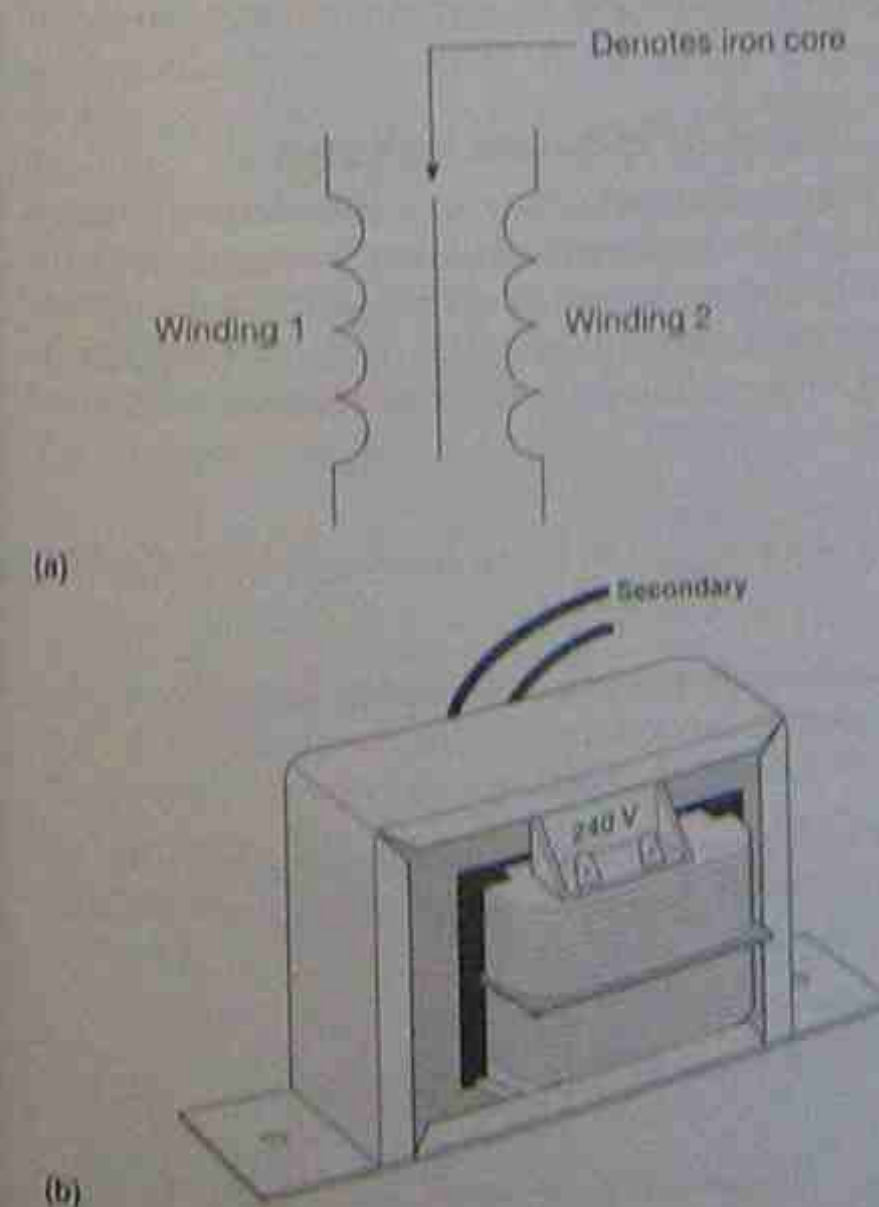


Figure 14.1 • Standard symbol for a single-phase, iron-cored transformer

### 14.2.1 No-load conditions

In Figure 14.2 the supply voltage is applied to the highly inductive primary winding. A self-induced voltage  $V_1'$ , only slightly less than the applied voltage, is produced in the primary winding and opposes the applied voltage. This results in a low effective voltage, causing a no-load or excitation current to flow. In many cases the excitation current can be as low as 1 to 3 per cent of the full-load current. It causes an alternating flux called the *mutual flux* to be set up in the core and linking both primary and secondary windings. The mutual flux causes a voltage to be induced in the secondary winding—the secondary voltage  $V_2'$ , but no current can flow until a load is connected.

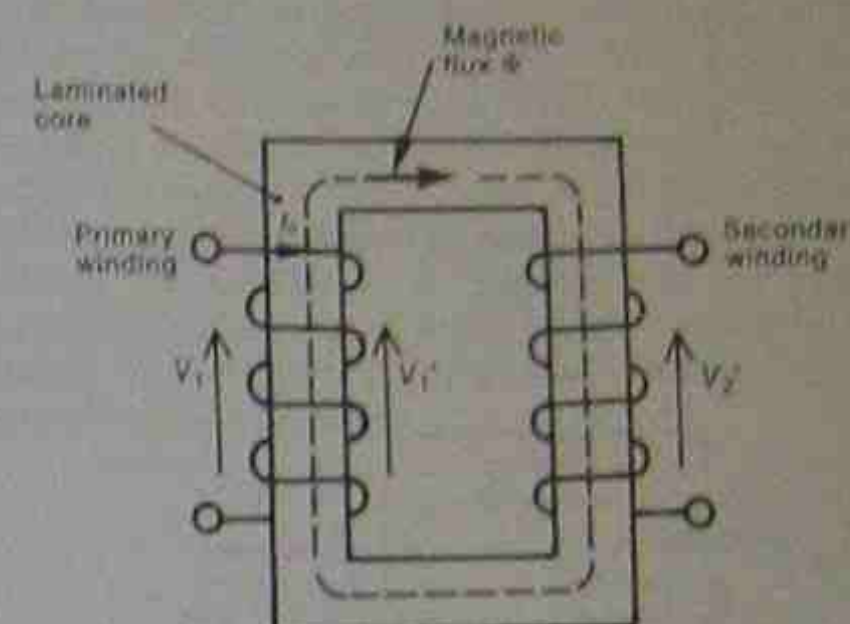


Figure 14.2 • Transformer on no load

The excitation current can be resolved into two rectangular components called the *energy* and *magnetising components*. The mutual flux produced by the magnetising component being common to both windings is used as the reference phasor when drawing phasor diagrams for transformers. The relationships are shown in Figure 14.3. The flux  $\Phi$  is shown as the reference phasor, and the magnetising component of the excitation current is in phase with it. Both  $\Phi$  and  $I_m$  represent the purely inductive part of the circuit and as such they will lag  $90^\circ$  behind the applied voltage  $V_1$ . This means that with flux as the reference phasor, the voltage will be leading it by  $90^\circ$ . The energy component of current  $I_e$  that represents the losses in the iron circuit and the small copper losses is resistive and will be represented by a component in phase with the voltage. A wattmeter connected into the primary circuit would show power being used to cover these losses. The phasor sum of  $I_m$  and  $I_e$  add up to the no-load current  $I_0$ . The large angle between  $V_1$  and  $I_0$  indicates a very poor power factor for a transformer on no load. The self-induced voltage  $V_1'$  in the primary winding, since it opposes the applied voltage, is  $180^\circ$  out of phase with it.

### 14.2.2 On-load conditions

When a load is applied to the secondary terminals, a secondary current  $I_2$  will flow and its magnitude and phase relationship with the secondary terminal voltage  $V_2$  is determined by the type of load. According to Lenz's law, the direction of this secondary current  $I_2$  will always be such as to oppose any change in the flux  $\Phi$ .



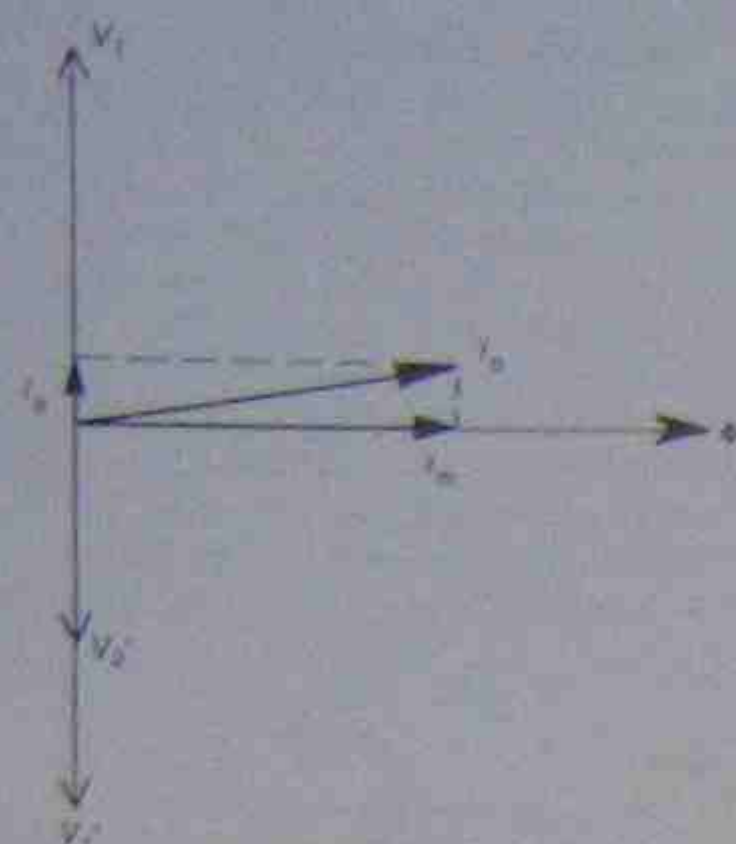


Figure 14.3 • Phasor diagram for a transformer on no load

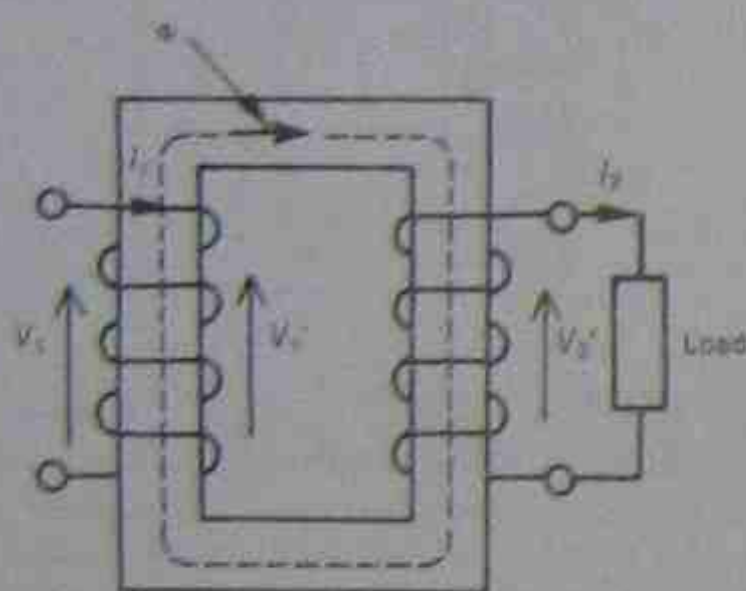


Figure 14.4 • Transformer on load

In Figure 14.4, it is assumed that at a particular instant the primary current  $I_1$  is flowing in the direction indicated, causing the flux to flow in a clockwise direction around the iron core. The secondary current  $I_2$  produces a secondary flux, sometimes referred to as the demagnetising flux, which opposes the mutual flux. To do this, the secondary flux must act in an anticlockwise direction and so  $I_2$  will flow in the direction shown.

Under those circumstances the effective flux in the core would be the resultant of the two opposing fluxes. However, a reduction in mutual flux would give a reduction in the self-induced voltage  $V_2'$ . A reduction in the self-induced voltage would allow the applied voltage  $V_1$  to increase the primary current  $I_1$  and so increase the mutual flux back to its original value. In reality all these happen together. The load causes a demagnetising flux; the mutual flux decreases; the self-induced voltage decreases; the primary current increases; the mutual flux rises to its original value. In practice it is assumed that the mutual flux in the iron core of a transformer stays at a constant value for all loads. Externally, an increase in secondary current output means an increase in primary current input.

The phasor diagram in Figure 14.5 shows the general case for loading a transformer. Assume for the purposes of

the diagram that the secondary voltage is equal to the primary voltage and the connected load is inductive, so that the secondary current  $I_2$  lags behind the induced voltage  $V_2'$  by the phase angle  $\phi_2$ . The equivalent current to supply this load will be the value  $I_1'$ . If the transformer was 100 per cent efficient, this value of primary current would be the actual current flowing into the transformer from the supply. Since the excitation current  $I_0$  is already flowing in the primary windings to cover core losses, the total primary current will be the phasor sum of these two currents. The phasor sum of  $I_1'$  and  $I_0$  gives the actual primary current of  $I_1$  flowing at a lagging phase angle of  $\phi_1$ . It should be noted that the excitation current has been enlarged for the sake of clarity and copper losses in the windings are considered negligible.

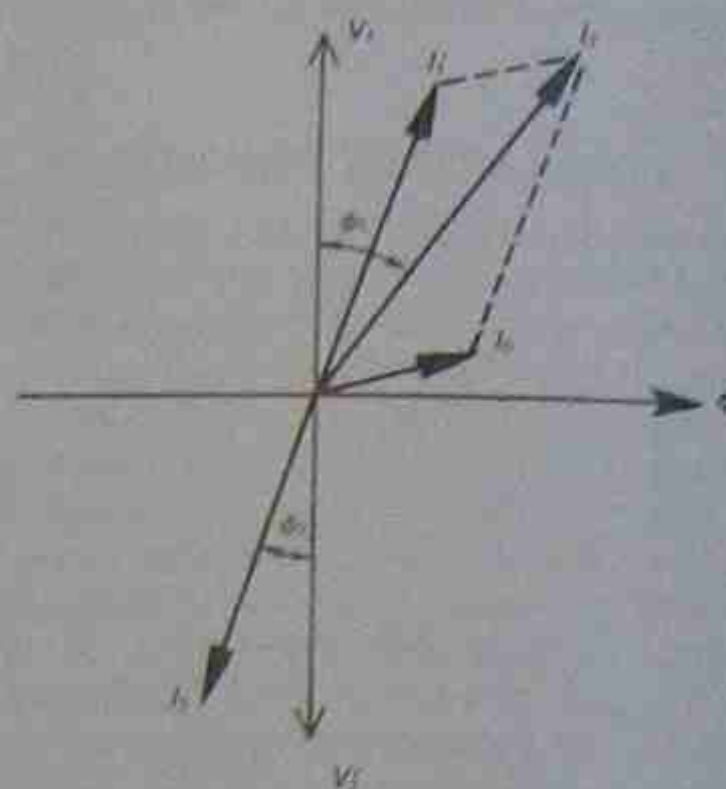


Figure 14.5 • Phasor diagram for a transformer on load

### 14.2.3 Value of induced voltage

The value of an induced voltage in a transformer depends on three factors: frequency, number of turns, and the maximum instantaneous flux. Provided that the current waveform, and consequently the flux distribution, is sinusoidal, the equation for the r.m.s. value of induced voltage is:

$$V' = 4.44 \phi_{\max} f N$$

where  $\phi_{\max}$  = maximum instantaneous flux  
 $f$  = frequency  
 $N$  = number of turns

Since transformer cores are usually designed on the basis of permissible flux density, the above equation may be expressed as:

$$V' = 4.44 B_{\max} A f N$$

where  $B_{\max}$  = maximum permissible flux density in Wb  
 $A$  = cross-sectional area of core in square metres

Note:  $\phi = BA$  (section 5.5.3).

## 14.3 TRANSFORMATION RATIOS

### 14.3.1 Voltage ratio

Because the mutual flux is common to each winding, it must induce the same voltage per turn in each winding. If  $V_1'$  is the total induced voltage in the primary winding having  $N_1$  turns, then the induced voltage per turn is  $V_1'/N_1$ . Similarly, the induced voltage per turn in the secondary winding is  $V_2'/N_2$ .

On no load, the applied voltage  $V_1$  and the self-induced voltage  $V_1'$  are almost equal and  $V_2 = V_2'$ , so the above ratios are transposed and usually expressed as:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

That is, on no load, the ratio of the voltages is equal to the ratio of the turns.

### Example 14.1

A transformer has 1000 turns on the primary winding and 200 on the secondary. If the applied voltage is 250 V, calculate the output voltage of the transformer.

$$\begin{aligned} \frac{V_1}{V_2} &= \frac{N_1}{N_2} \\ V_2 &= V_1 \frac{N_2}{N_1} \\ &= 250 \times \frac{200}{1000} = 50 \text{ V} \end{aligned}$$

### 14.3.2 Current ratio

When the transformer is connected to a load, the secondary current  $I_2$  produces a demagnetising flux proportional to the secondary ampere-turns  $I_2 N_2$ . The primary current increases, providing an increase in the primary ampere-turns  $I_1 N_1$  to balance the effect of the secondary ampere-turns. Because the excitation current  $I_0$  is so small compared with the total primary current on full load, it is usually neglected when comparing the current ratio of a transformer. Therefore the primary ampere-turns equal the secondary ampere-turns:  $I_1 N_1 = I_2 N_2$ .

This can be expressed as:

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

By comparing the current and voltage ratios, it can be seen that the current transformation ratio is the inverse of the voltage transformation ratio:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

## 14.4 TRANSFORMER LOSSES

### 14.4.1 Iron losses

#### Eddy currents

The magnetic core of a transformer consists of many laminations of a high-grade silicon steel of a definite thickness.

The power absorbed by the core of a transformer is called iron losses and is due to eddy currents and hysteresis.

When the alternating flux cuts the steel core, an e.m.f. is induced in each lamination, causing a current (called an eddy current) to flow in the closed electrical circuit of the lamination. Owing to this eddy current and resistance in each lamination, a certain amount of power will be absorbed, producing heat in each lamination and so also in the core. Although eddy-current losses are effectively reduced by using laminations for the core, they are never entirely eliminated.

#### Hysteresis

The alternating flux causes changes in the alignment of the molecules in the magnetic core. This change is energy consuming and heat is produced within the core. The energy loss is referred to as hysteresis loss, the degree of loss being dependent on the nature of the material used for the laminations. Silicon steel has suitable properties for electrical laminations because of its low hysteresis losses. Figure 14.6 shows a comparison of two hysteresis curves. It can be seen that the silicon steel curve has a smaller area, representing a lower energy loss and reduced heat production.

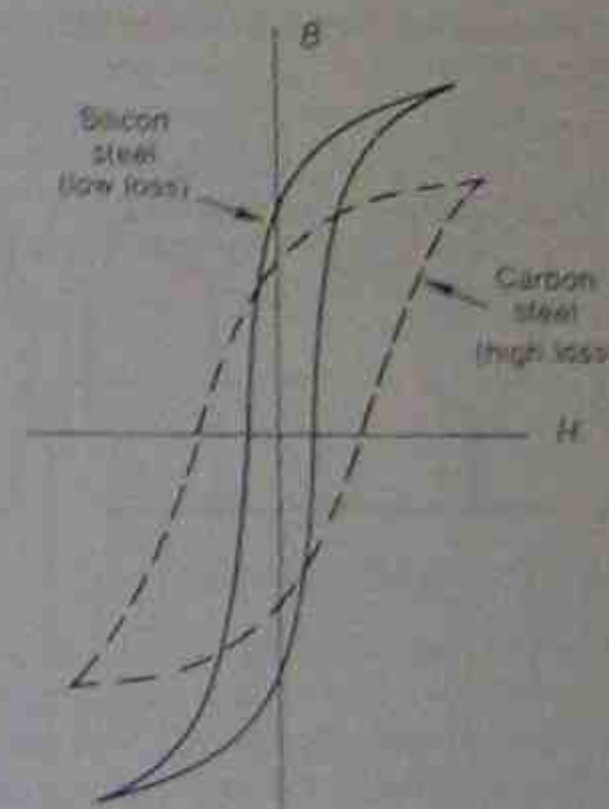


Figure 14.6 • Comparison of hysteresis loops

References to these losses have been made in section 5.7. The total iron losses represent the power absorbed by the iron core and so are proportional to  $I_0$ , the energy component of  $I_0$  in Figure 14.3. Because the mutual flux  $\phi$  remains fairly constant from no load to full load, it follows that the excitation current  $I_0$  producing that flux, and so  $I_w$  will also be constant. Therefore the iron losses will be constant irrespective of the load applied to the transformer (see Fig. 14.9). These iron losses can be obtained by measuring the power consumed on no load.

The transformer is connected as in Figure 14.7 to a supply at the rated voltage and frequency.

The primary current on no load is usually less than 3 per cent of the full-load current, so the primary  $I^2R$  loss on no load is negligible compared with the iron loss. The wattmeter reading can then be taken as being the total iron loss of the transformer.



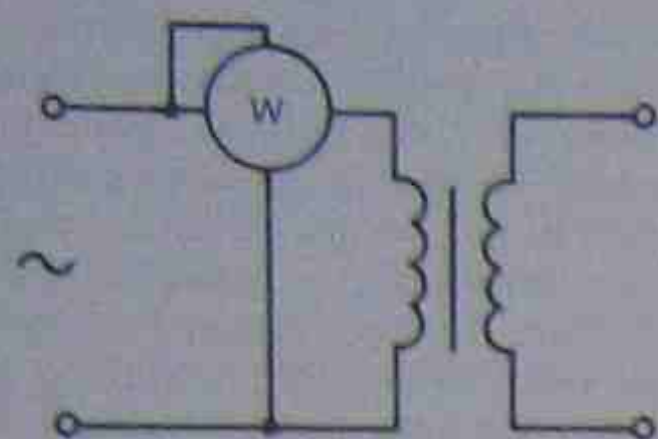


Figure 14.7 • Open-circuit test—iron losses

### 14.4.2 Copper losses

Another form of loss that occurs in a transformer is copper loss, which is the energy loss in the windings when the transformer is loaded. The resistance of each winding is relatively low, but since the power dissipated in each winding is proportional to the square of the current flowing through that winding, it follows that the copper loss is significant when the load current is high. The total copper loss is  $P_{cu} = I_1^2 R_1 + I_2^2 R_2$ , where  $R_1$  and  $R_2$  are the resistance values of the primary and secondary windings respectively. The copper losses are not constant, but vary according to the square of the load current. They can be obtained by using the short-circuit test, as shown in Figure 14.8. The typically shaped curve of copper losses can be seen in Figure 14.9.

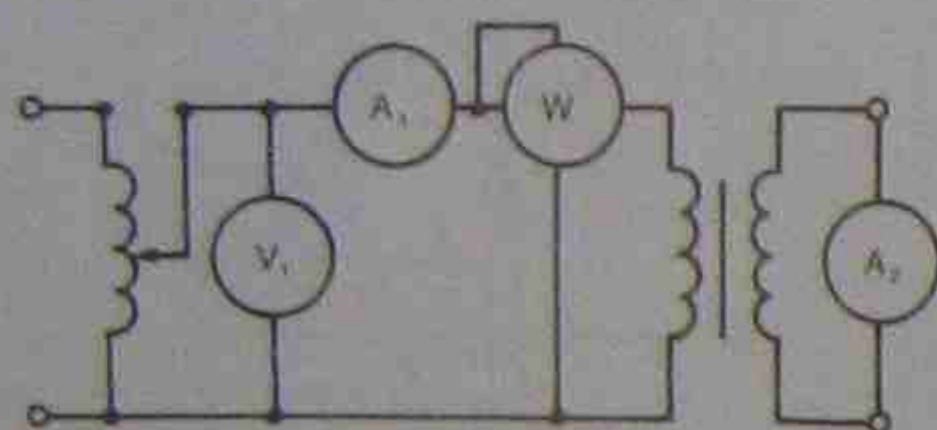


Figure 14.8 • Short-circuit test—copper losses

The adjustable transformer or autotransformer in Figure 14.8 provides a low-voltage supply to the primary winding of the transformer on test, and the secondary winding is shorted through the ammeter  $A_2$ . The output of the autotransformer is adjusted to circulate full rated

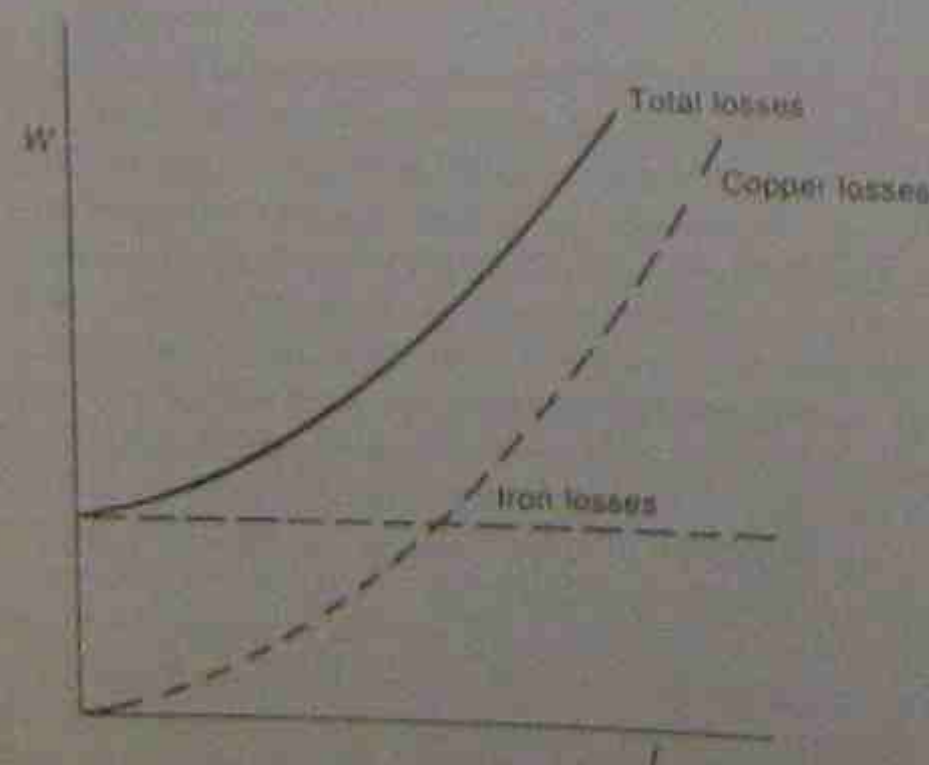


Figure 14.9 • Relation between copper and iron losses

currents in the primary and secondary circuits. Because the supply voltage to the transformer is low, the flux in the iron core is also low, and so the iron losses are negligible. The power registered on the wattmeter  $W$  can then be taken as the total copper losses in the transformer on full load. For details on autotransformers, see section 14.10.5.

### 14.4.3 Transformer efficiency

The efficiency of any machine is expressed as:

$$\eta = \frac{\text{output}}{\text{input}}$$

Because a transformer normally has a high efficiency, the difference between the output and input readings is very small (about 1–3%) and the efficiency is usually determined from the losses.

$$\eta = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}$$

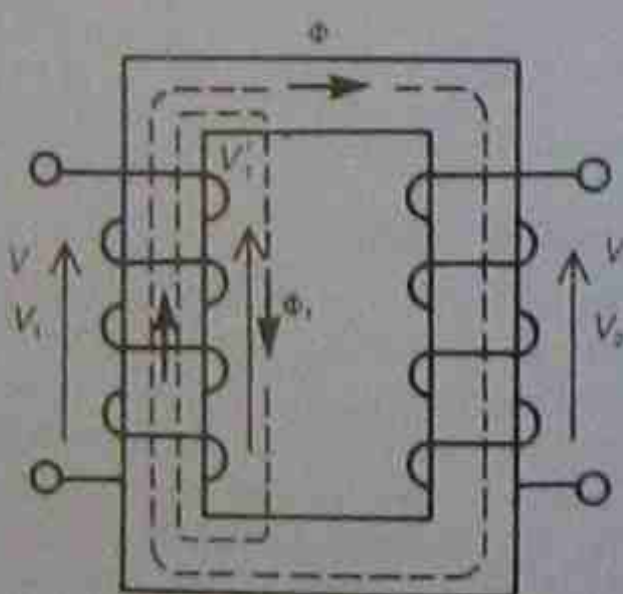
$$\eta = \frac{V_2 I_2 \lambda_2}{V_2 I_2 \lambda_2 + P_{cu} + P_{fe}}$$

that is,

where  $P_{cu}$  = copper losses

$P_{fe}$  = iron losses

Assuming the output voltage  $V_2$  remains constant, the only variables affecting the efficiency of a transformer are load current and power factor.

Figure 14.10 • Path for primary leakage flux ( $\Phi_1$ )

### 14.4.4 Flux leakage

It has been assumed so far that all the primary winding flux was magnetically linked with the secondary winding, thus creating a mutual flux that coupled both windings. In practice a small portion of the primary flux passes through the air gap and does not cut the secondary conductors. This flux is called the primary leakage flux and is shown as  $\Phi_1$  in Figure 14.10. The leakage flux helps in producing the self-induced voltage  $V_1$  in the primary winding but, in bypassing the secondary winding, plays no part in producing the voltage  $V_2$ , which is accordingly reduced slightly below the theoretical value.

When the transformer is on load, the secondary current  $I_2$  sets up a demagnetising flux opposing the mutual flux (section 14.2.2). Some of this secondary flux also passes through the air gap and is called the secondary leakage flux (indicated as  $\Phi_2$  in Fig. 14.11).

The primary and secondary leakage fluxes both induce

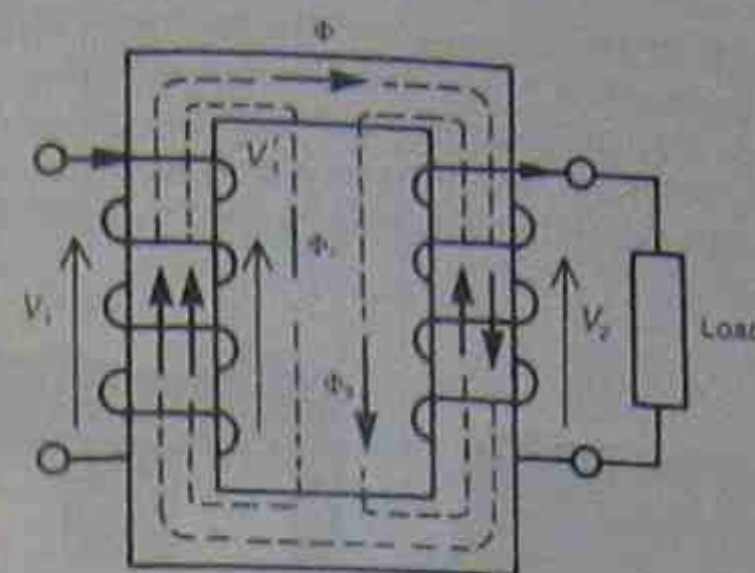


Figure 14.11 • Primary and secondary leakage flux paths

voltages in their respective windings and cause inductive reactances to be set up. As the load current increases, the leakage flux, and so the inductive reactance, increases. This inductive reactance and the winding resistance cause voltage drops on load, as shown in Figure 14.12.

In most transformer applications, leakage flux is a disadvantage and various methods are used to reduce it to a minimum. An arrangement such as in Figure 14.11, with the primary and secondary windings on separate limbs, is a poor design and is rarely used. To minimise leakage flux, transformers are designed with a short magnetic core path, a low flux density in the core, and a high reluctance path for the leakage flux. This is achieved by using a combination of winding arrangements and special core shapes, which are discussed in section 14.5.

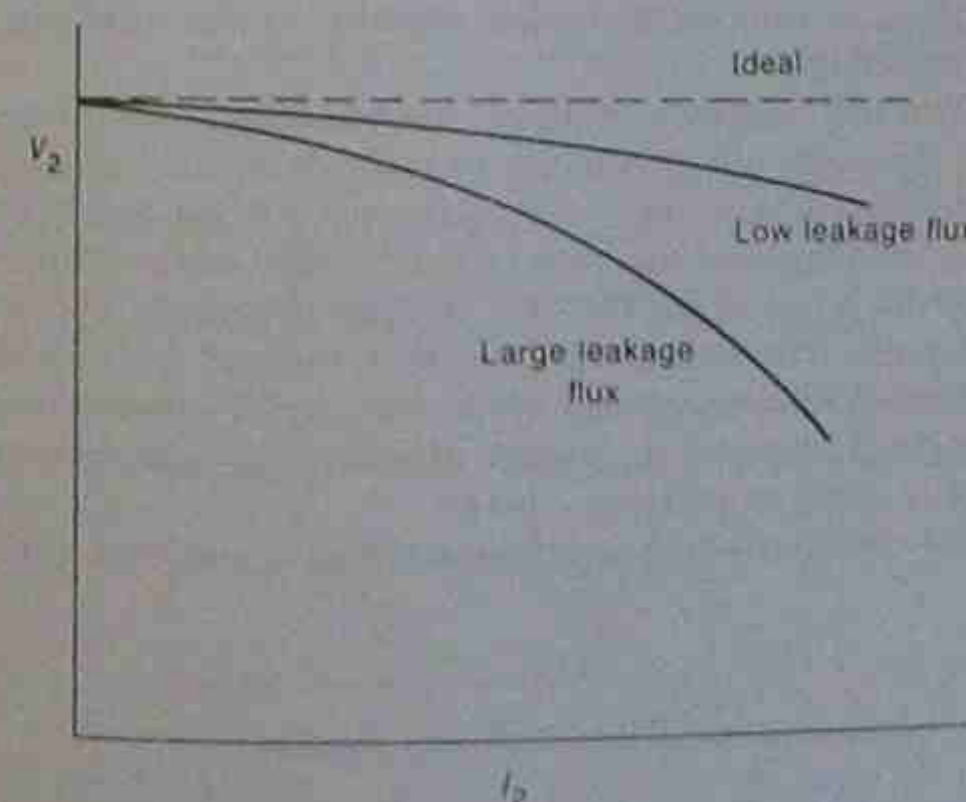


Figure 14.12 • Relationship between voltage, current and leakage flux

### 14.4.5 Voltage regulation

A transformer is expected to deliver a predetermined voltage at full load. The two major losses discussed in the previous section were:

1. magnetic losses, which include leakage flux and other magnetic core losses
  2. copper losses due to winding resistance.
- Because of these losses the full-load voltage will tend to be less than the no-load voltage.

To obtain a regulation value, the primary input voltage should be maintained at its rated value and the power

factor of the load must be known—the regulation value obtained is relevant only at this value of power factor for a particular transformer. The formula given is really only accurate for single-phase transformers. Voltage regulation of a transformer can be expressed as a percentage of its full-load voltage:

$$\text{voltage regulation} = \left[ \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 \right] \%$$

Note that the voltages used are all secondary values. Where a formula differs from the above, it should be checked to see whether equivalent or reflected values are to be used.

Care must be exercised when using a regulation value as a basis for comparison with another transformer. Comparisons with transformers of a different load, power factor, or voltage ratio are not valid.

## 14.5 TRANSFORMER CONSTRUCTION

### 14.5.1 Single-phase transformer cores

A transformer consists of a common magnetic circuit linking with the primary and secondary windings. The form of construction is determined by the arrangement of the laminations and the way they are stacked together. Figure 14.13 shows two methods for making up the stack for a transformer core. Figure 14.13(a) shows U–I shaped laminations, which are stacked in alternate directions to make a core-type magnetic circuit. Figure 14.13(b) shows E–I shaped laminations, which are also stacked in

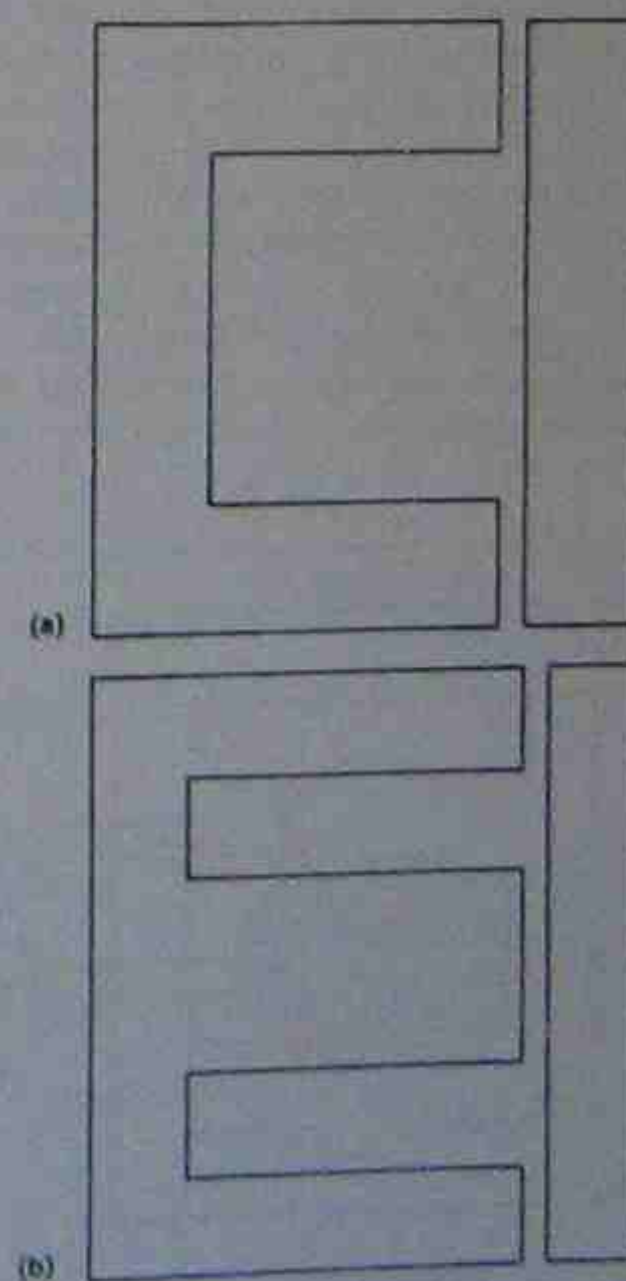


Figure 14.13 • Shapes of laminations for single-phase transformers



alternate directions to make a shell-type magnetic circuit. Although there are several modifications of these types of construction, transformers may in general be classified as one of these two types.

### Core type

With the core-type transformer, the windings surround the laminated core, as shown in Figure 14.14(a). To provide a uniform flux density throughout the magnetic core, the cross-sectional area of the core is uniform.

### Shell type

The shell-type construction has the magnetic core surrounding the windings, as shown in Figure 14.14(b). Because the core provides a parallel magnetic path for the flux, the centre limb is twice the cross-sectional area of the outer limbs, maintaining uniform flux density throughout the iron core.

By comparison, the core-type construction has a lighter core of smaller cross-sectional area, but a greater length of magnetic circuit. It also has a relatively greater number of turns, but these have shorter mean length. The core type, with its larger window space, is more suitable for higher voltages, requiring many turns and a larger space for insulation. The shell type is particularly suited for moderate voltages requiring fewer turns, less insulation, larger currents, and lower frequencies, with corresponding flux densities.

### Toroidal type

The toroidal core is made from a continuous ribbon of thin metal tape made from a special alloy. It is wound tightly around a former and consolidated under pressure into a solid mass. It is then sliced into two C-shaped pieces—the finished article is sometimes referred to as a C-core. The cut faces are ground to ensure good surface contact between the two halves. Two of these halves are placed around the transformer windings and clamped with a metallic band under moderate pressure to counter the effect of an air gap. For core-type construction, one pair of cores is used, while for shell-type construction, two pairs are used. Figure 14.15 shows this method. It is usual to place a third clamp around the pair of cores after

assembly to prevent noise and chafing by vibration. There are variations in types and shapes available. One type consists of rectangular strip laminations folded into shape and inserted into the transformer coils. The outer strips are longer, with the ends spot-welded to hold the core in one piece.



Figure 14.15 • Toroidal core construction

### 14.5.2 Single-phase transformer winding arrangements

The actual placement of the windings on the transformer core depends on the type of core and the intended use of the transformer. Other factors that influence this arrangement are the operating frequency and the size or power rating of the transformer. Some typical winding layouts are shown in Figure 14.16. While the core-type transformer construction is shown in the diagrams, the winding arrangement applies equally to the shell-type construction.

With the concentric method, one winding is wound on the top of the other (primary or secondary) and suitable insulation is installed between the two. A sandwich- or pancake-type winding is used where closely coupled windings are required, so that the magnetic leakage can be reduced to a minimum. The sandwich method is also used in large distribution transformers for ease of winding and handling, and also in smaller transformers operating at higher audio frequencies.

The type of winding arrangement that is now becoming

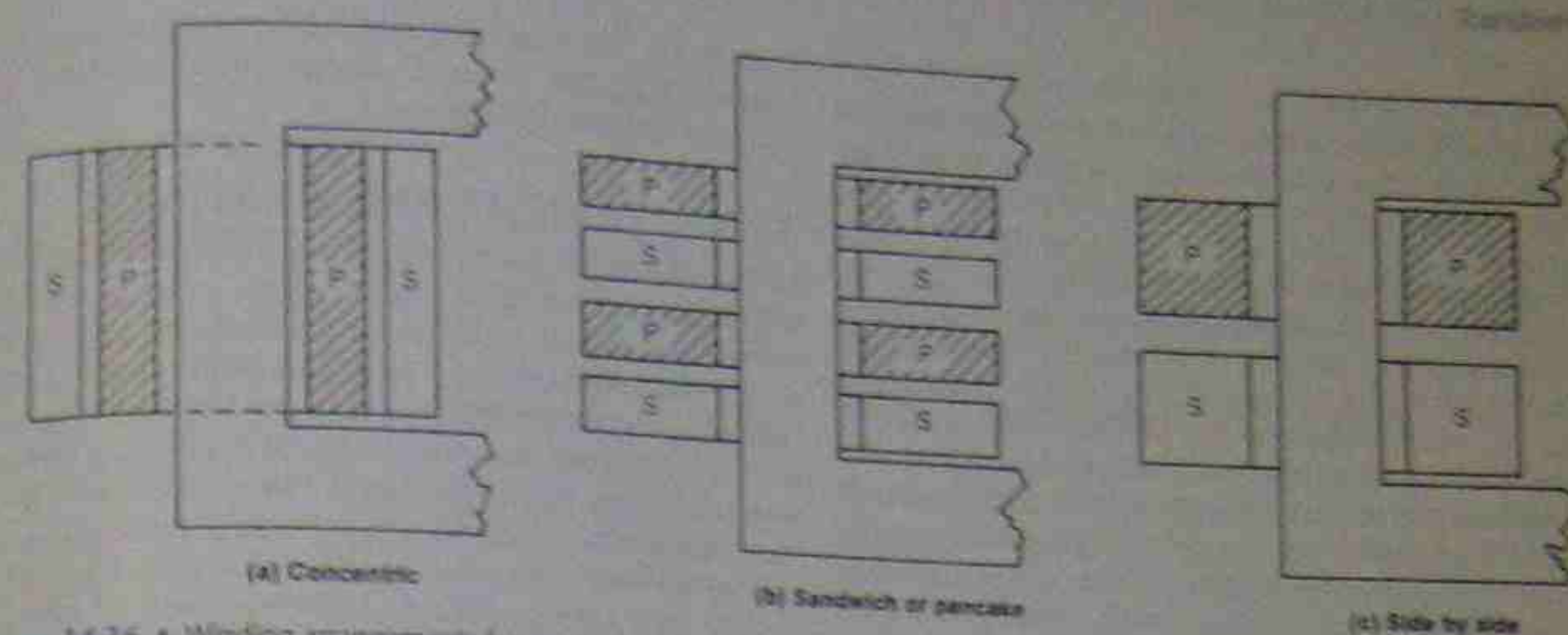


Figure 14.16 • Winding arrangements for single-phase transformers

more common for power transformers is shown in Figure 14.16(c). This is due in part to Standards Australia recommendations for insulation requirements between primary and secondary windings.

### 14.5.3 Three-phase transformer cores

The same variations in single-phase cores apply to three-phase cores. For single-phase, the majority of transformer cores use the shell-type construction, while for three-phase, the majority are of a core-type construction.

A three-phase transformer can be obtained by using

three identical single-phase transformers, but usually a common three-phase magnetic core is used, with three identical sets of primary and secondary windings mounted on it.

### Three-phase core type

The shape shown in Figure 14.17(a) is usually employed in smaller distribution-type transformers. The core-type construction has a shorter length per turn of winding than the shell type but has a longer magnetic path. While similar in appearance to the single-phase shell type, each leg of the core has an equal cross-sectional area.

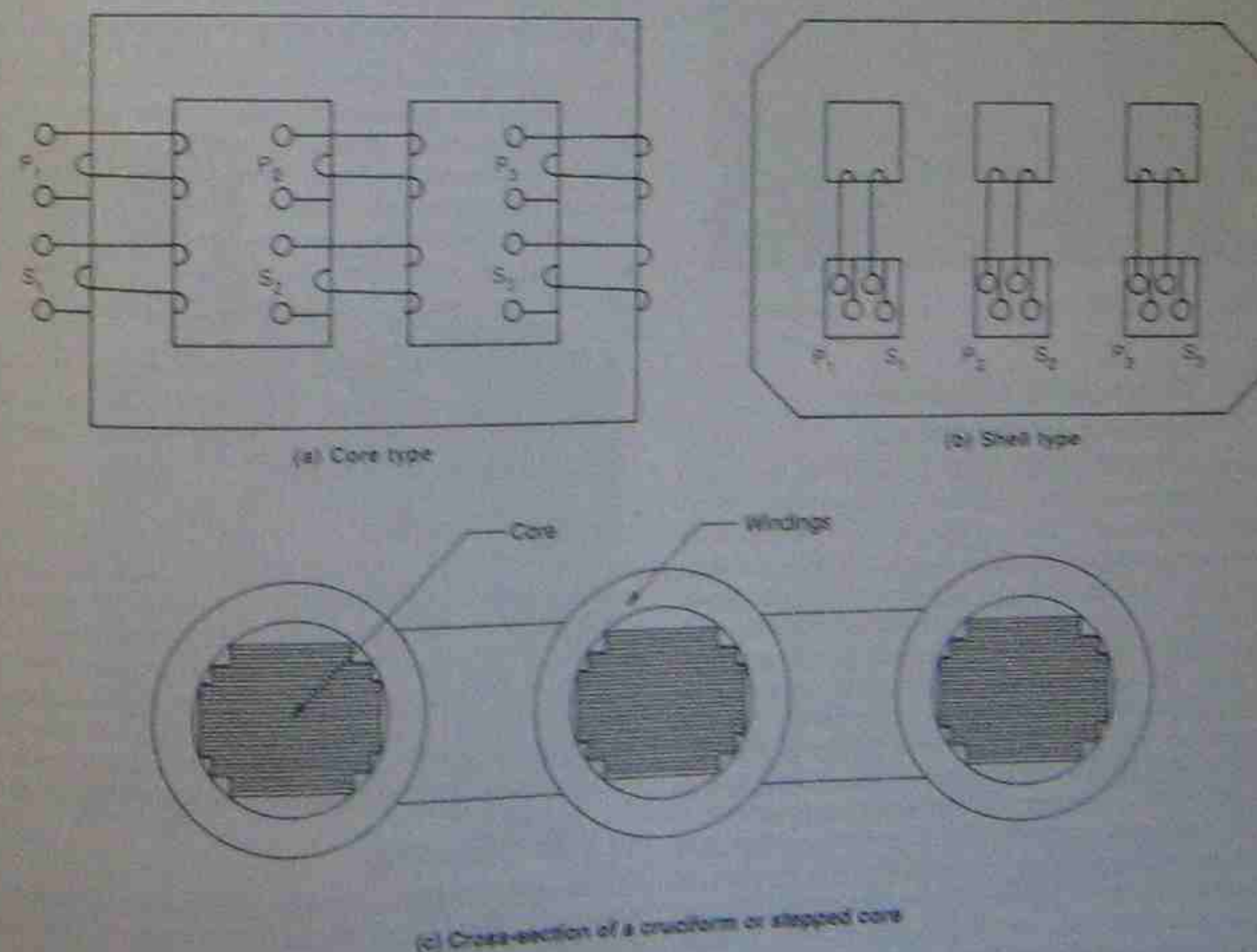


Figure 14.17 • Three-phase transformer cores

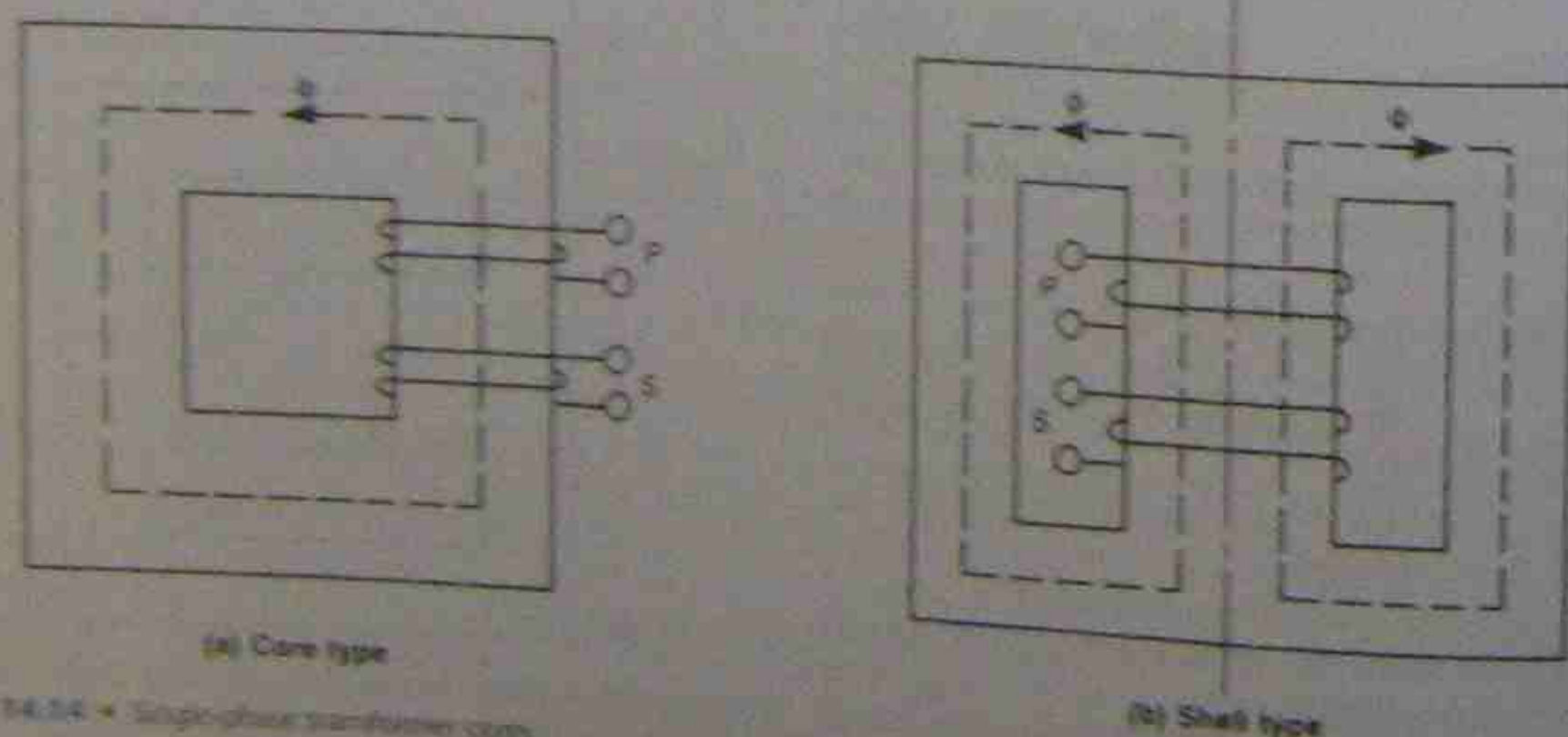


Figure 14.14 • Single-phase transformer cores



### Three-phase shell type

This shape of core overcomes the tendency of the core type to have unequal flux densities and is shown in Figure 14.17(b).

### Three-phase cruciform or stepped core

With conductors of large cross-sectional area, it becomes difficult to construct windings that have 90° bends in the conductors. With this shape of core the windings are wound on circular formers and the core is stepped (in cross-sectional area) to fill up the inside of the coil as far as possible with transformer laminations. The core is shown in cross-section in Figure 14.17(c) and it can be seen that a great number of different-size laminations are required. This form of construction is expensive and is generally used only on large transformers.

### Three-phase toroidal

This type of construction has been mentioned in section 14.5.1 and in general, toroidal cores can be obtained in most shapes for three-phase transformers. See Figure 14.18.



Figure 14.18 • Three-phase transformer with a toroidal core

### 14.5.4 Three-phase transformer winding arrangements

The same factors affecting windings and cores for single-phase transformers apply equally to three-phase transformers, although the majority of distribution transformers are wound in the sandwich or pancake style. The method lends itself to ease of construction and repair.

The degree to which the primary and secondary windings are magnetically coupled depends on the intended purpose of the transformer. A transformer is said to be close coupled when all the primary flux passes through the secondary turns. If a large proportion bypasses the secondary windings, the transformer is said to be loosely coupled. There are of course intermediate degrees of coupling. For example, a distribution transformer is less than close-coupled as a form of current limitation, to allow for the case of damage to overhead lines connected to its secondary. However, the degree of coupling for a high-tension transformer for an illuminated sign is far less than

that for a distribution transformer. In this case it is required that the on-load voltage be considerably less than the open-circuit voltage.

## 14.6 TRANSFORMER RATINGS

Manufacturing a transformer for a specified voltage and building it with the capacity to deliver a certain quantity of current is a matter of design. It is within the scope of the designer to specify the two quantities, voltage and current, but, once a transformer is placed in service, the load placed on it is beyond the immediate control of both the designer and the power supply authority. The actual load can be any combination of the total number of connected circuits.

Consequently a transformer is rated only in terms of its voltage and current ratings. It is expressed in terms of apparent power rather than true power because the power factor of the load is unable to be determined in advance. For example, a single-phase transformer capable of delivering 100 A at 500 V would be rated at 50 kVA ( $500 \times 100 = 50\,000\text{ VA}$ ). If the power factor of any given load is 0.5, then the power output would be 25 kW. At a power factor of 0.8 the power output would be 40 kW. In both cases a full-load current of 100 A would be flowing.

The current rating of the conductors in the windings is dependent on the rate at which the total heat generated in the transformer can be dissipated. The rating limitation of the transformer is a factor of the temperature rise of the unit on load and the ambient temperature. High ambient temperatures mean a lower rating and a low ambient temperature means a high rating.

## 14.7 TRANSFORMER COOLING

A transformer on load generates heat in both the core and the windings. For smaller units the surface area is great enough to remove the generated heat by convection and radiation. As transformer size increases, the surface area becomes proportionately smaller than the volume, and eventually the heat being generated cannot be dissipated quickly enough. As a result, the temperature of the transformer begins to rise and additional cooling methods must be used.

In general terms, there are two commonly used media for transformer cooling—air and oil. The methods and combinations for these two cooling materials, however, are many and varied.

### 14.7.1 Air cooling

The air-blast type of cooling is used on transformers where economy of space and weight is required, or where oil cooling may be a fire hazard. The transformer must be provided with ducts between the coils, and between the core and the housing, so that air can be blown through them to remove the heat. The air must be filtered so that dust cannot build up in the ducts. Air-blast cooling is seldom used in very large transformers, or for voltages above 20 kV.

### 14.7.2 Oil cooling

One common method used for cooling is to immerse the transformer in a tank of special transformer oil, providing as large a cooling surface area of the tank as possible by using external tubes, as shown in Figure 14.19.

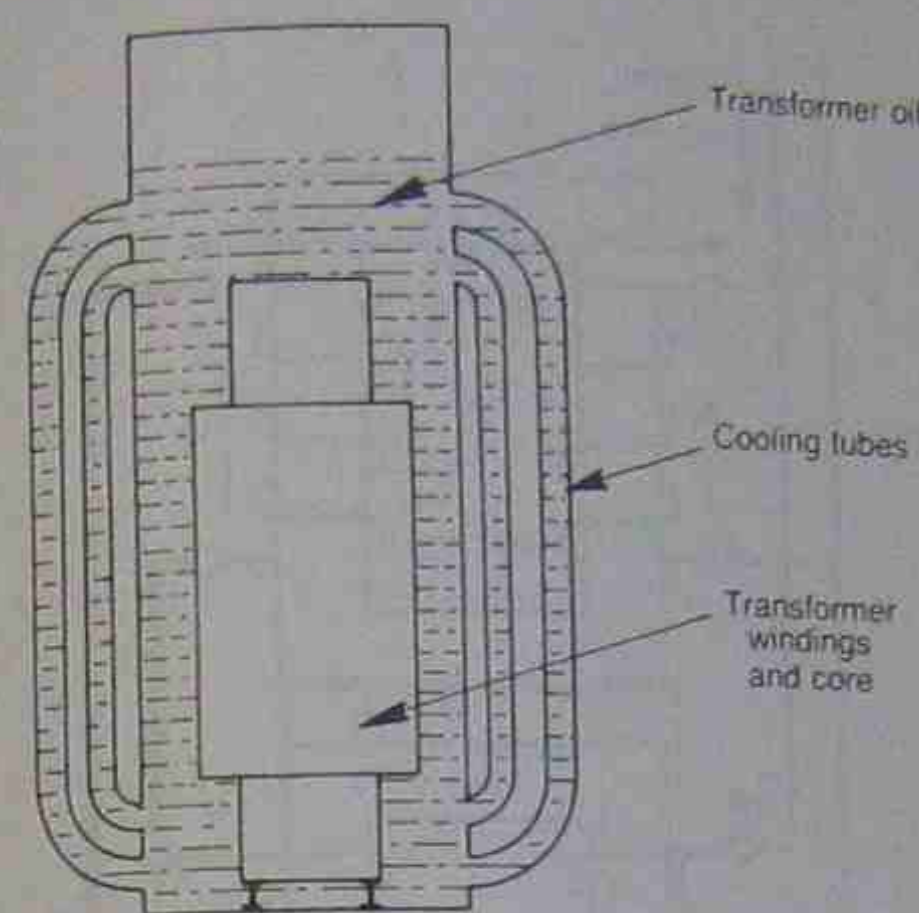


Figure 14.19 • Thermosiphon cooling of a transformer core

The oil serves the dual purpose of cooling and insulating. The oil conducts the heat from the core and the windings to the surface of the tank and the external tubes. There it is dissipated into the surrounding air, cooling the oil that circulates through the tank by means of natural convection.

For very large transformers, convection within the oil does not remove the heat quickly enough, so forced methods of oil cooling are needed. The oil is drawn off at the top of the tank and pumped through a water-cooled heat exchanger and then returned to the transformer tank. Figure 14.20 shows such a transformer.

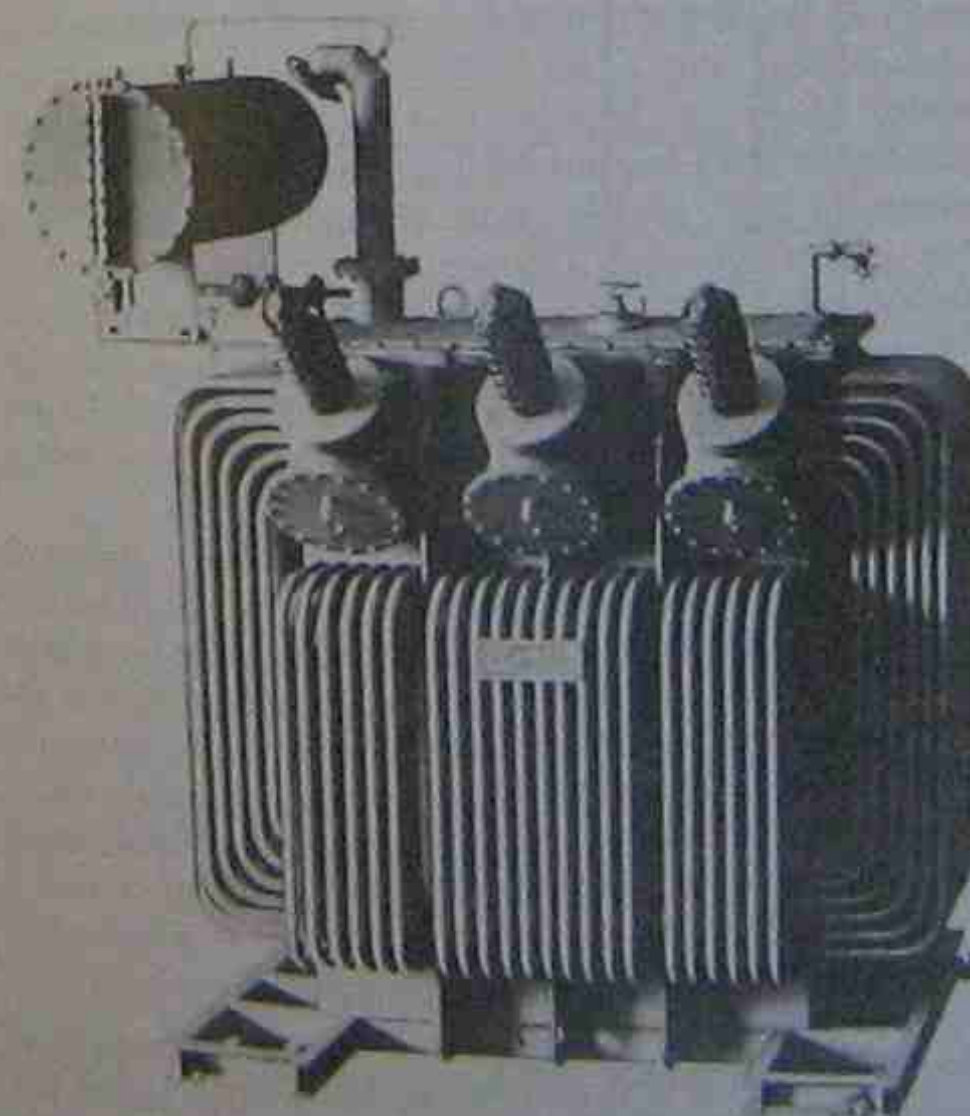


Figure 14.20 • Three-phase 1000 kVA oil-cooled transformer. The rated input voltage is 33 kV and output voltage is 11 kV

Elsa utilities

### 14.7.3 Tank colours

Polished metallic surfaces inhibit the removal of heat from transformer oil and casings. It has been found that colours such as low-sheen variations of black, green, or grey enable the oil to run at lower temperatures than would otherwise be the case. However, highly polished surfaces reflect the heat of the sun more than do the above colours.

## 14.8 WINDING POLARITIES

It is sometimes necessary to operate two or more transformers in parallel and, to do so, not only must the output voltages be equal, but the instantaneous polarities must be the same.

### 14.8.1 Single-phase transformers

#### Equal voltages

When two unequal voltage sources are connected in parallel, the phasor difference between the voltages causes a circulating current to be set up. The current flow is limited only by the impedances of the windings and will flow despite all other conditions for parallel operation being met.

Large quantities of heat are generated and the circulating current effectively renders both sources of power useless for any practical purposes.

#### Instantaneous polarities

The two transformers shown in Figure 14.21 have their primary windings wound in the same direction around the iron core. When the instantaneous polarity of line A is positive (indicated by the dot), the mutual flux  $\Phi$  in each transformer acts in the same direction.

The secondary windings in Figure 14.21 are shown

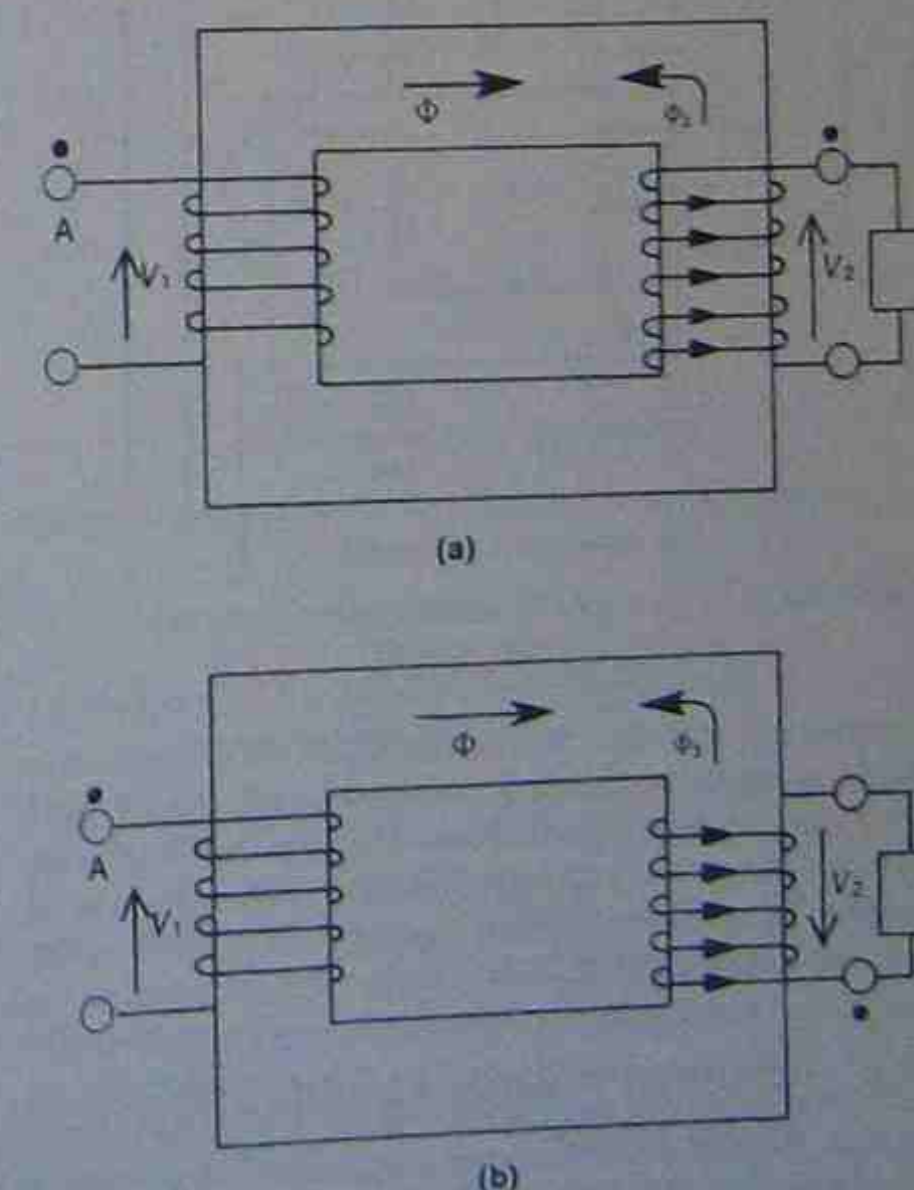


Figure 14.21 • Method for marking terminals of similar polarity



wound in opposite directions to each other. The induced voltage  $V_2$  acts in an upward direction in (a), while in (b)  $V_2$  acts downward. In both cases the secondary flux  $\Phi_2$  must oppose the mutual flux (Lenz's law). This condition is met by the induced voltage acting downward in (b) and producing an instantaneous current flow as indicated by the arrows in both figures. That is, when an instantaneously positive voltage is applied to the primary terminals indicated by dots, there will be an instantaneously positive voltage produced at the secondary terminals indicated by dots. In general terms the positioning of dots on winding ends is used to indicate the similar instantaneous polarities. For single-phase transformers to operate in parallel, their voltages must be equal and their instantaneous polarities must also be identical. The correct connections for two transformers in parallel are shown in Figure 14.22.

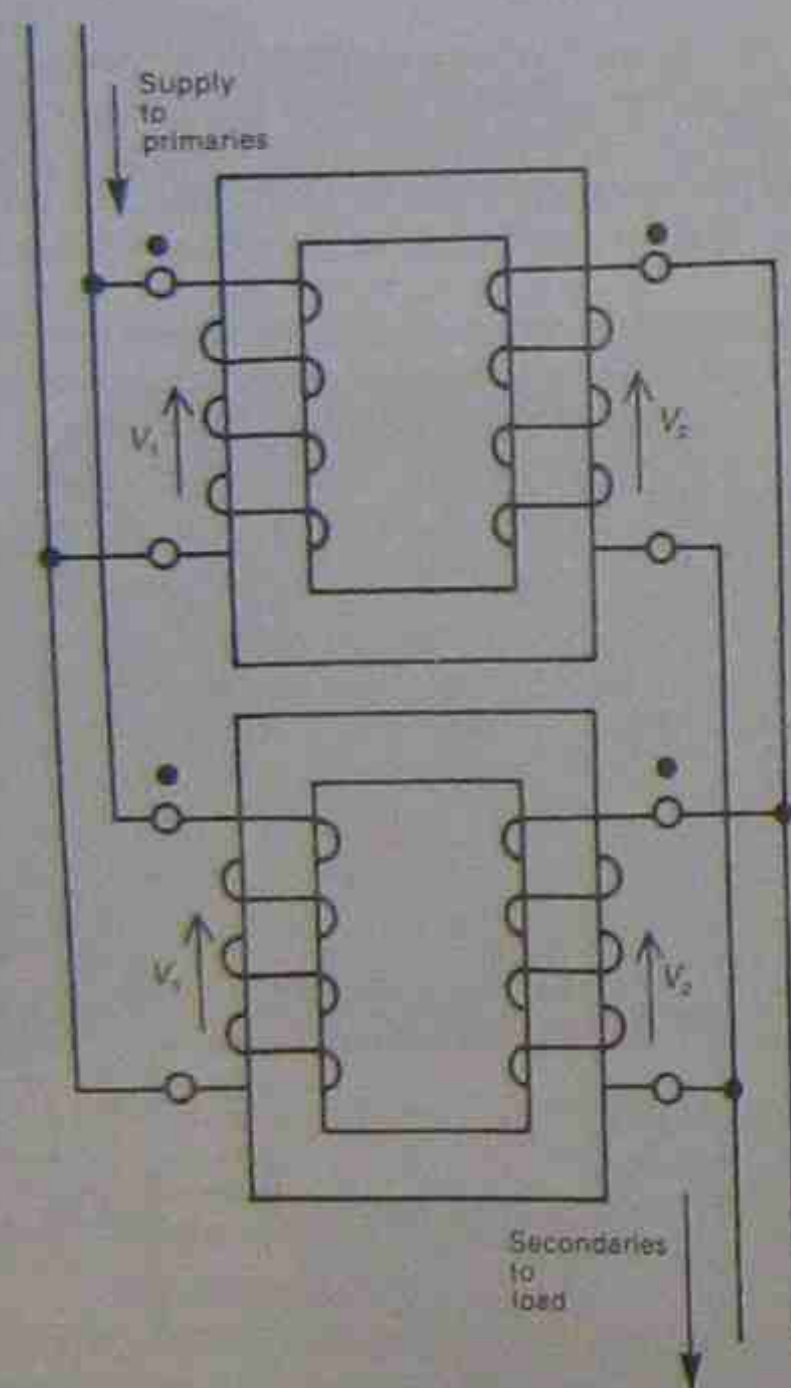


Figure 14.22 • Connections for parallel operation of two single-phase transformers

If terminals of the wrong polarity are connected together, a high circulating current is set up in both primary and secondary windings. Effectively the two secondary windings are connected in series and then short-circuited. The path for the circulating current is shown in Figure 14.23 as a thicker line.

### 14.8.2 Terminal polarity identification—single phase

When drawing sketches of transformers, the dot or a similar system of identification for winding ends is satisfactory.

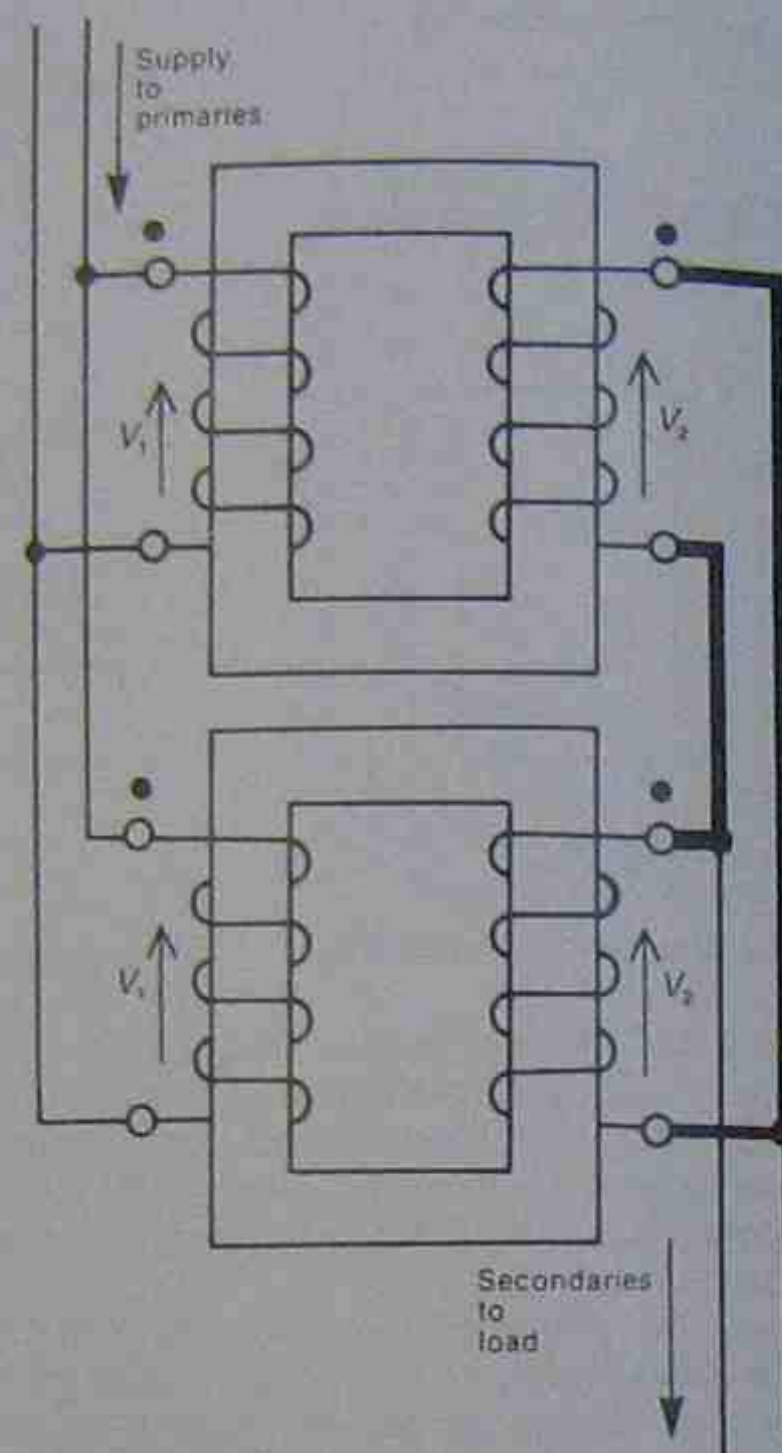


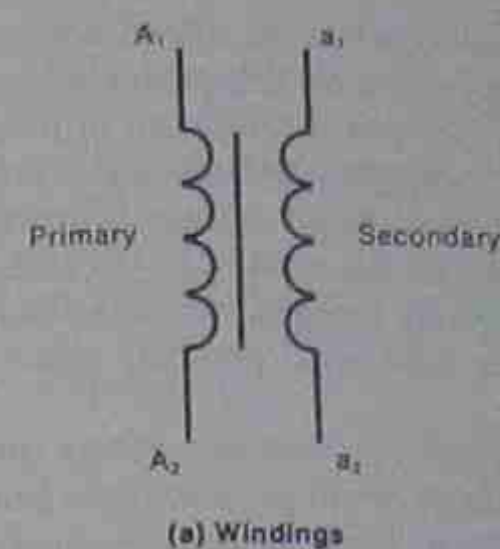
Figure 14.23 • Circulating current path for two incorrectly phased transformers

factory. In practice it is more usual to be confronted with a transformer and a row of terminals, making some general system of identification necessary. Australian Standard AS 2374 sets out such a system for power transformers. In brief, all terminals are given an identifying letter and a subscript number—for the higher voltage winding, capital letters are used, and for the lower voltage winding, lower-case letters are used. Where more than one end of a winding is brought out to a terminal, the higher number is the line terminal unless a specific phase shift is required.

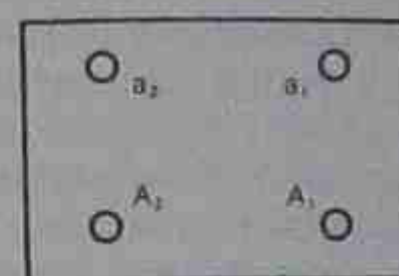
An example for a single-phase transformer is shown in Figure 14.24. The standard specifies that the identification be permanently marked on, or adjacent to, the terminals. Invariably this means stamping the identification into the metal of the terminal or the case adjacent to the terminal. In addition to this marking, supply authorities might require further markings on the transformer to assist them in installation or to match their phase sequence.

### 14.8.3 Three-phase transformers

A transformer can be used on a three-phase supply by using a three-legged core with primary and secondary windings on each leg, as shown in Figure 14.25. The fluxes established in the windings are  $120^\circ$  apart and their instantaneous sum will always be zero. Two of the fluxes will flow back through the third leg, in the same manner as the resultant current in any two lines of a



(a) Windings



(b) Standard terminal arrangements

Figure 14.24 • Terminal identification for single-phase transformer

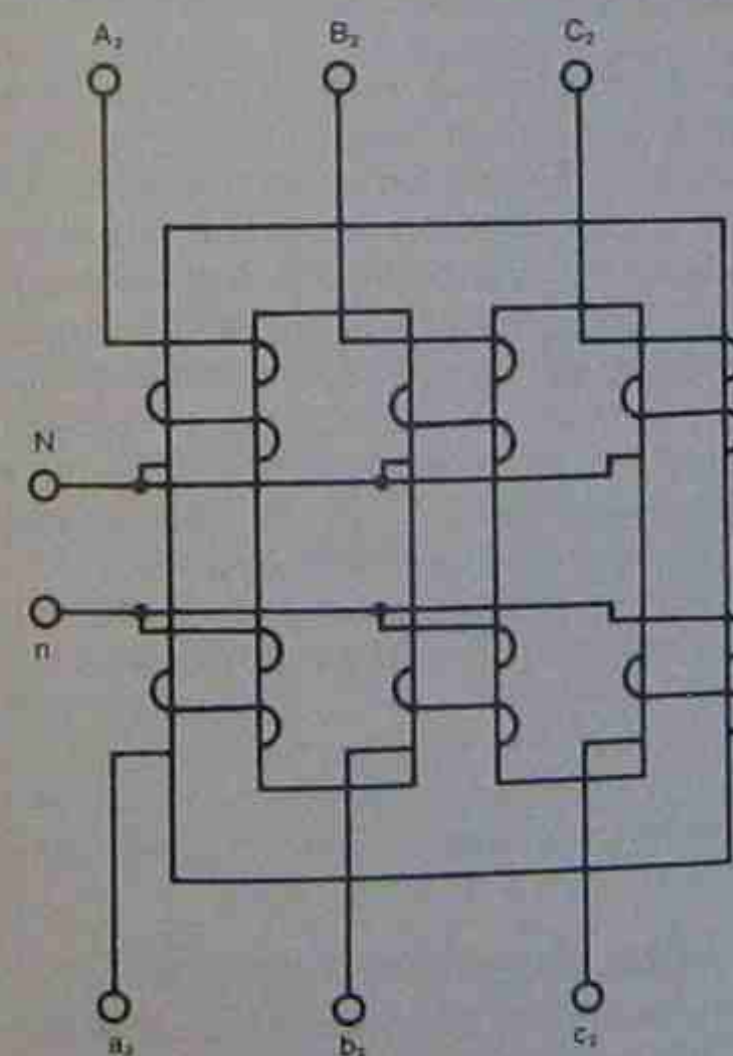


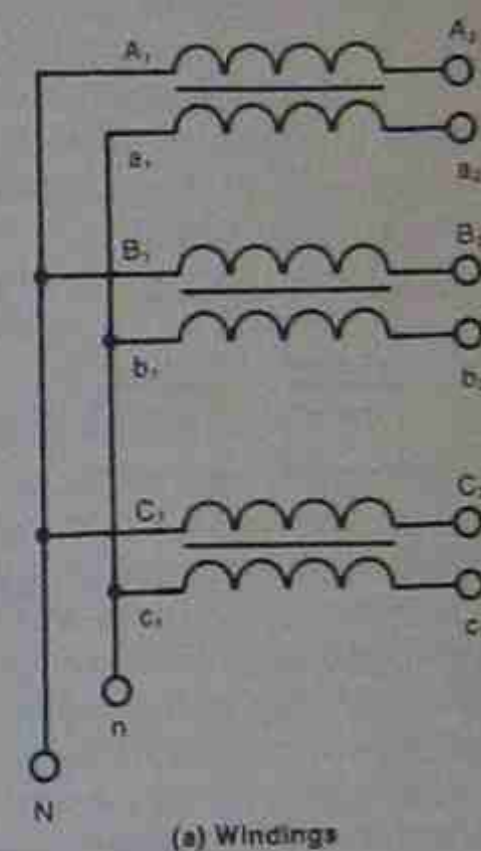
Figure 14.25 • Three-phase core-type transformer star-star connection

three-phase system will flow back through the third line. Because the three windings are on a common core, the three-phase transformer is smaller and lighter than three separate transformers for the same VA rating.

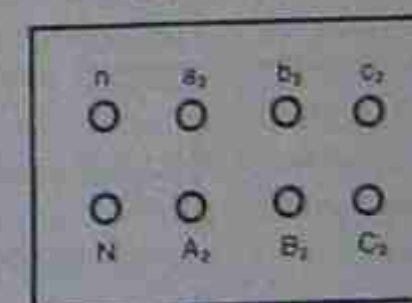
### 14.8.4 Terminal polarity identification—three phase

Standard AS/NZS 2374 sets out the same terminal arrangement and identification for both single- and three-phase transformers. There is now a greater variety of alternative connections available, so the system is necessarily

more complicated than that for single-phase transformers. Figure 14.26 shows the standard applied to a transformer connected in a star-star relationship with  $0^\circ$  phase shift. Capital letters with numerical subscripts are used for the higher voltage winding, with lower case for the lower voltage winding. The standard terminal arrangement is also shown for the transformer. AS/NZS 2374 states that the terminal arrangement shall be in the order A, B, C from left to right when looking from the high-voltage side. When a neutral is fitted, its terminal shall be on the extreme left-hand side. It should be noted that supply authorities do not necessarily follow this standard. One supply authority uses the sequence  $b_2, n, c_2, a_2$  in one situation and the sequence  $a_2, n, b_2, c_2$  in another. There are valid reasons for persisting with a non-standard order and these vary from one authority to another.



(a) Windings



(b) Standard terminal arrangements

Figure 14.26 • Terminal identification for a three-phase transformer with  $0^\circ$  phase shift

### 14.8.5 Three-phase transformer connections

The four most common methods of connecting the primary and secondary windings are star-star, delta-delta, delta-star, and star-delta. A fifth connection sometimes used is the zig-zag connection. It can be used in power transmission work although it may also be used for phase shifting or producing multiple phases in industrial applications.

The first four connections are shown in simple form in Figure 14.27. What cannot be readily shown in diagrams of this type is the phase shift introduced to the secondary voltages even when the primary voltages are in phase.



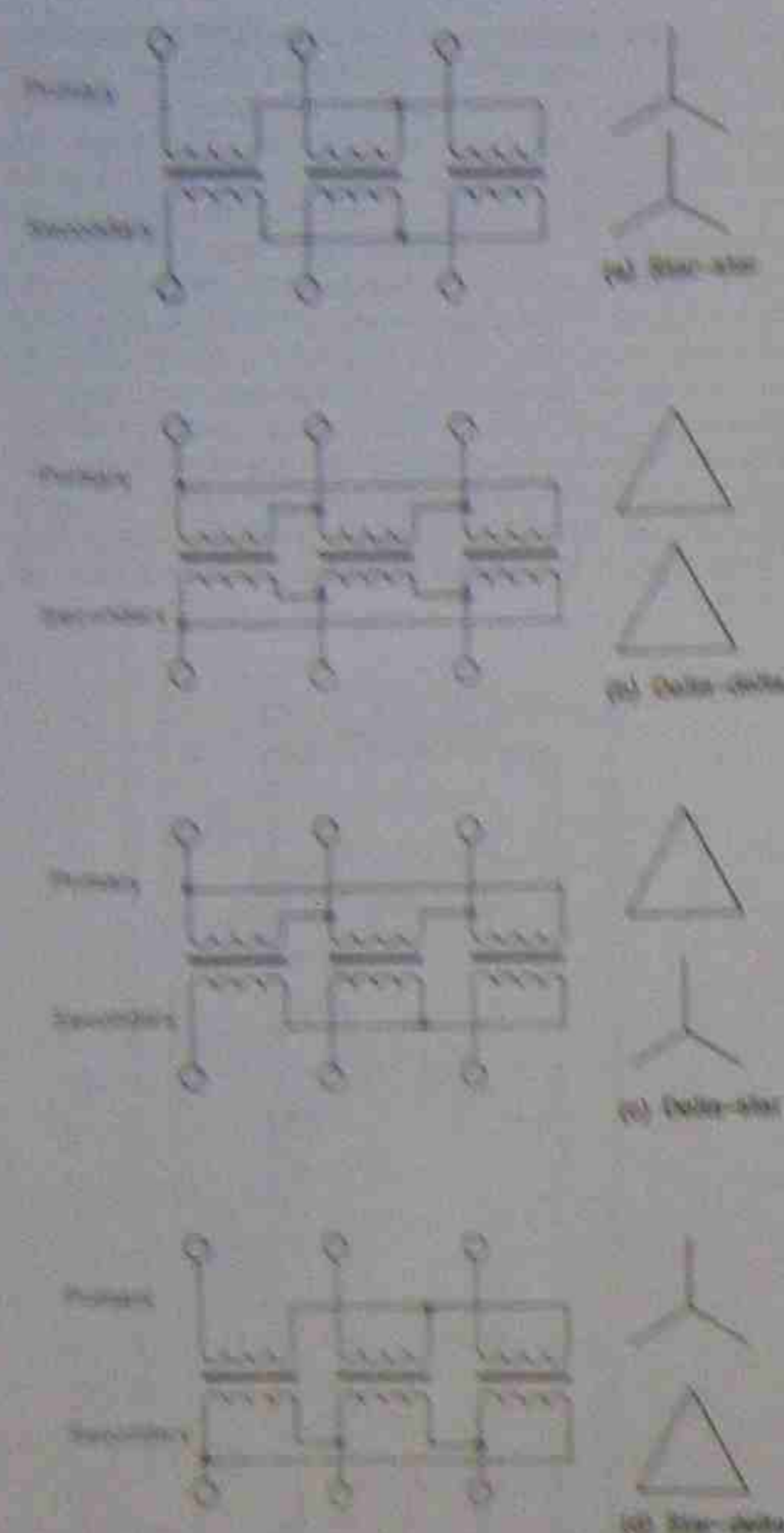


Figure 14.27 • Three-phase transformer connections

The paralleling factors for different combinations of transformer connections are discussed in section 14.8.

The four main connections have the following phase shifts:

- Star-star—no phase shift between primary and secondary.
- Delta-delta—no phase shift between primary and secondary.
- Delta-star—phase shift between line voltages,  $V_L$  lag  $V_L$  by  $30^\circ$ .
- Star-delta—phase shift between line voltages,  $V_L$  lead  $V_L$  by  $30^\circ$ .

Any of these connections can be used for suit applications and circumstances, but no distribution purposes the star-delta and delta-delta connections are used for step-up transformers and a delta-delta in medium voltages. The

star-delta connection has the added advantage of providing a grounding point on the primary for stability of the system and also for not introducing third harmonics.

Auto-delta connected transformers are not the best connection for very high voltage transmission systems. The combination of delta-star step-up and star-delta step-down is undoubtedly the best for long-distance, very high voltage systems. Grounded neutrals also help to make a stable system.

In general terms the voltages across the primary and secondary windings are in proportion to the turns ratio of the phase windings. The line voltages will be a function of the phase connections and will not always be equal to the phase voltages. For example, star-connected secondaries could have phase voltages of 100 V each and the line voltage would be 173 V. With a 2:1 turns ratio, the primary phase voltage would be 200 V and the supply voltage would be 200 V in a delta-connected primary or 346 V in a star-connected primary.

### Example 14.2

If a 415 V three-phase transformer has 200 turns per phase on the primary windings and 40 turns on the secondary, find the output line voltage for each of the four main types of connection.

(a) Star-star

$$(200/40) V_1 = 415 \text{ V}$$

$$V_1 = \frac{415}{1/2} = 249 \text{ V (or } V_L)$$

$$\frac{V_1}{N_1} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{V_1 N_2}{N_1} = \frac{249 \times 40}{200}$$

$$= 49.8 \text{ V (or } V_L)$$

$$(200/40) V_1 = 415 \text{ V}$$

$$= 1/2 \times 415 = 83 \text{ V}$$

(b) Delta-delta

$$(200/40) V_1 = V_L = 415 \text{ V (or } V_L)$$

$$\frac{V_1}{N_1} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{V_1 N_2}{N_1} = \frac{415 \times 40}{200}$$

$$= 83 \text{ V (or } V_L)$$

$$(200/40) V_1 = V_L$$

$$= 83 \text{ V}$$

(c) Delta-star

$$(200/40) V_1 = V_L = 415 \text{ V (or } V_L)$$

$$\frac{V_1}{N_1} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{V_1 N_2}{N_1} = \frac{415 \times 40}{200}$$

$$= 83 \text{ V (or } V_L)$$

$$(200/40) V_1 = V_L$$

$$= 1/2 \times 83 = 41.5 \text{ V}$$

(d) Star-delta

$$(200/40) V_1 = 415 \text{ V}$$

$$V_1 = \frac{415}{1/2} = 249 \text{ V (or } V_L)$$

$$\frac{V_1}{N_1} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{200}{40}$$

$$\frac{V_2}{N_2} = \frac{V_1 N_2}{N_1} = \frac{249 \times 40}{200}$$

$$= 49.8 \text{ V (or } V_L)$$

$$(200/40) V_1 = V_L = 48 \text{ V}$$

### 14.8.6 Three-phase tertiary windings

It can be shown that a transformer supplied with a sinusoidal waveform voltage will take a magnetising current having a proportion of third-harmonic current. It is partly because of the non-linearity of the magnetising characteristics of the iron core. Unless steps are taken to minimise or neutralise this component, there will be a portion of induced voltage and current flowing at a frequency three times that of the fundamental. Where there is a path from the transmission system neutral back to the alternator, the effect is minimised or even cancelled.

In the absence of a primary neutral path, the flux wave in the transformer becomes distorted and the third-harmonic effect is transmitted through to the secondary and then to the transmission line. With standard 50 Hz line frequencies there is a proportion of 150 Hz a.c. circulating, together with the normal frequency. This leads to electrical interference and poor voltage regulation along the line itself.

These third-harmonic currents can be suppressed by introducing a third winding to each phase of the transformer. They are called tertiary windings and are connected in delta configuration. Tertiary windings have no connected load, their only purpose being the suppression of the third harmonics.

With delta-connected primary windings, the third harmonics are less of a problem in transmission transformers because the delta connection tends to suppress them.

### 14.8.7 Changing transformer ratios

With long-distance transmission lines the characteristics of the line affect the voltage at the delivery end of the line. The conductors have an inherent capacitance between them and there is an inductive effect due to the length of the parallel conductors. Each conductor also has a fixed value of resistance.

At light loads the capacitive effect between lines is the dominant characteristic. Less current means less voltage drop and the inductive effect remains minimal because of the low currents. The result is a leading power factor on the line and a delivery voltage that might be higher than the source voltage.

With fully loaded lines, the voltage drop due to the line resistance increases in proportion to the current. While the inductive effect still remains minimal, there is now a significant coupling effect due to the magnetic field around the conductors. The inductive effect increases

and so does the voltage drop. Both these effects result in a reduced voltage at the load end of the line and at a leading power factor.

Variable capacitors can be used to correct the power factor and to correct the line voltage, but the more usual and cheaper way is to vary the line voltage with transformer tap changers at the source of the supply.

Tap changers are installed in situations where they can compensate for variations in voltage. A rising or falling voltage at the load end of the line can be corrected by the action of a tap changer at the supply end. There are two possible ways of doing this—off-load and on-load.

#### Off-load tap changing

The off-load tap-changing method merely involves disconnecting the transformer from the supply, reducing the turns ratio, and then reconnecting the transformer to the supply. The tap changing can be done only after disconnecting the transformer from the supply. To facilitate the changeover, these are usually built in overhead and the task only involves turning a handle or operating a lever. It always causes an interruption to the supply, unless there is a second transformer available, which must be connected to the supply before the first one is removed.

#### On-load tap changing

When it is necessary that a transformer provide a constant voltage into a supply system, a device must be found to alter the transformer ratio while the transformer is still on line, so ensuring that there is no interruption to the supply. On-load tap changing is more convenient to consumers and suppliers alike and the procedure leads itself to automatic operation so that line voltages can be regulated without manual intervention.

On-load tap changing is illustrated in Figure 14.28 for only one phase. In a three-phase system they must obviously be three such systems, all operating simultaneously.

In Figure 14.28(a), the primary winding is shown in two sections. Three taps only are shown at the other end of the primary winding and the switch mechanism tap is connected to the other line through a dual switch mechanism.

In Figure 14.28(b), one of the supply lines is connected to tap 1. The other part of the switching mechanism is open circuit.

In Figure 14.28(c), tap changing has been initiated. The second part of the switch has connected the low value resistor R to tap 2. The potential difference between taps 1 and 2 causes a circulating current to flow through the resistor.

In Figure 14.28(d), the switching mechanism has been connected to tap 2. Resistor R has been shorted out.

In Figure 14.28(e), the resistor R has again been isolated by the switching mechanism. The supply to the transmission lines has not been interrupted, yet the input to the transformer has been shifted to another tap.

Reactive tap changers are faster, cheaper and more compact than the previously used centre-tapped inductor tap-changer mechanisms. The operation process takes only a few cycles and is controlled by sensing the energy stored in a given under circuit.



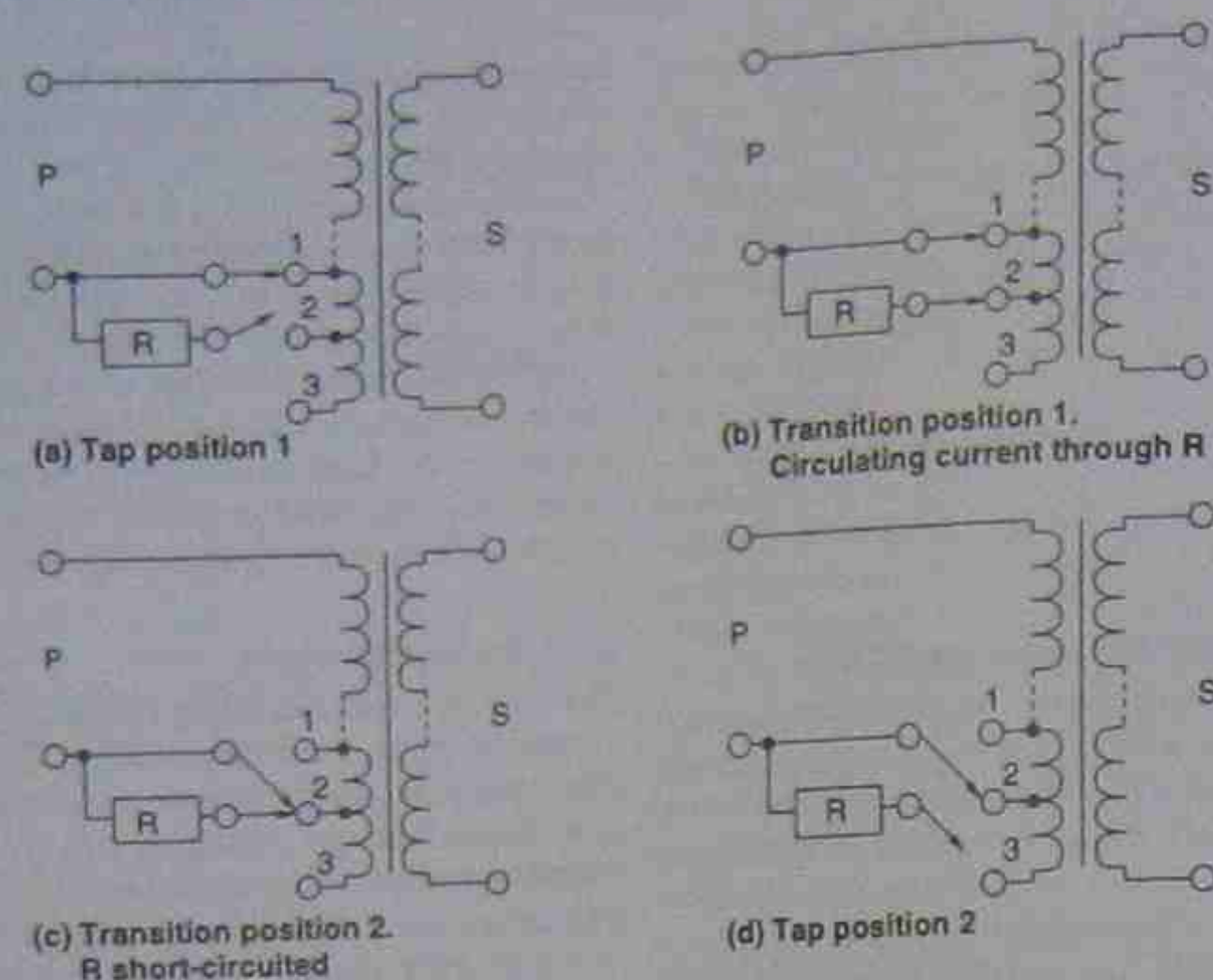


Figure 14.28 • On-load tap-changing

## 14.9 CONNECTING THREE-PHASE TRANSFORMERS IN PARALLEL

### 14.9.1 Phase shifts

When connecting three-phase transformers in parallel, care must be taken to ensure that the transformers are compatible, not only in phase sequence and voltage but also in additional phase shifts due to their internal connections. For example, in a transformer connected in delta primary and star secondary (delta-star), the secondary voltage is induced such that it lags the applied voltage by  $30^\circ$ . In the case of star-delta the induced secondary voltage leads the applied voltage by  $30^\circ$ . Because of the phase shifts, these two transformers must not be connected in parallel since the secondary voltages are out of phase with each other by a total of  $60^\circ$ .

### 14.9.2 Paralleling requirements

#### Equal voltages

If two unequal voltage sources are connected in parallel, a circulating current is set up between the two sources. Each transformer becomes a burden on the other and they are unable to supply power to an external load.

#### Same phase sequence

If different phase sequences are connected in parallel, the least that can occur is a short-circuit between the lines. Heavy circulating currents flow and cause damage to all sections of the installation.

#### Phase voltages to be in step

As previously mentioned, the transformer connections have to be compatible, owing to possible phase shifts. Satisfactory parallel operation can occur only when the two transformers belong to the same group and have the same phase shift. Parallel operation involves two or more transformers connected to a common source of supply, and their secondaries connected to a common load. Using transformers

belonging to different groups causes damage to both transformers and imposes a heavy drain on the supply.

### 14.9.3 Phasing transformer windings

#### Single-phase transformers

When the polarities of a transformer are not known, it can be phased out by interconnecting the two windings, as shown in Figure 14.29. If the voltmeter reading at the position shown in the diagram is greater than the supply voltage, the two voltages are aiding each other and the transformer is said to have dissimilar ends connected at the bridge between the two windings. If the voltmeter reads less, then the voltages are opposing each other and the windings have similar ends bridged.

#### Three-phase transformers

The same method can be applied to the windings of a three-phase motor or transformer. It must be remembered however, that these windings are  $120^\circ$  apart and that the induced voltage will be at the same angle.

Consequently the results will be opposite to that of the single-phase transformer. If the voltage is greater, then similar ends are joined by the bridge.

### 14.9.4 Testing final connections

Having connected a transformer in either star or delta configuration it should be checked before loading.

#### Star

Transformer secondaries connected in star configuration give three leads representing the lines and a fourth for the neutral. Before connecting to the load, all voltages should be tested. Each phase voltage should be identical when tested between line and neutral. There are three line voltages to be tested: A-B, B-C and C-A. These should all be identical and 1.73 times as great as the phase voltages. A reversed phase winding will be indicated by two of the line voltages being equal to the phase voltages.

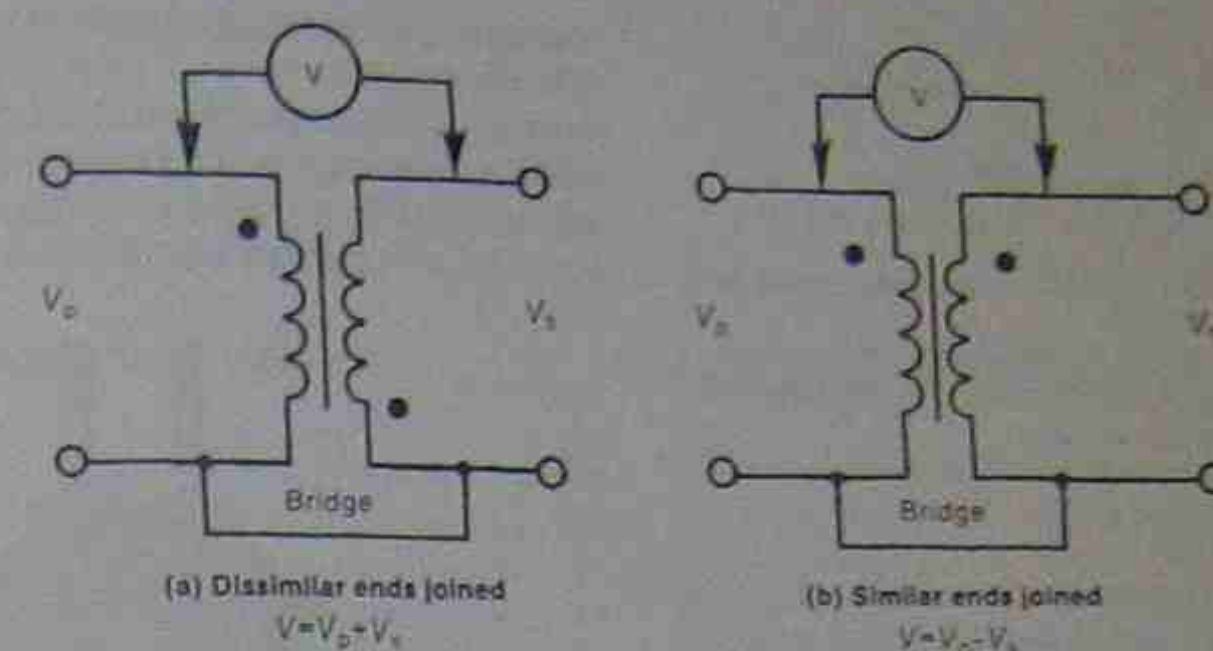


Figure 14.29 • Circuit for checking single-phase transformer polarities

### Delta

The delta connection for transformer secondaries is usually tested by leaving open one of the three bridges and connecting a voltmeter in lieu of the bridge. If the connections are correct, the voltmeter will indicate zero voltage. If the voltmeter reads double line voltage, one of the windings has been reversed.

### 14.9.5 Open-delta connection

The open delta is an asymmetrical connection for three phases. It is seldom used other than for small loads, or in an emergency when one phase winding of a three-phase transformer has failed. The connections are shown in Figure 14.30. It is a method for providing a three-phase supply from two transformers. It can also be used to provide two single-phase supplies for small consumers. Above a certain critical size it is more economical to provide normal three-phase working. Because of the unbalanced and out-of-phase currents, a transformer is reduced to 58 per cent of its normal capacity when working in open-delta connection. It is a common connection for autotransformer starting of three-phase motors. The transformer can be overloaded just for the starting period of the motor.

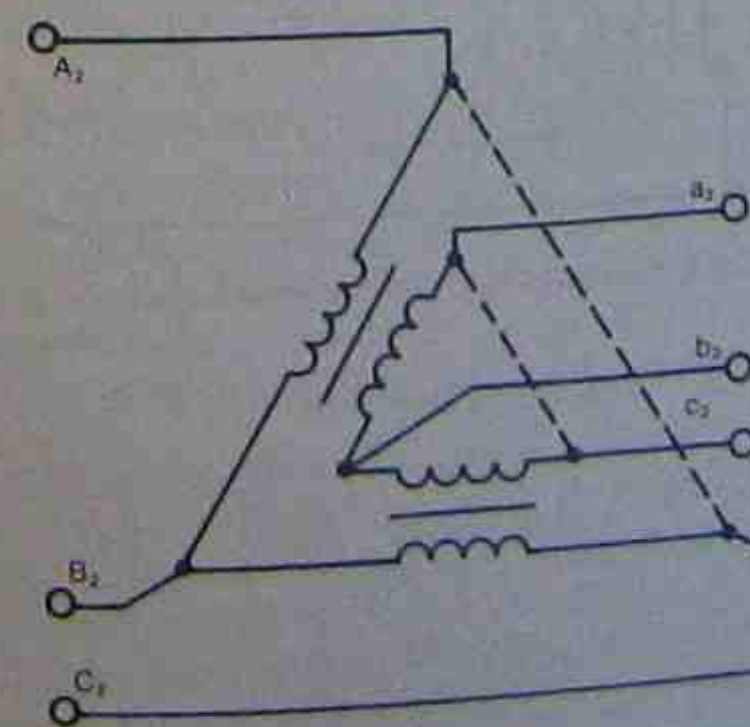


Figure 14.30 • Open-delta connection on a three-phase supply

## 14.10 SPECIAL TRANSFORMERS

### 14.10.1 Instrument transformers

It is unsafe to connect instruments and allied equipment to high voltage and current circuits, so instrument transformers are used to reduce these voltages and currents to more convenient values. The two types of instrument transformers used are potential and current transformers.

#### Potential transformers (PT or VT)

The potential or voltage transformer operates on the same principle as the power transformer, where the ratio of the primary and secondary voltages is proportional to the turns ratio of the primary and secondary windings (i.e.  $V_2 \propto V_1$ ). Potential transformers are designed to have a standard output voltage when the full rated voltage is applied to the primary windings. For single-phase work, AS/NZS 1243 specifies a secondary voltage of 110 V; where transformers are used in the star connection for control work in substations, the standard output voltage for each transformer is 63.5 V, giving a line-to-line voltage of 110 V. The secondary voltage is connected to suitable loads such as voltmeters, wattmeters and protection relays. Because the load is small, the VA ratings of potential transformers are also small. One terminal of the secondary winding is sometimes earthed as an added safety measure in the event of a breakdown in the insulation between primary and secondary windings.

The physical features are similar to those of a power transformer except that the primary has to be insulated for a much higher voltage and is often immersed in oil for extra protection.

Losses are of minor consequence in the design of a PT, the importance being placed on the accuracy of the voltage ratio and the elimination of phase-angle errors. A phase angle of  $0^\circ$  or  $180^\circ$  is desirable, particularly where a PT has to supply such instruments as wattmeters, which have more than one operating coil.

As a general guide, a potential transformer usually operates at low flux densities in iron cores of relatively large cross-sectional areas. The copper conductors have few turns and are large in cross-section.

The standard symbol for a PT is shown in Figure 14.31 and its connections in a test circuit are shown in Figure 14.33. The four terminals of a PT are designated, and care must be taken to see they are correctly connected.





Figure 14.31 • Standard symbols for instrument transformers. The standard secondary values for full-scale meter readings are also shown.

Figure 14.31 • Standard symbols for instrument transformers. The standard secondary values for full-scale meter readings are also shown.

### Current transformers (CT)

In an ordinary power transformer, the flux density in the core is high, the primary current depends largely on the secondary current, and the voltage ratio is the main consideration. However, for the current transformer the reverse applies. The core flux density is very low, the secondary current depends on the primary current, and the current ratio is the main consideration.

The primary winding of a current transformer is connected in series with the load and consists of one or a few turns of a heavy gauge conductor. Because the impedance of the primary winding is so low, the primary current  $I_1$  is not affected by the secondary load, but depends on the external load connected in the primary circuit. The secondary circuit consists of the current coils of ammeters, wattmeters, and protective relays. When the secondary circuit is closed, the secondary current produces a flux, which opposes the primary flux, limiting the flux density of the core to a low value.

The current ratio is equal to the inverse of the turns ratio and so there are more turns on the secondary winding. If the secondary becomes open-circuited, there will be no secondary flux to oppose the primary flux, and so the core flux density increases. Owing to the large ratio of secondary to primary turns, and the excessive core flux, the induced voltage at the secondary terminals increases greatly, producing a safety hazard and the possibility of insulation breakdown. The greater core flux might also cause excessive heat losses and saturation in the core. Consequently the secondary of a current transformer must never be open-circuited under any circumstances and a suitable short-circuiting link is normally provided for connection across the secondary terminals when the instruments are disconnected.

Current transformers are made in a number of forms, depending on requirements and current ratios. Some types have primary windings that have more than one turn, while others are variations of the one-turn primary stage. One variation of the single-turn primary type has a short straight conductor passing through a hole in the iron core and forms part of the transformer's construction. Another type has an opening in the iron core and the transformer is slipped over the busbar or cable. Some current transformers have a secondary winding wound on a circular iron core, which is also slipped over the busbar adjacent to a circuit breaker or power transformer.

The standard for current transformers (ASTM 1675) specifies two values—1 A and 5 A. The higher value is still used in many instances, but increasing use is being made of the lower value, especially in substation work where the instrumentation and control relays are some distance away from the transformers. At the lower value of current,

the resistance and impedance of the cable is of relatively less importance.

Figure 14.32 shows typical voltage and current transformers, and Figure 14.33 shows the connections of a typical instrument load to a high-voltage circuit, using potential and current transformers.



(a) Voltage transformer



(b) Current transformer

Figure 14.32 • Instrument transformers

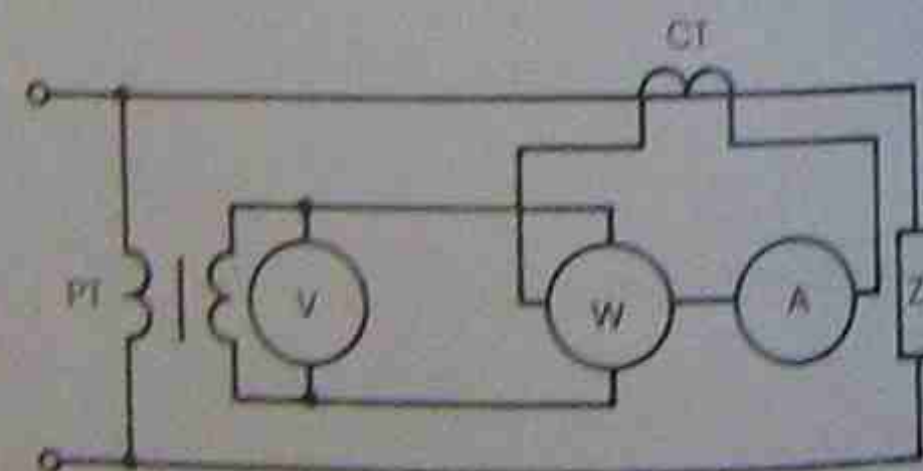


Figure 14.33 • Instrument transformer connections

### Instrument transformer burdens

Apart from a voltage ratio, a PT is also assigned a load or burden rating. This gives an indication of the full-load secondary current and also the load placed on the supply source. For example, a 200 VA potential transformer at 110 V would make available approximately 1.8 A of secondary current for meters and relays:

$$110 \text{ V} \times 1.8 \text{ A} = 200 \text{ VA}$$

Current transformers, however, have to help measure line currents without affecting the load in any way; consequently, while a CT might be able to handle high or low currents, the burden it imposes must be as low as possible (e.g., 5 VA). Because a CT must have a load on the secondary, the burden will exist at all times.

### 14.10.2 Safe-working procedures potential transformers

Potential transformers are designed to provide an instrument voltage at a fixed ratio to the primary voltage. The intention is to restrict the high voltage to a designated area and conduct a safe lower voltage to a monitoring point where it can be connected to instruments or relays. The value should always be proportional to the high voltage.

One side of the secondary is usually earthed and care must be taken in the choice of instruments and their handling to ensure that an additional earth is not introduced at some other point within the circuit. In some cases a non-magnetic shield is installed, during manufacture, between the primary and secondary windings. This is earthed as a means of protection for the operator.

When connecting meters to a PT, a short-circuit across the terminals must be avoided.

### Current transformers

Current transformers are used because it is not practical to handle high currents with normal instruments on a.c. The CT isolates the supply voltage from the operator, and at the same time smaller conductors can be taken from the CT to the measuring location.

Because of the construction principles, the secondary must not be open-circuited. With most CTs and associated instruments a shorting link is provided, and any connecting or disconnecting in CT circuits must follow an accepted procedure that ensures the CT is not open-circuited at any stage. An additional factor that should be taken into account is that an open circuit, apart from the high secondary voltage problem, can also lead to magnetic saturation occurring within the core. This can affect the accuracy of the CT for future use.

Current transformers must have all the windings held firmly in place to withstand the magnetic forces created during overloads, current surges, and fault conditions. The secondaries often have one side of the winding earthed for protection and in some cases a non-magnetic screen between the windings.

### 14.10.3 Transformers with multiple secondaries

There are instances where more than one secondary voltage is desired. The choice is then one of having two or more transformers to obtain the voltages, or having one transformer with one primary winding and more than one secondary.

On occasion it could be mandatory from a safety point of view to have separate transformers, but it is common and often cheaper to have one transformer with a slightly larger core and have as many secondaries as required. This is illustrated in Figure 14.34 where a transformer is shown with three secondary windings, each having different voltages.

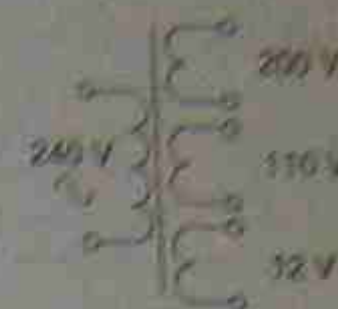


Figure 14.34 • Multiple transformer secondaries

The current and voltage ratios as discussed in section 14.3 still hold true for the individual windings, but it should be kept in mind that the volt-ampere rating of the transformer will be the sum of the individual ratings of each winding. For example, to use the windings of ratings of 50 VA, 55 VA and 40 VA, the transformer as a whole would have to be rated at the sum of these figures, or 145 VA.

If due regard is given to phasing the windings, it is only one further step to connect all three windings in series and have a total voltage of 322 V. This procedure then produces a winding with taps brought out at various voltages.

### 14.10.4 Tapped windings

Particularly for smaller transformers, it is common to see primary and secondary windings with tapings brought out to give a range of voltages from a common point. This method of obtaining various voltages is shown in Figure 14.35. It is also a variation of the autotransformer method that is discussed in section 14.10.5.

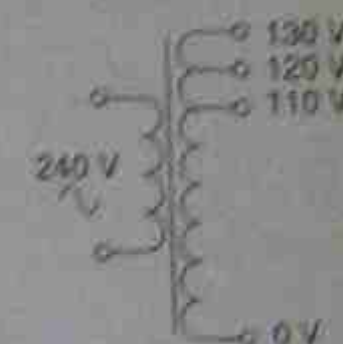


Figure 14.35 • Tapped transformer secondary

While the taps are shown here on the secondary windings, it must be appreciated that the method is not restricted to secondary windings. It is quite usual to see them on primary windings as well.

Once a transformer has its 'turns per volt' ratio established it is a straightforward matter of calculating the required number of turns to determine the location of a voltage tap on the winding. As in section 14.10.3, the volt-ampere rating of the transformer has to be observed.

### 14.10.5 Autotransformers

An autotransformer is one in which part of the winding is common to both the primary and the secondary circuits. The induced e.m.f. across any given number of turns in a transformer depends on the turns-per-volt ratio of the winding. If the winding is tapped at a convenient point, a nominal voltage is available across the terminals, as shown in Figure 14.36.

As in a double-wound transformer, if losses are neglected, the voltage ratio is equal to the turns ratio, and to the inverse of the current ratio:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$



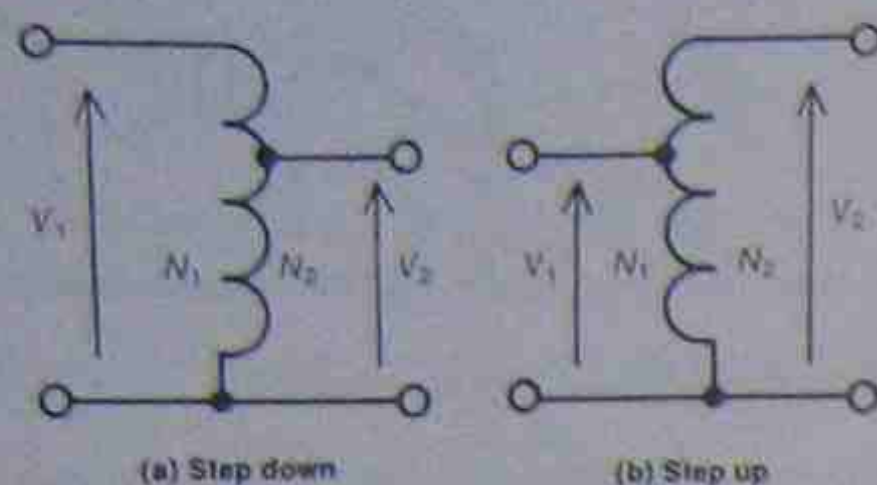


Figure 14.36 • Autotransformer connections

### Example 14.3

Figure 14.37 represents a step-down autotransformer with a total of 240 turns. If the applied voltage  $V_1$  is 240 V, then the turns-per-volt ratio is 1:1. A tapping is taken at point b at 180 turns. Find the output voltage of the transformer.

$$V_1 = 240 \text{ V}, N_1 = 240, N_2 = 180$$

$$\begin{aligned} V_2 &= V_1 \times \frac{N_2}{N_1} \\ &= 240 \times \frac{180}{240} \\ &= 180 \text{ V} \end{aligned}$$

### Example 14.4

If a 45  $\Omega$  non-inductive load is connected across the output terminals of the transformer in example 14.3, find the current in the load, and the current flowing into the transformer from the supply.

$$I = \frac{V}{R}$$

$$I_2 = \frac{180}{45} = 4 \text{ A}$$

$$I_1 = \frac{I_2 V_2}{V_1} = \frac{4 \times 180}{240} = 3 \text{ A}$$

If  $I_2$  flowing away from point b is 4 A, and  $I_1$  flowing into point b is 3 A, a resultant current of 1 A flows through the common winding, from point c towards point b. In a step-up transformer, the direction of this current is reversed and would flow from b towards c.

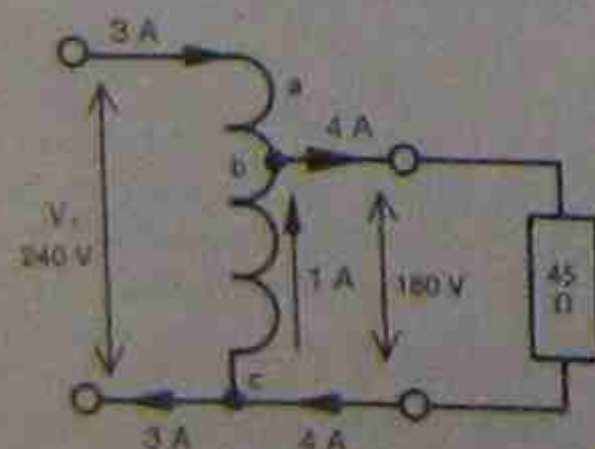


Figure 14.37 • Circuit for examples 14.3 and 14.4

Because this common winding only carries the difference between the primary and secondary currents, the autotransformer requires less copper than a double-wound transformer of a similar rating. Also, the  $I^2R$  loss is lower and the efficiency is higher.

Autotransformers are suitable for applications requiring a voltage transformation of near unity, such as in boosting the distribution voltage to compensate for voltage drop in the lines. Another common use for autotransformers is to reduce the applied voltage to an a.c. motor during the starting process.

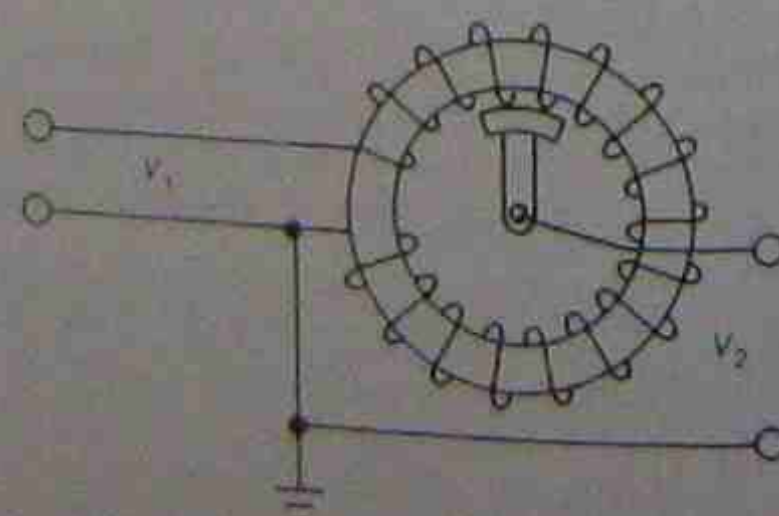
Autotransformers are not considered safe for interconnecting high-voltage and low-voltage circuits because the input and output terminals are connected electrically through the winding. If an open circuit develops in the common winding, the full primary voltage occurs across the secondary circuit. Standard AS/NZS 3000 indicates the limitations placed on the use of autotransformers for general use. In general, the rules stipulate that except in special circumstances the secondary voltage should not vary by more than  $\pm 25$  per cent of the primary voltage.

A variable autotransformer is shown in Figure 14.38. It has a circular laminated core with the winding wound on it. A small part of each turn is left exposed for the various contact points. The contact is made by a carbon brush, and a variable a.c. supply is obtained by sliding the brush along the exposed surface of the winding.



Figure 14.38 • Variable autotransformer

H. Rowe and Co.



### 14.10.6 High-reactance or leakage transformers

When designing transformers, the highest possible efficiency is usually desired, and design features are incorporated to reduce the leakage flux. In some applications, however, transformers with poor efficiency may be deliberately designed to meet particular requirements. Such transformers, called high-reactance or leakage transformers, produce a very high no-load voltage and a comparatively small short-circuit current. The design is such as to permit a low flux leakage on no-load, but a high flux leakage on increasing load. This is achieved by spacing the primary and secondary windings some distance apart on the core, and by using either fixed or variable magnetic shunts (see Fig. 14.39).

On no load, the primary winding produces a flux in the core which cuts the secondary winding, inducing a voltage in it. The leakage flux is reasonably low because the air gaps in the magnetic shunt circuits produce a reasonably high reluctance in the shunt circuits.

The secondary voltage can be calculated using the transformation ratio. However, when the transformer is loaded, the secondary current produces a flux that tends to oppose the primary flux. Because of this opposition, some of the primary flux is diverted through the magnetic shunts, reducing the value of flux cutting the secondary turns. This reduces the value of secondary voltage

at an increasing rate. Figure 14.40 shows the secondary voltage decreasing as the load current increases. Transformers using this principle are found in such applications as furnace ignition, gaseous discharge lighting and welding machines. Long narrow cores can achieve the same result as magnetic shunts, the length of the core governing the degree of leakage. Distribution transformers have a small leakage factor built into them as protection against excessive currents in the event of transmission line failures.

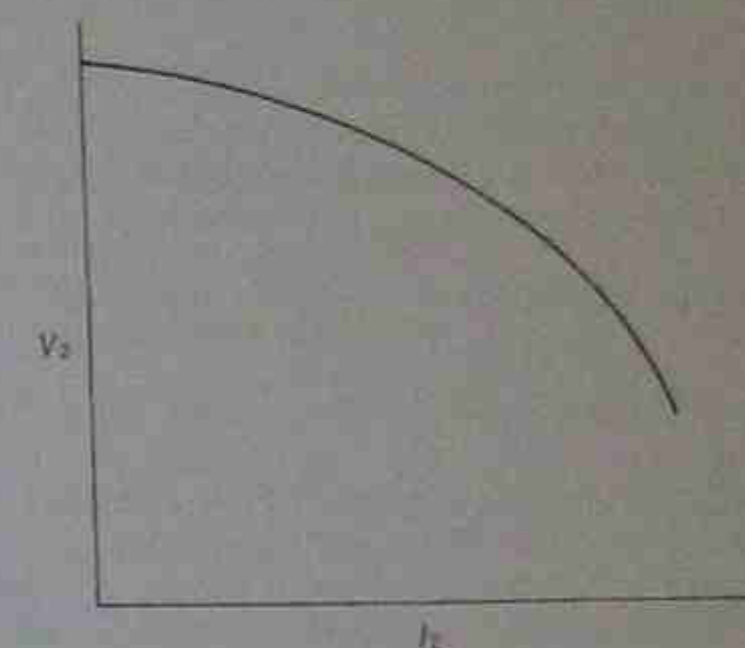


Figure 14.40 • Voltage characteristics of a high-reactance transformer

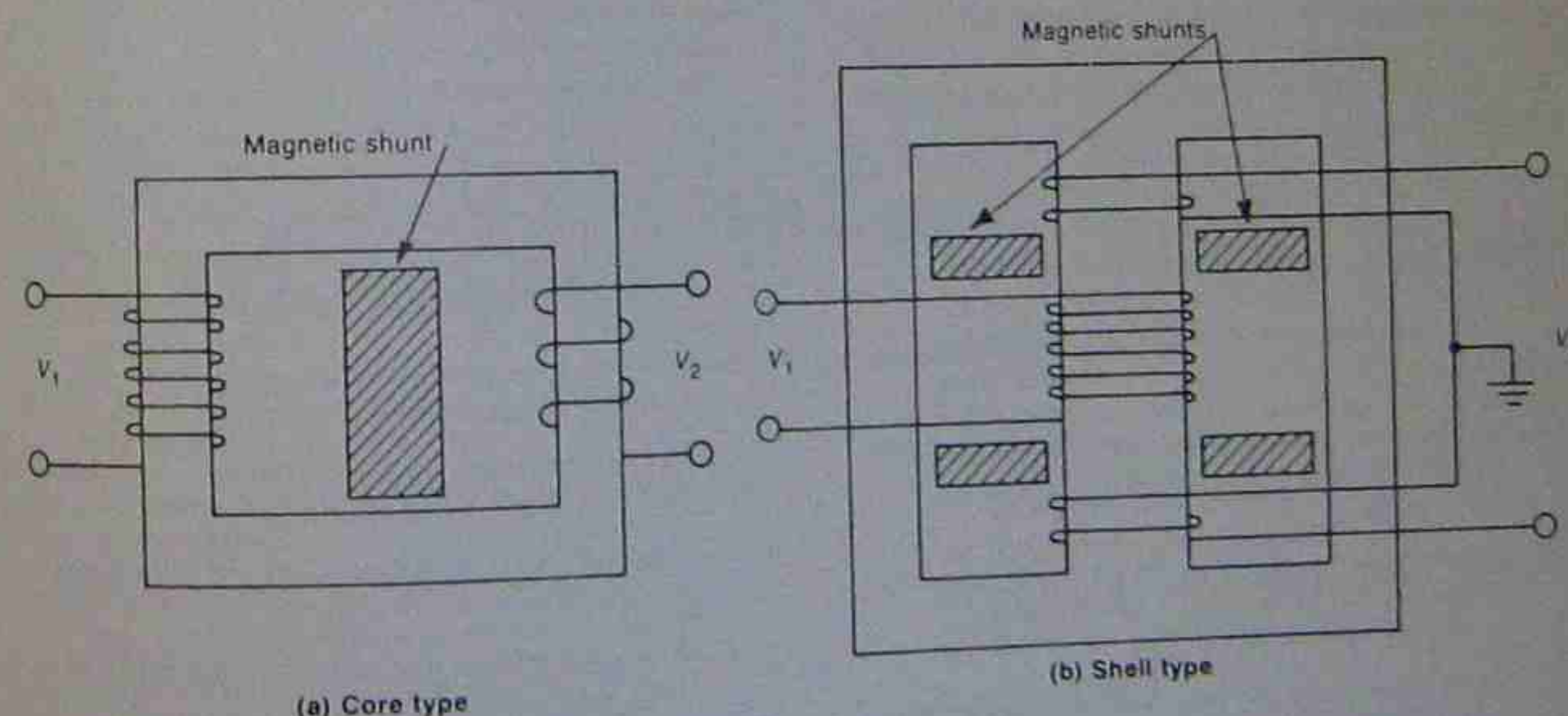


Figure 14.39 • High-reactance transformer construction



## SUMMARY

- Transformers operate on the principle of mutual induction. Alternating current creates an alternating magnetic flux that cuts both windings and generates a self-induced voltage in the first or primary winding and a mutually-induced voltage in the second winding.
- The secondary voltage can be greater or less than the applied voltage, depending on the number of turns on the two windings. Transformation ratios are:

$$V_1/N_2 = V_2/N_1$$

$$V_1/I_1 = V_2/I_2$$

- Transformer losses are due to copper and iron losses and affect the above ratios in practical situations.
- Transformer efficiency =  $\frac{\text{output}}{\text{output} + \text{losses}}$
- Voltage regulation =  $\frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$
- Transformer cores can be shell type or core type. This applies to both single-phase and three-phase use. Cores are usually laminated with special grades of steel to reduce iron losses. Some smaller transformer cores may be made from powdered iron cores set in a medium to hold their shape.
- There is a growing trend to C-cores that are preformed from special grade steel and stress-relieved before use.
- Coil winding arrangements depend on the use to which the transformer is put. Windings may be tightly or loosely coupled.

- Transformer cooling is essential on larger transformers. It may be air or oil cooling. There are many variations and combinations of cooling methods. Even the colour of the tank holding the transformer has an effect on cooling.
- Winding polarities are necessary in order to phase transformers out for paralleling purposes.
- Three-phase transformer connections can cause phase shifts in secondary voltages.
- Factors affecting parallel operation of transformers are: voltages, frequencies, instantaneous polarities, and phase relationships affected by connections.
- Commercial transformers have to conform to Australian and New Zealand standards as regards terminal-plate layouts.
- Transmission transformers may have a tertiary winding to suppress third harmonics in the system.
- In long-distance transmission lines it might become necessary to change transformer ratios while on line to maintain voltage levels.
- Two methods for changing ratios are off-line and on-line tap changing.
- Special purpose transformers comprise:
  - potential and current transformers
  - multiple secondaries
  - tapped secondaries
  - autotransformers
  - variable autotransformers
  - high-reactance transformers.

## EXERCISES

- What is meant by the terms *primary* and *secondary* windings?
- Explain the relationship between the voltages and number of turns of the two windings of a transformer.
- Explain how a transformer regulates the amount of primary current required to supply a given secondary load.
- What is meant by the term *leakage flux*, and how is it kept to a minimum?
- What are the major losses in a transformer and how are they affected by the load?
- Explain why the polarities of transformers must be known when the transformers are to be connected in parallel.
- Using a diagram, show the method of connecting the instruments required to measure voltage, current and power in a high-voltage a.c. circuit.
- Describe the construction of a current transformer.
- Compare the operation of a current transformer with that of a potential transformer.
- Why is it necessary for the secondary of a current transformer to be kept closed?
- What is an autotransformer? List the advantages and disadvantages of autotransformers.
- What are the four types of connection for three-phase transformers?
- A transformer with a 32 V output is to be rewound to deliver 12 V, maintaining the same VA rating.
  - Explain why it is not necessary to rewind the primary winding.
  - Explain why it is necessary to rewind completely the secondary winding.
  - What effect will the rewinding have on the iron losses of the transformer?
  - What effect will the rewinding have on the copper losses of the transformer?

## SELF-TESTING PROBLEMS

- The primary winding of a 440/55 V transformer has 400 turns. How many turns are there on the secondary winding?
- A 100 kVA 11000 V/250 V transformer operates at 6 V per turn. Find the number of turns and current rating of each winding.
- The 110 V output of a transformer is applied to a 22  $\Omega$  resistive circuit, causing 0.22 A to flow in the primary winding. Calculate the primary voltage.
- 240 V is applied to the primary winding of a transformer having 1100 turns. If the secondary has 900 turns, calculate the secondary voltage.
- A voltmeter, ammeter and wattmeter are connected to a single-phase circuit, by means of the appropriate instrument transformers, and the following results are obtained:
 

• CT ratio	100:5
• PT ratio	11 000:110
• voltmeter reading	10 800 V
• ammeter reading	95 A
• wattmeter reading	872 kW.

 Calculate the actual voltage, current, volt-amperes and power in the secondary circuit.
- Three single-phase transformers with a transformation ratio of 20:1 are connected to an 11 000 V three-phase supply as step-down transformers. Calculate the secondary line voltage if the transformers are connected in:
  - star-star
  - star-delta
  - delta-delta
  - delta-star.
- Tests on a transformer rated at 19 kV to 480 V at 50 Hz establish:
  - open-circuit test—iron losses = 586 W.
  - short-circuit test—copper losses = 600 W.
 If the transformer supplies a resistive load of 9.6  $\Omega$ , calculate the efficiency of the transformer.
- An autotransformer is used to boost the voltage on a 7700 V feeder to 8000 V. If the load on the secondary is 72 kW at unity power factor, find:
  - the secondary or output current
  - the primary or input current
  - the current in the common section of the winding.
 Neglect all losses.
- A 240/115 V single-phase transformer has 960 turns on its primary winding. Calculate the number of turns required on the secondary winding.
- The load on the secondary of a 240/32 V single-phase transformer is 3 A. Calculate the primary current if the transformer efficiency is 75 per cent.
- A 240 V 50 Hz single-phase transformer has a core area of 25 cm<sup>2</sup>. If it is to work at a maximum flux density of 1.1 T, find the number of turns required for the primary winding.
- The maximum flux of a 50 Hz transformer is 0.001 Wb. If the primary is wound with 1080 turns, find the applied primary voltage and then calculate the number of turns required for a 15 V secondary.
- An 11 kV star-delta distribution transformer has 326 turns on each of its primary windings. Calculate the number of turns required on each secondary winding if the delta-connected secondary output is 6.6 kV.
- An 11 kV step-up distribution transformer is connected in delta-star configuration. The delta-connected primary windings have 566 turns each. Ignoring losses, calculate the number of turns required on the star-connected secondary windings if its line output is 33 kV. Given an output current of 150 A at a power factor of 0.95 leading, calculate:
  - the primary line current
  - the primary phase current
  - the output power being delivered
  - the output rating in kVA.



# Chapter 15

## Direct current power supplies

### 15.1 INTRODUCTION

At the heart of most electrical and electronic equipment in use today is a power supply. Without this power supply the equipment will not operate. A typical everyday example is the motor car. No matter how sophisticated the engine, transmission and suspension in the vehicle, it cannot operate if the electrical system is not functioning, or is removed. Another example is the programmable controller (PC). This piece of equipment is responsible for major advances in the control of industrial processes. Again, if the power supply in this equipment fails, or is inoperative for some reason, the PC will not perform its intended functions.

This chapter introduces the principles of basic single- and three-phase power supplies. The operating principles of the major components and circuit building blocks will be examined. This will include the rectifier diode, single- and three-phase rectifier circuits, filter circuits and voltage regulator circuits.

The purpose of most power supplies is to ensure that a load is supplied with a constant, stable and well-protected power source. This will ensure the long-term reliability of the load. In most cases the load will be a piece of electrical or electronic equipment. This may vary from something as simple as a battery charger, to a piece of computing equipment, or an electronic motor-speed controller.

### 15.2 SEMICONDUCTOR MATERIALS

All elements are made up of atoms, which consist of a nucleus of protons and neutrons with electrons orbiting the nucleus in layers or shells (see Ch. 2).

Good conductors have few electrons in their outermost layer. Called valence electrons, they are loosely bound to the nucleus. In insulating materials the outermost electron layers are complete and consequently strongly bound to the nucleus.

Most electronic components are manufactured from materials known as semiconductors. In their pure or intrinsic state these materials are neither good conductors nor good insulators.

Silicon and germanium are the two major semiconductor materials. In their pure state they are simultaneously poor conductors and poor insulators. This is due to the fact that each material has four valence electrons in its outermost layer or shell. The adjacent atoms in these materials form covalent bonds that are strong and as a result there are few electrons available as current carriers.

#### 15.2.1 p-type and n-type semiconductor materials

To make use of semiconductor materials, impurities are deliberately added to change their characteristics. The impurities are added in very small quantities, typically one part in ten million. The process of adding the impurities is called *doping*.

Doping changes a semiconductor's electrical characteristics significantly. The conductivity of the material improves dramatically. Semiconductor materials can be doped in one of two ways:

- doping with elements that have only three valence electrons. This leaves a vacancy, or 'hole', for an electron to move into, and is called *acceptor doping*
- doping with elements that have five valence electrons. This leaves a spare electron in the bonding process, and is called *donor doping*.

Adding trivalent impurities produces holes in the bonds formed between adjacent atoms. Because these holes will readily accept an electron, they represent a positive charge. If an electron moves into a hole, a hole is created elsewhere in the structure and the hole is said to move. In this case most of the current flow in the material is due to the movement of holes, and since holes represent a positive charge, the material is called *p-type semiconductor material*, shown in Figure 15.1.

Accepter doping produces holes as majority current carriers and the material is p-type semiconductor material.

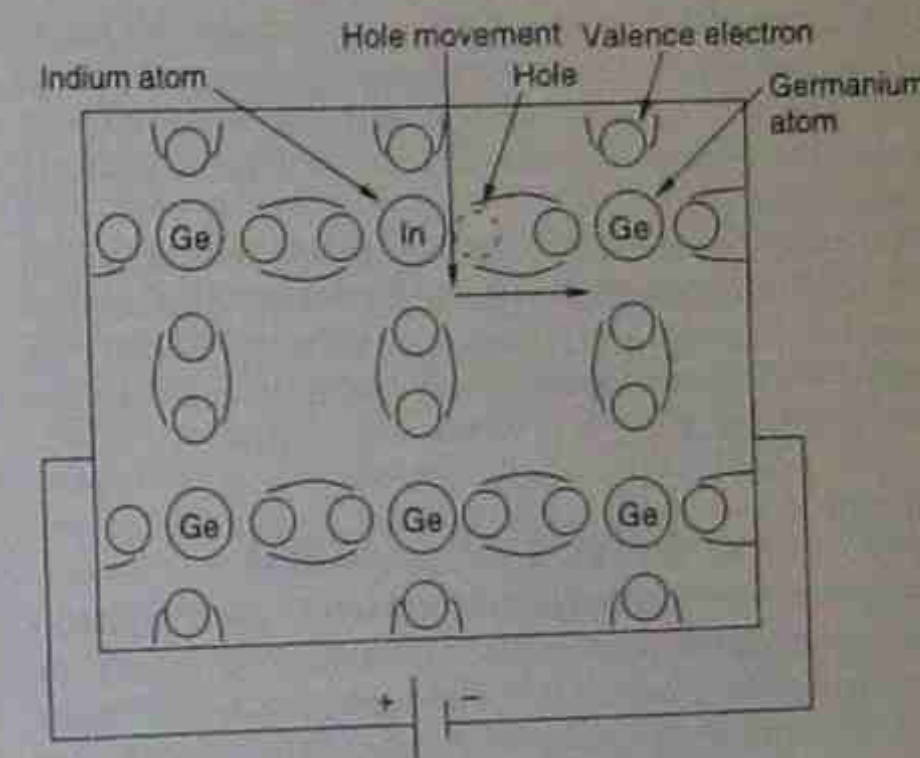


Figure 15.1 • p-type lattice structure

Adding pentavalent impurities produces spare electrons in the bonds formed between adjacent atoms. The spare electrons represent a negative charge. The spare electrons are free to move about the material. In this case most of the current flow in the material is due to the movement of electrons and, since electrons exhibit a negative charge, the material is called *n-type semiconductor material*, shown in Figure 15.2.

Donor doping produces electrons as majority current carriers and the material is n-type semiconductor material.

In both cases it is important to note that the overall charge on the material is neutral. The terms *p-* and *n-type* material refer only to the polarity of the majority current carriers.

As the temperature of a semiconductor material increases, electrons break away from the crystal lattice structure; subsequently holes are also developed. This is



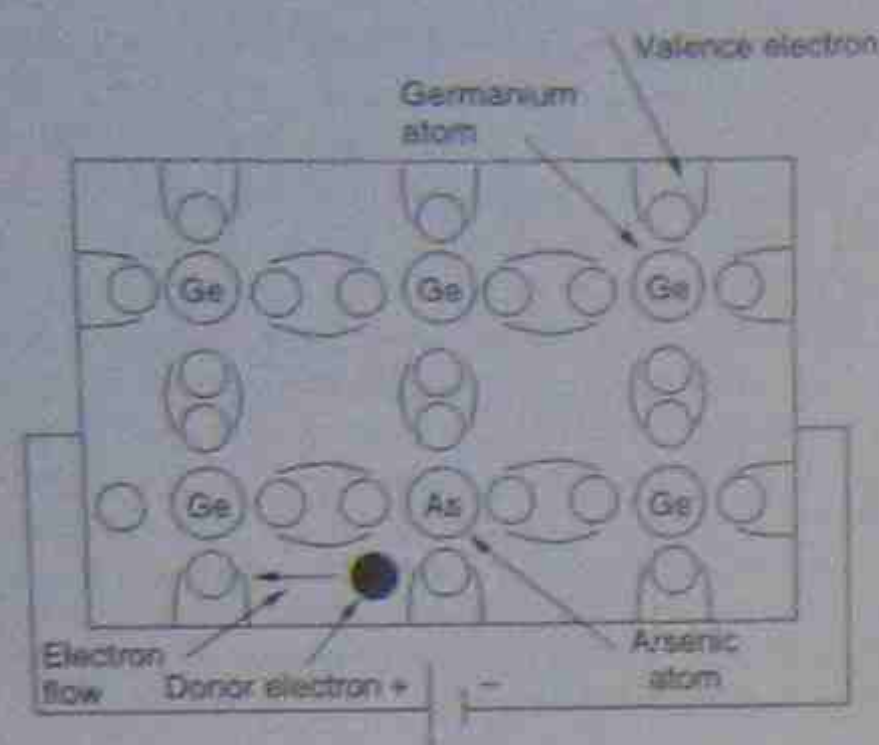


Figure 15.2 • n-type lattice structure

called thermal generation of electron/hole pairs and is due to the increased energy in the material as the temperature increases.

The thermally generated current carriers are very few in number and are therefore called *minority current carriers*. It is the minority current carriers that are responsible for most of the leakage currents that occur in semiconductor components.

The p-type and n-type semiconductor materials that have been developed have few applications when used on their own. It is only when they are used together that they become very useful. Joining the two materials together forms a p-n junction.

### 15.3 p-n JUNCTION DIODE

Fusing together pieces of p-type and n-type semiconductor materials forms a junction in which current carriers are combined. This junction is called a p-n junction. It is the basis of most semiconductor devices. Whether they are silicon or germanium, their actions are identical.

When the junction is formed, electrons from the n-type material move into the p-type material and combine with holes. As a result, the area in which this occurs becomes depleted of current carriers. As an electron leaves the n-type material, it leaves behind a positive charge and creates a negative charge on the p-type material. As more and more current carriers combine, the resultant charge increases, resulting in a voltage appearing across the junction. A p-n junction is shown in Figure 15.3.

This voltage is called the *barrier potential*. At some point

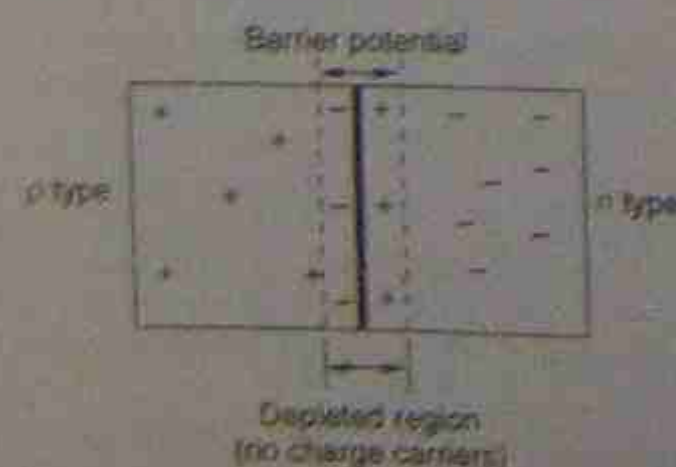


Figure 15.3 • Diode depletion layer

this potential will prevent further combination of holes and electrons. Even though this potential exists across the junction, the overall potential or charge on the diode is still electrically neutral.

The barrier potential created across the junction is 0.6 V for silicon devices and 0.3 V for germanium devices.

The area around the junction that becomes depleted of current carriers is called the *depletion layer*. The way in which the depletion layer is affected is important in the operation of the junction diode. When biased in one way, current may flow; when biased in the opposite way, current flow is blocked.

The standard symbol used to identify a diode is shown in Figure 15.4.



Figure 15.4 • Diode symbol

#### 15.3.1 Forward biased p-n diode

If the diode is connected as in Figure 15.5, that is, with the anode positive with respect to the cathode, the diode is said to be forward biased.

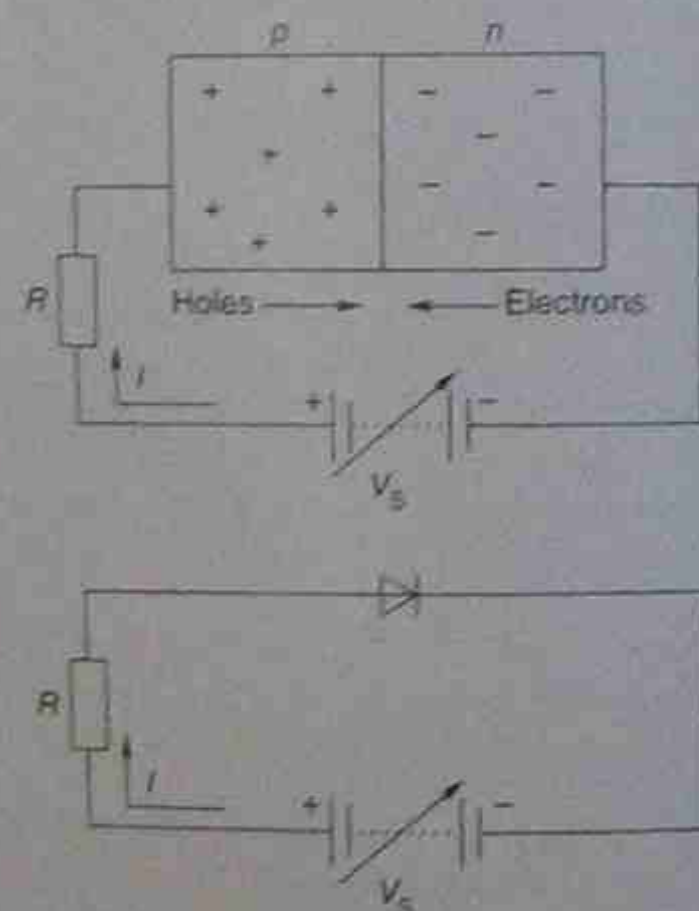


Figure 15.5 • Forward biased p-n diode

As a result of this connection the positive terminal of the supply is a source of holes and the negative terminal is a source of electrons. Holes and electrons both drift towards the junction and the width of the depletion layer is reduced.

As the supply voltage is gradually increased from zero, the current flow is small. As the voltage approaches the value of the barrier potential, the depletion layer almost disappears and large numbers of majority current carriers cross the junction. When the supply voltage exceeds the barrier potential, the resistance of the device decreases to a very low value and current flows freely. The diode is said to be forward biased.

When a p-n diode is forward biased, current flows from the anode to the cathode.

#### 15.3.2 Reverse biased p-n diode

When the diode is connected as in Figure 15.6, that is, with the anode negative with respect to the cathode, the diode is said to be reverse biased.

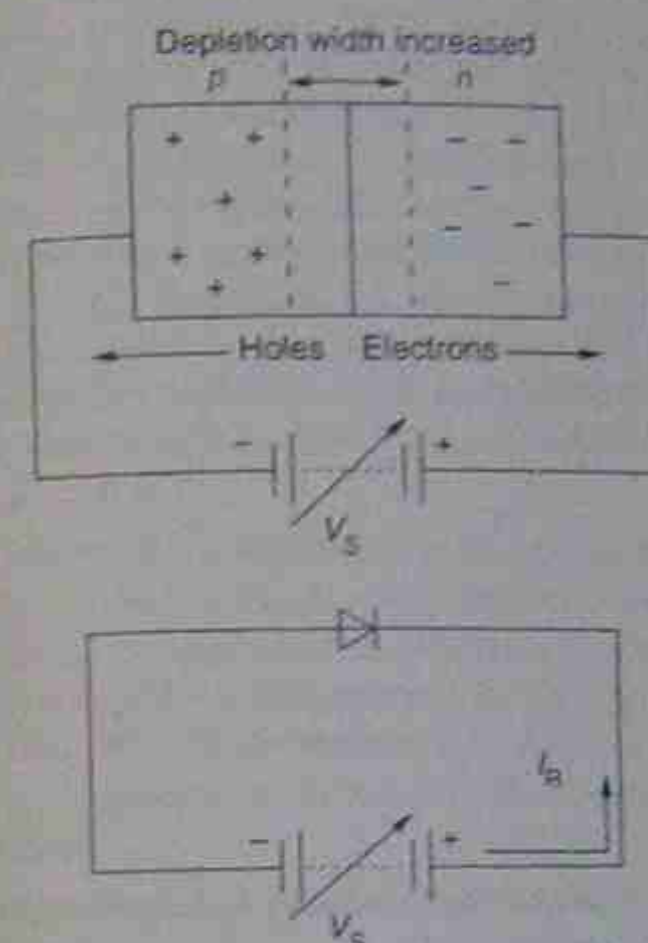


Figure 15.6 • Reverse biased p-n diode

As a result of this connection the positive terminal of the supply tends to draw electrons away from the junction, and the negative terminal of the supply tends to draw holes away from the junction. The depletion layer increases in width. In this situation, majority current carriers are prevented from moving across the junction and the current flow due to majority carriers will therefore be zero. Some thermally generated minority current carriers will cross the junction in these circumstances, resulting in a very small current flow.

The current flow is so small, particularly in silicon devices, that it is usually ignored. This current flow due to the minority carriers is called a *leakage current* and flows from cathode to anode.

When reverse biased, a p-n diode blocks current flow. Current will only flow if the reverse voltage becomes so large as to cause a breakdown of the depletion layer in the device. This usually results in device failure.

#### 15.3.3 p-n diode characteristics

The characteristics of the p-n diode may be determined from the circuit in Figure 15.7. In the forward direction the diode voltage drop is measured for various values of current.

The forward characteristic reveals that until the forward voltage is sufficient to overcome the barrier potential, the diode has a high resistance and current flow is only small. When the barrier potential is overcome, the resistance changes abruptly to a very low value and the current flow increases.

As current flow increases, the forward resistance of the diode decreases. This results in a relatively constant forward voltage drop across the diode and the voltage drop will be equal to the barrier potential. Therefore, the

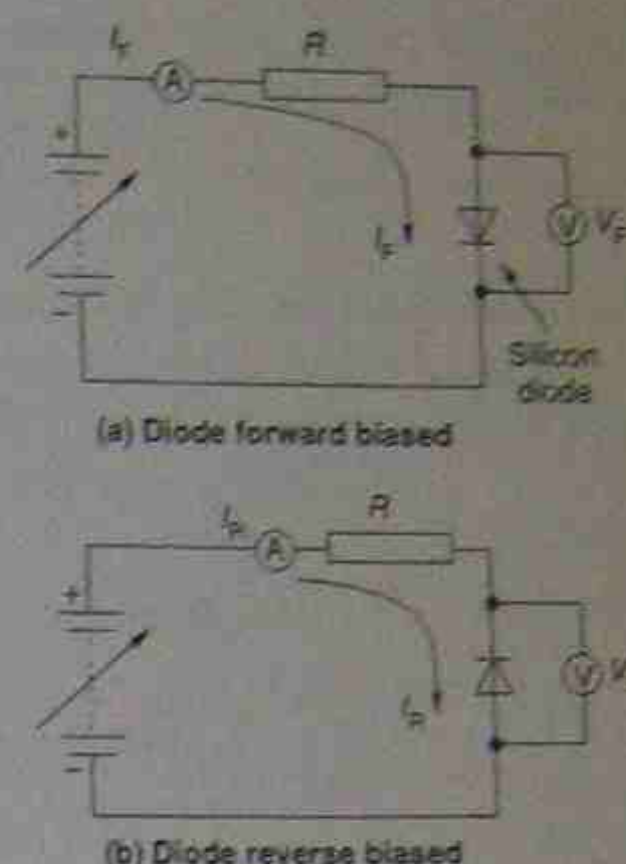


Figure 15.7 • Diode characteristics—test circuits

forward voltage drop across a p-n diode will be equal to:

- 0.6 V for silicon diodes
- 0.3 V for germanium diodes.

The reverse characteristic reveals that p-n diodes have a very high resistance. This value may in fact be in excess of 1.0 MΩ. The current flow is very low, measured only in microamperes (μA).

If the reverse voltage becomes excessive, an 'avalanche' effect occurs and the diode conducts heavily, usually resulting in permanent damage to the diode. The maximum reverse voltage that a diode can withstand is called the *peak reverse voltage (PRV)* or *peak inverse voltage (PIV)*. The reverse leakage current in a germanium diode is much higher than the corresponding current in a silicon diode.

#### 15.3.4 Effects of temperature on p-n diodes

The characteristics of a p-n diode will be affected by changes in temperature that might be due to changes in ambient temperature or heat generated within the diode when current flows. Both forward and reverse characteristics are affected. The barrier potential across the diode when forward biased will decrease with increases in temperature. The designated values of 0.6 V for silicon and 0.3 V for germanium are specified at a temperature of 25°C. For every Celsius degree rise in temperature, the barrier potential will decrease by approximately 2.5 mV.

Thus, if the temperature increases to 45°C the barrier potential of a silicon diode will decrease by 50 mV (2.5 mV × 20°), from 0.6 V to 0.55 V.

When reverse biased, the current flow in a diode is due mainly to thermally generated electron/hole pairs; it follows that if the temperature increases, the number of thermally generated current carriers will increase.

Thus as the temperature of the diode increases, the reverse saturation current will increase. For both silicon and germanium diodes, this current will approximately double for every 10°C rise in temperature. Owing to the higher initial reverse saturation current of the germanium



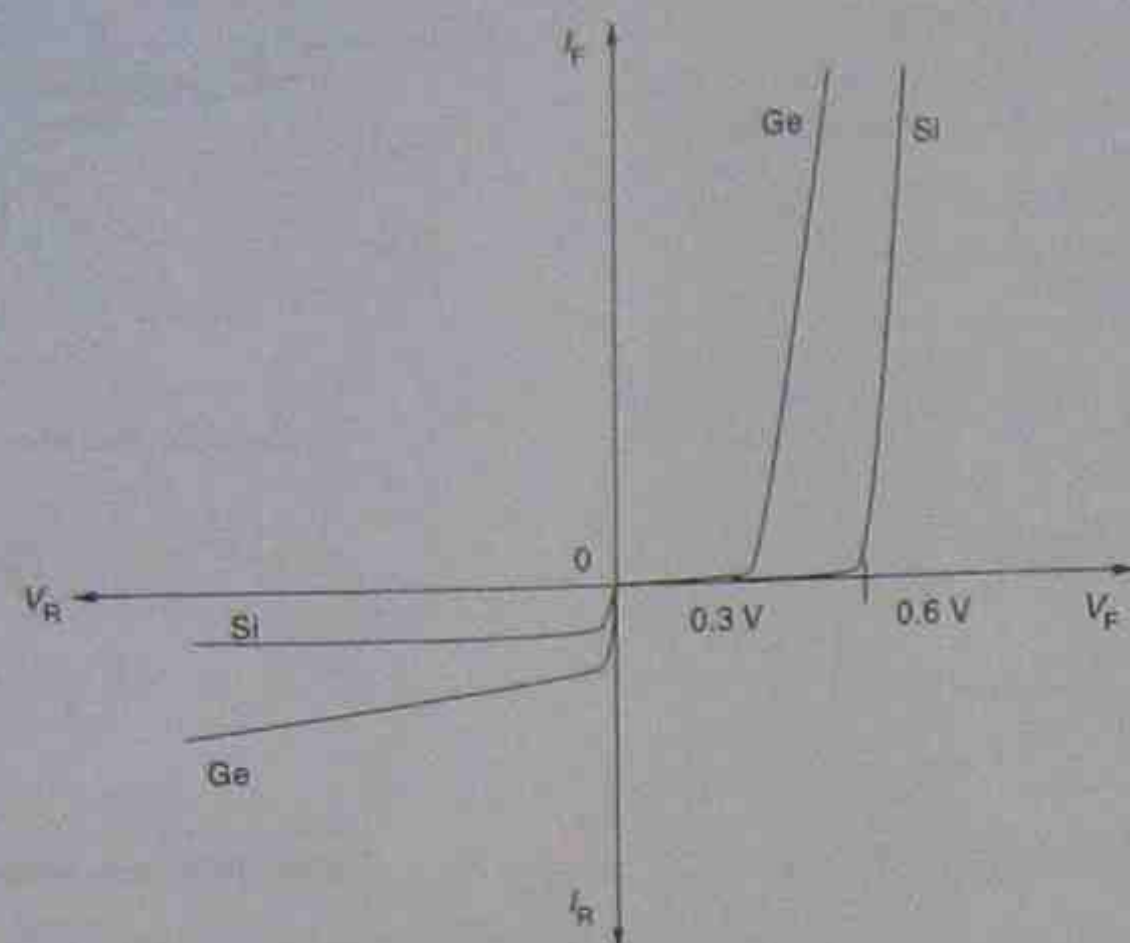


Figure 15.8 • Forward and reverse characteristics—silicon and germanium diodes

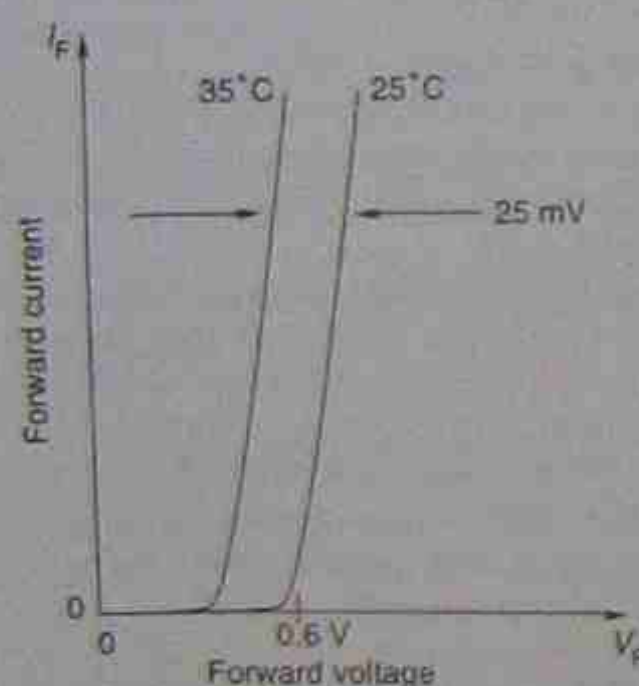


Figure 15.9 • Effect of temperature on barrier potential in a p-n diode

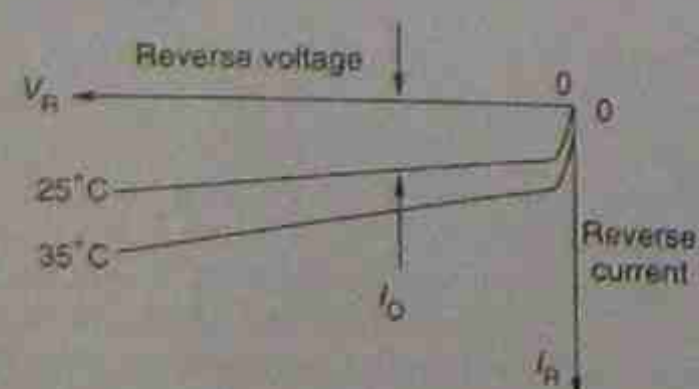


Figure 15.10 • Effect of temperature on leakage current in a p-n diode

diode, the effect of an increase in temperature on reverse current will be more obvious in the germanium diode than in the silicon diode.

Many diodes are intended to be mounted on a heat sink to aid in the dissipation of heat. The purpose is to minimise the junction temperature as much as possible. A heat sink may take the form of a finned aluminium extrusion. Ideally a heat sink will have very good thermal

conductivity, a high heat capacity, and a large surface area for a given mass.

### 15.3.5 Voltage and current ratings

Semiconductors, or p-n diodes, are available in voltage and current ratings from very low values up to currents in excess of 1000 A and voltages around 5 kV. When selecting a diode for a particular application, the two most important electrical ratings are:

- **Average forward current ( $I_{F(max)}$ )**—this is the maximum average value of forward current that can be carried continuously. It may require the diode to be mounted on a heat sink.
- **Peak reverse voltage (PRV)**—this is the maximum peak reverse voltage that may be continuously applied to the diode when reverse biased. As the temperature of a diode increases, the risk of diode failure if the PRV rating is exceeded increases.

In some cases the surge current and voltage ratings must be taken into account. These values are usually much higher than the continuous ratings, but apply only for a very short period of time, say one or two cycles, and are not repetitive.

### 15.3.6 Testing of diodes

In normal fault investigation and servicing, it is often necessary to test diodes for their service condition. A simple test may be carried out with a multimeter that will, in a large majority of cases, allow a technician to identify a good diode from a faulty diode. This test is best done using an analogue multimeter. For this test it is essential for the output voltage from the multimeter, when on the ohms range, to be high enough to overcome the barrier potential of the diode. Care also needs to be taken to ensure that the output voltage from the multimeter is not so high that the diode is damaged by the testing process.

The output voltage from the multimeter must exceed the barrier potential of the diode under test: 0.6 V for

germanium. Most digital multimeters have only a very low output voltage when switched to a resistance range. This voltage is usually too low for satisfactory testing of semiconductor components. Digital multimeters are often equipped with a diode test facility to overcome this.

Care also needs to be taken because most analogue multimeters reverse their polarity markings when switched to an ohms range. A simple procedure to prevent confusion is to connect a red lead into the terminal marked 'Negative' and a black lead into the terminal marked 'Positive'. Then treat the red lead as positive and the black as negative, ignoring the polarity markings on the terminals of the multimeter. As in any test using an ohmmeter, the leads must be shorted together to adjust the zero reading with the multimeter set on an appropriate range, a suitable one being:

- $\Omega \times 1$  (or  $R \times 1$ )
- $\Omega \times 100$  (or  $R \times 100$ )—usually represents a 1 k $\Omega$  range.

The anode and cathode of the diode must then be identified. This is usually evident when the body of the diode is examined. Some examples are given in Figure 15.11.

Only two tests are necessary:

- forward bias the diode—anode positive, cathode negative
- reverse bias the diode—anode negative, cathode positive.

The results will clearly indicate the condition of the diode. Essentially three conditions are possible:

- serviceable diode
- open-circuited diode—usually caused by excessive forward current

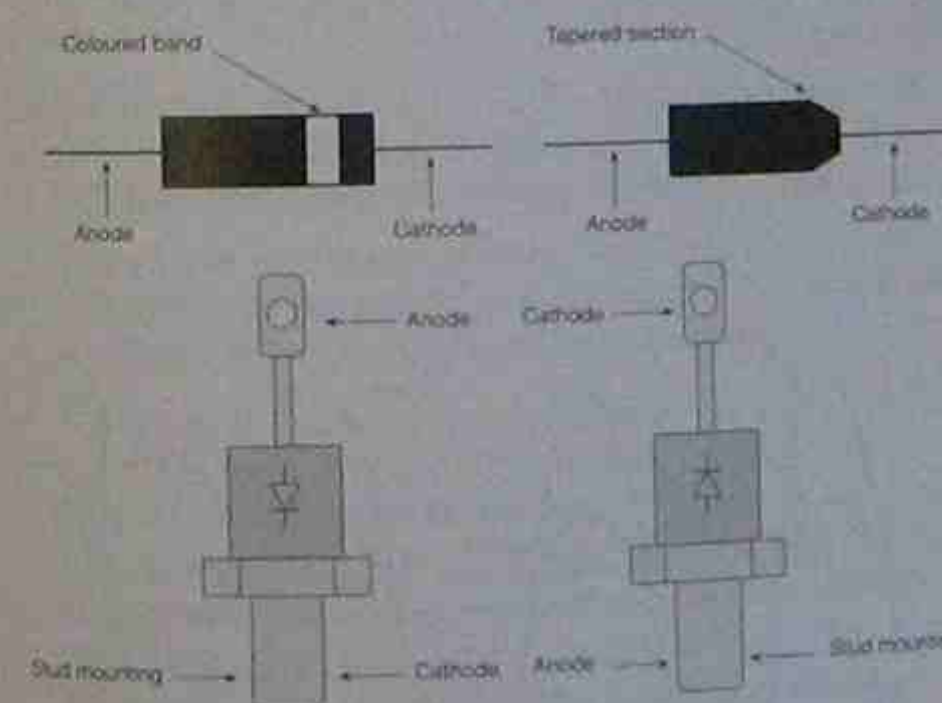


Figure 15.11 • Diode terminal identification

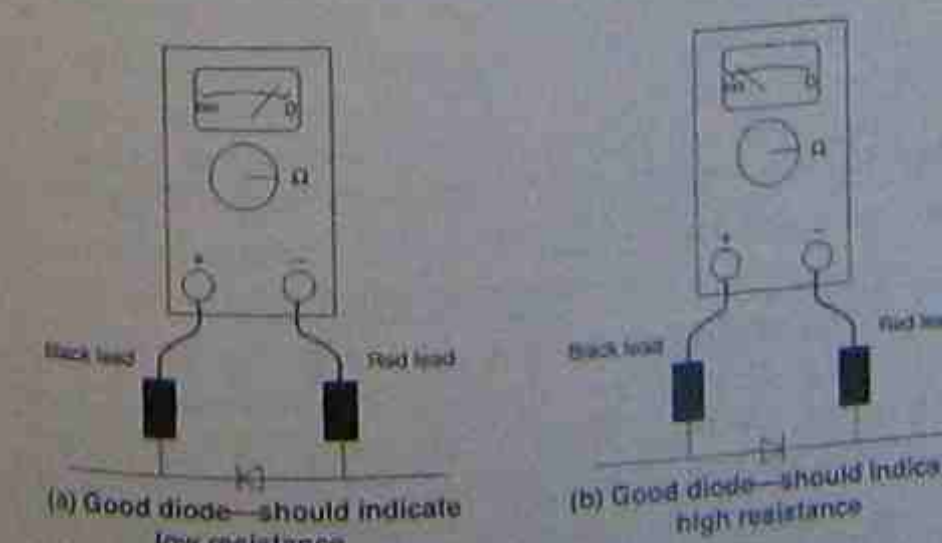


Figure 15.12 • Diode testing using an analogue multimeter

- short-circuited diode—usually caused by excessive reverse voltage, but can also occur from excessive forward current.

The expected results for this test are outlined below in Table 15.1.

Table 15.1 • Diode test results—analogue ohmmeter

Diode condition	Anode polarity	Cathode polarity	Expected resistance
Diode okay	+	-	Low
	-	+	High
Open-circuit diode	+	-	High
	-	+	High
Short-circuit diode	+	-	Low
	-	+	Low

While these results are generally reliable for low to medium current diodes, in some cases a diode may appear to be serviceable but fail when subjected to high temperatures in service. Diodes that fail in this way usually become short-circuited rather than open-circuited. This will be evident if the diode is tested immediately after the supply is isolated. Disconnect one lead of the diode and test it before it cools down. Alternatively an oscilloscope may be used to observe the waveform across the diode. If the diode is short-circuited, the voltage across it will be very near zero in both directions.

If a digital multimeter is used to test a diode, different results will be obtained. It should also be noted that digital multimeters rarely reverse their polarity when switched to a resistance or diode test range. A digital multimeter passes a constant current through the junction under test and measures the voltage drop across it. The expected results for a silicon diode, tested with the diode test facility on a digital multimeter, are given in Table 15.2.

Table 15.2 • Diode test results—digital multimeter

Diode condition	Anode polarity	Cathode polarity	Multimeter display
Diode okay	+	-	0.6
	-	+	8888
Open-circuit diode	+	-	8888
	-	+	8888
Short-circuit diode	+	-	0
	-	+	0

Multimeter display will flash, indicating an overload

Germanium diodes will give similar results except that a reading of 0.3 V replaces the 0.6 V for the silicon diode.



### 15.3.7 Diode applications

Diodes are used in a variety of applications, the majority being in a.c. to d.c. converters (rectifiers) and d.c. to a.c. converters (inverters). They are also used in circuits as current guides or blocking devices in some configurations and to protect analogue meter movements.

Silicon diodes are generally preferred to germanium diodes because they have much higher junction temperature ratings and can therefore carry higher currents. Silicon diodes also have much lower reverse leakage currents. Silicon diodes are now used so universally that unless otherwise stated, it may be assumed that a diode in any given circuit is a silicon diode.

## 15.4 DIRECT CURRENT POWER SUPPLIES

A d.c. power supply is made up of a number of component blocks. The overall purpose of these blocks is ultimately to provide a stable, well-regulated and smooth (ripple-free) d.c. supply. More complex power supply circuits incorporate very sophisticated protection circuits to protect both the load and the components in the power supply. Only a basic power supply configuration will be considered in this chapter. Figure 15.13 (below) is a block diagram of a basic d.c. power supply. Note the standard symbol for each of the component blocks.

The function of each of the blocks is as follows:

- **The a.c. supply**—consists of the actual a.c. supply, usually derived from the mains, and a transformer. The purpose of the transformer is to provide electrical isolation between the mains and the power supply and to adjust the mains voltage to a level suitable for a given application.
- **The rectifier**—The rectifier is one of the most crucial component blocks in a power supply circuit. It converts the a.c. supply into a d.c. supply. The resultant d.c. supply is a pulsating d.c. supply; it is said to contain a ripple voltage.
- **The filter**—The purpose of the filter is to remove as much of the ripple from the d.c. supply as possible. Ripple in the supply interferes with the operation of equipment, particularly computer and measuring equipment.
- **The regulator**—provides a stable and constant value of d.c. voltage, essential for most electronic equipment. This part of the supply will make adjustments to the output voltage to take into account variations in input voltage and load current.

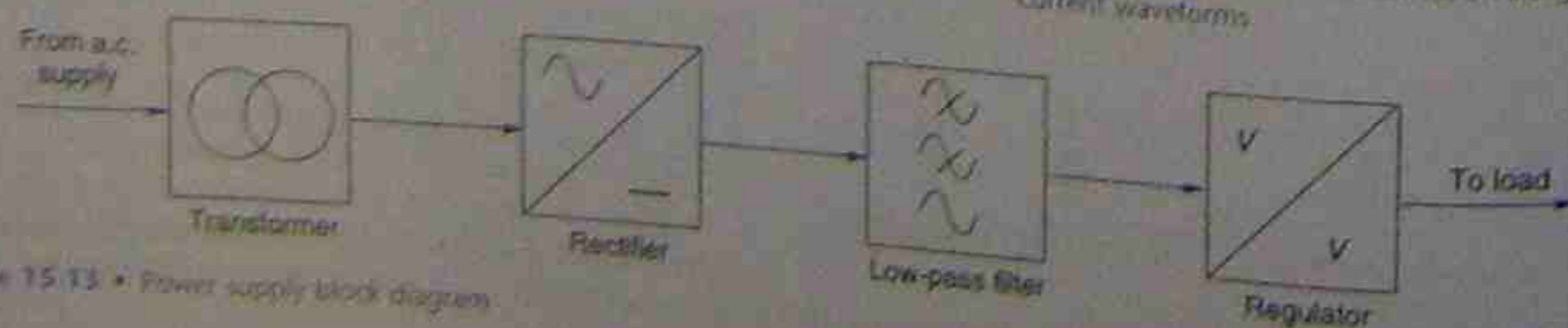


Figure 15.13 • Power supply block diagram

### 15.4.1 Single-phase half-wave rectifier circuit

In this most basic of all possible rectifier configurations, as the name implies, only half of the a.c. input waveform is used. In this circuit a single p-n diode is interposed between the a.c. supply and the load. When the diode is forward biased, it conducts, and when reverse biased, it blocks current flow.

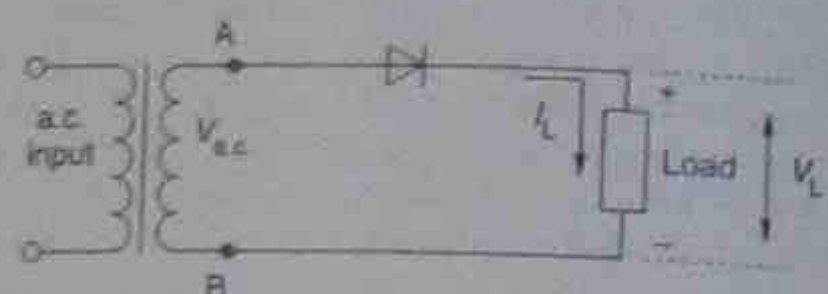


Figure 15.14 • Single-phase half-wave rectifier

In the circuit of Figure 15.14 the diode is forward biased. When terminal A is instantaneously positive, the diode conducts and current flows through the load. When terminal B is instantaneously positive, the diode is reverse biased and blocks current. If reverse leakage current is ignored, the current flow is zero.

Current only flows in the load in the positive half-cycle of the supply, hence the term *half-wave rectifier*.

Given that the load is resistive, the load current waveform will take the same shape as, and be in phase with, the load voltage. The waveforms for the single-phase half-wave rectifier are shown in Figure 15.15.

In determining the voltages and currents in the loads connected to rectifiers, certain definitions need to be examined:

- **Average d.c. output**—This value is the average height of the pulsating d.c. output. It is the value of steady, unvarying d.c. that would do the same amount of

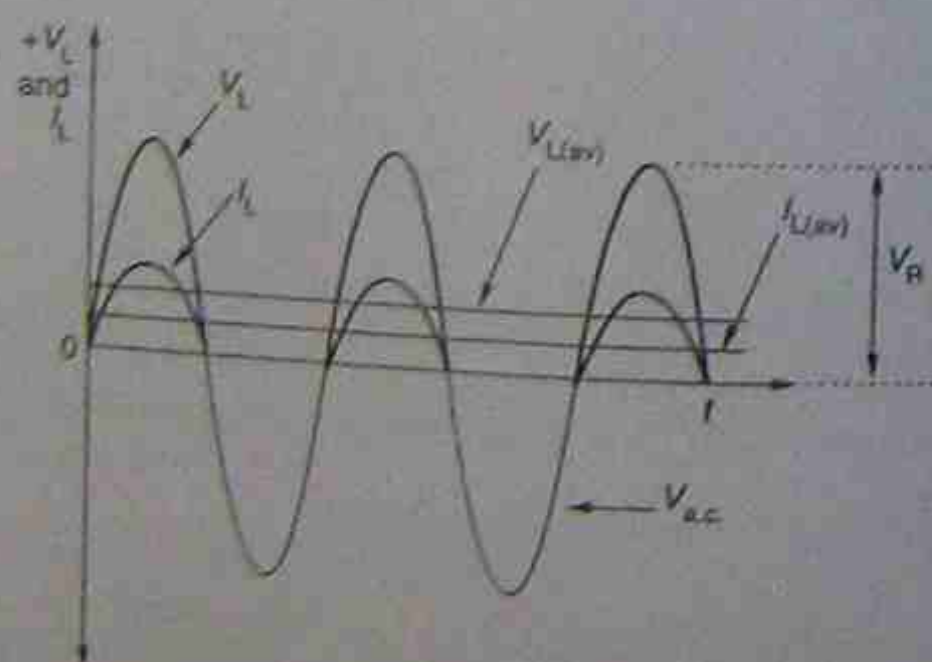


Figure 15.15 • Single-phase half-wave rectifier load voltage and current waveforms

work as the rectifier output. This is the value measured by a d.c. (moving coil) meter.

- **Maximum or peak value**—This is the maximum value that the d.c. output rises to at any point in time. It is usually equal to the peak of the a.c. input. The value may be observed on an oscilloscope, or measured with a peak-reading meter.
- **Ripple**—This is the peak-to-peak variations in the output pulses. Its value may be easily measured with an oscilloscope.
- **Ripple frequency**—This is the frequency of the pulses in the output waveform. Its value is related to the supply frequency and the rectifier configuration.

For the single-phase half-wave rectifier, the following relationships apply. It is assumed that the rectifier is connected to a sinusoidal supply and that the load is resistive:

- **Load voltage:**  $V_L = 0.45V_{ac}$
- **Load current:**  $I_L = \frac{V_L}{R_L}$
- **Ripple voltage:**  $V_R = V_{max} = \sqrt{2}V_{ac}$
- **Ripple frequency:**  $f_R = f_{supply}$
- **Peak reverse voltage (PRV):**  $PRV = \sqrt{2}V_{ac}$

Note that it is assumed that the forward voltage drop across the diode is negligible. This assumption will not cause any real errors unless the a.c. supply is a very low value, say less than 6.0 V.

Although this rectifier circuit is very simple and relatively inexpensive to construct, it has a number of disadvantages:

- The d.c. output is low for a given a.c. input when compared with other rectifier circuits.
- The ripple frequency is very low. This coupled with a relatively high ripple voltage makes it difficult to construct filter circuits to remove the ripple.
- A common connection exists between the a.c. supply and the load. This is due to the return path of the current, which must return to the supply or the supply transformer. In most situations where a transformer is used to adjust the a.c. input to the rectifier, the rectifier and load are electrically isolated from the mains, reducing any hazards that might otherwise be present.
- The d.c. current returning through the transformer winding causes distortion of the transformer primary current waveform. This current will have a d.c. component causing saturation of the core, resulting in high values of magnetising current. This might necessitate the use of larger transformer cores than would otherwise be necessary.

When selecting a diode for the single-phase half-wave rectifier, the average forward current and the PRV are taken into consideration. In both cases the rating of the diode selected must be equal to or greater than the values expected in the circuit. It is usual practice to allow for some margin of safety, should the supply voltage increase.

### Example 15.1

For the circuit in Figure 15.16, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

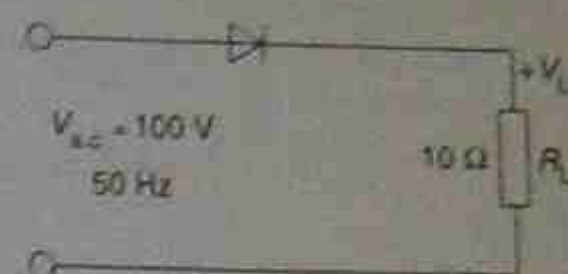


Figure 15.16 • Single-phase half-wave rectifier

- $V_L = 0.45V_{ac} = 0.45 \times 100$   $V_L = 45.0$  V
- $I_L = \frac{V_L}{R_L} = \frac{45.0}{10.0}$   $I_L = 4.5$  A
- $V_R = \sqrt{2}V_{ac} = \sqrt{2} \times 100$   $V_R = 141.4$  V
- $f_R = f_{supply}$   $f_R = 50$  Hz
- $PRV = \sqrt{2}V_{ac} = \sqrt{2} \times 100$   $PRV = 141.4$  V

From the above results a suitable diode would be one with a current rating of at least 5.0 A and a PRV rating of at least 150 V. In practice a 5.0 A 200 V diode would be selected.

### Example 15.2

For the circuit in Figure 15.17, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

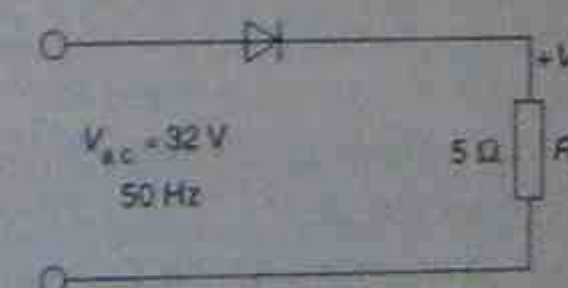


Figure 15.17 • Single-phase half-wave rectifier

- $V_L = 0.45V_{ac} = 0.45 \times 32$   $V_L = 14.4$  V
- $I_L = \frac{V_L}{R_L} = \frac{14.4}{5.0}$   $I_L = 2.88$  A
- $V_R = \sqrt{2}V_{ac} = \sqrt{2} \times 32$   $V_R = 45.25$  V
- $f_R = f_{supply}$   $f_R = 50$  Hz
- $PRV = \sqrt{2}V_{ac} = \sqrt{2} \times 32$   $PRV = 45.25$  V

For this application, select a 3.0 A 50 V diode. Alternatively, a more reliable choice might be a 5.0 A



When determining the PRV rating of a diode in a single-phase half-wave rectifier, the nature of the load should be taken into account. One of the more common applications for this circuit is as a simple battery charger. In this case the voltage across the diode when reverse biased is the peak of the a.c. supply plus the battery voltage. Thus, for battery charging circuits:

$$\text{PRV} = \sqrt{2}V_{\text{a.c.}} + V_{\text{batt}}$$

Assume that the circuit in Figure 15.17 has a 12.0 V d.c. supply connected to its output and determine the required PRV rating of the diode.

$$\begin{aligned}\text{PRV} &= \sqrt{2}V_{\text{a.c.}} + V_{\text{batt}} = (\sqrt{2} \times 32) + 12.0 \\ \text{PRV} &= 57.25 \text{ V}\end{aligned}$$

If a capacitor is connected across the output, as is the case with some filter circuits, the voltage on the capacitor must be taken into consideration. Since the capacitor may charge up to the peak of the a.c. supply, it effectively doubles the PRV of the diode because this voltage is connected in series with the supply and adds to the supply when the supply is reversed. A single-phase half-wave rectifier with a capacitive load is shown in Figure 15.18.

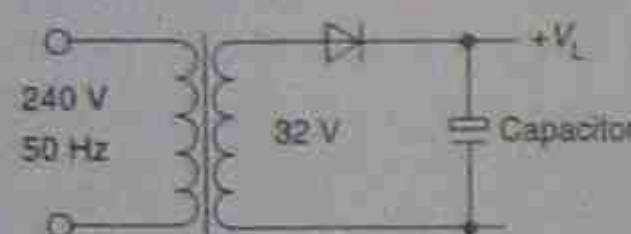


Figure 15.18 • Single-phase half-wave rectifier with capacitive load

In this case:

$$\begin{aligned}\text{PRV} &= \sqrt{2}V_{\text{a.c.}} = 2 \times \sqrt{2} \times 24 \\ &= 67.88 \text{ V}\end{aligned}$$

Owing to its low output, high ripple component and low ripple frequency, the single-phase half-wave rectifier has few applications. This circuit, however, is the basis for all other rectifier circuits.

### 15.4.2 Single-phase full-wave centre-tap rectifier circuit

This circuit is a development of the half-wave rectifier. It is actually two half-wave rectifiers connected in parallel but with supply voltages that are 180° out of phase. The two out-of-phase voltages are obtained from a transformer with a centre-tapped secondary winding, therefore it is essential to use a transformer with this rectifier configuration. Figure 15.19 shows the circuit configuration for a single-phase full-wave centre-tap rectifier.

The two secondary voltages of the transformer are of course in phase; however, owing to the way in which the rectifier is connected to the transformer, the two supplies to the rectifier,  $V_{\text{a.c.(1)}}$  and  $V_{\text{a.c.(2)}}$ , are 180° out of phase. This is due to the fact that when terminal 1 on the secondary is instantaneously positive, terminal 2 is instant-

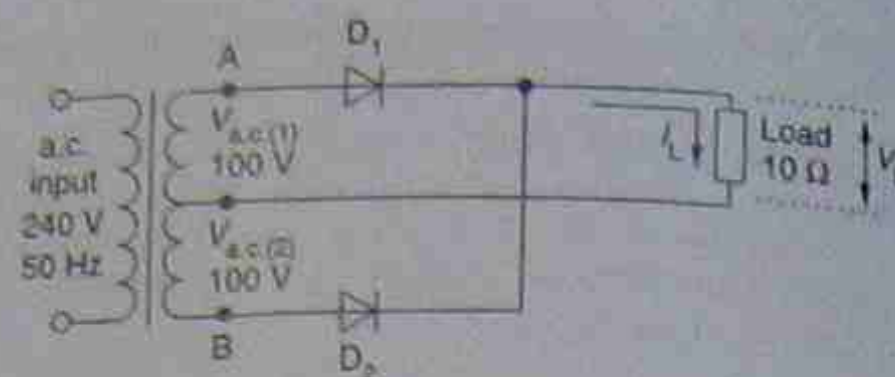


Figure 15.19 • Single-phase full-wave centre-tap rectifier

aneously negative. When the supply reverses, both terminals also reverse polarity. The circuit operates in the following manner:

- When terminal A is positive with respect to the centre tap of the transformer,  $D_1$  is forward biased, load current flows through  $D_1$  to the load and returns to the centre tap of the transformer. At the same time  $D_2$  is reverse biased by the negative potential on terminal B and will block current.
- When terminal B is positive with respect to the centre tap of the transformer,  $D_2$  is forward biased, load current flows through  $D_2$  to the load, and returns to the centre tap of the transformer. At the same time,  $D_1$  is reverse biased by the negative potential on terminal A and will block current.

The waveforms produced by this rectifier are shown in Figure 15.20.

At any given time, only one of the two diodes in the circuit will be conducting. The diodes are operating on a 50 per cent duty cycle. The current in each half of the transformer secondary is in fact a direct current like that in the half-wave circuit, but because the two currents are 180° out of phase, the flux in the core due to the load current is an alternating flux. Transformers used to supply single-phase centre-tap rectifiers do not have the same saturation problems as transformers supplying single-phase half-wave rectifiers.

This rectifier circuit produces a higher d.c. output for a given a.c. input than the half-wave circuit. The ripple frequency is also higher, making it easier to remove the ripple from the output. The diodes in this circuit are subjected to a higher peak reverse voltage, owing to the two transformer secondary voltages being in series.

If this circuit is connected to a sinusoidal supply and the load is resistive, the following relationships apply:

- Load voltage:  $V_L = 0.9V_{\text{a.c.}}$
- Load current:  $I_L = \frac{V_L}{R_L}$
- Ripple voltage:  $V_R = \sqrt{2}V_{\text{a.c.}}$
- Ripple frequency:  $f_R = 2f_{\text{supply}}$
- Peak reverse voltage (PRV):  $\text{PRV} = 2\sqrt{2}V_{\text{a.c.}}$

It is important to note that in this circuit the input voltage to the rectifier  $V_{\text{a.c.}}$  is the voltage on one-half of the transformer secondary. The circuit relationships are specified in this manner because only half of the transformer secondary winding is used at any given time.

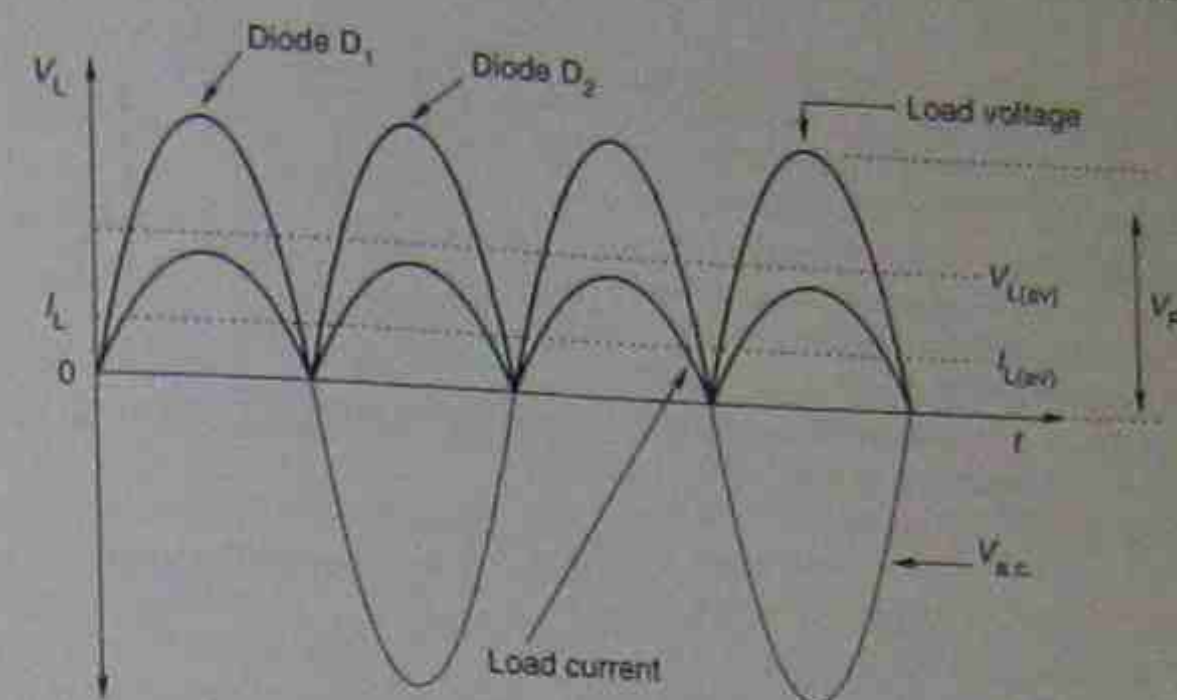


Figure 15.20 • Single-phase full-wave centre-tap rectifier—load current and voltage waveforms

### Example 15.3

For the circuit in Figure 15.19, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

- $V_L = 0.9V_{\text{a.c.}} = 0.9 \times 100 \quad V_L = 90 \text{ V}$
- $I_L = \frac{V_L}{R_L} = \frac{90}{10} \quad I_L = 9.0 \text{ A}$
- $V_R = \sqrt{2}V_{\text{a.c.}} = \sqrt{2} \times 100 \quad V_R = 141.4 \text{ V}$
- $f_R = 2f_{\text{supply}} = 2 \times 50 \quad f_R = 100 \text{ Hz}$
- $\text{PRV} = 2\sqrt{2}V_{\text{a.c.}} = 2\sqrt{2} \times 100 \quad \text{PRV} = 282.8 \text{ V}$

For this application a suitable diode would be a 10 A, 400 V diode, owing to the fact that the diodes are on only a 50 per cent duty cycle. A 7.5 A diode would suffice if suitable heat sinking is provided. The actual average current in each diode is in fact only 4.5 A.

### Example 15.4

For the circuit in Figure 15.21, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

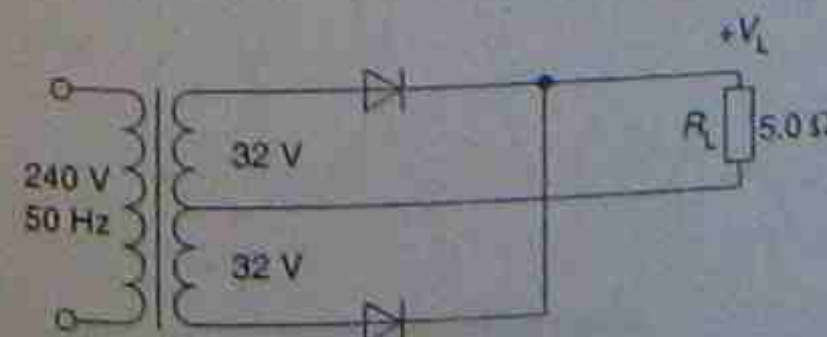


Figure 15.21 • Single-phase full-wave centre-tap rectifier

- $V_L = 0.9V_{\text{a.c.}} = 0.9 \times 32 \quad V_L = 28.8 \text{ V}$
- $I_L = \frac{V_L}{R_L} = \frac{28.8}{5.0} \quad I_L = 5.76 \text{ A}$
- $V_R = \sqrt{2}V_{\text{a.c.}} = \sqrt{2} \times 32 \quad V_R = 45.25 \text{ V}$
- $f_R = 2f_{\text{supply}} = 2 \times 50 \quad f_R = 100 \text{ Hz}$
- $\text{PRV} = 2\sqrt{2}V_{\text{a.c.}} = 2 \times \sqrt{2} \times 32 \quad \text{PRV} = 90.5 \text{ V}$

For this application, 5.0 A 100 V diodes would be suitable, but for better long-term reliability, 200 V diodes may be selected.

This rectifier configuration is popular for many low-power applications. For higher power outputs the transformer cost becomes significant, because a centre-tap transformer is more expensive than a transformer with a single secondary winding.

### 15.4.3 Single-phase full-wave bridge rectifier circuit

The bridge rectifier achieves full-wave rectification without the use of a centre-tapped transformer. To achieve this, a bridge configuration of four diodes is set up. In the bridge, two diodes will be conducting at any given time. It is not essential to use a transformer with this circuit. It may be connected direct to the mains, but for safety reasons it is often isolated from the mains with a transformer. It might of course be necessary to use a transformer to provide the necessary a.c. input voltage. Figure 15.22 shows the circuit configuration for a single-phase full-wave bridge rectifier.

The circuit operates in the following manner:

- When terminal A is positive with respect to terminal B, diodes  $D_1$  and  $D_4$  are forward biased. Current flows from the supply via  $D_1$  through the load and returns via  $D_4$ . Diodes  $D_2$  and  $D_3$  are reverse biased and will block current.
- When terminal B is positive with respect to terminal A, diodes  $D_2$  and  $D_3$  are forward biased. Current flows from the supply via  $D_2$  through the load and returns via  $D_3$ . Diodes  $D_1$  and  $D_4$  are reverse biased and will block current flow.



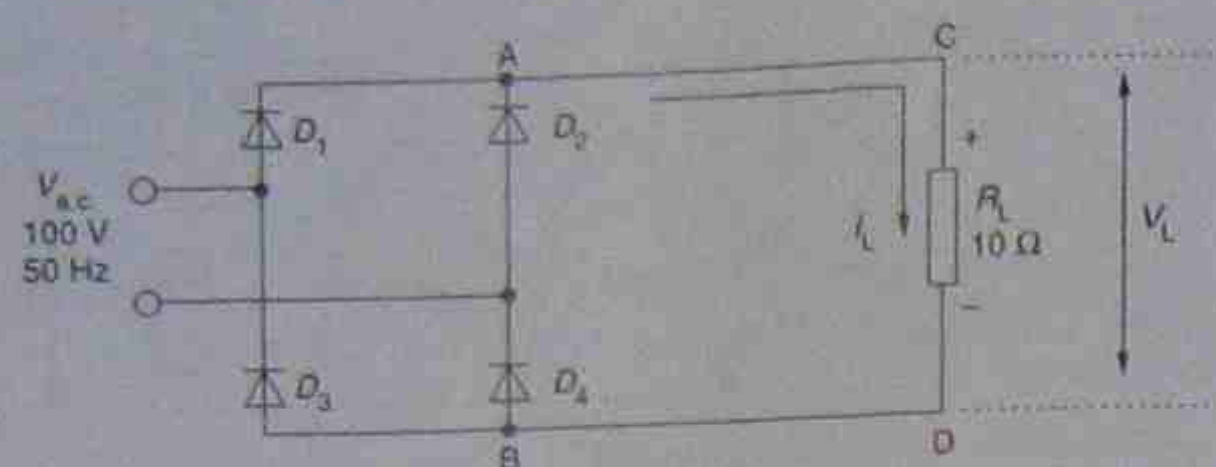


Figure 15.22 • Single-phase full-wave bridge rectifier

The pairs of diodes in this circuit conduct only for 180° at a time and are on a 50 per cent duty cycle.

The output waveforms for the bridge circuit in Figure 15.22 are identical to those of the full-wave centre-tapped circuit (Fig. 15.23).

If this circuit is connected to a sinusoidal supply and the load is resistive, the following relationships apply:

- Load voltage:  $V_L = 0.9V_{a.c.}$
- Load current:  $I_L = \frac{V_L}{R_L}$
- Ripple voltage:  $V_R = \sqrt{2}V_{a.c.}$
- Ripple frequency:  $f_R = 2f_{supply}$
- Peak reverse voltage (PRV):  $PRV = \sqrt{2}V_{a.c.}$

Note that with the exception of the PRV rating of the diodes, this circuit has the same input/output relationships. The lower PRV rating in this case is due to the fact that only a single a.c. voltage is required, not two a.c. voltages as in the centre-tapped rectifier configuration.

### Example 15.5

For the circuit in Figure 15.22, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

$$(a) \quad V_L = 0.9V_{a.c.} = 0.9 \times 100 \quad V_L = 90.0 \text{ V}$$

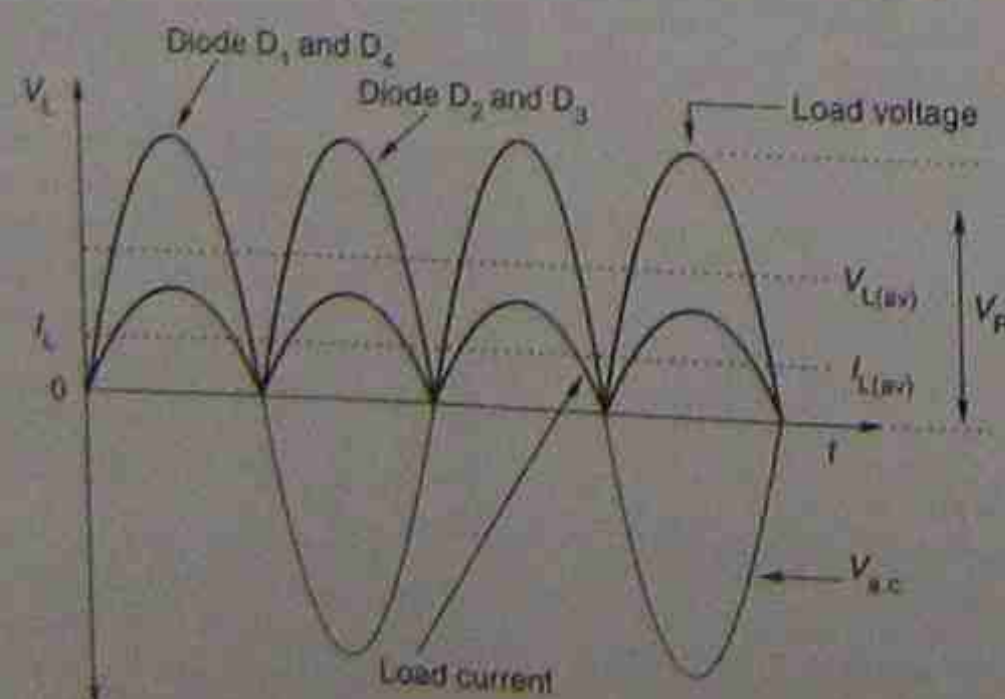


Figure 15.23 • Single-phase full-wave bridge rectifier—load current and voltage waveforms

$$(b) \quad I_L = \frac{V_L}{R_L} = \frac{90.0}{10} \quad I_L = 9.0 \text{ A}$$

$$(c) \quad V_R = \sqrt{2}V_{a.c.} = \sqrt{2} \times 100 \quad V_R = 141.4 \text{ V}$$

$$(d) \quad f_R = 2f_{supply} = 2 \times 50 \quad f_R = 100 \text{ Hz}$$

$$(e) \quad PRV = \sqrt{2}V_{a.c.} = \sqrt{2} \times 100 \quad PRV = 141.4 \text{ V}$$

In this case, a 10 A 200 V diode would be suitable. Alternatively, if the 50 per cent duty cycle of the diodes is taken into consideration, a 7.5 A 200 V diode would suffice.

### Example 15.6

For the circuit in Figure 15.24, determine:

- the load voltage
- the load current
- the ripple voltage
- the ripple frequency
- the PRV.

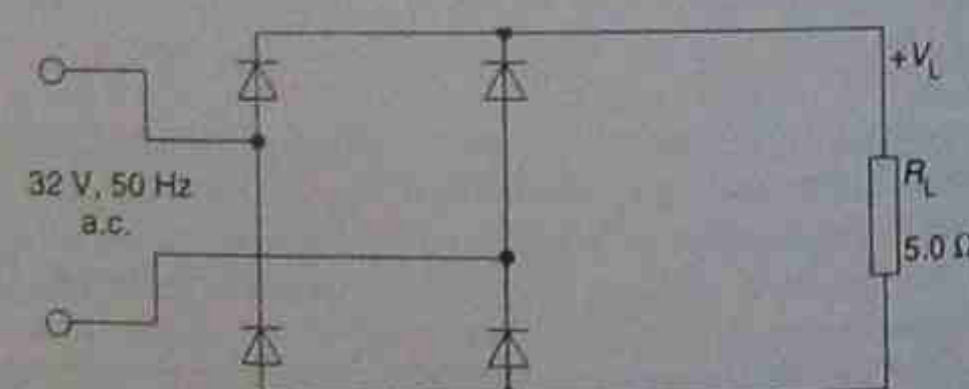


Figure 15.24 • Single-phase bridge rectifier

$$(a) \quad V_L = 0.9V_{a.c.} = 0.9 \times 32 \quad V_L = 28.8 \text{ V}$$

$$(b) \quad I_L = \frac{V_L}{R_L} = \frac{28.8}{5} \quad I_L = 5.76 \text{ A}$$

$$(c) \quad V_R = \sqrt{2}V_{a.c.} = \sqrt{2} \times 32 \quad V_R = 45.25 \text{ V}$$

$$(d) \quad f_R = 2f_{supply} = 2 \times 50 \quad f_R = 100 \text{ Hz}$$

$$(e) \quad PRV = \sqrt{2}V_{a.c.} = \sqrt{2} \times 32 \quad PRV = 45.25 \text{ V}$$

In this example, a 5.0 A 50 V or 5.0 A 100 V diode would be suitable.

The single-phase bridge rectifier is very popular for low to medium power output applications, particularly since bridge rectifiers are available as a bridge module. These bridge modules are a four-terminal package with two a.c. input terminals and two d.c. output terminals.

Bridge modules are very convenient components for mounting and connection. However, they have the disadvantage that the entire module must be replaced even when only one diode fails.

### 15.4.4 Three-phase half-wave rectifiers

A disadvantage of all single-phase rectifiers is the high magnitude of the ripple voltage. In all three circuits examined, the peak-to-peak value of the ripple voltage is

equal to the peak of the a.c. supply. The d.c. output falls back to zero at the completion of each half-cycle.

The filtering of such waveforms is difficult and expensive where the current demand is appreciable. To reduce the ripple voltage output from a rectifier, a polyphase rectifier may be used.

The three-phase half-wave rectifier actually consists of three single-phase half-wave rectifiers, each connected to one of the phases in a three-phase supply. This results in a.c. supply voltages to the rectifier being 120° out of phase. Figure 15.25 shows the circuit configuration for a three-phase half-wave rectifier.

It should be noted that the d.c. load current returns via the neutral conductor. A four-wire supply is essential for this rectifier circuit. This may be obtained direct from the supply if the voltage is suitable, or from a transformer with a star-connected secondary.

With higher load currents, the local supply authorities might require that an isolating transformer be used. The intention is to minimise the amount of d.c. flowing in the system's conductors. Direct current flowing in the neutral conductor can also lead to additional voltage drop problems.

Each diode in this circuit will conduct when it is forward biased. This occurs when the phase it is connected to is more positive than the other two phases. In this situation the other two diodes are reverse biased and will block current. An examination of the waveforms in Figure 15.26

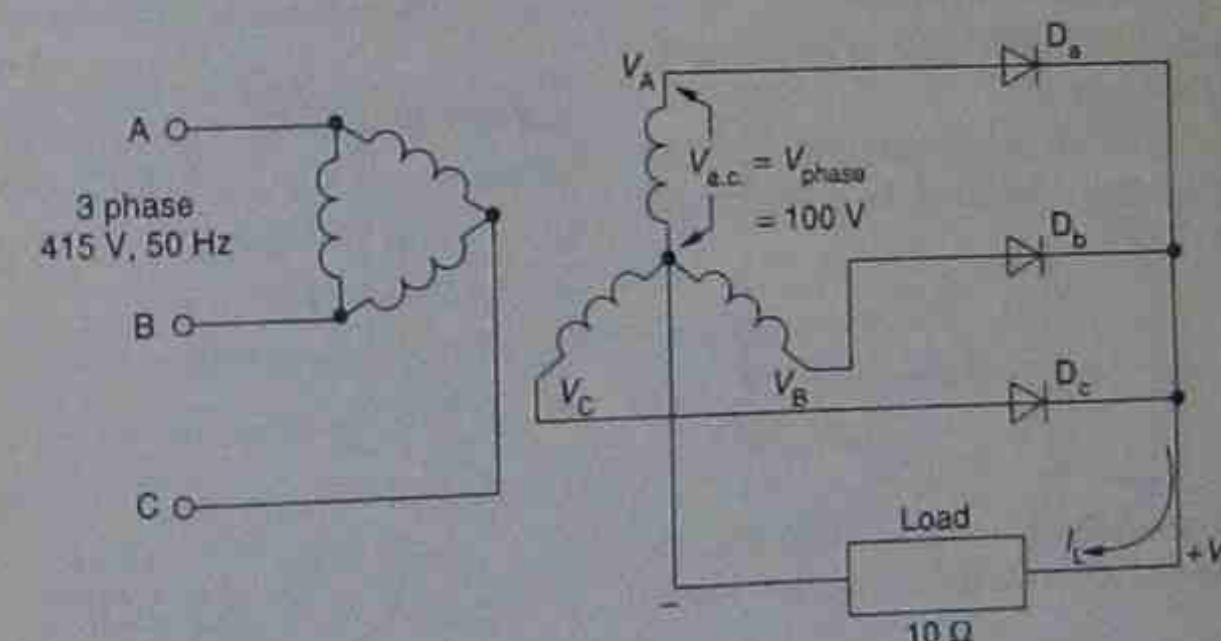
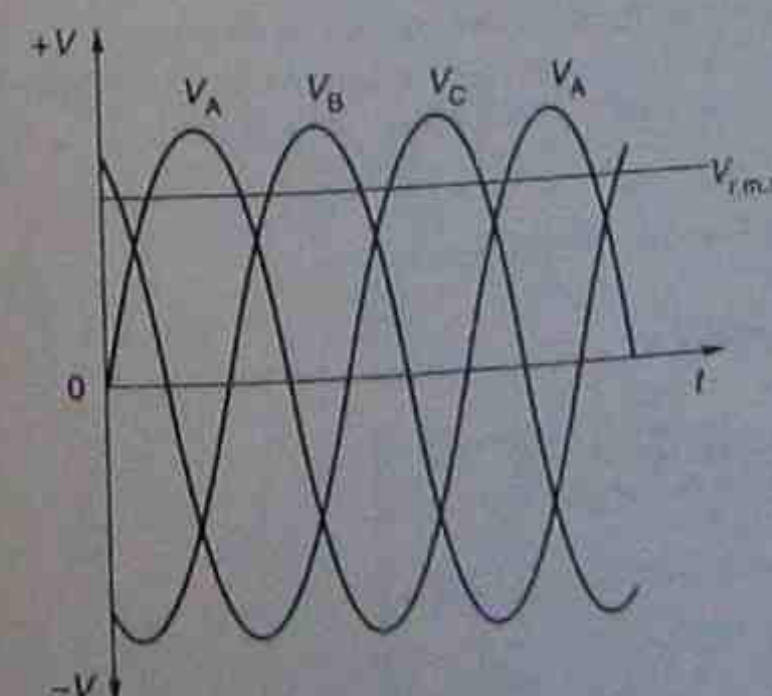
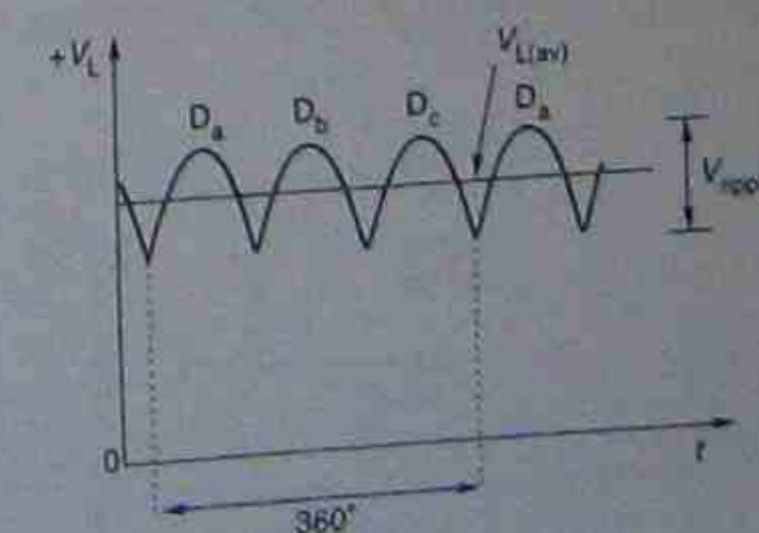


Figure 15.25 • Three-phase half-wave rectifier



(a) Input phase voltages



(b) d.c. output voltage

Figure 15.26 • Three-phase half-wave rectifier—voltage waveforms



will reveal that each of the phases in turn is more positive than the other two for a period of  $120^\circ$ .

Transfer of conduction from one diode to the next occurs as the phases cross, for example:

- As the A phase decreases from its maximum positive value, the B phase is increasing towards its maximum positive value.
- At a point  $30^\circ$  after the start of the positive half-cycle of the B phase (or  $150^\circ$  after the start of the A phase positive half-cycle), the two phases have the same instantaneous value.
- The diode in the A phase will commutate (turn off).
- As the B phase becomes more positive than the A phase, the diode in that phase will start to turn on. It will have fully turned on when the B phase is  $0.6\text{ V}$  more positive than the A phase.

The process of transferring conduction from one diode to the next takes only a few microseconds when the load is resistive.

Important features of this circuit are:

- Only one diode is conducting at any given time and each diode conducts for a period of  $120^\circ$ . The diodes therefore conduct for only one-third of each cycle of the supply.
- The resultant d.c. output voltage never falls back to zero. The ripple is much smaller than that in the output from single-phase rectifier circuits.
- Each diode is subjected to a PRV that is equal to the peak of the a.c. line voltage.

Where this circuit is connected to a sinusoidal, symmetrical three-phase supply and the load is resistive, the following relationships apply:

• Load voltage:  $V_L = 1.17V_{a.c.}$

• Load current:  $I_L = \frac{V_L}{R_L}$

• Ripple voltage:  $V_R = 0.707V_{a.c.}$

(This is included for information only, to demonstrate that the ripple voltage is much lower than that produced by a single-phase rectifier circuit.)

• Ripple frequency:  $f_R = 3f_{\text{supply}}$

• Peak reverse voltage (PRV):  $\text{PRV} = 2.45V_{a.c.}$

The a.c. input voltage ( $V_{a.c.}$ ) to this rectifier is the phase voltage, phase to neutral, of the supply. The constant 2.45

for the PRV rating in this circuit is derived from the fact that the PRV is the peak of the line voltage, which is higher than the phase voltage, owing to the star connection of the supply. Therefore:

$$\text{PRV} = \sqrt{2} \times \sqrt{3} \times V_{a.c.}$$

$$\text{PRV} = 2.45V_{a.c.}$$

### Example 15.7

For the circuit in Figure 15.25, determine:

- the load voltage
- the load current
- the ripple frequency
- the PRV.

(a)  $V_L = 1.17V_{a.c.} = 1.17 \times 100$   $V_L = 117\text{ V}$

(b)  $I_L = \frac{V_L}{R_L} = \frac{117}{10}$   $I_L = 11.7\text{ A}$

(c)  $f_R = 3f_{\text{supply}} = 3 \times 50$   $f_R = 150\text{ Hz}$

(d)  $\text{PRV} = 2.45V_{a.c.} = 2.45 \times 100$   $\text{PRV} = 245\text{ V}$

A suitable rating for the diodes in this example would be 10.0 A 400 V. The actual average current in each diode would be only around 4.0 A, but a 10 A diode may be preferable to a 5 A diode because of the high peak value of the current (around 14.0 A).

### Example 15.8

For the circuit in Figure 15.27, determine:

- the load voltage
- the load current
- the ripple frequency
- the PRV.

(a)  $V_L = 1.17V_{a.c.} = 1.17 \times 32$   $V_L = 37.44\text{ V}$

(b)  $I_L = \frac{V_L}{R_L} = \frac{37.44}{5.0}$   $I_L = 7.48\text{ A}$

(c)  $f_R = 3f_{\text{supply}} = 3 \times 50$   $f_R = 150\text{ Hz}$

(d)  $\text{PRV} = 2.45V_{a.c.} = 2.45 \times 32$   $\text{PRV} = 78.4\text{ V}$

Suitable ratings for the diodes in this example would be 5 A 100 V. To provide a greater safety margin for the PRV rating, 200 V diodes may be selected.

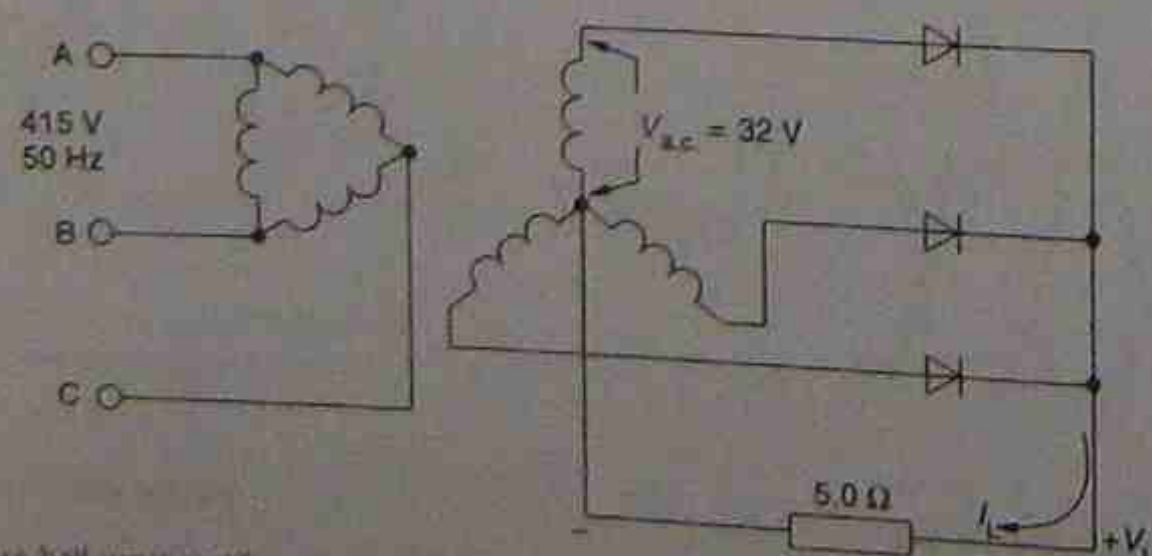


Figure 15.27 • Three-phase half-wave rectifier

It is worth noting that in the three-phase half-wave rectifier circuit, the d.c. output voltage is higher than the a.c. input voltage. This is the case for all polyphase rectifier circuits and is considered to be a significant advantage.

This rectifier circuit is very popular for medium- to high-power output supplies. The circuit should, however, be supplied from a three-phase transformer, rather than three single-phase transformers connected to form a three-phase bank. This is due to the fact that the secondary currents in each phase winding of the transformer are actually d.c. currents, as is the case with the single-phase half-wave rectifier. If a three-phase transformer is used, the fluxes set up by the d.c. currents in each phase cancel one another out, eliminating the problems that might be caused by saturation of the core.

### 15.4.5 Three-phase full-wave bridge rectifier circuit

This circuit uses six diodes in a bridge configuration, connected to a three-phase supply. In this case the supply need only be a three-wire supply, because no neutral is required.

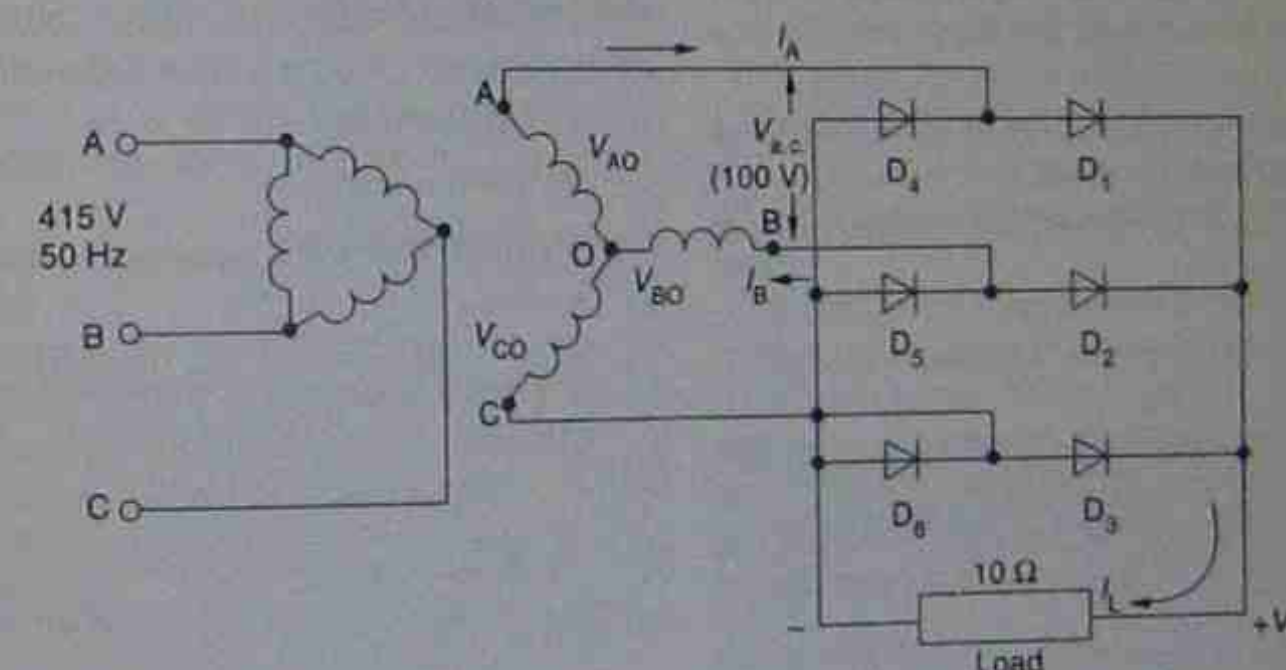


Figure 15.28 • Three-phase full-wave bridge rectifier

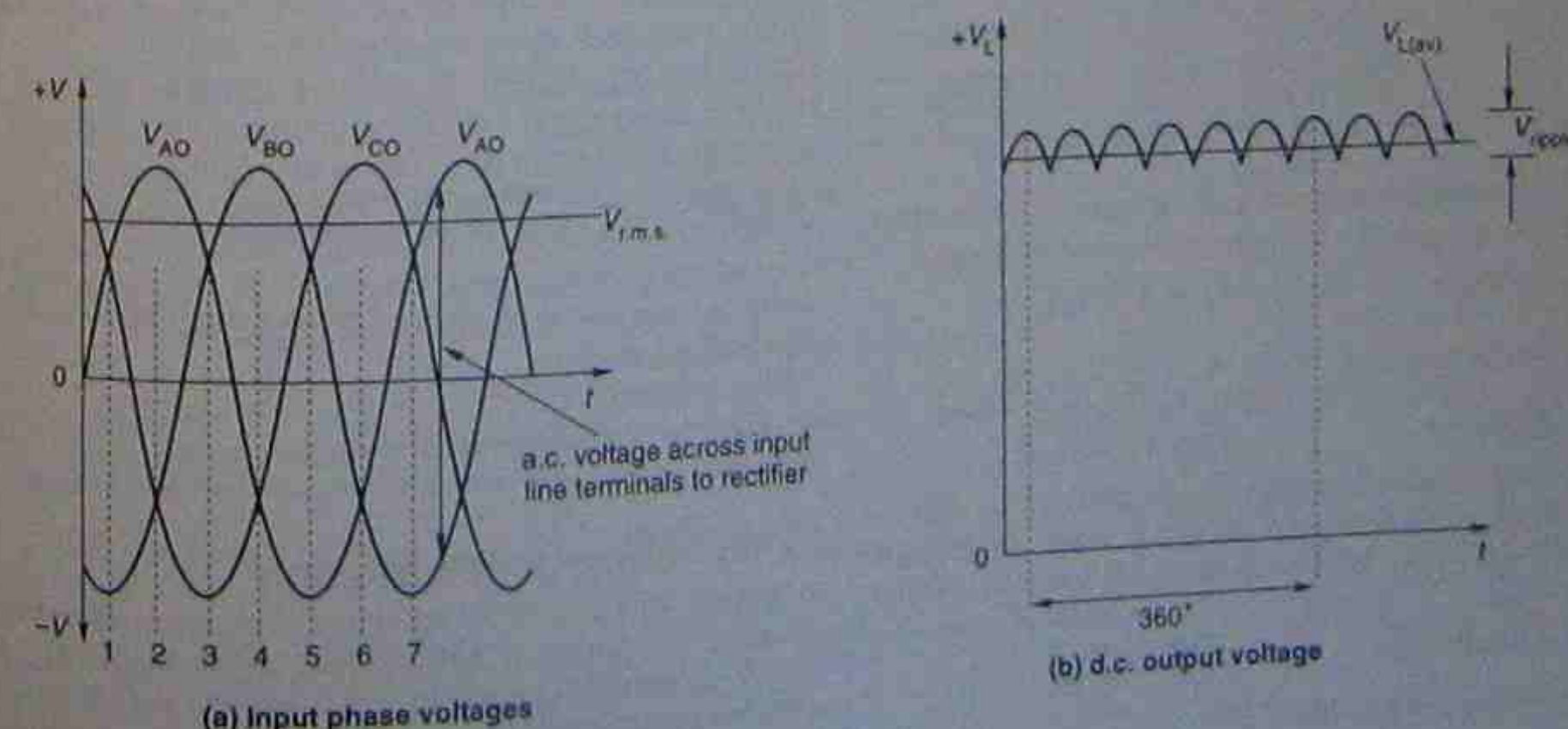


Figure 15.29 • Three-phase full-wave bridge rectifier—voltage waveforms

The circuit may be supplied direct from the supply, or via a transformer to set the voltage to the required level and to provide electrical isolation from the supply. Figure 15.28 shows the circuit for a three-phase full-wave bridge rectifier.

The secondary winding of the supply transformer may be star- or delta-connected. The different secondary connections have no effect on the operation of the rectifier. They will only cause different voltages to be applied to the rectifier, varying the output voltage.

As with the single-phase full-wave bridge, two diodes will be conducting at any given time. The two diodes that are conducting at any given time are the one in the phase that is the most positive, and the one in the phase that is the most negative. Once a diode commences conducting, it will conduct for  $120^\circ$ ; each diode therefore conducts for one-third of a cycle. This rectifier is sometimes referred to as a six-pulse rectifier because there are six distinct operating periods in one cycle of the supply, producing a ripple frequency six times the supply frequency.

An examination of the circuit waveforms in Figure 15.29 reveals the six operating periods:

- In period 1-2 the A phase is the most positive and the B phase the most negative; diodes 1 and 5 are forward biased. Load current flows from the A phase through



$D_1$ , then the load, returning to the supply via  $D_2$  and the B phase.

- In period 2-3, the A phase is the most positive and the C phase the most negative; diodes 1 and 6 are forward biased. Load current flows from the A phase through  $D_1$ , then the load, returning to the supply via  $D_6$  and the C phase.

- In period 3-4, the B phase is the most positive and the C phase the most negative; diodes 2 and 6 are forward biased. Load current flows from the B phase through  $D_2$ , then the load, returning to the supply via  $D_6$  and the C phase.

- In period 4-5, the B phase is the most positive and the A phase the most negative; diodes 2 and 4 are forward biased. Load current flows from the B phase through  $D_2$ , then the load, returning to the supply via  $D_4$  and the A phase.

- In period 5-6, the C phase is the most positive and the A phase the most negative; diodes 3 and 4 are forward biased. Load current flows from the C phase through  $D_3$ , then the load, returning to the supply via  $D_4$  and the A phase.

- In period 6-7, the C phase is the most positive and the B phase the most negative; diodes 3 and 5 are forward biased. Load current flows from the C phase through  $D_3$ , then the load, returning to the supply via  $D_5$  and the B phase.

- The next period of conduction would be the same as period 1-2; the cycle repeats itself.

The operation of this rectifier is summarised in Table 15.3.

Table 15.3 • Three-phase bridge rectifier—diode conducting sequence

For time period	a.c. line voltage	a.c. line currents	Diodes conducting
1-2	$V_{AB}$	$I_A = I$	$D_1$ and $D_2$
2-3	$V_{BC}$	$I_B = I$	$D_2$ and $D_3$
3-4	$V_{CA}$	$I_C = I$	$D_3$ and $D_4$
4-5	$V_{AB}$	$I_A = I$	$D_4$ and $D_5$
5-6	$V_{BC}$	$I_B = I$	$D_5$ and $D_6$
6-7	$V_{CA}$	$I_C = I$	$D_6$ and $D_1$

If this rectifier is connected to a symmetrical, symmetrical three-phase supply, the following relationships apply:

- Load voltage:  $V_L = 1.35V_{LL}$
- Load current:  $I_L = \frac{V_L}{R}$
- Ripple frequency:  $f_R = 6f_{\text{supply}}$
- Peak reverse voltage (PRV):  $PRV = \sqrt{2}V_{LL}$

(This is included as information only, to demonstrate that the ripple voltage is much lower than that produced by a single-phase rectifier circuit and the three-phase half-wave rectifier circuit.)

- Ripple frequency:  $f_R = 6f_{\text{supply}}$
- Peak reverse voltage (PRV):  $PRV = \sqrt{2}V_{LL}$

The d.c. input voltage ( $V_{LL}$ ) to this circuit is the line-to-line voltage, because no neutral is connected to the circuit. If the supply transformer is star-connected, a higher line voltage will of course be obtained than if the secondary were delta-connected.

### Example 15.9

For the circuit of Figure 15.28, determine:

- the load voltage
- the load current
- the ripple frequency
- the PRV.

$$(a) \quad V_L = 1.35V_{LL} = 1.35 \times 100 \quad V_L = 135 \text{ V}$$

$$(b) \quad I_L = \frac{V_L}{R} = \frac{135}{10} \quad I_L = 13.5 \text{ A}$$

$$(c) \quad f_R = 6f_{\text{supply}} = 6 \times 50 \quad f_R = 300 \text{ Hz}$$

$$(d) \quad PRV = \sqrt{2}V_{LL} = \sqrt{2} \times 100 \quad PRV = 141.4 \text{ V}$$

Suitable diodes for this application could be rated at 10 A, 200 V.

### Example 15.10

For the circuit of Figure 15.30, determine:

- the load voltage
- the load current
- the ripple frequency
- the PRV.

$$(a) \quad V_L = 1.35V_{LL} = 1.35 \times 17.77 \quad V_L = 24.0 \text{ V}$$

$$(b) \quad I_L = \frac{V_L}{R} = \frac{24}{4.0} \quad I_L = 6.0 \text{ A}$$

$$(c) \quad f_R = 6f_{\text{supply}} = 6 \times 50 \quad f_R = 300 \text{ Hz}$$

$$(d) \quad PRV = \sqrt{2}V_{LL} = \sqrt{2} \times 17.77 \quad PRV = 25.13 \text{ V}$$

Suitable diodes for this example would have ratings of 6 A and 50 V.

This particular rectifier circuit produces the highest d.c. output and lowest ripple voltage of the rectifier circuits discussed in this chapter. To obtain higher d.c. outputs and even lower ripple voltage, a complex arrangement of transformers would be required to produce a supply of six or more phases. While this is certainly technically possible, the cost of such a system is warranted only in cases where very high power outputs virtually free from ripple voltage are required, for example, an electroplating supply.

This rectifier is one of the most widely used for medium- to high-power output applications.

### 15.4.6 Power supply filtering

In section 15.4 it was stated that the purpose of a filter circuit is to remove as much of the ripple from the d.c. supply as possible. Ripple in a d.c. supply may interfere with the operation of the equipment being supplied. This is particularly the case with computing equipment,

measuring and instrumentation equipment, and amplifying equipment.

There are some instances where ripple in the supply is tolerable and does not present any real problem, for example, the supply to the field winding of a d.c. motor or a battery charger.

Filter circuits have many forms, particularly when used in electronic communication equipment. Filters may be designed to allow signals of certain frequencies to pass relatively unimpeded, while blocking others. A filter circuit used in conjunction with a rectifier circuit is a low-pass filter circuit, that is, it allows low frequency, or d.c. signals to pass, while blocking or trapping higher frequencies.

The effect of an ideal low-pass filter is demonstrated in Figure 15.31.

A low-pass filter may be configured in a number of ways. The actual filter circuit will depend largely on the load current. While some filters might be satisfactory at very low currents, they might not be satisfactory at high levels of current.

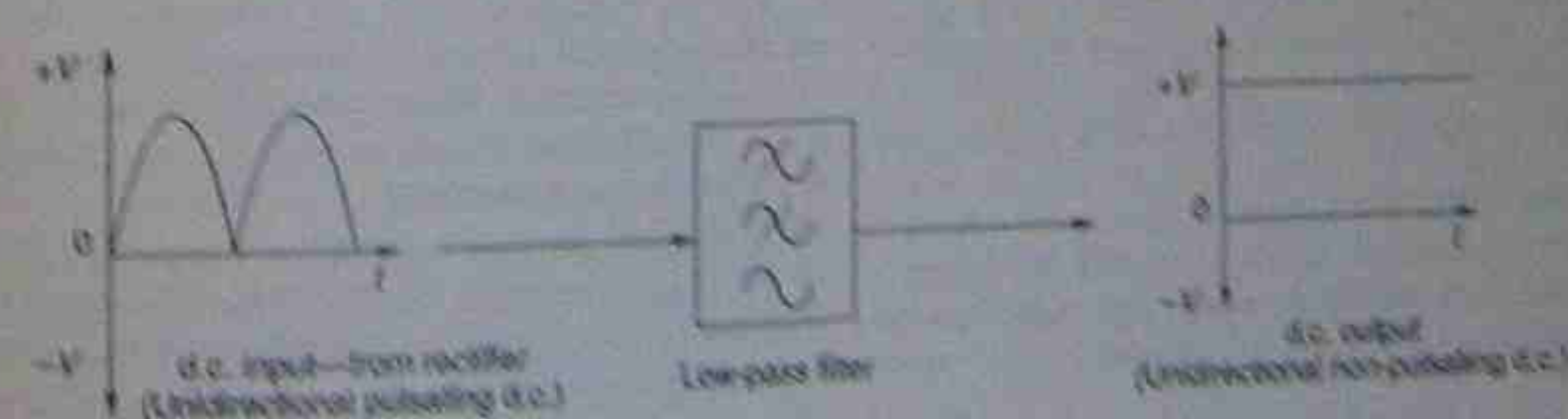


Figure 15.31 • Ideal power supply filter

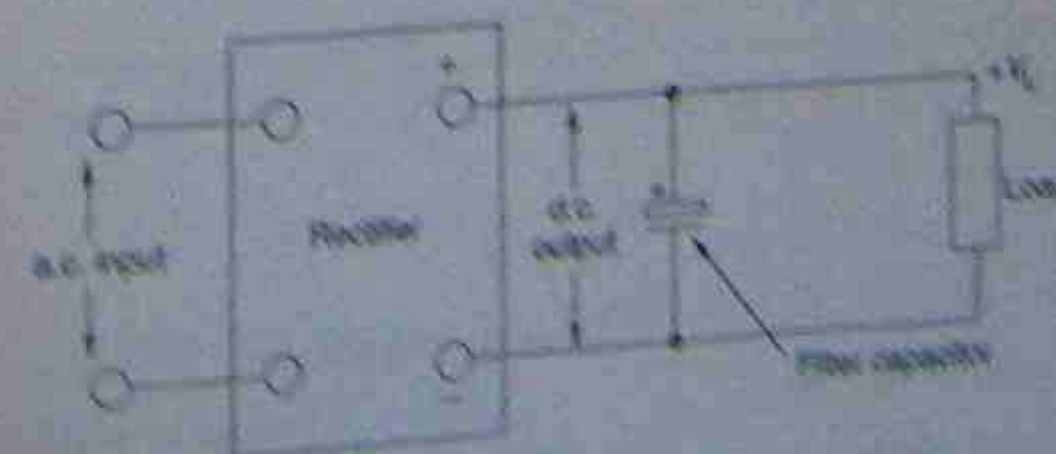


Figure 15.32 • Capacitor filter circuit

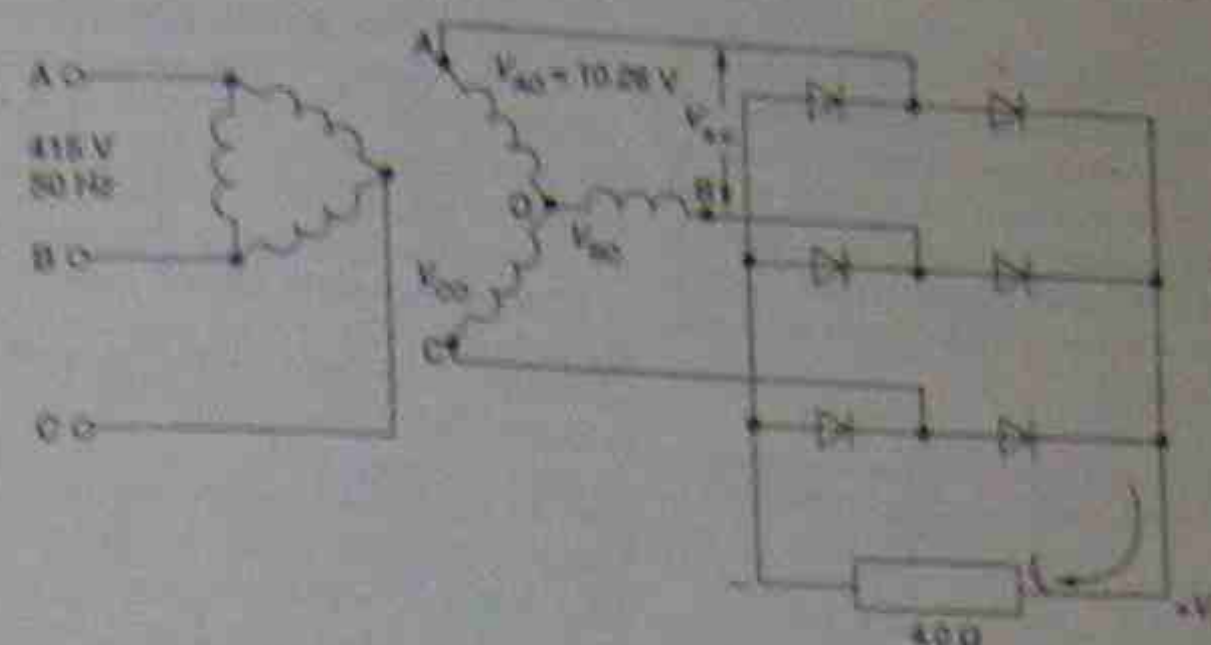


Figure 15.30 • Three-phase bridge rectifier

### 15.4.7 Capacitor filter circuits

The filter circuit in Figure 15.32 consists of a capacitance connected across the output of the rectifier circuit. The filter capacitor is effectively connected in parallel with the load.

The capacitor stores energy in the form of an electrostatic field. As the output from the rectifier falls, the charge on the capacitor tends to keep the load voltage more constant. The capacitor will discharge through the load but at a slower rate than it is charged by the rectifier output.

The larger the value of capacitance used in the filter, the more effective the filter will be. To obtain the large values of capacitance and at the same time minimise the physical size of the filter, electrolytic capacitors are generally used.

An electrolytic capacitor is a polarised capacitor; that is, it must be connected into the circuit with the correct polarity. If an electrolytic capacitor is connected incorrectly it will be damaged and in some cases might explode. Every precaution must be exercised by service technicians to ensure that electrolytic capacitors are connected, or polarised, correctly.



### Capacitor filter with no load

When there is no load connected to the output of a rectifier circuit, the filter capacitor will charge up to the maximum or peak value of the rectifier output when the output is not connected. Figure 15.33 shows a full-wave rectifier circuit and capacitor filter circuit with no load connected and Figure 15.34 shows the waveforms for this circuit condition.



Figure 15.33: A full-wave rectifier circuit with no load

When the capacitor is charged up to the peak of the rectifier output, it will remain at that voltage even when the rectifier output decreases from its peak output value.

The capacitor voltage remains at that peak value. At the next peak of the rectifier output, the capacitor will charge back up to the peak of the rectifier output. The capacitor voltage will be equal to the peak of the rectifier output. A circuit must be designed when nothing is connected to the output of a rectifier circuit. The change in the capacitor voltage will be dangerous, particularly if the voltage is too high. The supply may be turned off for about 100 ms to allow the capacitor to discharge. The output voltage for this circuit will be:

$$V_o = V_m$$

### Example 15.11

In the a.c. input voltage of the circuit of Figure 15.33 is 240 V, calculate the peak output voltage.

$$V_o = V_m = \sqrt{2} \times 240 = 339.4 \text{ V}$$

At no load, the capacitor will charge up to the peak value of the rectifier output. The capacitor will discharge when the supply is disconnected from the output.

### Capacitor filter with load

When a load is connected to the output of the rectifier circuit, the capacitor will discharge back to the peak of the rectifier output. Current is also supplied to the load from the capacitor. The output voltage for this circuit will be:

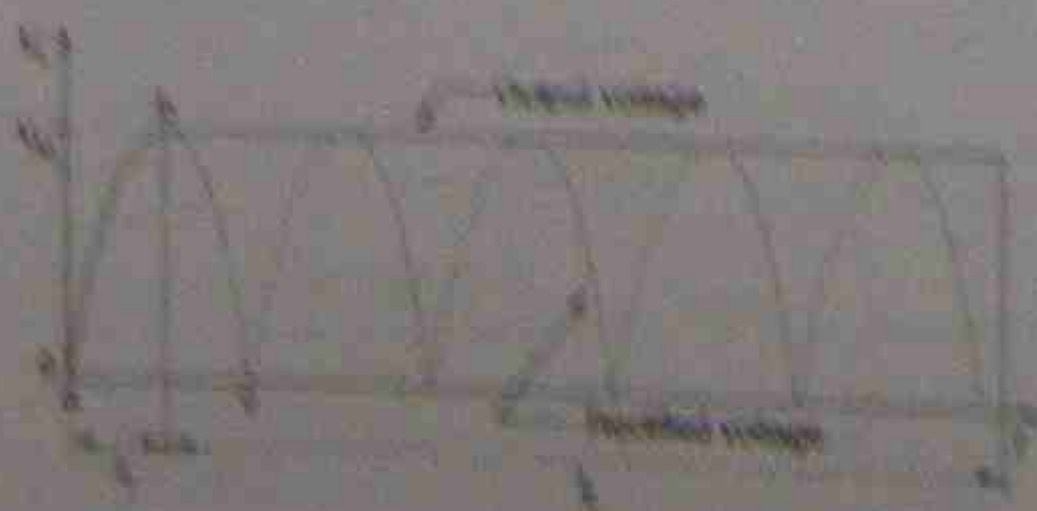


Figure 15.34: Capacitor filter with no load



Figure 15.35: A full-wave rectifier circuit with a load connected

When the circuit is first connected, the capacitor will charge to the peak of the rectifier output. Then as the rectifier output decreases, the capacitor will give up its charge. It cannot discharge back through the diode because the diode is reverse biased. The capacitor discharges through the load. However, it will discharge more slowly than it was charged. The amount by which the capacitor voltage falls is dependent on the load current and on the time between rectifier output pulses (ripple frequency).

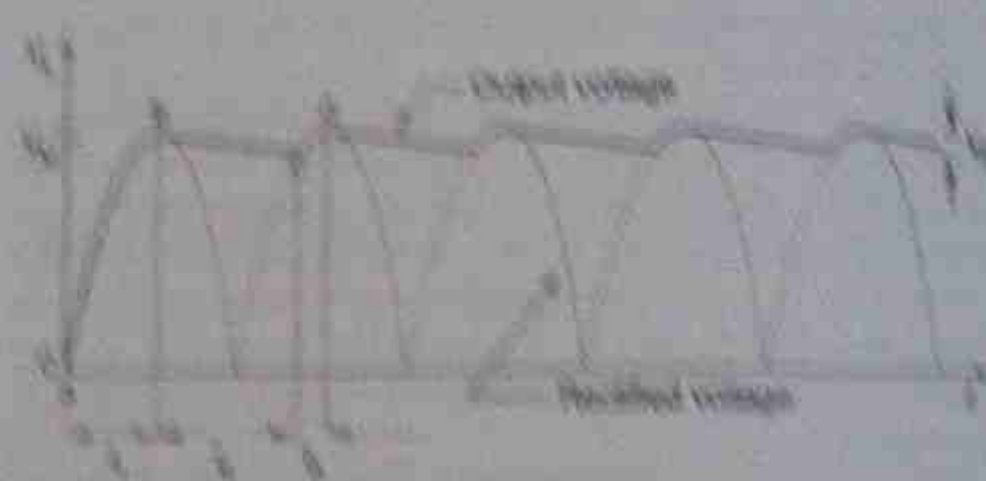


Figure 15.36: Capacitor filter output with load connected

With regard to the waveforms in Figure 15.36, the operation of the filter capacitor may be summarized as follows:

1. In the period a to b, the capacitor is charged up from the supply. Current is also supplied to the load in this period.
2. In the period b to c, the capacitor voltage is higher than the rectifier output. This reverse biases the diode in the rectifier. Load current is supplied from the capacitor as it discharges.
3. In the period c to d, the rectifier output is again higher than the capacitor voltage. The capacitor recharges back to the peak of the rectifier output. Current is also supplied to the load from the rectifier in this period.

This sequence of events is repeated for each output pulse from the rectifier.

From Figure 15.36, it is also apparent that the time in which the capacitor is charged or recharged is much shorter than the discharge time. It follows, therefore, that the peak value of the capacitor charging current will be much higher than the load current. This current could in fact be up to 100 times the load current when the circuit is initially connected. It is often this charging current that causes the diode current rating, rather than the load current, to be the limiting factor of the circuit. The r.m.s. heating effect of the charging current, which is in the form of short pulses, is quite high. If a diode does not have a surge current rating or sufficient margin, the junction might overheat and the diode might be damaged. The load and diode current waveforms are shown in Figure 15.37.

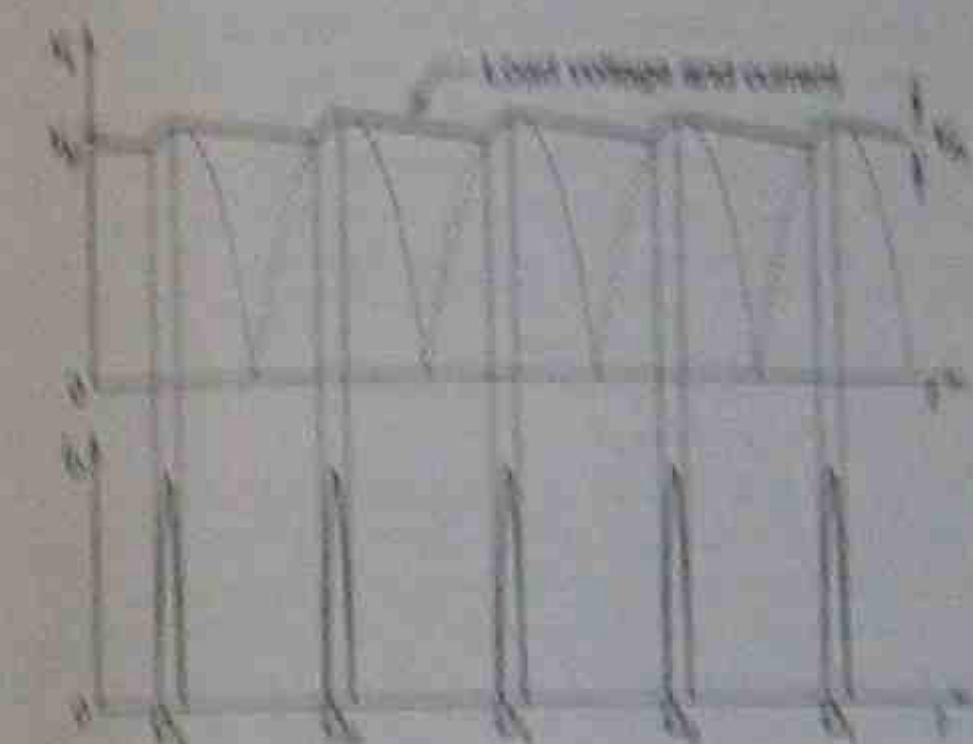


Figure 15.37: Load voltage, load current and diode current waveforms

At the load connected to a given rectifier filter combination, the amount by which the capacitor discharges between rectifier output pulses increases. The discharge increases in the ripple voltage.

At the ripple voltage increases, the average voltage decreases, as shown in Figure 15.38.

The decrease in load voltage may be overcome by using higher values of capacitance. This will decrease the ripple voltage for a given load current. However, increasing the capacitance will also increase the peak value of the diode current and may necessitate the use of diodes with higher current ratings.



(a) Capacitor filter with light load

### 15.4.8 Inductor filter

The inductor filter, sometimes referred to as a 'choke' filter, consists simply of an inductor connected to the output of the rectifier. It is such a filter that it is in series with the load. An inductor filter circuit is shown in Figure 15.39.



Figure 15.39: Inductor filter

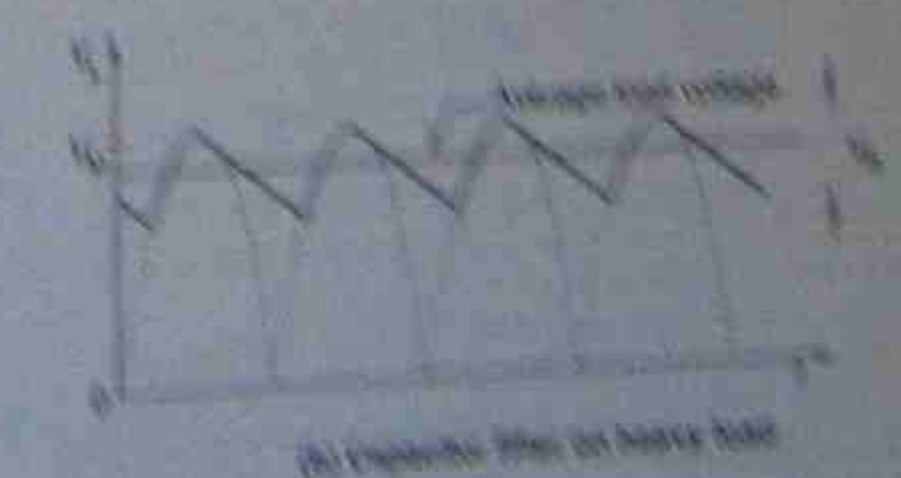
This filter depends, for its action, on the ability of an inductor or choke to oppose any change in current. As the current tries to change its value, a voltage is induced in the choke opposing that change. As the current decreases, the induced voltage acts in such a direction as to maintain the original value of the current. A similar action occurs when the current tries to increase; the induced voltage opposes the increase. The net result is that the ripple is decreased.

The choke provides a high impedance to varying currents, but offers little impedance to unvarying d.c. currents. The degree of filtering offered by a choke filter is dependent on:

1. The load current. As load current increases, the amount of the flux in the core increases, thereby increasing the induced voltage. This increases the filtering effect of the choke. At no load the choke provides no filtering.
2. The inductance of the choke. For a given load current, the filtering effect increases as the inductance is increased.
3. The ripple frequency. As the ripple frequency increases, the filtering effect of a given choke increases.

The choke filter provides a relatively constant output voltage to the load. Compare this with the capacitor filter where the average load voltage decreases as the load decreases. A feature of the choke filter is that the ripple voltage decreases as the load increases. Inductor filter output voltage waveforms are shown in Figure 15.40.

The choke filter is common in large high-current applications. Chokes are expensive and physically large. Even in some large high-current applications, a small choke may



(b) Capacitor filter with heavy load



The terminals of the Zener diode are identified in the same manner as those for the normal diode. The body of the diode will have some distinctive marking or shape, or in the case of the large high-power Zener diodes, the symbol might be printed on the body of the diode.

When forward biased, the Zener diode behaves in exactly the same manner as a normal silicon diode; that is, it will conduct when the barrier potential of 0.6 V is overcome. The forward resistance is then a very low value and decreases as current increases, providing a forward voltage drop that is substantially constant.

It is the reverse characteristic that is quite different. When the reverse voltage reaches a particular value, the Zener diode will conduct and the resistance decrease to a low value. Again the voltage drop is substantially constant as the current varies. The voltage at which reverse conduction takes place is called the Zener voltage ( $V_Z$ ). Zener diode  $V-I$  characteristics are shown in Figure 15.48.

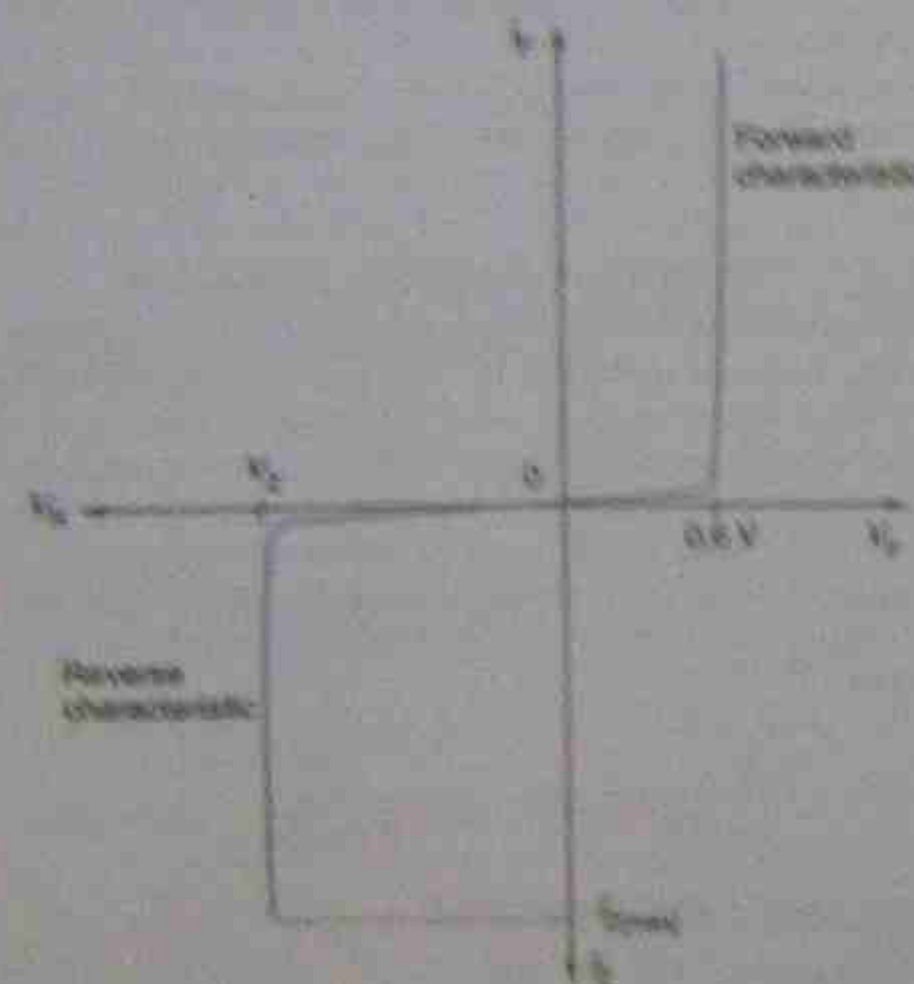


Figure 15.48 • Zener diode  $V-I$  characteristics

The action that occurs in the Zener diode at the Zener voltage is different to that which occurs in a normal diode when the PIV is exceeded. Provided the power dissipation in the Zener is kept to a safe level, the Zener is not damaged by the reverse current and will again have a high resistance if the reverse voltage is decreased to a value below the Zener voltage.

Zener diodes are available with a wide range of Zener voltages, the range being from a low of 2.4 V through to a high of 270 V. A large number of standard values are available in this range, providing a wide selection for many applications. The Zener voltages specified are subject to a tolerance. Values of 5 per cent to 20 per cent are available.

The power dissipation in the Zener diode is important when reverse biased. Typical power ratings are from 400 mW to 40 W.

Normal diodes are selected on the basis of forward current and PIV. Zener diodes are selected on the basis of

• Zener voltage ( $V_Z$ )

• power dissipation ( $P_Z$ )

The power dissipation in a Zener diode is determined from the Zener voltage and the reverse current:

$$P_{Z(max)} = V_Z I_{Z(max)}$$

where  $P_{Z(max)}$  = maximum allowable Zener power dissipation in watts

$V_Z$  = Zener voltage rating in volts

$I_{Z(max)}$  = maximum allowable Zener current in amperes

The maximum Zener current may be determined from this relationship. This is necessary when designing Zener voltage regulator circuits.

### Example 15.13

Determine the maximum Zener current for a 6.3 V 400 mW Zener diode.

$$P_{Z(max)} = V_Z I_{Z(max)}$$

$$I_{Z(max)} = \frac{P_{Z(max)}}{V_Z} = \frac{0.4}{6.3}$$

$$I_{Z(max)} = 0.0635 \text{ A or } 63.5 \text{ mA}$$

### Example 15.14

Determine the maximum Zener current for a 5.0 V 1 W Zener diode.

$$I_{Z(max)} = \frac{P_{Z(max)}}{V_Z} = \frac{1}{5.0} \quad I_{Z(max)} = 0.2 \text{ A or } 200 \text{ mA}$$

It is not in practice that Zener diodes are operated up to their maximum power handling capacities. In the interest of long-term reliability, the power dissipation is limited to some value below the maximum.

In the interest of better voltage regulation, the Zener diode is operated at a level of Zener current such that the minimum current flowing through it at any time is just the knee of the curve and into the linear portion of the characteristic. Therefore, to ensure good long-term reliability and voltage regulation, the practical operating limits for a Zener diode are in the range of 10 per cent to 80 per cent of  $I_{Z(max)}$ . The working range of reverse currents for a Zener diode is shown in Figure 15.49.

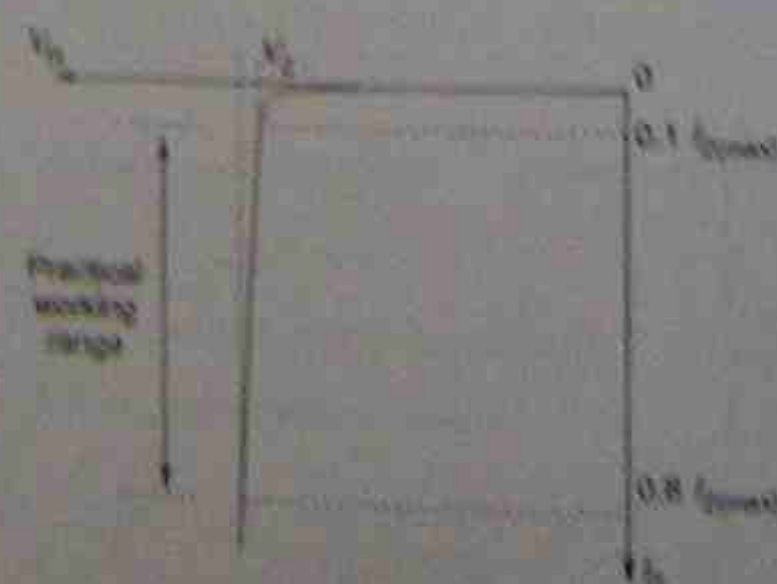


Figure 15.49 • Zener diode reverse characteristic working range of currents

### Example 15.15

Determine the practical operating range of the Zener current for a 5.0 V 2 W Zener diode.

$$I_{Z(max)} = \frac{P_{Z(max)}}{V_Z} = \frac{2.0}{5.0}$$

$$I_{Z(max)} = 0.4 \text{ A or } 400 \text{ mA}$$

Therefore:

$$I_Z = 0.1 I_{Z(max)} = 0.1 \times 400 = 40 \text{ mA}$$

$$I_Z = 0.8 I_{Z(max)} = 0.8 \times 400 = 320 \text{ mA}$$

Thus,  $I_Z = 40 \text{ mA}$  to  $320 \text{ mA}$

The reverse characteristic is utilized in a simple circuit to provide regulation of the voltage across a load. The fact that this reverse voltage is substantially constant once the Zener voltage is reached means that any part of a circuit connected in parallel with the Zener will experience the same voltage.



Figure 15.50 • Zener diode shunt regulator

In the circuit of Figure 15.50, the voltage across the load will be the same as the voltage across the Zener. It will remain substantially constant, provided the Zener current is in the range  $0.1 I_{Z(max)}$  to  $0.8 I_{Z(max)}$ .

The series resistor  $R_S$  is placed in the circuit to limit the power dissipation in the Zener diode. Without this resistor, the Zener current would be excessive and would most likely destroy the Zener diode. The value of the series resistor is chosen so that the Zener current will always be in the range  $0.1 I_{Z(max)}$  to  $0.8 I_{Z(max)}$ , ensuring the best possible regulation and long-term reliability.

Determination of the circuit in Figure 15.51 will reveal certain circuit relationships.

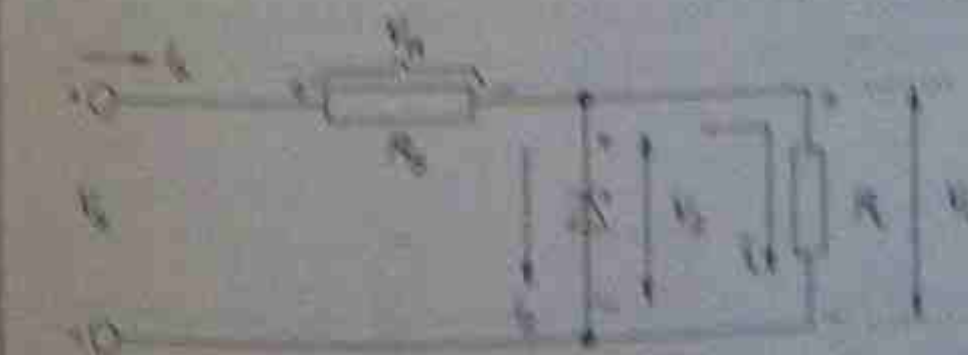


Figure 15.51 • Voltage and current relationships in a Zener diode shunt regulator

In this circuit:

$$V_S = V_Z + V_L = V_Z + V_L$$

$$I_S = \frac{V_S}{R_S} = \frac{V_Z + V_L}{R_S} \quad I_S = I_Z + I_L$$

$$R_S = \frac{V_S - V_Z}{I_S}$$

where  $V_S$  = supply voltage  
 $V_L$  = load voltage  
 $I_S$  = load current  
 $I_Z$  = Zener current

Using these relationships, the resistance and power rating of the series resistor may be determined.

### Example 15.16

For the circuit of Figure 15.51, determine:

- the load voltage
- the load current
- the practical range of Zener currents
- the resistance of the series resistor
- the power rating of the series resistor



Figure 15.52 • Zener diode shunt regulator

$$(a) \quad V_L = V_Z = 10.0 \text{ V} \quad V_L = 10.0 \text{ V}$$

$$(b) \quad I_L = \frac{V_L}{R_L} = \frac{10}{100} \quad I_L = 100 \text{ mA}$$

$$(c) \quad I_{Z(max)} = \frac{P_{Z(max)}}{V_Z} = \frac{0.2}{10} \quad I_{Z(max)} = 20 \text{ mA}$$

$$I_Z = 0.1 I_{Z(max)} \text{ to } 0.8 I_{Z(max)}$$

$$I_Z = 0.1 \times 20 \text{ mA to } 0.8 \times 20 \text{ mA}$$

$$I_Z = 2 \text{ mA to } 16 \text{ mA}$$

$$I_S = 100 \text{ mA to } 122 \text{ mA}$$

$$I_S = 100 \text{ mA to } 122 \text{ mA}$$

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$$I_S = 100 \text{ mA to } 122 \text{ mA}$$

$$I_S = 100 \text{ mA to } 122 \text{ mA}$$



**Example 15.17**

For the circuit of Figure 15.53, determine:

- the load voltage
- the load current
- the practical range of Zener currents
- the resistance of the series resistor
- the power rating of the series resistor

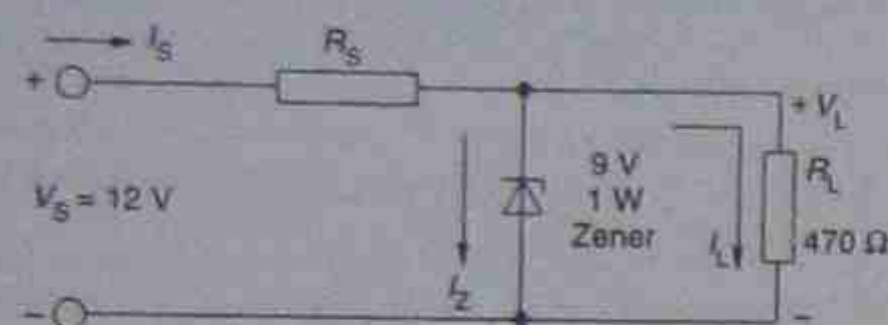


Figure 15.53 • Zener diode shunt regulator

- $V_L = V_Z = 9.0 \text{ V}$
- $I_L = \frac{V_L}{R_L} = \frac{9.0}{470} = 19.15 \text{ mA}$
- $I_{Z(\max)} = \frac{P_{Z(\max)}}{V_Z} = \frac{1.0}{9.0} = 111.1 \text{ mA}$   
 $I_Z = (0.1 \times 111.1) \text{ to } (0.8 \times 111.1)$   
 $I_Z = 11.1 \text{ mA to } 88.8 \text{ mA}$   
 In this case, select  $I_Z = 25 \text{ mA}$ .
- $I_S = I_Z + I_L = 25 + 19.5 = 44.5 \text{ mA}$   
 $R_S = \frac{(V_S - V_Z)}{I_S} = \frac{(12 - 9)}{0.0445} = 67.9 \Omega$   
 $R_S = 68.0 \Omega \text{ (NTPV)}$
- $P_{R_S} = I_S^2 R_S = 0.0445^2 \times 68 = 1.32 \text{ W}$   
 Select a 0.5 W resistor.

Therefore, in the circuit of Figure 15.53, the series resistor is a 68  $\Omega$  0.5 W resistor.

For the regulator to be effective, the supply voltage must be greater than the Zener voltage. As a rule of thumb, it is considered that the supply voltage must be at least 2 V or 3 V higher than the Zener voltage. If this margin is not maintained, the Zener may 'drop out' of regulation and variations in load voltage will be experienced.

The Zener regulator maintains a constant load voltage by varying the Zener current as either the load current or supply voltage varies. For example, if the supply voltage is constant and:

- the load current increases, Zener current will decrease as the supply current remains constant to maintain a voltage drop across the series resistor that is equal to the difference between the supply voltage and the Zener voltage.
- the load current decreases, Zener current will increase to maintain a constant value of supply current.

If the fluctuations in load current are high, the power rating of the Zener diode will also have to be high, to allow for large changes in Zener current.

If the load current is constant and:

- the supply voltage increases, the Zener current will increase. This is necessary to allow the supply current to increase to maintain a voltage drop across the series resistor that is equal to the difference between the supply voltage and the Zener voltage.
- the supply voltage decreases, the Zener current decreases, allowing the supply current to decrease.

Again, if the variations in supply voltage are significant, the power rating of the Zener diode might need to be high.

Zener diode shunt regulators are ideal for situations where the supply voltage and load current are relatively constant and the load current is low. In cases where the variations in supply voltage or load current become significant, the power rating of both the Zener diode and the series resistor become high. The circuit then becomes relatively expensive to construct. A better practice in these cases is to use a series regulator of some type.

### 15.5.2 Three-terminal integrated circuit voltage regulator

This regulator is a series regulator. It is connected in series with the load. The three-terminal regulator is actually an integrated circuit that contains a large number of components in a complex circuit arrangement.

The demands of many loads dictate that very precise control of load voltage be provided, together with features such as over-current and short-circuit protection, over-temperature protection, high ripple rejection and good transient response (fast acting). To construct circuits from discrete components that provide these features is very time consuming and expensive. This led to the development of integrated circuits that provide all the required features at low cost and small physical size, with the minimum number of external components to be connected. The basic circuit for a voltage regulator using a three-terminal integrated circuit regulating device is shown in Figure 15.54.

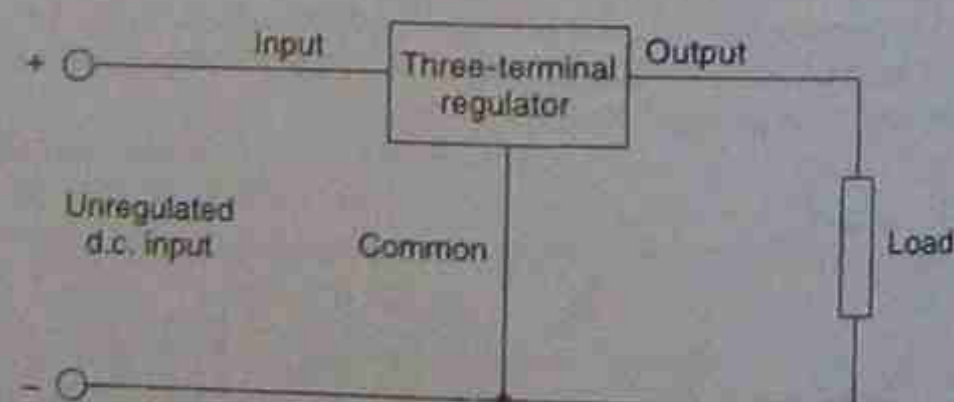


Figure 15.54 • Three-terminal integrated circuit regulator—basic circuit

The three-terminal regulators are very simple to use and require only connection of the three terminals, as well as very few external components. The three terminals are designated as follows:

- input**—supplied from the rectifier/filter combination
- output**—supplies current to the load
- common**—reference lead; provides a reference for the regulator to ground.

The three-terminal regulators are also relatively inexpensive and therefore are even used in place of simpler regulator circuits with fewer features. Three-terminal regulators are available in the following configurations:

- positive output voltage—fixed or variable output
- negative output voltage—fixed or variable output.

The regulators are also available in a wide range of voltage and current ratings, typically 5 to 24 V and currents of 100 mA up to 15 A. Typical case outlines are shown in Figure 15.55.

To determine the lead configuration and rating of a particular three-terminal regulator, a manufacturer's data book should be consulted.

The most common range of three-terminal regulators is the 78 (positive outputs) and 79 (negative outputs) series. These are a series of fixed-voltage output regulators with a current rating of 1.5 A and they are available in a range of voltage outputs. The output voltage for each of the regulators in this series can be identified from the type number, the last two digits indicating the voltage output, for example:

- 7805—5 V positive output
- 7905—5 V negative output
- 7815—15 V positive output
- 7915—15 V negative output

The basic connection method for the positive and negative regulators appears in Figure 15.56. Note that both regulators are referenced to a ground terminal and the negative regulator supplies a voltage that is negative with respect to ground.

Important three-terminal regulator ratings, or characteristics, are as follows:

- Nominal output voltage**—the nominated output voltage as specified by the manufacturer. The actual output voltage from a three-terminal regulator might not be exactly equal to the specified value, but the tolerance is quite small and the load voltage will not vary if the regulator is operated in accordance with the manufacturer's specification. For example, a 7805 regulator will have an output voltage that falls in the range 4.8 V to 5.2 V. Similarly a 7812 regulator will have an output in the range 11.5 V to 12.5 V.
- Maximum output current**—the maximum value of output current the regulator can supply while maintaining the

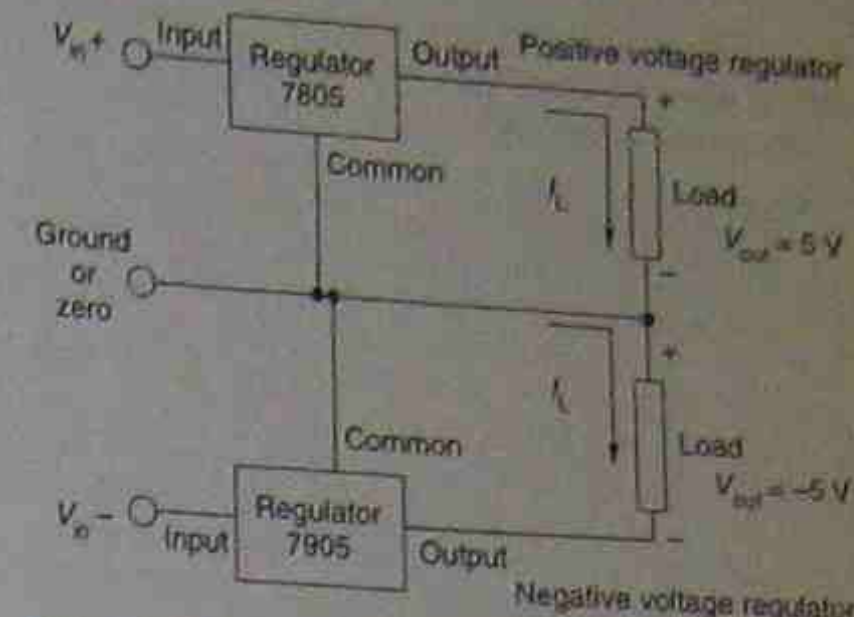


Figure 15.56 • Three-terminal regulator connections—positive and negative regulators

output voltage at the specified value. If the current exceeds this value, an internal current sensor will cause the output voltage to be decreased to ensure that the current is not allowed to increase further to the point where the regulator might be damaged.

- Maximum power dissipation**—the maximum power dissipation that allows the regulator to operate without overheating. This value is determined from the voltage drop across the regulator and the current through the regulator:

$$P_D = (V_{IN} - V_{OUT})I_L$$

where  $P_D$  = regulator power dissipation in watts

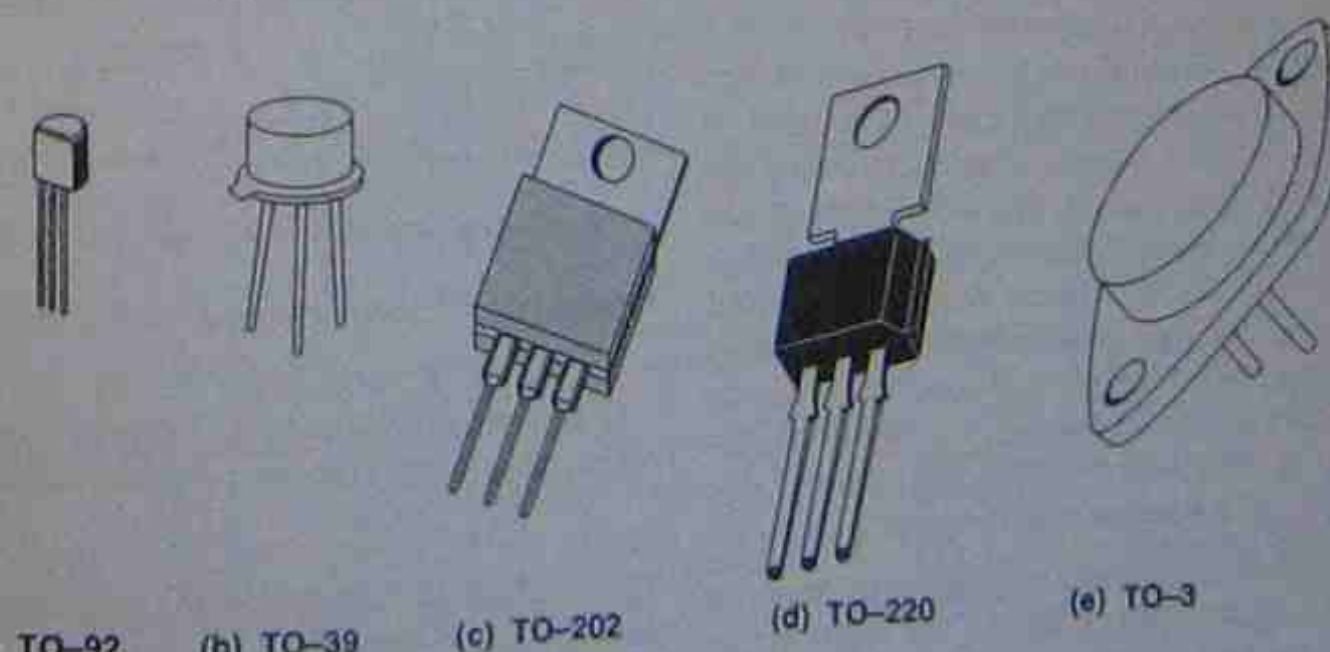
$V_{IN}$  = regulator input voltage in volts

$V_{OUT}$  = regulator output voltage in volts

$I_L$  = load current supplied by the regulator in amperes.

- Maximum input voltage**—the maximum voltage that may be applied to the input of the regulator. Exceeding this value might cause damage to the regulator. The maximum input voltage for the 78 and 79 series IC regulators is typically 35 V.

- Ripple rejection ratio**—the ability of the regulator to reject input ripple in such a way that the ripple, or only a very small part of the ripple voltage, appears at the output. Three-terminal regulators usually have a ripple rejection ratio (RRR) of around 1000:1. This means that for every 1 V of ripple at the input to the



(a) TO-92 (b) TO-39 (c) TO-202

(d) TO-220

(e) TO-3

Figure 15.55 • Three-terminal regulator case styles



regulator there will be only 1 mV at the output. The RRR is often quoted in decibel notation (dB). A ratio of 1000:1 is equivalent to 60 dB.

- **Over-temperature protection**—integrated circuit regulators have an inbuilt capacity to monitor their own temperature. If the power dissipation is such that the internal temperature becomes excessive, the regulator will shut down until the temperature falls. This protects the regulator against excessive power dissipation, even if the output current is within the prescribed limits and also protects against the situation where the heat dissipation away from the regulator is impaired. For all but the low-current regulators, a heat sink of some type should be used to aid in the dissipation of heat away from the regulator.
- **Safe area protection**—this form of protection is provided to ensure that the internal power dissipation is not above the prescribed limit, 15W for the 78 and 79 series regulators. If this value is exceeded, the regulator shuts down.
- **Drop-out voltage**—the minimum input-to-output voltage differential required for reliable and stable voltage regulation. For the 78 and 79 series regulators this value is around 2.5 V. This means that the minimum input voltage for a 7805 regulator is 7.5 V. It is essential that this be the minimum input voltage, not the average input voltage. If there is any ripple present at the input, the minimum value of the ripple must not be below 7.5 V. The average value of the input would be higher than this value.

The circuit in Figure 15.57 is for a complete three-terminal IC positive regulator.

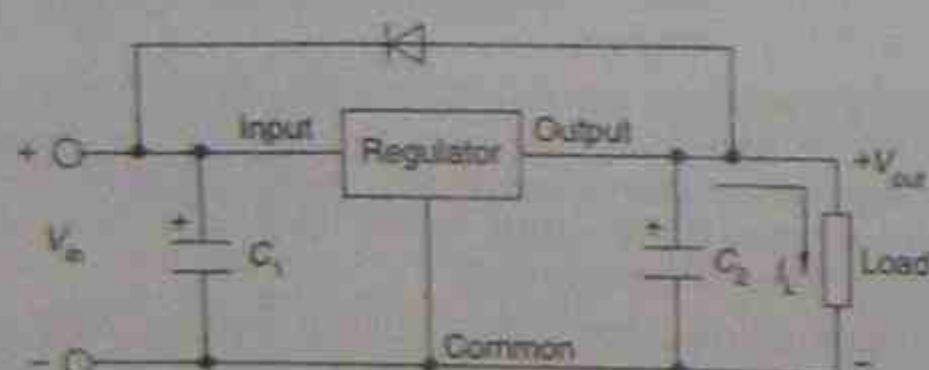


Figure 15.57 • Three-terminal IC regulator circuit

Note that it is only necessary to have three components external to the regulator. Their purpose is:

- **Capacitor  $C_1$** —installed to provide stability in the regulator output. If the regulator is more than 50 mm from the main filter capacitor, this component is essential. If it is not used, electromagnetic or electrostatic fields may cause stray voltages to be induced in the input leads to the regulator. These can cause the regulator to oscillate at a high frequency, which in turn causes excessive internal temperature and thermal shutdown. The capacitor, which must be mounted physically as close as possible to the regulator, can be either a 100–200  $\mu$ F ceramic disc capacitor, or a 2  $\mu$ F tantalum capacitor.
- **Capacitor  $C_2$** —added to improve the transient response of the regulator. This is the ability of the regulator to cope with very sudden changes in load current that

may otherwise cause a change in load voltage. The capacitor may also be a 2  $\mu$ F tantalum capacitor.

- **Diode  $D_1$** —to protect the regulator in the event of a short-circuit on the input side of the regulator. This might cause the output capacitor,  $C_2$ , to discharge back through the regulator and will result in permanent damage to the regulator.

In constructing a circuit like that in Figure 15.57, the selection of input voltage is important. The drop-out voltage must be taken into account, as well as the maximum power dissipation in the regulator. Select an input voltage high enough for the drop-out voltage not to become a problem, and low enough for the power dissipation to be not too high for a particular application.

If the input voltage is selected carefully and a suitable heat sink is used, the regulator circuit in Figure 15.58 will provide a very reliable, stable and ripple-free output voltage.

When using circuits such as in Figure 15.57, care must be taken to ensure that the supply is turned off when removing or installing the IC regulators. If the common, or ground, connection becomes open-circuited, the voltage on the output terminal will be almost equal to the input voltage. This might damage components connected to the output. In some equipment this might necessitate considerable work to replace what might be a large number of integrated circuits. If the ground pin is disconnected, or connected while the supply is on, the regulator itself might be damaged. It is always advisable to disconnect the supply and discharge large filter capacitors when installing or removing three-terminal regulators.

### 15.5.3 Variable output three-terminal regulators

A disadvantage of the three-terminal regulators examined in section 15.5.2 is that the output is fixed. Many situations exist where a variable output voltage is required, or where a voltage needs to be set that is not equal to any of the standard output voltages available in the three-terminal regulator range. The circuit connection in Figure 15.58 will allow the output voltage to be adjusted from the nominal value up to some higher value.

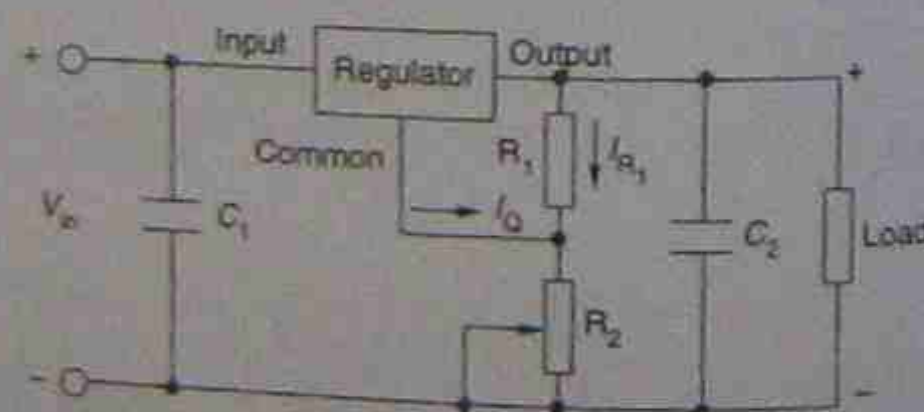


Figure 15.58 • Variable output three-terminal regulator circuit

In this circuit the voltage drop across  $R_2$  is added to the nominal output. The total output voltage is therefore:

$$V_L = V_{R1} + V_{R2}$$

$V_{R1}$  is equal to the nominal regulator output, while  $V_{R2}$  may be found from:

$$V_{R2} = I_{R2} R_2$$

The current in  $R_2$  is made up of the current flowing through  $R_1$  plus the quiescent current that is needed for the regulator to operate. This value is usually around 8 to 10 mA:

$$I_{R2} = I_{R1} + I_Q \text{ and } I_{R1} = \frac{V_1}{R_1}$$

$$\text{Therefore: } I_{R2} = \left( \frac{V_1}{R_1} \right) + I_Q$$

for the circuit of Figure 15.58:

$$I_{R2} = \left( \frac{V_1}{R_1} \right) + I_Q = \left( \frac{12}{330} \right) + 0.008 = 44.4 \text{ mA}$$

$$V_{R2} = I_{R2} R_2 = 0.0444 \times 220 = 9.76 \text{ V}$$

$$V_L = V_{R1} + V_{R2} = 12 + 9.76 = 21.76 \text{ V}$$

With  $R_2$  set to zero, the load voltage would be 12 V, therefore the range of output voltages for the circuit in Figure 15.58 is 12 V to 21.76 V. A disadvantage of this arrangement is that the maximum output voltage is equal to the nominal output from the regulator. This may be overcome by the use of specially designed adjustable regulators. An example is the LM723. With this regulator the minimum output voltage is 1.2 V because the voltage difference between the output and the common is always 1.2 V. The circuit arrangement is identical to that in Figure 15.59.

With the LM317 regulator configured as in Figure 15.58, and with a suitable supply voltage, it is possible to have a supply that is variable from 1.2 V up to around 35 V with an output current of 1.0 A.

### 15.6 BIPOLAR POWER SUPPLIES

Many applications exist where a supply is required that has two voltages, one that is positive with respect to earth, and the other that is negative with respect to earth. These voltages might or might not need to be the same value. This type of supply is called a bipolar power supply. By employing a positive-output and a negative-output three-terminal regulator, it is possible to set up a very simple but effective bipolar supply.

Equipment typically requiring a bipolar supply includes:

- instrumentation amplifiers
- audio amplifiers
- operational amplifiers
- microprocessor equipment
- laboratory power supplies.

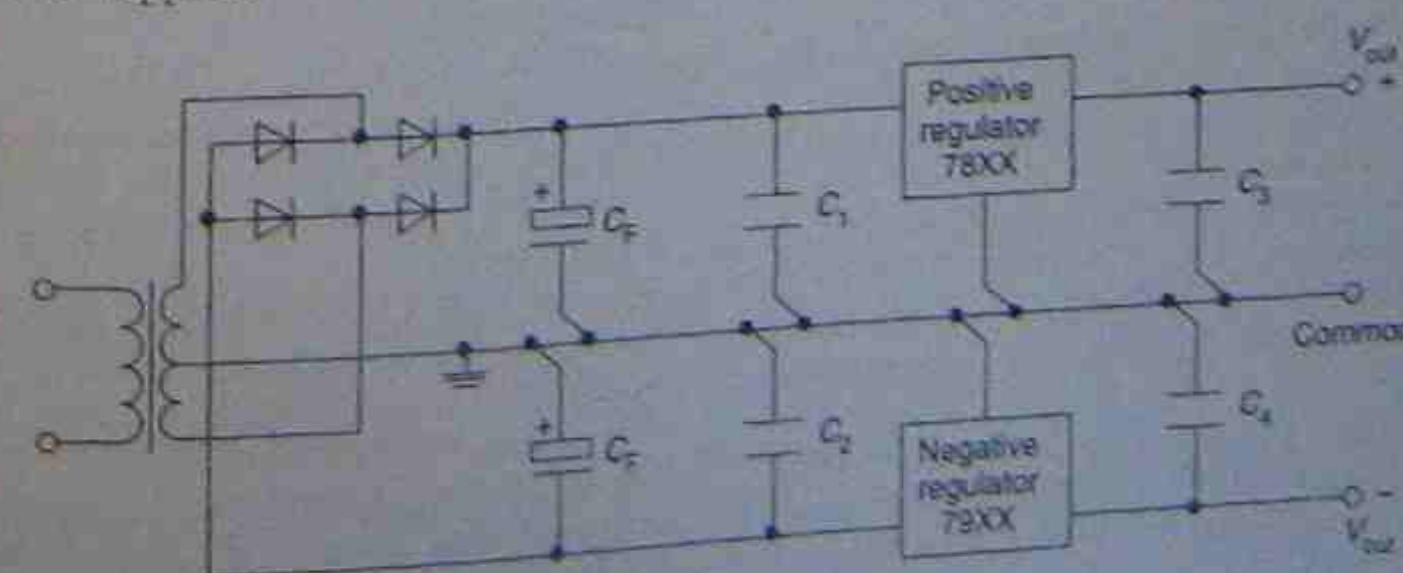


Figure 15.59 • Bipolar power supply circuit

A complete bipolar supply is shown in Figure 15.59. Note that this circuit uses the 78 and 79 series regulators. The supply is therefore a fixed supply in this configuration.

This circuit contains all component blocks of a power supply, that is, the a.c. supply including a transformer, a rectifier, a filter and a voltage regulator. The various components in this circuit serve exactly the same purpose as they did in circuits examined earlier in this chapter.

If the 78 and 79 series regulators were replaced by adjustable three-terminal regulators configured as in Figure 15.59, the output would be variable. This arrangement is very common in laboratory-type power supplies.

### 15.7 FAULT FINDING IN POWER SUPPLIES

Most of the failures in electronic equipment are due to power supply faults. A power supply is the most vulnerable part of any system. It must cope with unusual occurrences in the supply, faults or problems in the load, as well as the reliability of its own components.

It is usually very obvious that a power supply is not working. Determining exactly where the fault is, and if possible the cause of the fault, is a more difficult task. However, with suitable instruments and an organised approach, fault finding is not as difficult as it might seem at first. Adopting a systematic approach will save time by identifying a majority of faults sooner and minimising the chances of missing a fault, particularly where more than one fault exists.

A procedure that might be useful for fault finding in power supplies is outlined as follows:

- Visually inspect the equipment. Faulty components are often obvious from signs of stress, burning, or discoloration.
- Obtain a copy of the circuit diagram. If not available, one might need to be developed.
- Test the power supply output. Is it high, low or not present at all? This is particularly useful where the supply has more than one output, such as a bipolar supply. This step might allow the fault to be isolated to one section of the power supply.
- Test the incoming supply. This will determine whether or not the input voltage level is correct, or whether all phases are present.



- Check the voltage levels and waveforms at key points in the circuit, such as the rectifier input, rectifier/filter output, and regulator output.
- From the measurements taken above, identify the faulty section of the supply and take more detailed measurements around the components in this section to isolate the components at fault. The circuit around the faulty component should be checked carefully to determine the cause of the fault. It might be that one faulty component caused another to fail.
- Replace the faulty components and check all voltage levels and waveforms. Do not assume that only one fault is present. Often one fault will cause another and the faults might need to be eliminated one by one in more complex circuits.
- In the case of faults in or near the output stage of a power supply, the load should be checked, as a fault of some type in the load might have caused the power supply to fail.
- Carefully examine the power supply for potential problems. A little preventative maintenance might prevent a major problem at a later time.

Fault finding becomes easier as practical experience is gained. If faults are documented, the process of fault finding can become very simple, because it is surprising how often faults in equipment recur. If a fault and its symptoms are documented, it is very quickly identified and rectified when it recurs.

## SUMMARY

- Pure or intrinsic semiconductor material is doped to produce *p*- and *n*-type semiconductor materials.
- Silicon and germanium are the commonly used semiconductor materials, with silicon being preferred in most applications.
- Electrons are the majority current carriers in *n*-type semiconductor material.
- Holes are the majority current carriers in *p*-type semiconductor material.
- Fusing *p*- and *n*-type semiconductor materials together forms a junction. At this junction, holes and electrons combine to form a depletion layer.
- The device formed when *p*- and *n*-type materials are fused together is called a *p-n* diode.
- The barrier potential formed across a *p-n* junction is 0.6 V in silicon, and 0.3 V in germanium.
- When forward biased, a *p-n* diode will conduct, provided the barrier potential has been overcome.
- When reverse biased, a *p-n* diode blocks current flow.
- Diodes are rated in terms of average forward current and peak reverse voltage (PRV).
- If the PRV of a diode is exceeded, the junction may break down and allow a high current to flow, destroying the diode.
- The forward voltage drop across a conducting diode is relatively constant and is equal to 0.6 V in a silicon diode and 0.3 V in a germanium diode.
- Reverse or leakage current in a *p-n* diode is due mainly to thermally generated minority current carriers.
- The reverse leakage current is much higher in germanium diodes than in silicon diodes.
- The leakage current in a silicon diode doubles for every 10°C rise in temperature.
- The forward voltage drop across a silicon diode decreases by about 2.5 mV for every Celsius degree rise in temperature.
- Diodes may be tested for current operation with an ohmmeter switched to a suitable range. When forward biased, a low resistance is displayed, and when reverse biased, a high resistance is displayed.
- A complete power supply made up from an a.c. supply (including a transformer), a rectifier, a filter and a voltage regulator.
- A single-phase half-wave rectifier consists of only one diode in series with the load.
- The single-phase half-wave rectifier produces an output that is 0.45  $V_{a.c.}$ , a ripple frequency equal to the supply frequency, a ripple voltage that is equal to the peak of the a.c. input, and requires a PRV equal to the peak of the a.c. input.
- The single-phase full-wave centre-tapped rectifier produces an output that is 0.9  $V_{a.c.}$ , a ripple frequency equal to twice the supply frequency, a ripple voltage that is equal to the peak of the a.c. input, and requires a PRV equal to twice the peak of the a.c. input.
- The single-phase full-wave bridge rectifier produces an output that is 0.9  $V_{a.c.}$ , a ripple frequency equal to twice the supply frequency, a ripple voltage that is equal to the peak of the a.c. input, and requires a PRV equal to the peak of the a.c. input.
- The three-phase half-wave rectifier produces an output that is 1.17  $V_{a.c.}$ , a ripple frequency equal to three times the supply frequency, a ripple voltage that is equal to half the peak of the a.c. input, and requires a PRV equal to 2.45 times the a.c. input.
- A three-phase half-wave rectifier relies for its operation on a four-wire supply, the d.c. load current returning via the neutral conductor.
- The three-phase full-wave rectifier produces an output that is 1.35  $V_{a.c.}$ , a ripple frequency equal to six times the supply frequency, a ripple voltage that is 0.26 of the peak of the a.c. input, and requires a PRV equal to the peak of the a.c. input.
- The purpose of a filter circuit is to remove as much of the ripple from the d.c. output as possible.
- Filter circuits may be constructed from capacitors, inductors, or a combination of both.
- Capacitor filters are limited to low-output supplies, since with high-load currents, the peak charging currents for the capacitors necessitate the use of very large diodes.
- The output voltage from a capacitor filter decreases as the load increases and the ripple voltage increases.

- Inductor filters are often used on high-current supplies. The cost of the inductors might be high and the inductors may be large.
- Inductor filters provide little or no filtering at low levels of current. As the current increases, the ripple decreases. The load voltage remains relatively constant as load varies.
- An inductor and a capacitor are combined to form a choke-input filter.
- The choke-input filter is suited to higher load currents because of the dual filtering action and better voltage regulation.
- By combining two capacitors and an inductor, a  $\pi$  filter is formed.
- $\pi$  filters provide an output virtually free from ripple. They are limited to lower load currents as the peak charging currents might damage the rectifier diodes.
- The function of a voltage regulator is to minimise the voltage variations that might occur at a load.
- Load voltage variations might be caused by:
  - load current variations
  - supply voltage variations
  - temperature variations.
- The regulation of a power supply is the degree to which the output voltage changes as the load changes.
- The Zener diode is similar to a normal silicon diode, but has a different reverse characteristic.
- When the reverse voltage applied to a Zener diode reaches a certain value, the Zener diode will conduct. If the power dissipation is controlled to safe limits, the Zener diode will not be damaged by the reverse current.
- Zener diodes are rated in terms of Zener voltage and maximum power dissipation.
- In the interests of good voltage regulation and long-term reliability, the Zener diode current working range is 10 to 80 per cent of the maximum Zener current.
- A Zener diode may be used in conjunction with a series resistor to form a shunt regulator.
- Zener diode shunt regulators will maintain a relatively constant load voltage provided the load current and supply voltage variations are not large.
- Zener diode shunt regulators maintain a constant load voltage by changing the Zener current as load current and supply voltage change.

## EXERCISES

- Under what conditions is a rectifying diode forward biased? Refer to voltage polarities at each terminal.
- Under what conditions is a rectifying diode reverse biased?
- What ratings of a diode have to be considered when selecting that diode for a particular purpose?
- Draw the Australian standard symbol for a diode.
- Describe what happens to the depletion layer of a semiconductor diode when it is reverse biased.
- Describe the effect that a rise in operating

- Zener diode shunt regulators are ideal for situations where the load current is low and does not vary by large amounts, and the circuit is supplied from a source that does not vary significantly.
- The three-terminal integrated-circuit regulator is a complete regulating circuit in an integrated-circuit package with three terminals: an input, an output and a common terminal.
- Three-terminal IC regulators provide:
  - excellent voltage regulation
  - over-current protection
  - high ripple rejection
  - over-temperature protection.
- Three-terminal regulators are available in output voltages from 5 V up to 24 V, with current ratings from 0.1 A up to 15 A. The regulators are available as both positive output and negative output regulators.
- A complete regulator circuit may be formed from a three-terminal regulator, two capacitors, and a diode for protection of the regulator.
- Three-terminal regulators should never be removed from, or installed in, a circuit when the supply is switched on. This can cause damage to the regulator or other circuit components.
- The output of a three-terminal regulator may be adjustable if the common terminal is connected to the centre point of a voltage divider, which in turn is connected across the load.
- The output available from a three-terminal regulator set up to be adjustable is from the nominal output voltage, up to some value determined by the ratio of the resistors in the voltage divider.
- A purpose-designed adjustable regulator can, in a suitable circuit, provide output voltages as low as 1.2 V.
- A positive and a negative regulator can be configured, together with other components, to form a bipolar power supply.
- A bipolar power supply provides two voltages, one that is positive with respect to ground, and the other that is negative with respect to ground.
- It is important when fault finding in power supply circuits to adopt a logical systematic approach.
- Failures in electronic equipment are mainly due to power supply failures.

- temperature has on the reverse leakage current of a diode.
- Explain why the d.c. magnetising current of a transformer supplying a single-phase half-wave rectifier is high when the load current is also high.
- What is meant by a 50 per cent duty cycle in relation to the diode in a single-phase half-wave rectifier circuit?
- With reference to Figure 15.60 (overleaf), describe what effect would be apparent at the output if one-half of the secondary winding became open-circuited.



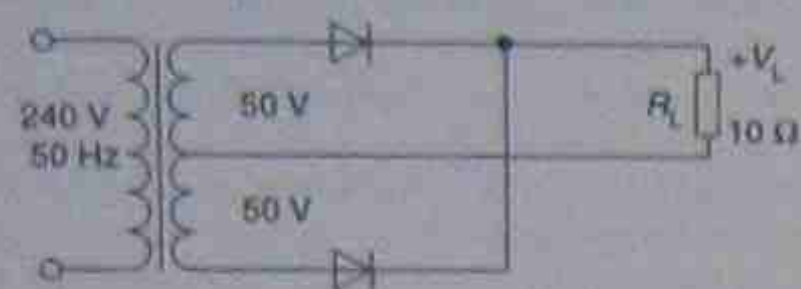


Figure 15.60 • Full-wave centre-tap rectifier

15.10 With reference to the circuit of Figure 15.61, describe what effect would be apparent at the output if:

- one diode was open-circuited
- one diode was short-circuited.

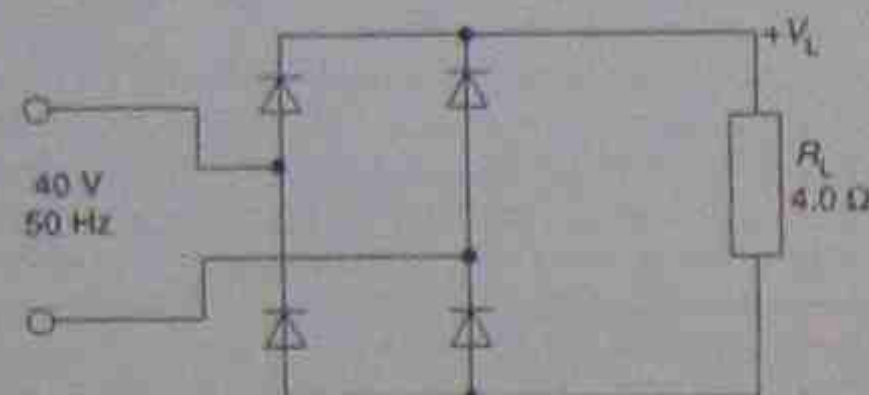


Figure 15.61 • Full-wave bridge rectifier

15.11 What is meant by *ripple* in the output of rectifier circuits, and why is it undesirable?

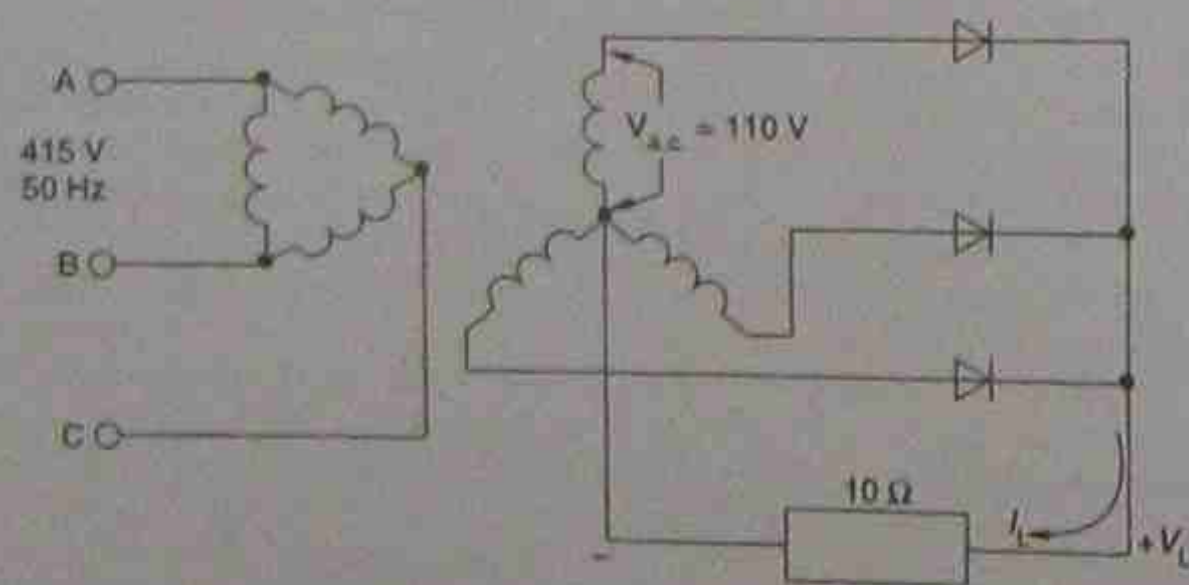


Figure 15.62 • Three-phase half-wave rectifier

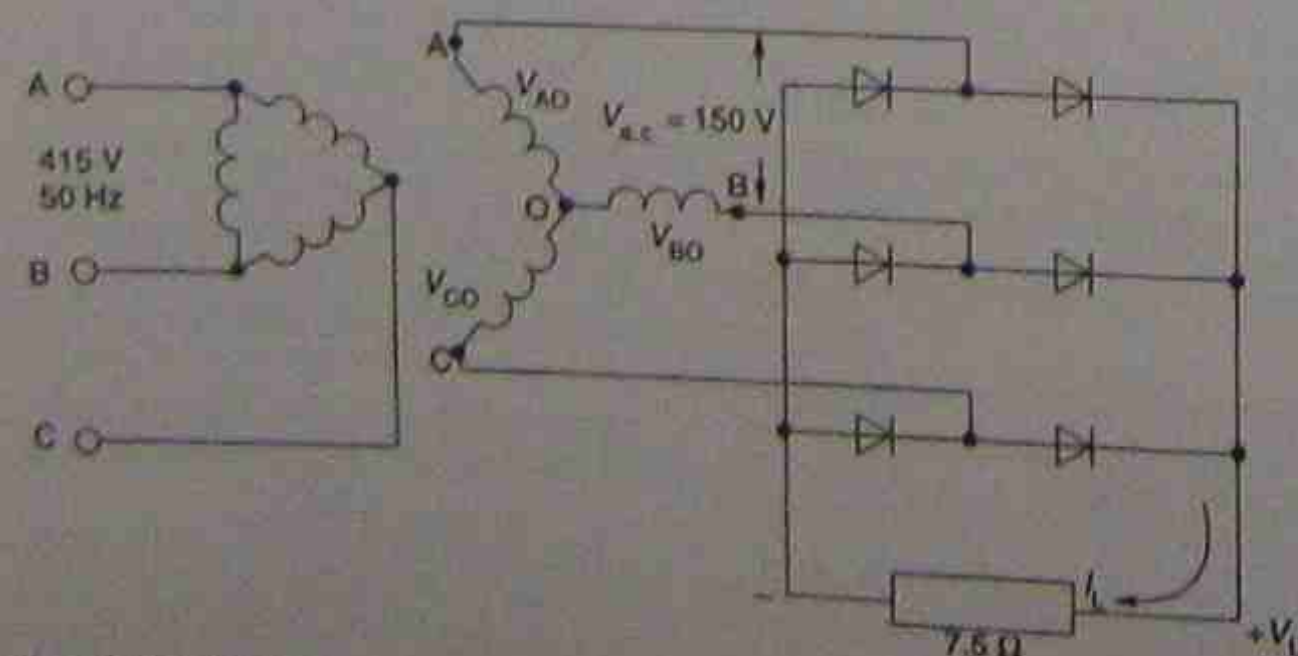


Figure 15.63 • Three-phase bridge rectifier

15.12 With reference to the circuit in Figure 15.62, what effect would be apparent at the output if one of the diodes became open-circuited?

15.13 With reference to the circuit in Figure 15.63, explain what effect would be apparent at the output if one of the diodes became short-circuited.

15.14 Explain why the three-phase full-wave rectifier circuit produces a smaller ripple voltage than either three-phase half-wave or a single-phase full-wave rectifier circuit.

15.15 Explain the purpose of a filter circuit when used in conjunction with a rectifier circuit.

15.16 Why are electrolytic capacitors generally used in capacitor filter circuits?

15.17 If a load is connected to the output of the circuit in Figure 15.64, how will it affect:

- the output voltage?
- the ripple voltage?

15.18 With reference to the rectifier/capacitor filter circuit shown in Figure 15.64, indicate from Figure 15.65 the period in which the diode will conduct.

15.19 With reference to Figure 15.65, indicate the period when the capacitor filter will supply current to the load.

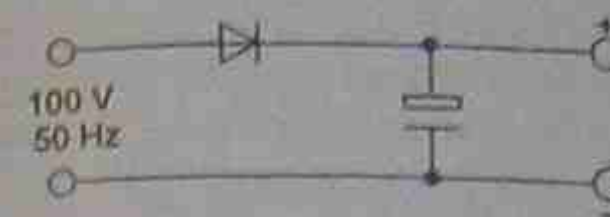


Figure 15.64 • Capacitor filter—no load

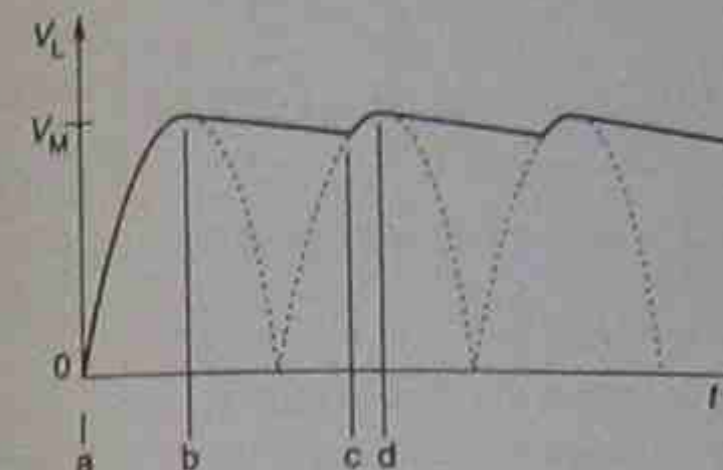


Figure 15.65 • Capacitor filter output waveforms

15.20 Explain the practical limitations on the use of capacitor filters in removing ripple from the output of rectifier circuits.

15.21 What safety precautions must be observed when working with electrolytic capacitors in filter circuits?

15.22 Explain why a choke-input filter is better suited to supplying higher current loads than a capacitor filter.

## SELF-TESTING PROBLEMS

15.33 The a.c. input voltage to a single-phase half-wave rectifier circuit is 100 V. Calculate the average d.c. output voltage.

15.34 The a.c. input voltage to a single-phase half-wave rectifier circuit is 100 V. Calculate the value of the peak reverse voltage across the diode.

15.35 A single-phase half-wave rectifier circuit is connected to a 30 V a.c. supply. It is used to charge a 12 V battery connected directly across the output. Find the minimum peak reverse voltage rating of the diode.

15.36 The a.c. input voltage to a single-phase full-wave rectifying circuit is 100 V. Determine the d.c. output voltage.

15.37 For the circuit shown in Figure 15.60, determine:

- the load voltage
- the load current
- the ripple frequency
- the peak reverse voltage on the diodes
- the average diode current.

15.38 For the circuit in Figure 15.61, determine:

- the load voltage
- the load current

- the ripple frequency
- the peak reverse voltage of the diodes
- the average diode current.

15.39 What is the minimum number of diodes needed to connect a three-phase half-wave rectifier circuit?

15.40 What is the minimum number of diodes needed to connect a three-phase full-wave rectifier circuit?

15.41 For the circuit of Figure 15.62, find:

- the load voltage
- the load current
- the ripple frequency
- the peak reverse voltage of the diodes
- the average diode current.

15.42 For the circuit shown in Figure 15.63, find:

- the load voltage
- the load current
- the ripple frequency
- the peak reverse voltage of the diodes
- the average diode current.

15.43 Find the no-load output voltage for the circuit shown in Figure 15.64.



- 15.44 What is the minimum number of rectifying diodes needed for a single-phase full-wave rectifying circuit?
- 15.45 With reference to the a.c. input frequency, what is the ripple frequency of the output of a single-phase full-wave centre-tap rectifier?
- 15.46 Determine the maximum allowable Zener current for a 6.3 V 400 mW Zener diode.
- 15.47 Find the practical working range of a 9.0 V 1.7 W Zener diode.
- 15.48 For the circuit shown in Figure 15.66, determine:

- (a) the working range of Zener currents  
 (b) the load voltage  
 (c) the load current  
 (d) a suitable value of series resistance, assuming a Zener current of 25 mA.

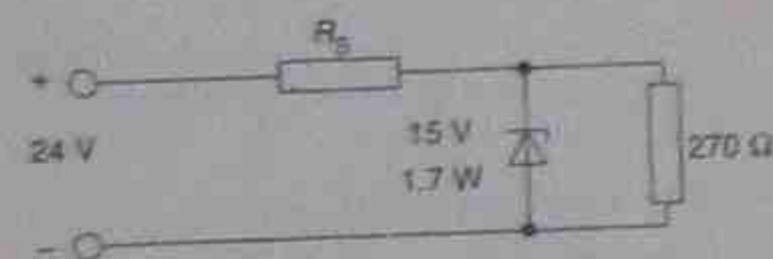


Figure 15.66 • Zener diode shunt regulator

- 15.49 For the circuit shown in Figure 15.67, find:
- (a) the load voltage

- (b) the load current  
 (c) a suitable value for the series resistance ( $R_S$ ). Assume that the Zener current is 15 mA  
 (d) a suitable power rating for  $R_S$ .

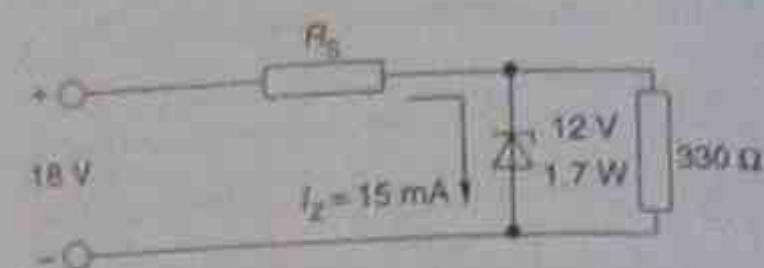


Figure 15.67 • Zener diode shunt regulator

- 15.50 For the circuit shown in Figure 15.68:

- (a) determine the load voltage  
 (b) determine the load current  
 (c) determine the power dissipated in the regulator  
 (d) explain the purpose of capacitors  $C_1$  and  $C_2$ .

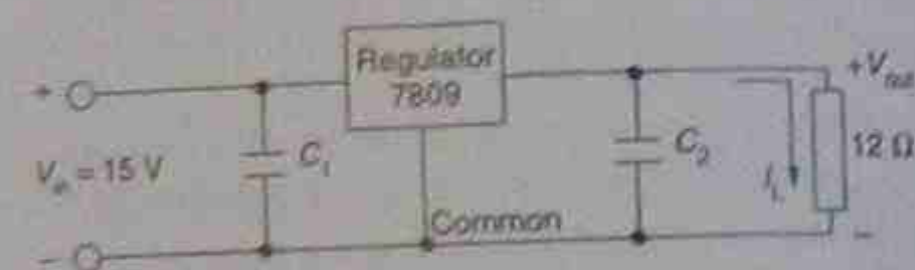


Figure 15.68 • Three-terminal regulator circuit

# Chapter 16

## Power control devices



## 16.1 INTRODUCTION

This chapter introduces electronic devices and circuits commonly used to control the power in a load. The features and applications of each device and circuit are outlined in sufficient detail to lead to an understanding of electronic power control and to make comparisons with more traditional methods, particularly in relation to operational efficiency, ease of application, and cost effectiveness. The need arises in many situations where it is either desirable, or in some cases essential, to control the power dissipated in a load.

Control of power in a load may be employed for one or more of the following reasons:

- to limit or control the load power, for example, controlling illumination to levels required for a particular application
- to provide automatic control over a process, such as accurately controlling the temperature of a heating process. This could be applied across a wide range of equipment from a furnace through to a domestic cooking appliance
- to control motor speed and acceleration. This may be required to limit torque shocks on a load, to control air flow from a fan, or control the speed of a conveyor
- to manage the consumption of electrical energy. This is a relatively new and rapidly expanding application, where energy is managed by controlling air-conditioning units, lighting systems, heating applications, fans, and pumps.

## 16.2 POWER CONTROL METHODS

A wide variety of methods have been developed to control the power in a load. Some have found widespread use, while others are very specialised in their application. Load power may be controlled by a switching method, where the load is turned on and off, or linear methods, where the load power is controlled by providing continuous or infinite control of load voltage.

### 16.2.1 Switched control

In principle the switched method is the simplest method of controlling power. As shown in Figure 16.1, control consists of a switch either to connect or to disconnect the load from the supply. Control is limited to a simple on/off action. The power dissipated by the load is determined by the load current and voltage.

This form of control is limited to situations where on/off control is all that is required, for example, controlling the temperature of stored water where the switch is actually a thermostat and cycles the load according to changes in temperature.

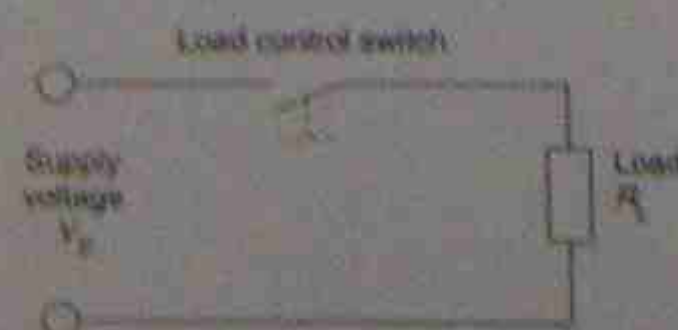


Figure 16.1 • Switched load control

A variation of switched control is *simmer stat* control. A simmer stat is a switch that is cycled on and off by a small heating element inside the simmer stat. The actual switch contact is a bimetal strip that bends as its temperature changes, opening and closing the switch. The average power dissipated by the load is controlled by the relative on/off times of the simmer stat. The switching action is independent of the power actually being dissipated in the load. This may be a disadvantage in some situations. The simmer stat is widely used for the control of heating elements such as the hotplates on electric ranges, and electric blankets.

The advantages of this method are that it is simple and relatively inexpensive. The disadvantages are that it provides coarse control, is relatively unreliable and inaccurate and suffers from contact wear and/or fatigue.

### 16.2.2 Rheostat control

Rheostat control uses a series-connected rheostat (variable resistance), as depicted in Figure 16.2, to control load power. As resistance is introduced in series with the load, the load voltage, and hence power, is reduced. The reduction in load voltage is caused by the voltage drop across the rheostat. Power may be controlled from a very low value, up to full power. However, for a wide range of control the rheostat may be physically very large; it may in fact be larger than the load. To control the load, power must be dissipated in the rheostat. This is a power loss and results in poor efficiency at low load settings. When the load power is reduced to 50 per cent, the power dissipated in the rheostat is equal to the load power.

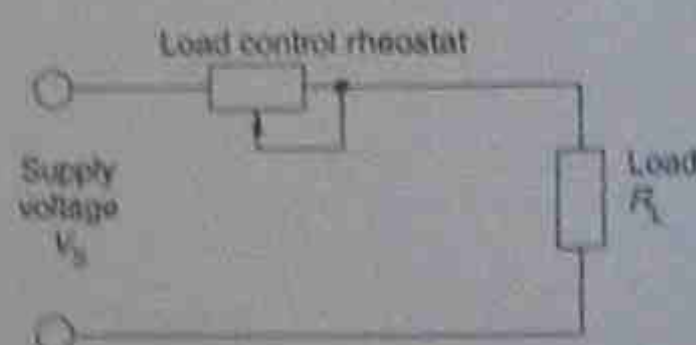


Figure 16.2 • Rheostat load control

For example, assume that the load in Figure 16.2 has a resistance of 10  $\Omega$  and the supply voltage is 100 V. If the rheostat is set to 5  $\Omega$ , determine the load power, input power and efficiency.

$$I_L = \frac{V_s}{(R_L + R_R)} = \frac{100}{(10 + 5)} = 6.67 \text{ A}$$

$$P_L = I_L^2 R_L = 6.67^2 \times 10 = 444.4 \text{ W}$$

$$P_{in} = V_s I_L = 100 \times 6.67 = 666.6 \text{ W}$$

$$\eta = \frac{P_L}{P_{in}} \times 100 = \frac{444.4}{666.6} = 66.7\%$$

If the rheostat in Figure 16.2 were set to 10  $\Omega$ , the load power would be further reduced to 250 W. The efficiency would also decrease; in this example, to 50 per cent. As the load power is reduced even further, the efficiency also decreases.

This form of control is widely used in equipment of older design. Owing to its low efficiency and generally poor

performance, it has now been largely superseded by more modern methods.

Apart from poor efficiency, an undesirable aspect of this method is the manner in which the load voltage varies if the load current varies. This is termed *poor load regulation* and may be overcome by using automatic voltage regulators, but this becomes very expensive when the load power is high and still does not overcome the poor efficiency of the method.

This method of power control has the advantage that it is very simple. The disadvantages are that it is very inefficient, bulky, very expensive (when the running costs are taken into consideration), and has poor load regulation.

### 16.2.3 Voltage control

This method controls the load power in the same manner as rheostat control, that is, by varying the load voltage, but uses either a Variac or a tapped inductor. These methods are suited only to a.c. supplies and loads. The use of the Variac or the tapped inductor overcomes the poor efficiency of the rheostat method.

Variacs and inductors are very efficient devices compared with rheostats. A Variac is a form of transformer. It is a variable autotransformer. These devices are efficient but they have the disadvantage that they are bulky, heavy and expensive, particularly where the load power is high. Power may be controlled from zero to rated power. Figure 16.3 shows a Variac connected to control load power.

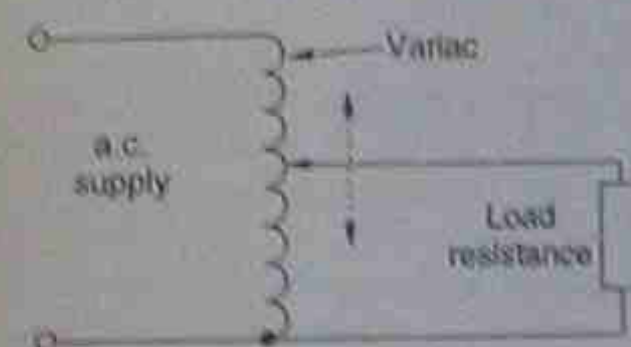


Figure 16.3 • Variac power control

This method is very efficient (efficiencies in excess of 90% can be expected), offers fine control, and displays quite good load voltage regulation. Owing to the high cost and mass of the Variac, it is usually limited to low-power applications. The sliding contacts in the Variac may also have wear problems.

The tapped inductor method is a variation of the adjustable autotransformer system. It has a limited number of adjustments and effectively adds impedance in series with the load. The method is more efficient than the rheostat method, but still does not provide very good load regulation. Figure 16.4 shows a tapped inductor connected to control the power in a load.

The method is used for the speed control of ceiling fans and other low-power applications. Control of high values of load power with this method would necessitate large, expensive inductors.

The advantages of the method are that it is simple and efficient, while it has the disadvantages that it is costly for medium- to high-power loads, has poor load regulation and provides control only in discrete steps.

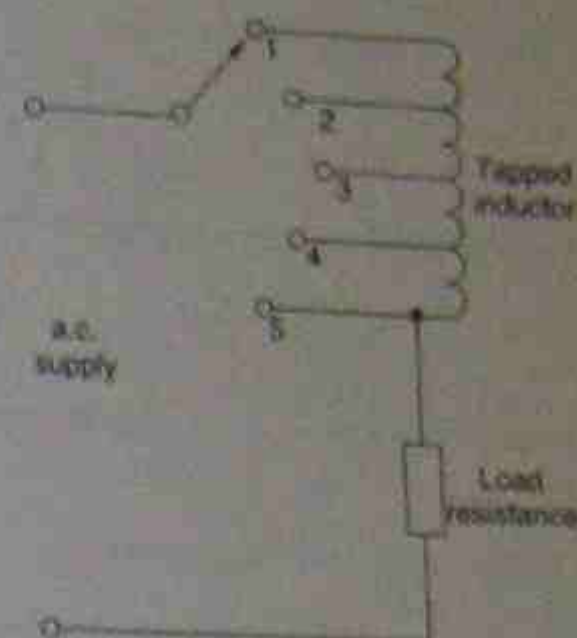


Figure 16.4 • Tapped inductor power control

### 16.2.4 Thyristor power control

Thyristor control has largely superseded all other methods of power control. It offers efficient and cost-effective control of power in most applications from very low to very high power levels. Figure 16.5 shows a simplified diagram for a thyristor power controller.

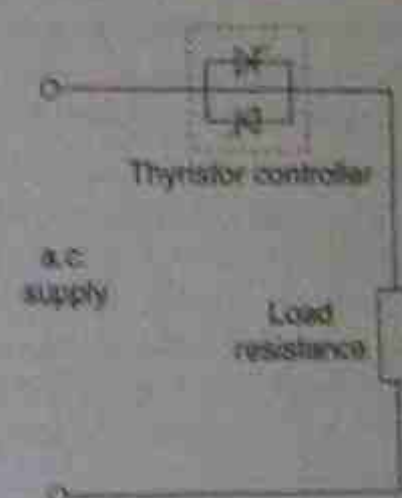


Figure 16.5 • Thyristor power control

Thyristors are a family of electronic devices designed specifically to provide power control functions. They are in effect controlled switches. Thyristors are turned on by a pulse of gate current, the gate being the control lead on the device. Once turned on, these devices offer very little resistance and hence dissipate very little power, resulting in high efficiencies.

Thyristor controllers achieve efficient power control by one of two methods:

1. **Phase control**—the a.c. waveform is 'chopped up' to achieve varying values of load voltage. The load voltage waveforms are no longer sinusoidal, but in many applications this is not a problem. The variable voltage is obtained by delaying the 'triggering' of the thyristor and hence reducing the conduction time. An advantage of this method is that it may be applied to a.c. or d.c. loads being supplied from an a.c. supply. It has the disadvantage that it produces radio frequency interference (RFI) when the thyristor is triggered. The waveforms in Figure 16.6 represent typical load voltage waveforms supplied from a phase-controlled thyristor controller.
2. **Zero voltage switching**—this method of control was



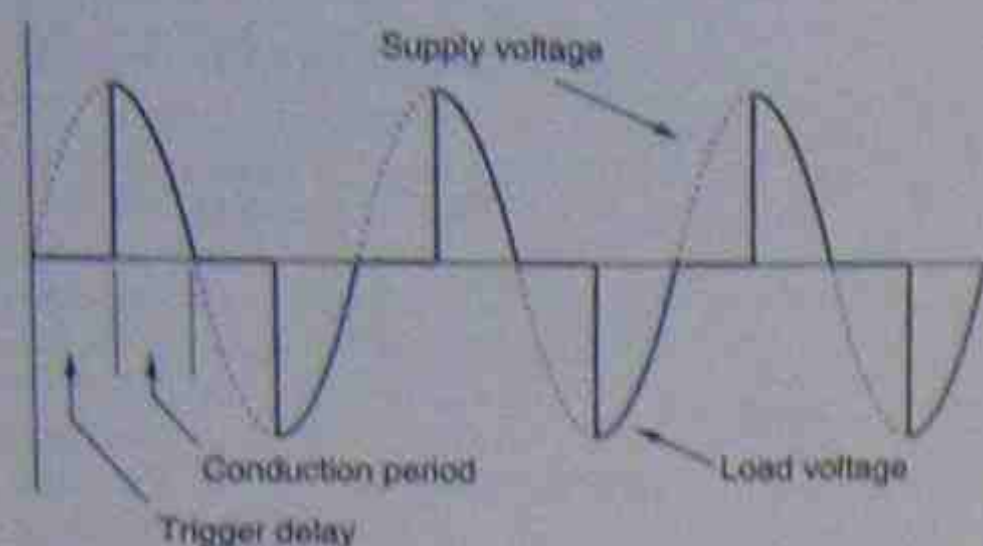


Figure 16.6 • Phase control load voltage waveforms

designed to overcome the RFI generated by phase-control techniques. It operates in a similar manner to a simmer stat in that the load voltage is controlled by controlling relative on/off times. In this case, however, the on and off times will be measured in cycles. For high power, the thyristor will be turned on for a larger number of cycles than it is off, and the reverse applies for low power. To minimise RFI, the thyristor is switched as the supply voltage crosses zero or is at zero volts. Unlike simmer stat control, this method may employ feedback from the load to provide accurate control. This method is suited only to resistive loads such as heating elements. It is unsuited to inductive loads. Typical waveforms are shown in Figure 16.7.

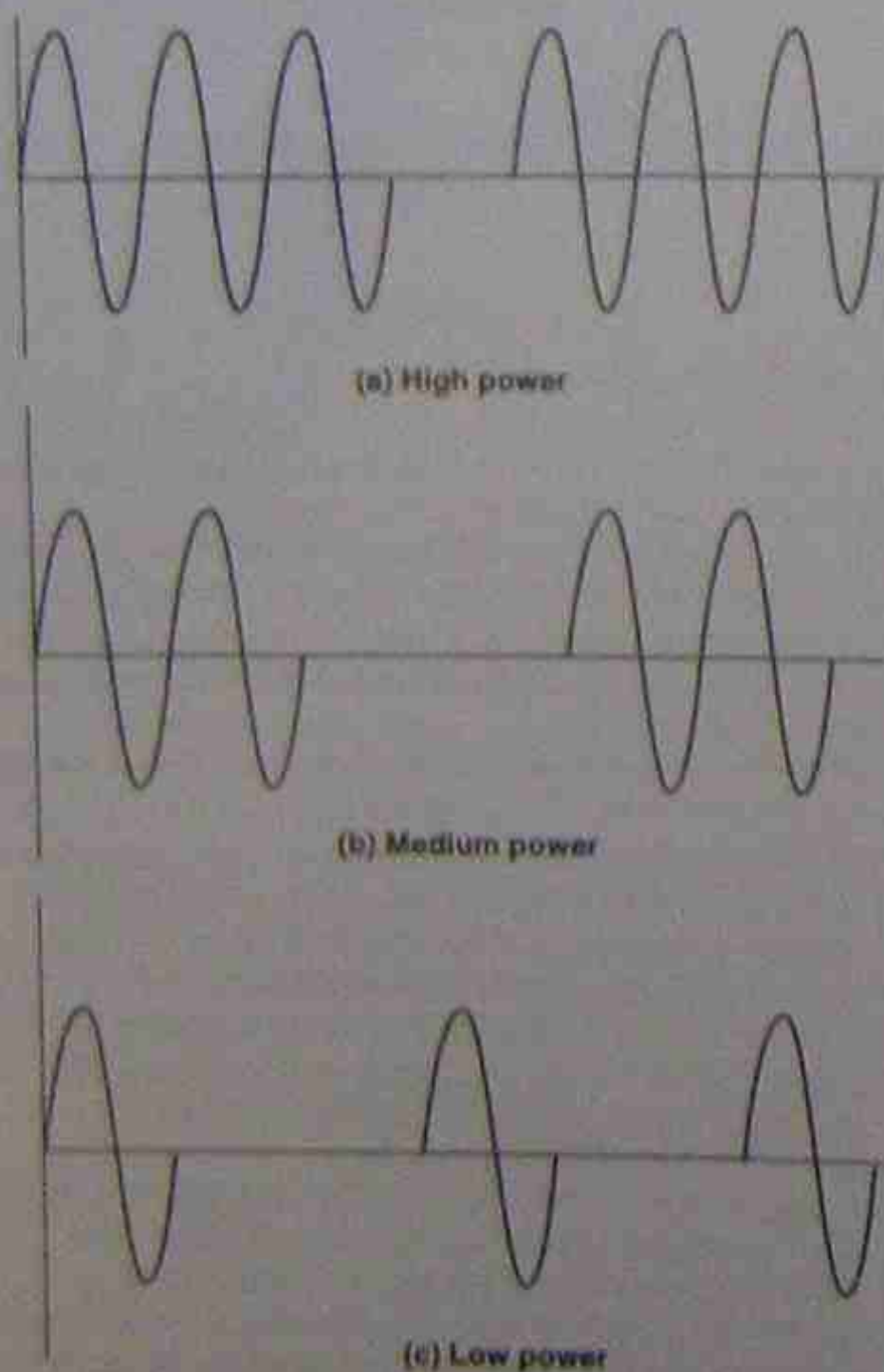


Figure 16.7 • Load waveforms for zero voltage switching

Thyristor controllers are widely used in the control of power in industrial and domestic applications. A thyristor controller may be designed and constructed to control a lamp in a domestic situation or to control loads such as a 1500 kW motor in industry.

Thyristor controllers have the advantage that they are relatively inexpensive (taking running costs into account), highly efficient, reliable, adaptable to most situations, have good load regulation, and are relatively compact. The disadvantages are that they might require complex trigger or control circuits. Phase-control circuits produce radio-frequency interference (RFI) and most controllers produce non-sinusoidal waveforms that tend to generate harmonics in the supply.

The thyristor devices most commonly used to control the power in a load are:

- silicon controlled rectifiers (SCRs)
- gate-turn-off thyristors (GTO thyristors)
- triacs.

Thyristors are switching devices. They are triggered (switched) on by a current pulse through a gate terminal. A thyristor must be accompanied by a suitable triggering circuit in which the active component is known as a *trigger device*. Trigger devices discussed in this text are:

- unijunction transistors (UJT)
- programmable unijunction transistors (PUT)
- diacs.

## 16.3 SILICON CONTROLLED RECTIFIERS

The SCR is a silicon, unilateral three-terminal thyristor. It is the most commonly used and highest power-rated thyristor currently available. The SCR is available in current ratings from around 1.0 A, up to values in excess of 1000 A, and voltage ratings up to 5 kV.

The device performs in much the same manner as a *p-n* diode; that is, it will allow a current to flow in one direction, and it will block current in the other direction. The major difference is that forward conduction can be controlled in the SCR. Conduction is controlled by passing current through the gate terminal.

The SCR symbol is shown in Figure 16.8.



Figure 16.8 • SCR standard symbol

SCRs are produced in a variety of case styles, largely depending on the SCR ratings. Some case styles are shown in Figure 16.9.

### 16.3.1 Construction

The SCR is a four-layer silicon device, the layers being alternately *p*- and *n*-type semiconductor materials. This structure is referred to as *p-n-p-n*. Three semiconductor junctions are therefore formed in the device. Figure 16.10 is a representation of the layer construction in an SCR.

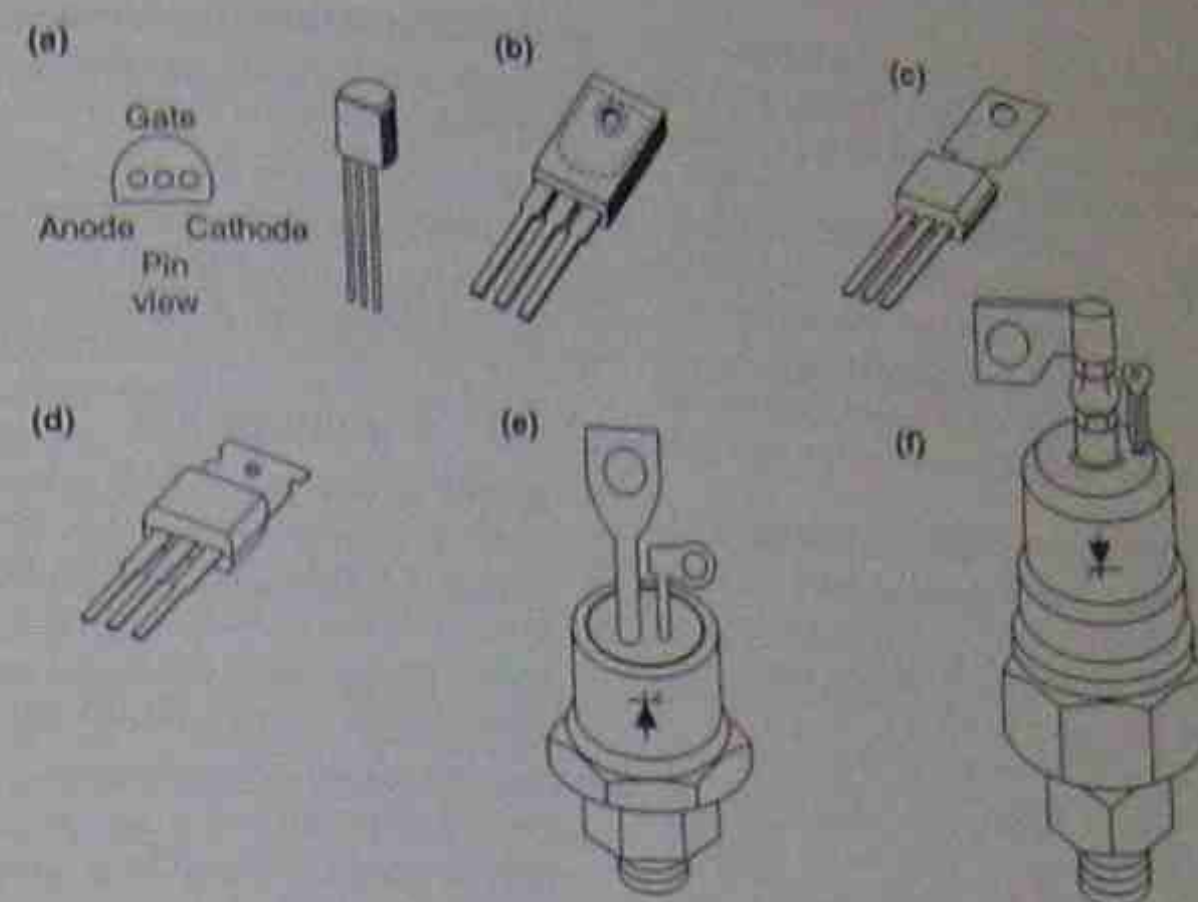


Figure 16.9 • SCR case styles

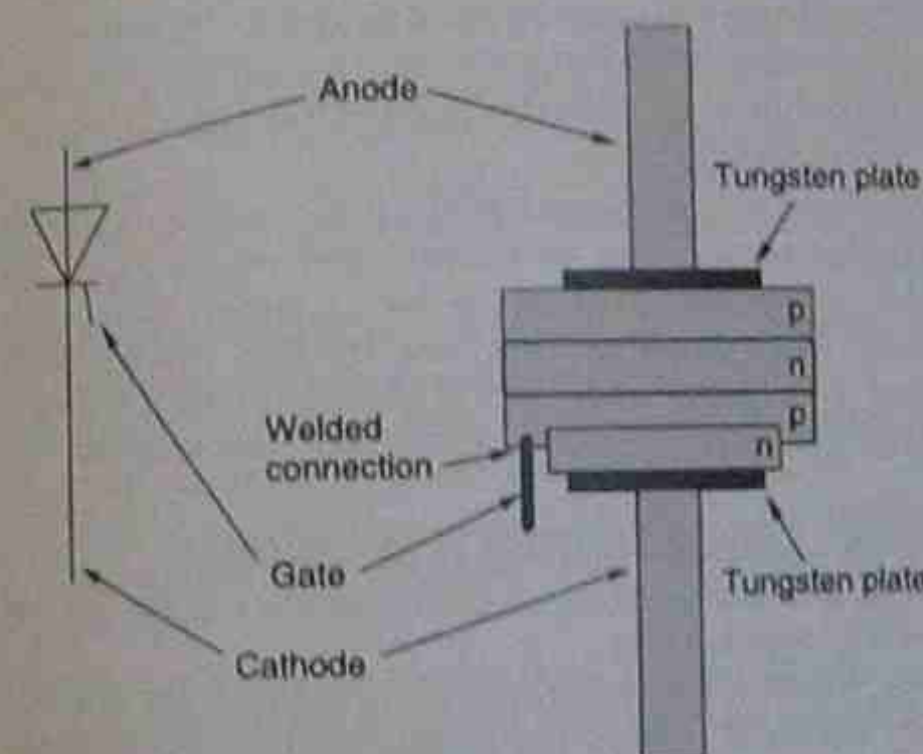


Figure 16.10 • SCR layer construction

When the device itself is forward biased, that is, anode positive with respect to the cathode, two of the junctions will be forward biased, while the third is reverse biased. It is this reverse-biased junction that allows the SCR to block anode current until gate current flows. The actual size of the silicon wafer will be varied at the time of manufacture to achieve required 'on state' voltage and current ratings. The higher the power-handling capabilities of the SCR, the larger is the wafer.

While an SCR is essentially a three-terminal device, some SCRs may appear to have only two terminals. This is due to either the anode or the cathode being connected to the case.

Some larger industrial SCRs may also appear to have four terminals. This is due to the provision of a 'gate reference' lead. This lead is connected to the cathode and twisted together with the actual gate lead. This minimises the possibility of induced voltages in the gate lead causing incorrect triggering.

### 16.3.2 Operation

As stated in section 16.3.1, the SCR will block forward current until it is triggered into the on state by a trigger pulse. This is the normal mode of operation of an SCR. Like a *p-n* diode, an SCR must be forward biased to allow anode current (forward current) to flow. This means that the anode must be positive with respect to the cathode.

An SCR will switch from the off state to the on state if the forward voltage is excessive. The voltage that causes the SCR to switch from the off state to the on state is called the *forward break-over voltage* ( $V_{BR}$ ). This mode of operation is not normally used as there is no real control over the SCR. This break-over voltage causes the SCR to turn on as it overcomes the reverse-biased junction in the device.

The normal mode of operation is to control conduction with the gate current. Current is passed from gate to cathode. This means that the gate-cathode junction must be forward biased; that is, the gate is positive with respect to the cathode.

Consider the circuit in Figure 16.11. If the gate switch ( $S_1$ ) is open, no gate current flows, therefore the SCR will not be triggered into the on state (provided that the anode voltage does not exceed the break-over voltage rating of the device).

If  $S_1$  is closed, a small gate current flows. This will cause the SCR to switch to the on state and anode current will flow. Once the SCR has turned on, and provided the anode current is high enough, the gate current can be turned off and the SCR will continue to conduct. It now acts just like

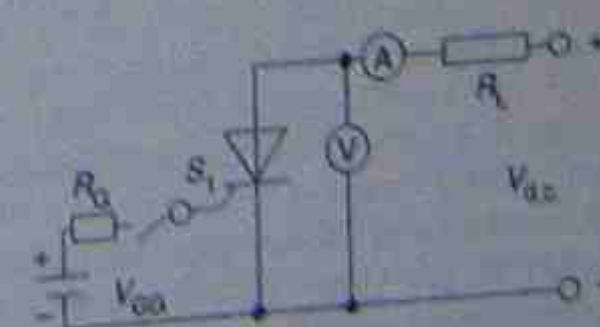


Figure 16.11 • SCR operation



a p-n diode. The forward voltage drop is relatively constant and has a nominal value of 0.6 V. In practice this value will be found to be nearer 1.0 V and may be as high as 2.0 V for very high-current SCRs.

In some cases it might be found that the SCR turns back off when the gate current is removed. This means that the SCR has not 'latched on' properly. For an SCR to latch on, the anode current must rise to a value known as the 'latching current'. Once this value is exceeded the SCR will latch on and continue to conduct, even when the gate current is removed.

For the SCR to turn off, the anode current must be reduced to near zero. If the anode current falls below a value known as the 'holding current' it will relax back to the off state. The processes involved in reducing the anode current to this value are discussed in section 16.3.3.

The holding and latching currents for a particular SCR are always very small values when compared with the anode current rating. The latching current is slightly higher than the holding current. For example, a C122E SCR has the following current ratings:

- Anode current: 8.0 A
- Latching current: 25 mA
- Holding current: 20 mA

The reverse operation of an SCR is identical to that of a p-n diode. It will block current until breakdown occurs. This is caused by the reverse voltage exceeding the peak reverse voltage (PRV) rating of the device.

The forward operation of an SCR may be demonstrated with an SCR and an analogue ohmmeter:

1. Switch the ohmmeter to the  $\Omega \times 1$  range and short the leads together to zero the reading. In carrying out this test, remember that an analogue multimeter will reverse the polarity of its terminals when switched to an ohms range. To avoid confusion, connect a red lead into the terminal marked negative and a black lead into the terminal marked positive. Then consider the red lead to be positive and the black lead to be negative.
2. Identify the lead configuration for the SCR using the manufacturer's data sheets.
3. Connect the positive lead to the anode and the negative lead to the cathode of the SCR. Observe the reading. This reading should be high (near infinity) because the SCR should be in a forward blocking mode.
4. Connect a second positive lead from the multimeter to the gate terminal and observe the effect. The reading should fall to a low value (around 20  $\Omega$ ).
5. Remove the lead from the gate terminal and observe the effect. The reading should remain low as the SCR should be latched on.

It is important to appreciate that this test is not reliable on high current SCRs because the ohmmeter might not be capable of delivering sufficient current to cause the SCR to latch on. Similar tests can be conducted using a d.c. supply and a suitable load.

From this examination of the operation of an SCR, it should be noted that to cause an SCR to switch from the off state to the on state, and remain in the on state, the following conditions must be satisfied:

- the SCR must be forward biased
- a pulse of current must flow from the gate to the cathode
- the anode current must rise to a level above the latching current to allow the SCR to latch into the on state
- the anode current must remain above the holding current to remain in the on state.

### 16.3.3 Commutation

The process of causing an SCR to turn off is known as *commutation*. To commutate an SCR, the anode current must be reduced to a value below the holding current. Commutation may be forced in several ways, for example:

1. *Reduce or disconnect the supply voltage*—this method is not practical in most situations.
2. *Momentarily short the anode and cathode terminals of the SCR*—the method would be dangerous on high current and/or high voltage circuits. It is not practical in most situations.
3. *Reverse bias the SCR and inject a short duration pulse of current from cathode to anode*—this is the most successful and widely used method of providing forced commutation of an SCR. It may be achieved by providing auxiliary circuits to connect a charged capacitor or an external pulse across the SCR to cause commutation.

When an SCR is connected to an a.c. supply to provide controlled rectification or control over an a.c. load, the anode current will fall to zero as the a.c. supply voltage falls to zero. When the supply reverses, the SCR will be reverse biased. This means that the SCR is commutated by the a.c. supply voltage and is known as *a.c. line commutation*.

### 16.3.4 Characteristics and ratings

Typical forward and reverse characteristics of an SCR are shown in Figure 16.12.

Like many other electronic components, an SCR has many electrical ratings. The ratings that are the most significant in a practical situation, particularly for component replacement, are:

1. *peak reverse voltage (PRV)*—the maximum peak value of voltage that the SCR can withstand continuously while reverse biased

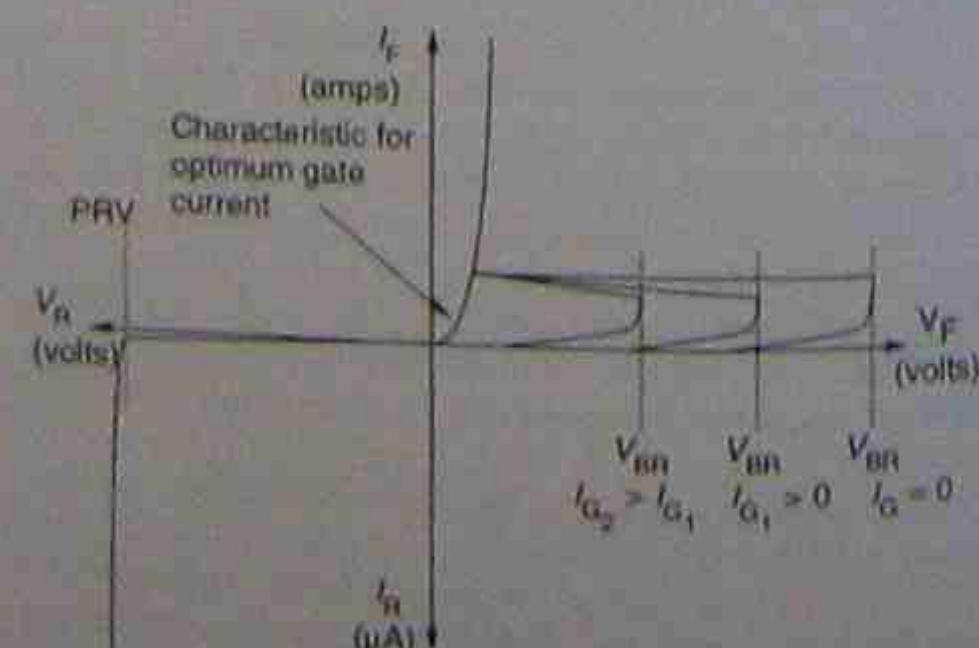


Figure 16.12 • SCR forward and reverse characteristics

*forward break-over voltage ( $V_{BO}$ )*—the maximum value of a forward voltage that can be applied to the SCR, while forward biased, without causing the SCR to switch to the on state

*average forward current ( $I_{T(av)}$ )*—the maximum average forward anode current that the SCR can carry. To carry this value of current without damage to the SCR it may be necessary to mount the SCR on a heat sink to dissipate the heat developed in the junctions in the device

*holding current ( $I_H$ )*—the minimum anode current that will support conduction in the SCR. If the anode current falls below this value the SCR will switch from the on to the off state

*latching current ( $I_L$ )*—the minimum anode current that will cause the SCR to latch into the on state. If the anode current does not rise above this value when triggered on by the gate current, the SCR will relax back to the off state when the gate current is removed

*$dv/dt$* —the maximum rate of rise of anode voltage that the SCR can withstand when turned off, without switching back to the on state. This value is normally measured in volts per microsecond

*$di/dt$* —the maximum rate of rise of anode current that is permitted in the SCR when switched from the off to the on state. If the anode current rises too quickly the current density in the silicon wafer might be too high

*maximum reverse gate voltage ( $V_{RGM}$ )*—a similar quantity to the PRV rating of the SCR, but applies to the gate-cathode junction. This value is the maximum reverse voltage that may be applied to the gate-cathode junction. The value is usually significantly lower than the PRV rating of the SCR

*maximum on-state voltage ( $V_T$ )*—the maximum forward voltage drop that may be expected when the SCR is in the on state.

To obtain all necessary information relating to a particular SCR it may be necessary to refer to manufacturers' data sheets. Technicians and tradespeople working in situations where thyristor devices are used might find it useful to obtain a full set of data sheets from a manufacturer.

### 16.3.5 Gate requirements

To ensure accurate and reliable triggering of SCRs, the trigger pulses must satisfy certain requirements as follows:

- the gate current and voltage must be high enough to trigger the SCR
- the gate current and voltage must not be high enough to cause damage to the gate-cathode junction
- the gate pulse must be applied for a period that allows the SCR to turn fully on.

As the gate current in an SCR increases, the voltage required to cause the SCR to break over into conduction decreases. The sensitivity of an SCR also increases with increase in temperature. Figure 16.13 shows the relationship between gate current and break-over voltage.

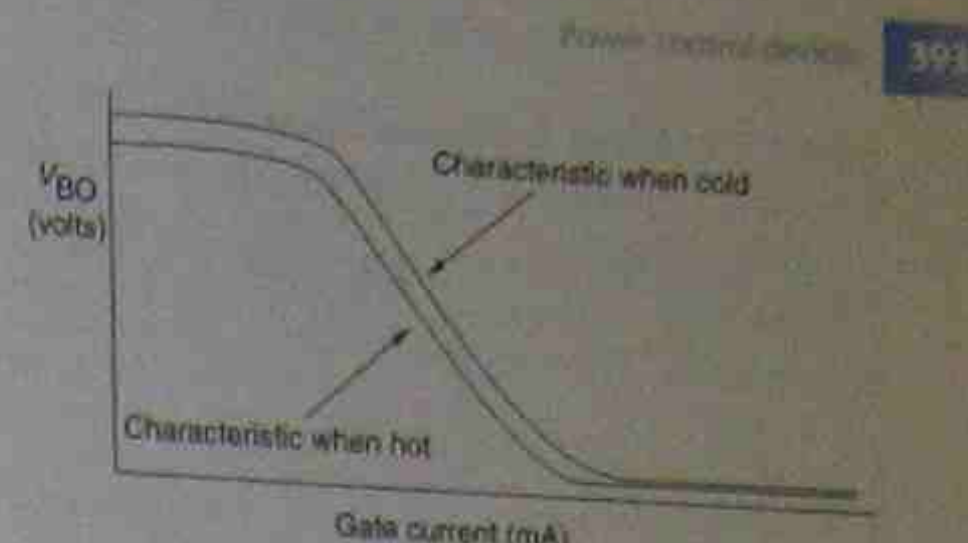


Figure 16.13 • Effect of gate current on SCR break-over voltage

Not only are the magnitudes of the gate current and voltage important, but also the actual shape and the duration of the pulse. A gate current pulse should have a very fast rise time to allow conduction to spread throughout the silicon wafer as quickly as possible. This allows the SCR to turn on more quickly. Ideally a gate current pulse should have a rise time of less than 1  $\mu$ s.

The gate current pulse should be of sufficient duration to allow the turn on process to be completed. The turn on process is complete when the SCR is latched on. In a simple resistive circuit this might take only a few microseconds, while in an inductive circuit the process may take longer. To ensure that an SCR turns fully on before the gate current is removed, the duration of the gate should be around 50  $\mu$ s to 200  $\mu$ s.

The amplitude and duration of the gate pulse will depend on the type of SCR and the nature of the load. Figure 16.14 shows a typical gate pulse for an SCR.

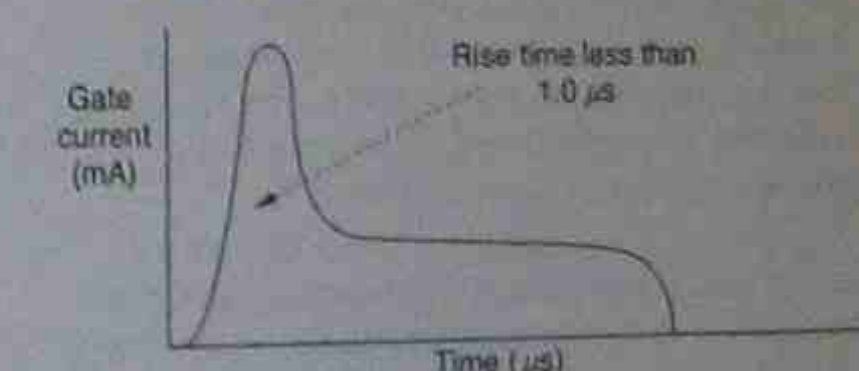


Figure 16.14 • Typical SCR gate current pulse

In some cases, where the load is highly inductive it is necessary to have a 'train of pulses' rather than a one-shot pulse. This is to ensure that the SCR turns on and latches before the gate current is removed. A 'pulse train' consists of a series of single pulses of around 20  $\mu$ s in duration with a delay of about 100  $\mu$ s between each pulse.

The switching characteristics of SCRs make them ideal for many applications. An SCR can be turned on and off very quickly. SCRs are classified according to their turn-on and turn-off times. They will be classified as either:

- phase control SCRs—typical turn-on time 20  $\mu$ s, typical turn-off time 40  $\mu$ s or
- inverter SCRs—typical turn-on time 10  $\mu$ s, typical turn-off time 20  $\mu$ s.

It is important to note that the time taken for an SCR to turn on or off can be affected by the characteristics of the load. Switching times are longer when the load is highly inductive than when the load is resistive.



### 16.3.6 Cooling and protection

While an SCR presents a cost-effective means of controlling power, some high-current SCRs are very expensive and can cost several hundred dollars each. It is therefore worth investing a reasonable sum of money in components or devices to protect the SCR.

SCRs require protection against:

- excessive current (short-circuit protection)
- rapidly rising currents
- rapidly rising forward voltages
- excessive junction temperature.

1. **Short-circuit protection**—special fuses are installed in series with the SCR. These fuses can limit the prospective fault current as well as interrupt the supply. They are a variation of the normal HRC fuse. They are sometimes called *semiconductor fuses* or *amp trap fuses*.

2. **Rapidly rising current ( $di/dt$ )**—if the anode current rises too quickly, the current density in the silicon wafer might become too high and damage the SCR, even when the actual value of current has not exceeded the current rating of the SCR. To minimise the chances of this occurring, an inductance is connected in series with the SCR to restrict the rate of rise of anode current when the SCR is turned on.

3. **Rapidly rising forward voltages ( $dV/dt$ )**—when the SCR is operating in the forward blocking mode and the anode voltage rises too quickly, the SCR may turn on, causing incorrect operation of the circuit. This usually occurs when the SCR has just been turned off. To prevent it, a resistor and a capacitor are connected in series. This series combination is connected in parallel with the SCR. The RC network is known as a *snubber network* and restricts the rate of rise of forward voltage across the SCR.

4. **Excessive junction temperature**—even though the power dissipated in an SCR is relatively low, the junction temperature may become excessive due to the relatively small mass of the device. To prevent excessive build up of heat, SCRs are usually mounted on a heat sink. This may be a flat piece of aluminium or an extruded aluminium heat sink with fins to improve heat dissipation. To improve heat conductivity between the device and the heat sink, a heat-sink compound (silicone grease or beryllium oxide) is often smeared between the device and the heat sink. Heat dissipation is further improved if the heat sink is black anodised aluminium. In extreme cases the heat sinks may be fan and/or liquid cooled.

The following circuit (Figure 16.15) shows the connection of protective devices to an SCR.

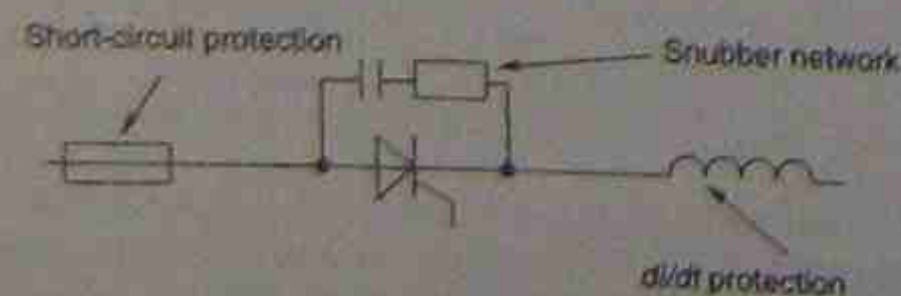


Figure 16.15 • SCR protection

In some equipment using thyristor devices, other, more complex, protection methods may be employed. This may include techniques that prevent an SCR from turning on when a fault in the load is detected.

### 16.3.7 Testing

A number of in-circuit tests can be carried out on an SCR. These are simple tests that give an indication of the condition of an SCR. For example:

1. **Measure the forward voltage drop**—this should be around the nominal value of 0.6 V if the SCR is on, or around the supply voltage if the SCR is off. If the SCR appears to be on, and the forward voltage drop is 0 V, the SCR is most likely short-circuited. This fault is usually caused by excessive reverse voltage.
2. **Use an oscilloscope (or high impedance voltmeter) to detect the presence of trigger pulses.** If no trigger pulses appear to be present, this may be due to either a faulty trigger circuit or a short-circuited gate-cathode junction.
3. **If the trigger circuit is suspected to be faulty, disconnect the gate and very carefully connect a resistor between the anode and the gate (a suitable value may be around 1 k $\Omega$ ).** If the SCR is not faulty, this action will usually trigger it on. If this fails to turn it on, the SCR should be removed from the circuit for more thorough testing.

Out-of-circuit testing may be carried out using a suitable analogue multimeter switched to the  $\Omega \times 1$  range. Remember that most analogue multimeters reverse their polarity when switched to an ohms range.

Measure the resistance between each of the terminals with either polarity, then compare the results with a standard set. The expected resistances are specified below in Table 16.1.

If an SCR appears to be satisfactory according to the resistances measured, it may be further tested to determine if it can be triggered on and latched on. For small SCRs this may be carried out using the ohmmeter. This is achieved by connecting the ohmmeter so that the SCR is forward biased; anode positive, cathode negative; the reading on the ohmmeter should be near infinity.

Connect a second lead to the positive terminal of the ohmmeter as shown in Figure 16.16(b). Connect the other end of this lead to the gate terminal of the SCR, and the reading on the ohmmeter should fall to a low value. If this gate lead is then disconnected and the ohmmeter reading

Table 16.1 • SCR test results—serviceable SCR

Test polarity		Expected resistance
Positive (+)	Negative (–)	
Anode (A)	Cathode (K)	High (infinite)
Cathode (K)	Anode (A)	High (infinite)
Anode (A)	Gate (G)	High (infinite)
Gate (G)	Anode (A)	High (infinite)
Gate (G)	Cathode (K)	Low (20 $\Omega$ )
Cathode (K)	Gate (G)	Medium (200 $\Omega$ )

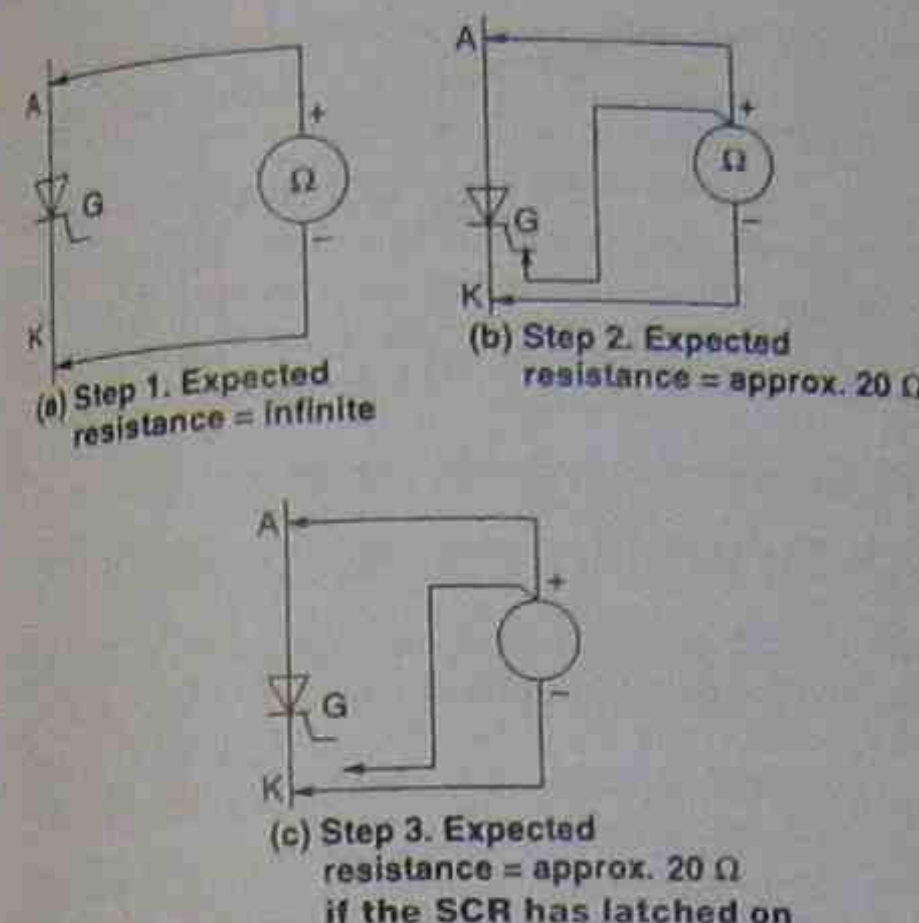


Figure 16.16 • SCR testing

remains low, it is an indication that the SCR has latched on. If the ohmmeter reading rises to near infinity, the SCR has not latched on. The test is depicted in Figure 16.16(c).

This test is a little more complex on a high-current SCR. It might be necessary to use a d.c. power supply and a suitable load to ensure that there is sufficient current for the SCR to latch on.

In most cases the faults that occur with SCRs are very obvious. They will generally be:

- short-circuit between anode and cathode—caused by excessive reverse voltage
- open circuit between anode and cathode—caused by excessive anode current
- short-circuit between gate and cathode—caused by excessive reverse gate voltage
- open circuit between gate and cathode—caused by excessive gate current.

It should also be kept in mind that excessive forward current between anode and cathode can cause internal temperatures to rise and destroy the wafer by fusion. The result is that the SCR becomes short-circuited. A similar situation can occur with excessive gate currents permanently damaging the gate-cathode junction.

### 16.3.8 Applications

The SCR is one of the most widely used power control devices. It is used in countless applications in equipment designed for domestic, commercial and industrial use, including:

- controlled rectifiers
- a.c. controllers
- motor speed controllers
- high-output furnaces
- welding equipment
- d.c./d.c. converters
- heating equipment
- battery chargers
- inverters (d.c./a.c. converters).

## 16.4 GATE TURN-OFF (GTO) THYRISTOR

A significant disadvantage of the SCR when used on d.c. supplies is the difficulty that might be encountered when turning the SCR off. This process is particularly difficult when the load is inductive.

The gate turn-off thyristor was developed to overcome this difficulty. It may be turned off by passing current from cathode to gate.

The standard symbol for a GTO thyristor is shown in Figure 16.17, while the anode and gate current directions for turn-on and turn-off conditions are shown in Figure 16.18. A feature of the GTO thyristor is that the gate current required to turn the device off is relatively high. It may be as high as 20 per cent of the anode current. This fact is considered to be a disadvantage of the device.

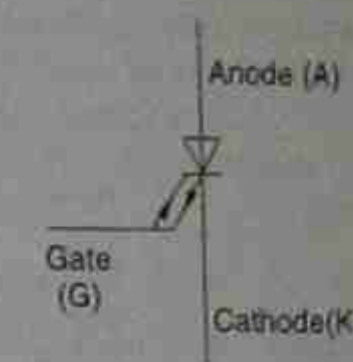


Figure 16.17 • GTO thyristor symbol

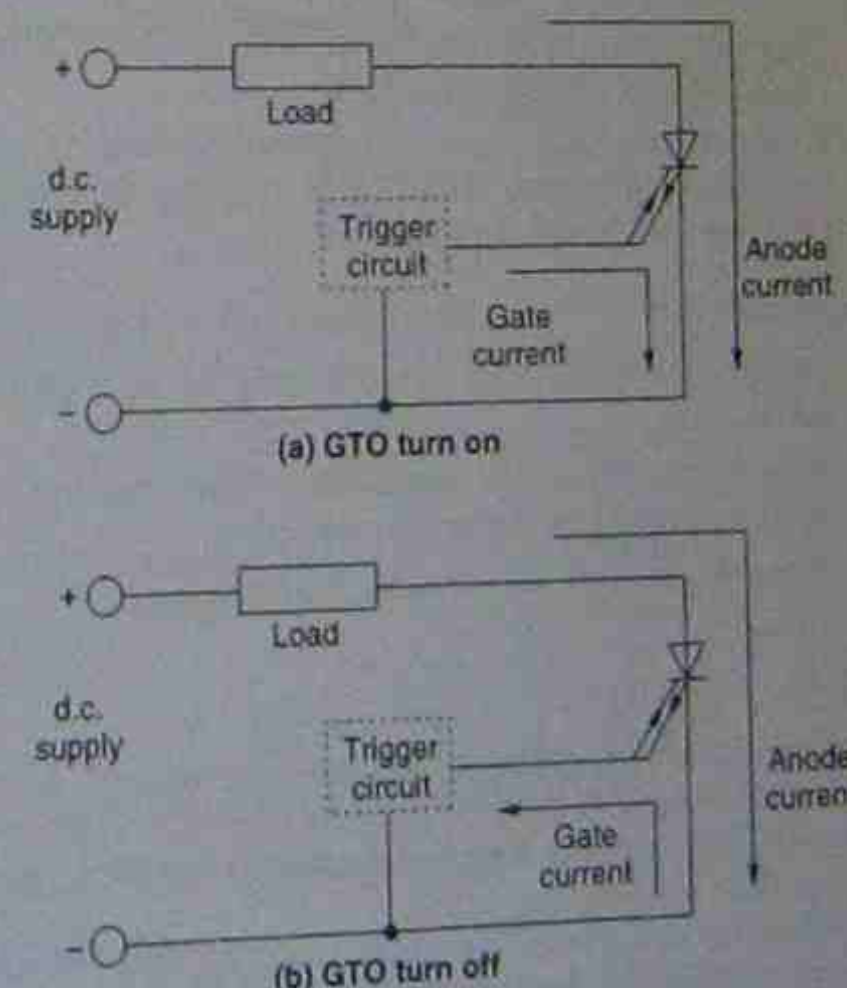


Figure 16.18 • GTO thyristor turn-on and turn-off currents

A second important feature of the operation of a GTO thyristor is the manner in which the characteristics change for low values of gate current. For very low values of gate current the GTO acts like a bipolar junction transistor (BJT). When the gate current increases beyond a certain value, the device latches on like a thyristor. Once the GTO is latched on, a negative gate pulse is required to turn it off.



The principle involved in turning the GTO off is the same as for a conventional SCR; that is, the anode current is reduced to a value below the holding current. A typical characteristic curve is shown in Figure 16.19.

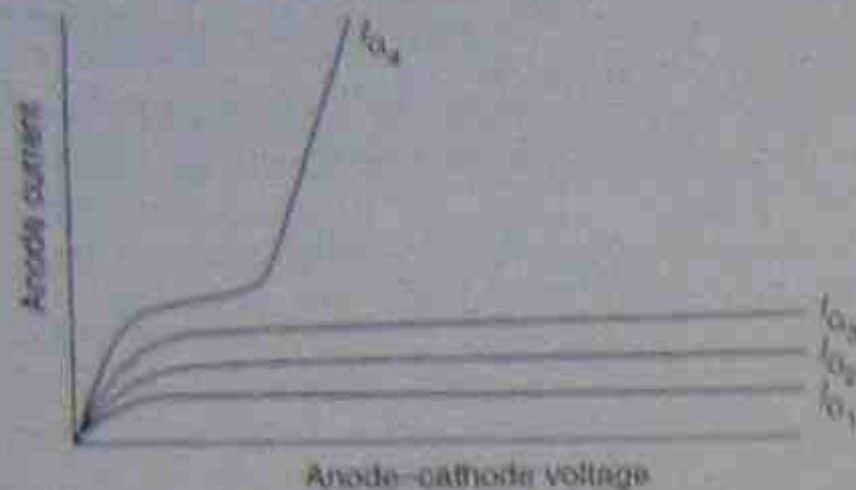


Figure 16.19 • GTO thyristor characteristics

A GTO thyristor can be used in almost any application where a conventional SCR can be used. Compared with a conventional SCR, a GTO thyristor has a number of advantages and disadvantages, the more significant being described below.

#### Advantages

- Faster turn-off times. This allows higher operating frequency.
- Elimination of complex commutating circuits, reducing the cost and physical size of equipment.
- Reduction of electromagnetic and acoustic noise produced by commutating chokes.
- Owing to the elimination of commutating components and faster switching times, it is possible to design converters with higher efficiencies.

#### Disadvantages

- Higher on-state voltage drop. It may be as high as 3.5 V.
- Poor reverse-blocking capabilities. This requires a series-connected diode for a.c. operation.
- Higher initial cost of the actual thyristor.

### 16.5 TRIACS

In many situations, control of a.c. power is required. Both the SCR and the GTO thyristor conduct current in only one direction. They are therefore not suited to controlling a.c. power when used alone.

To control a.c. power, two SCRs may be used in an inverse parallel connection, as shown in Figure 16.20.

With this circuit arrangement, each SCR conducts in alternate half-cycles of the supply. While this arrangement is popular for high-current applications, the two SCRs can be replaced by a single device called a triac. Triacs are available with current ratings up to about 150 A.

#### 16.5.1 Construction

The triac is a three-terminal bi-directional thyristor. It was developed as a device to control a.c. power. The triac

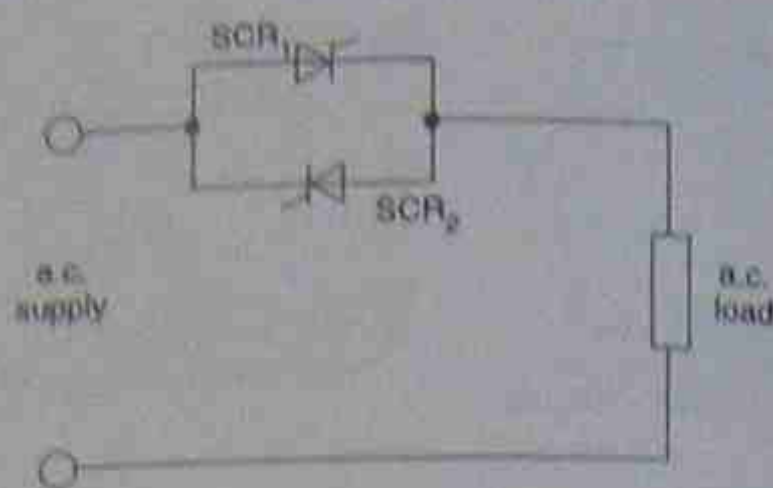


Figure 16.20 • Control of a.c. power—Inverse parallel SCRs

replaces a pair of inverse parallel-connected SCRs. For low- to medium-current applications (up to about 100 A) the triac is less costly than two SCRs. For currents above 100 A, two inverse parallel-connected SCRs might prove to be more economical than a single triac.

A triac operates in the same manner as an SCR but has the added ability to conduct in both directions. The layer construction of a triac is quite complex. A simplified representation, together with the standard symbol, is shown in Figure 16.21.

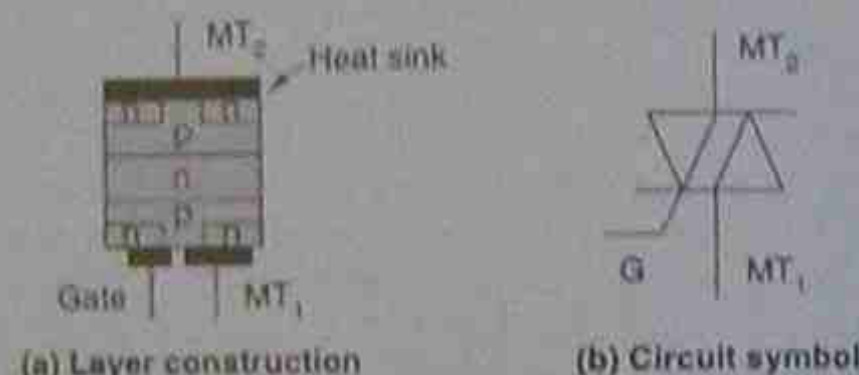


Figure 16.21 • Triac layer construction and circuit symbol

The terminals of the triac are referred to as main terminal 1 (MT<sub>1</sub>) and main terminal 2 (MT<sub>2</sub>), owing to the fact that it is a bi-directional device and therefore really does not have an anode and a cathode. The gate terminal is the control terminal, as is the case with the SCR.

#### 16.5.2 Operation

A triac operates in the same manner as an SCR, but conducts in both directions. Triac operation may be summarised as follows:

- Conduction is blocked until the forward or reverse blocking voltage is exceeded.
- Conduction may be initiated by a gate-trigger pulse, with either MT<sub>1</sub> or MT<sub>2</sub> positive, and with either positive or negative gate pulses.
- If MT current exceeds the latching current, the triac will remain on (latched on) when the gate pulse is removed.
- If MT current falls below the holding current, the triac will turn off.
- The voltage drop across a conducting triac is relatively constant and is approximately 1.0 to 2.0 V.

Like the SCR, the latching and holding currents are very small values, the latching current being slightly greater than the holding current. Typical values for a 400 V 8.0 A triac are:

- holding current—8.0 mA
- latching current—10.0 mA

#### 16.5.3 Triggering

Given that the triac can conduct in both directions, it is possible to establish four methods or modes of triggering. These modes relate to the polarity of terminals MT<sub>2</sub> and the gate with respect to MT<sub>1</sub>. The four modes are specified in Table 16.2.

The four triggering modes are represented in Figure 16.22.

The triggering sensitivity of a triac (the value of gate current needed to turn the triac on) is best in modes 1 and 2. Mode 3 is sometimes slightly less sensitive than 1 and 2, while mode 4 is the least sensitive and is not usually recommended.

When gate-trigger pulses of both positive and negative polarity are available, a triac will be triggered in modes 1 and 2. In situations where trigger pulses of one polarity only are available, the gate is made negative with respect to MT<sub>1</sub>, so that the triac is triggered in modes 2 and 3. The actual trigger circuits are discussed in sections 16.6.4, 16.7.4 and 16.8.3.

Table 16.2 • Triac triggering modes

Triggering mode	Polarity (with respect to MT <sub>1</sub> )	
	MT <sub>2</sub>	Gate
Mode 1	Positive	Positive
Mode 2	Negative	Negative
Mode 3	Positive	Negative
Mode 4	Negative	Positive

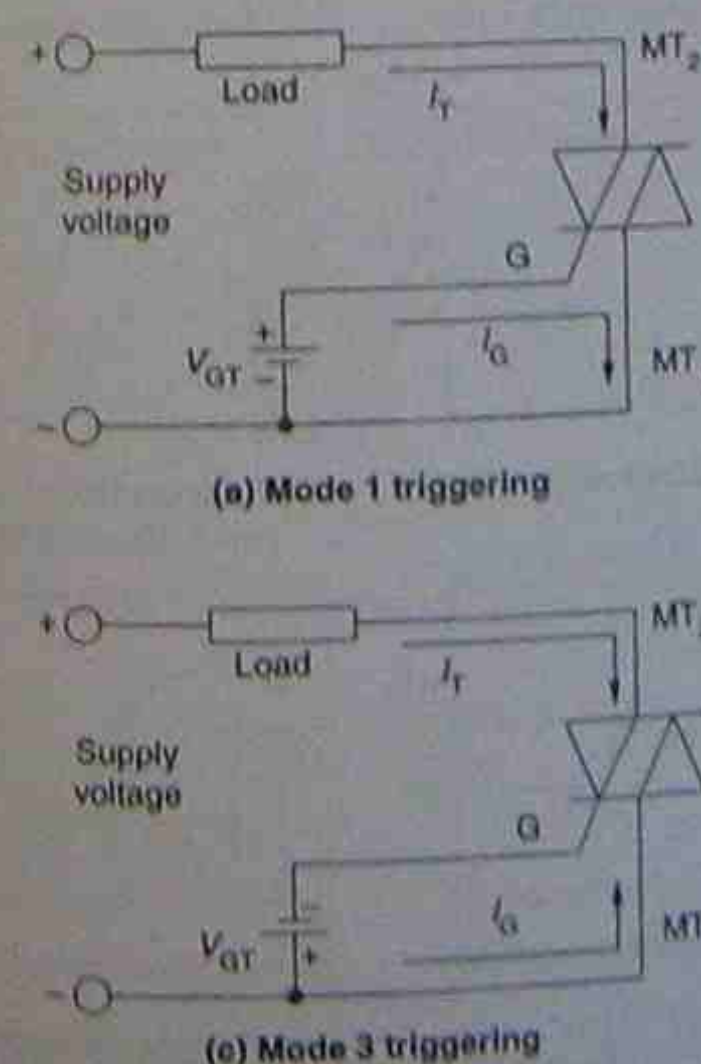


Figure 16.22 • Triac triggering modes

#### 16.5.4 Characteristics and ratings

The forward and reverse characteristics of a triac are shown in Figure 16.23. It should be noted that the characteristics are the same in both directions, unlike a p-n diode or an SCR.

Like the SCR, the triac has a number of electrical ratings, the most significant being:

1. **blocking voltage ( $V_{BR}$ )**—the maximum voltage that the triac can block in either direction when the gate current is zero.
2. **maximum on-state current ( $I_{T(RMS)}$ )**—the maximum continuous r.m.s. value of current that the triac can safely carry. It may be necessary to mount the triac on a heat sink to dissipate the heat developed in the device at this value of current.
3. **maximum peak one-cycle non-repetitive current ( $I_{TSM}$ )**—maximum peak value of current that the triac can safely carry for only one cycle of the supply. This value is usually much greater than the maximum on-state current.

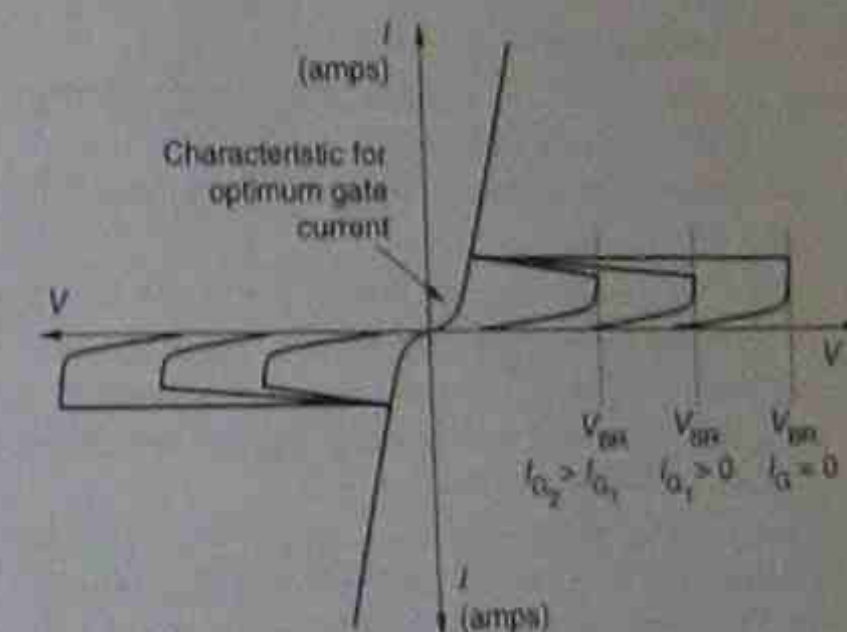
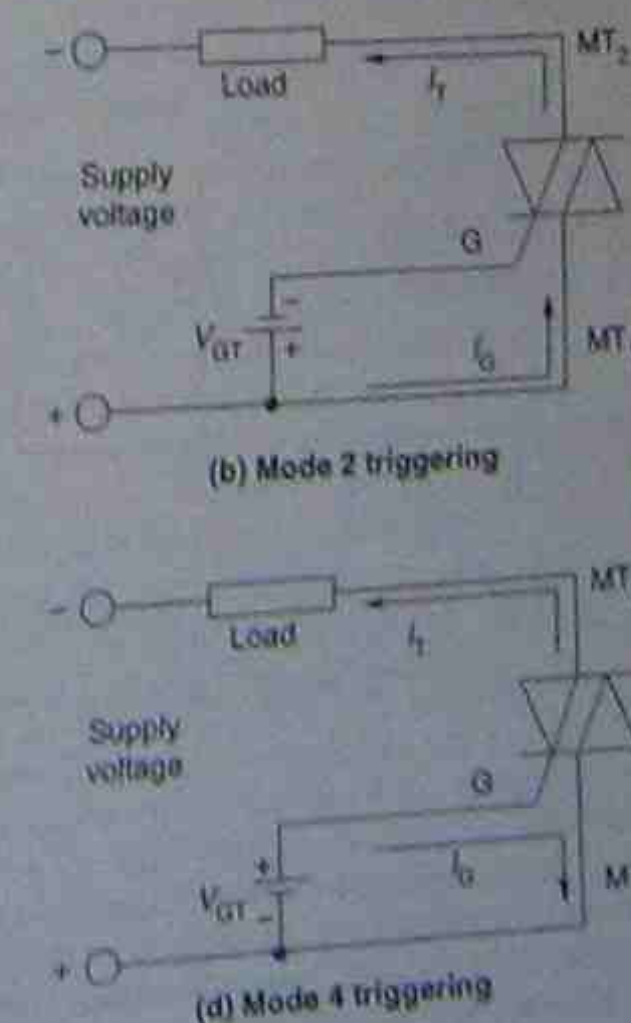


Figure 16.23 • Triac characteristics





4. **maximum rate of rise of current ( $di/dt$ )**—the maximum rate of rise of  $MT_1$  current when the triac is switched from the off to the on state. If the current rises too quickly, the current density in the silicon wafer might be high enough to damage the device.
5. **holding current ( $I_H$ )**—the minimum current that will support conduction. If the current falls below this value, the triac will relax back to the off state.
6. **latching current ( $I_L$ )**—the minimum current required to latch the triac into the on state. If the current does not rise above this level the triac will turn back off when the gate current is removed.
7. **rate of rise of off-state voltage ( $dv/dt$ )**—the maximum rate of rise of off-state voltage, in either direction. If the off-state voltage rises at a faster rate than this value, the triac may switch back to the on state.
8. **on-state voltage drop ( $V_{T_{on}}$ )**—the maximum expected voltage drop measured across the triac in the on state.

### 16.5.5 Protection

A triac requires protection against the same occurrences as an SCR. In summary they are:

- **short circuits**—protection is provided by special HRC fuses.
- **rapidly rising currents**—series inductors may be used to limit the rate of rise of current ( $di/dt$ ).
- **rapidly rising off-state voltages**—a snubber network is connected in parallel with the triac to limit the rate of rise of off-state voltage ( $dv/dt$ ).
- **excessive junction temperature**—triacs are usually mounted on a heat sink to limit junction temperature. Manufacturers' data usually provides information on the required heat-sink type.

The circuit in Figure 16.24 shows how electrical protection may be applied to a triac.

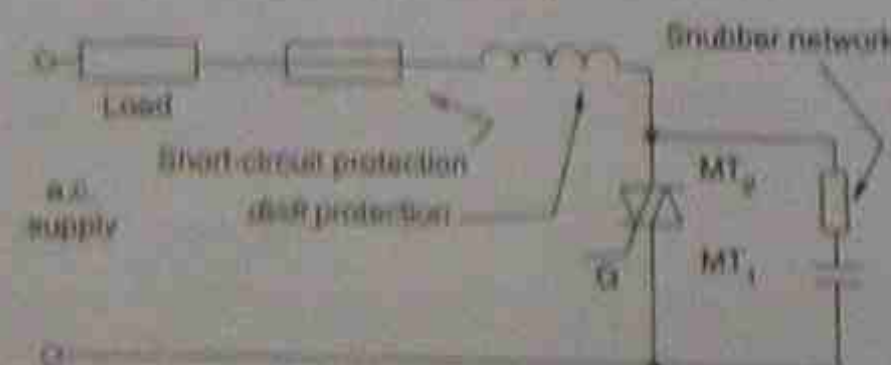


Figure 16.24 • Triac protection

In some lower-power applications the special HRC fuse and the series inductor may be omitted. This is due to the high cost of these components when compared with the cost of the triac.

### 16.5.6 Testing

A number of 'in circuit' tests can be carried out on a triac in a similar fashion to those for the SCR. A simple test, using an analogue ohmmeter, may be used. This is similar to a test of an SCR using an ohmmeter. Table 16.3 outlines the expected results from this test.

Table 16.3 • Triac test results—serviceable triac

Test polarity		
Positive (+)	Negative (−)	Expected resistance
(a) $MT_2$	$MT_1$	High (infinite)
(b) $MT_1$	$MT_2$	High (infinite)
(c) $MT_2$	$MT_1$	High (infinite)
(d) $MT_1$ & gate	$MT_2$	High (infinite)
(e) $MT_2$ & gate	$MT_1$	Low (20 $\Omega$ )
(f) $MT_1$	$MT_2$	Low (20 $\Omega$ )
	& gate	

If from these results the triac appears to be serviceable, it may be further tested to determine if it can be triggered and latched on, in a similar manner to the SCR. However, some caution needs to be exercised in this test. High current triacs might not be able to be triggered by the current available from an ohmmeter. The tests are shown in Figure 16.25.

If the multimeter used cannot deliver sufficient current to cause a triac to trigger on and latch, it may be necessary to conduct more extensive and complex testing to determine the condition of the triac.

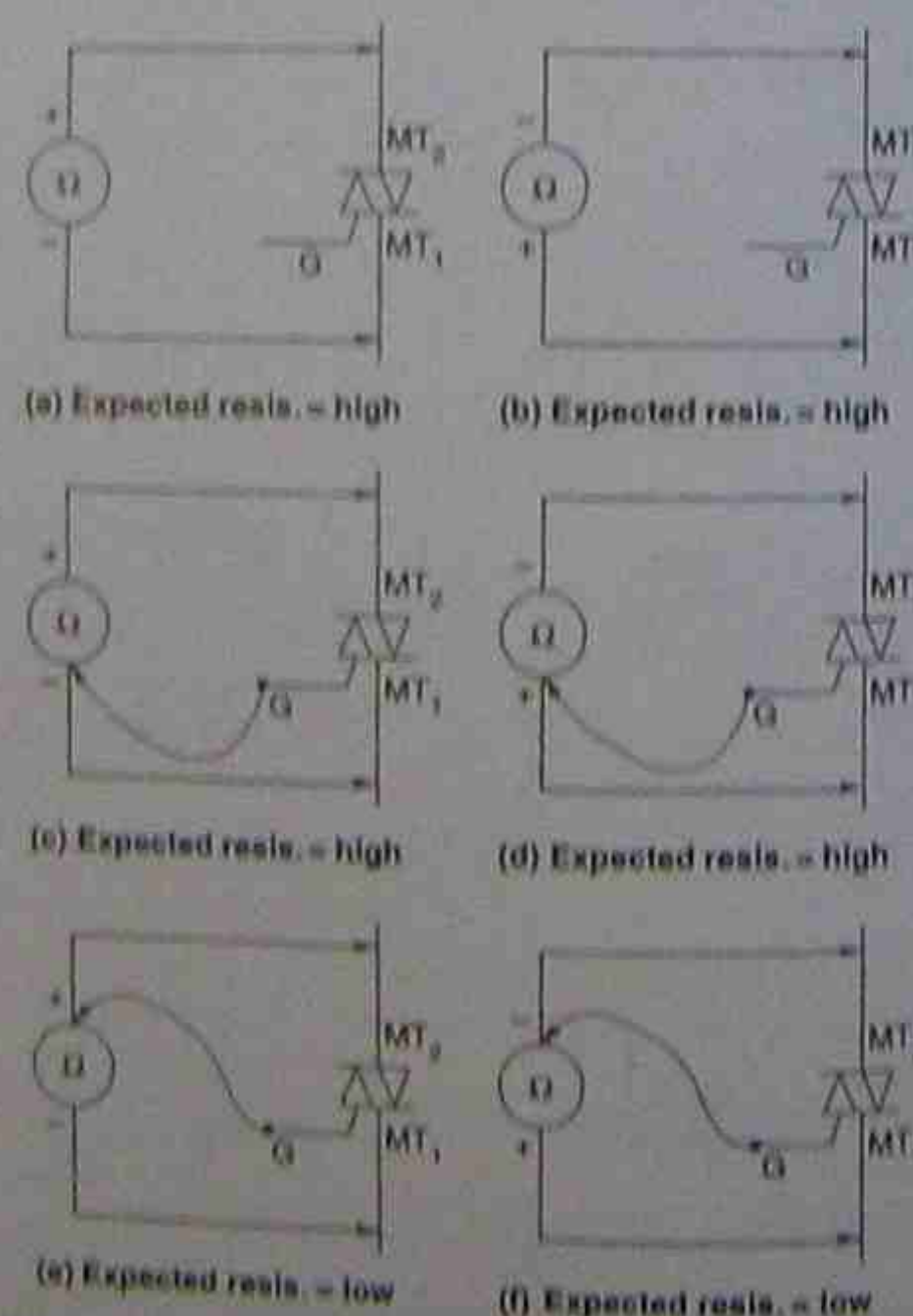


Figure 16.25 • Triac testing. Note that the triac will attempt to conduct more readily when a voltage exists between  $MT_1$  and the gate

### 16.5.7 Applications

Triacs are used extensively in low- to medium-power applications. For higher a.c. power and variable frequency control of a.c. motors, SCRs are preferred. Typical applications are:

- illumination control (lamp dimmers)
- fan speed control (ceiling fans)
- heating loads
- welding equipment
- motor speed control (with limitations)
- a.c. electromagnets
- solid-state relays (replaces a contactor).

## 16.6 UNIUNCTION TRANSISTOR (UJT)

The devices examined so far in this chapter are the actual devices that control or carry load power. As stated in section 16.2.4, these thyristor power control devices must be accompanied by a circuit that provides pulses of current to the gate terminal to cause the thyristors to turn on.

The UJT is one of the more common trigger devices used in conjunction with thyristor power control devices.

### 16.6.1 Construction

The UJT is the simplest of all the trigger devices. It is a three-terminal silicon device with only one semiconductor junction, hence the term *unijunction*. The UJT consists of a lightly doped n-type wafer of semiconductor material known as the *channel*. A small current flow is established in this channel to set up internal voltage drops that are the key to the operation of the UJT. Diffused into the channel is a heavily doped p-type region known as the *emitter*. It provides the current carriers for the current pulse produced by a UJT. The construction and graphical symbol are shown in Figure 16.26.

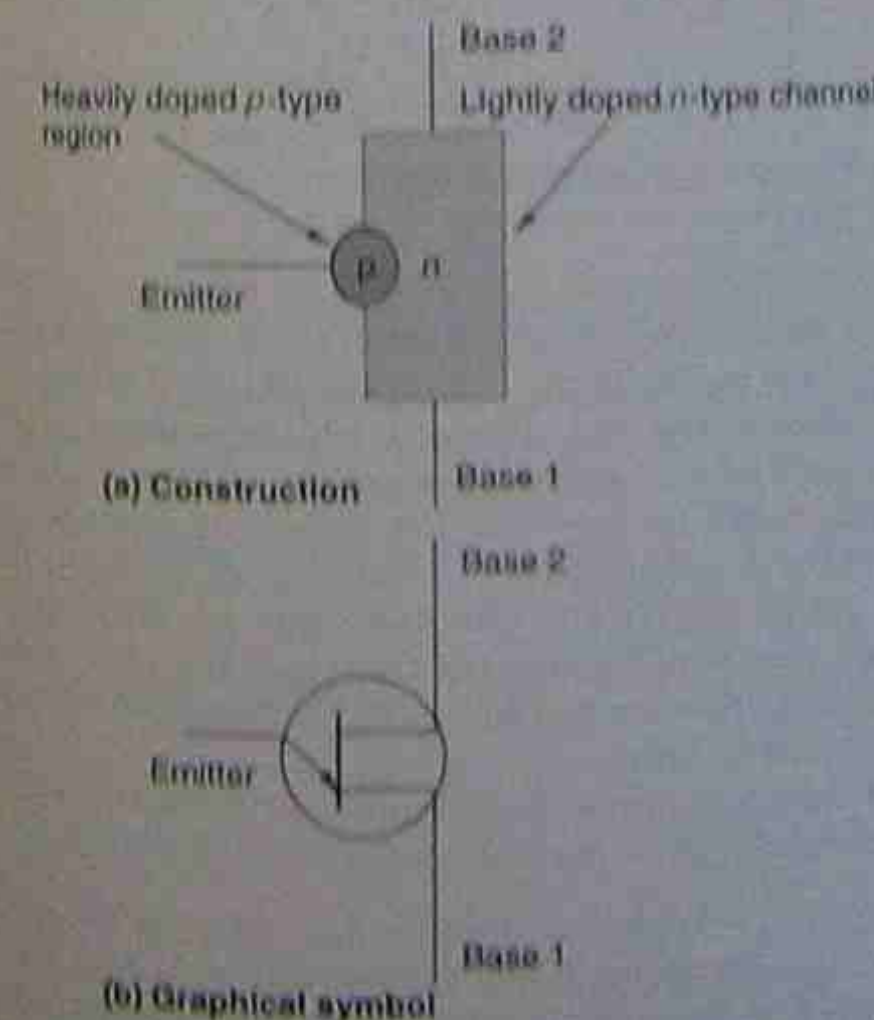


Figure 16.26 • UJT construction and symbol

The UJT is used extensively as a triggering device for thyristors.

### 16.6.2 Operation

A simple way to examine the operation of the UJT is to consider it to be a voltage divider and a p-n diode. The manner in which the device is manufactured is such that the interbase resistance, that is, the resistance between base 1 and base 2, is high. This value will be in the range 5 to 10 k $\Omega$ . The interbase current will therefore be very low, only a few milliamperes. This current establishes a voltage drop across the internal resistance of the device ( $r_{B1}$  and  $r_{B2}$ ). The relative values of  $r_{B1}$  and  $r_{B2}$  are dependent on the physical location of the emitter region in relation to the ends of the channel. The polarity of these voltage drops is shown in Figure 16.27.

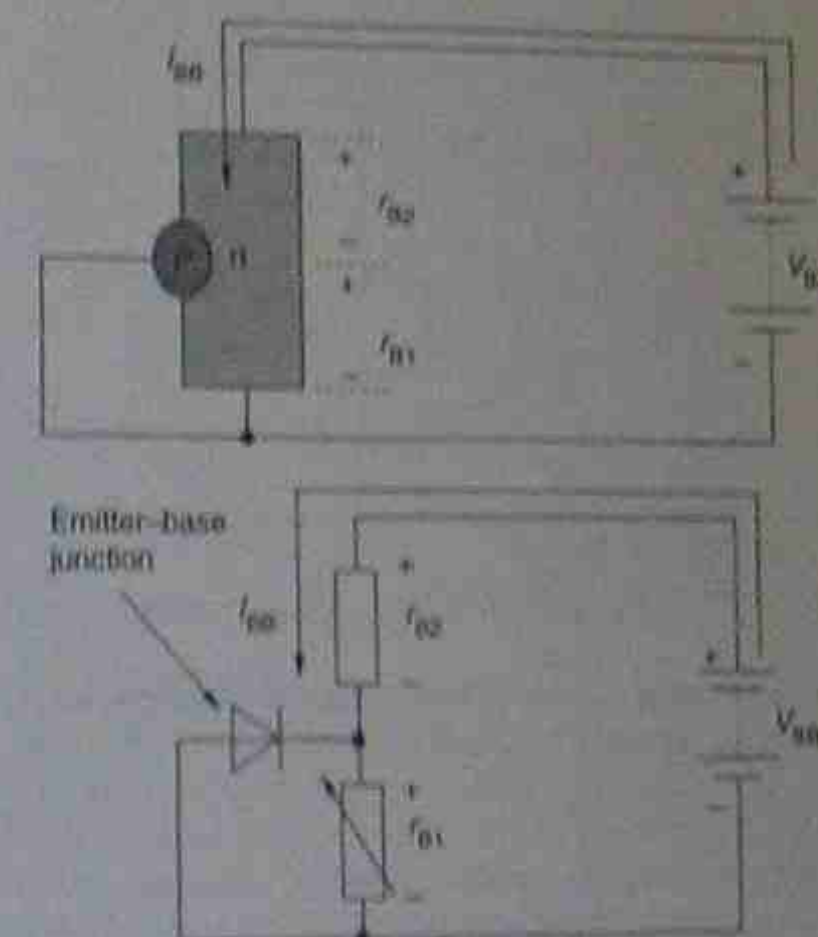


Figure 16.27 • UJT internal voltage drops

The relative values of the voltage drops in the UJT are dependent on the relative values of the internal resistances. The ratio of  $r_{B1}$  to the total interbase resistance ( $r_{B1} + r_{B2}$ ) will fix the value of the voltage at the cathode terminal of the emitter-base junction.

This voltage will be between 0.3 and 0.85 of the base-to-base voltage ( $V_{BB}$ ). The ratio of  $r_{B1}$  to ( $r_{B1} + r_{B2}$ ) is known as the *intrinsic standoff ratio* ( $\eta$ ). This value is fixed at manufacture and cannot be altered.

Under the bias conditions specified above, a very small leakage current flows out of the emitter terminal and returns to the negative of the supply. This current is very small and is usually ignored. If a supply is connected to bias the emitter with respect to base 1, this leakage current will decrease as the emitter-base voltage increases. When the emitter-base voltage is equal to the internal voltage drop across  $r_{B1}$  the emitter current will be zero.

As the emitter voltage becomes more positive, the emitter becomes forward biased. When the emitter voltage is 0.5 V greater than  $V_{B1}$ , the emitter conducts heavily. This results in very large numbers of current carriers being



injected into the channel. The resistance of the channel ( $r_{ch}$ ) decreases rapidly to a value that may be as low as a few hundred ohms. The emitter voltage at which this conduction takes place is termed the peak point voltage ( $V_p$ ).

The current flow under this set of conditions is shown in Figure 16.28.

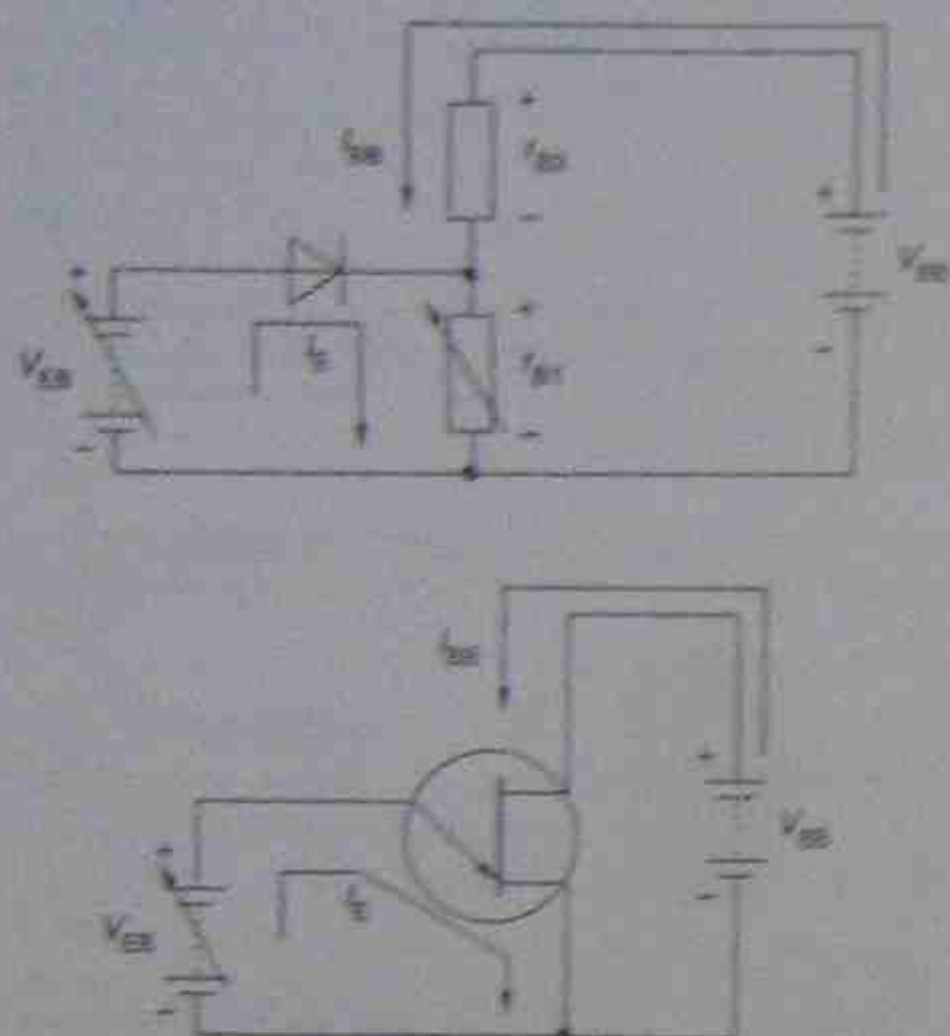


Figure 16.28 • UJT emitter current

The peak point voltage will be determined by the supply voltage ( $V_{BB}$ ) and the standoff ratio ( $\eta$ ).

$$V_p = \eta V_{BB} + 0.5$$

where  $V_p$  = peak point voltage in volts  
 $V_{BB}$  = base-to-base voltage in volts  
 $\eta$  = intrinsic standoff ratio

### Example 16.1

Assume that the UJT in Figure 16.28 has a standoff ratio of 0.65 and the supply voltage is 30.0 V. Determine the peak point voltage for the UJT.

$$\begin{aligned} V_p &= \eta V_{BB} + 0.5 \\ &= (0.65 \times 30) + 0.5 \\ &= 19.5 \text{ V} \end{aligned}$$

It is important to remember that the standoff ratio is fixed and that the peak point voltage is determined by the supply voltage. If a different peak point voltage is required, the supply voltage may be altered, or a UJT with a different standoff ratio substituted.

### 16.6.3 Characteristics

The characteristics of the UJT make it ideal for use in a circuit intended to trigger thyristor power-control devices. If the UJT is used in conjunction with an RC timing circuit it will produce an output that consists of short duration

pulses with a very fast rise time, ideal for the triggering of SCRs, GTO thyristors and triacs.

From the emitter characteristic ( $V$ - $I$ ) curve shown in Figure 16.29 it can be seen that the resistance of the UJT (emitter to base  $B_1$ ) decreases significantly once the peak point voltage is reached. The decrease occurs quite rapidly

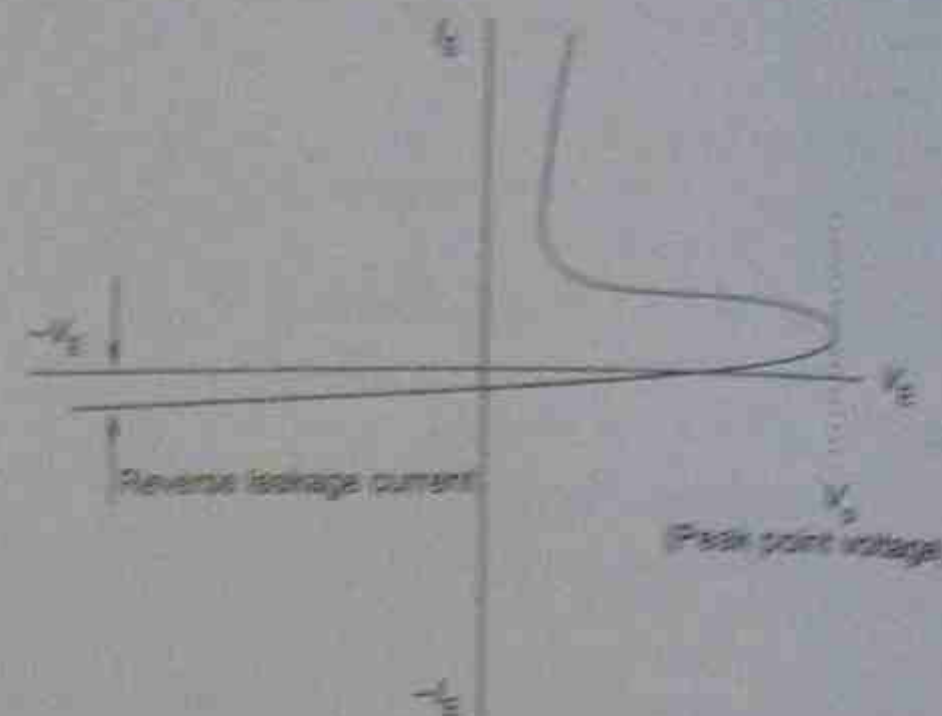


Figure 16.29 • UJT emitter characteristic

### 16.6.4 UJT relaxation oscillator

The circuit shown in Figure 16.30 is applicable to low-level power control applications with SCRs and triacs. The only modification to the circuit may be to use a pulse transformer. This is discussed in section 16.10.3.

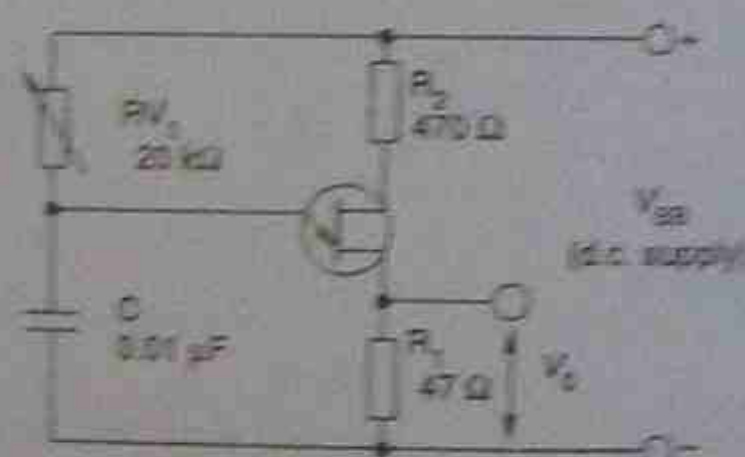


Figure 16.30 • UJT relaxation oscillator

The circuit consists of the UJT and an RC timing circuit. Refer to section 6.4.3 for more detail on RC timing circuits.

When the supply to the timing circuit is first turned on, the voltage across the capacitor will increase at a rate determined by the values of the resistor and the capacitor. The time taken for the capacitor voltage to reach 63 per cent of the supply voltage is referred to as the time constant ( $\tau$ ) of the circuit. The time may be modified by varying either the value of the resistor or the value of the capacitor. In practice it is found that it is easier to alter the value of the resistor.

The operation of a UJT relaxation oscillator is straightforward and may be summarised as follows:

- When the supply is first turned on, the capacitor charges via the variable resistor  $RV_1$  at a rate determined by the setting of the resistor and the size of the capacitor.

When the capacitor voltage is equal to the peak point voltage, the emitter conducts. The emitter will conduct heavily, with the internal resistance of the UJT falling to a very low value.

When the emitter conducts, the capacitor will discharge through the UJT and  $R_1$ . The resistance of the discharge path is much lower than that of the charging path, so the capacitor will discharge much more quickly than it charges.

The resulting current through  $R_1$  develops the output voltage pulse required to trigger an SCR or a triac. Since the discharge time for the capacitor is very short, the current will have a relatively high peak value and a fast rise time.

Altering the value of  $RV_1$  will only change the time it takes for the capacitor to charge to the peak point voltage. It does not alter the peak point voltage. Altering the time constant of the circuit will alter the frequency of the output pulses from the oscillator.

When the capacitor has discharged, the UJT will return back to the off state, hence the same relaxation oscillates. The cycle then recommences.

### Example 16.2

$V_{BB}$  is equal to 15 V in the circuit in Figure 16.30 and the standoff ratio is 0.63. Determine the peak point voltage.

$$\begin{aligned} V_p &= \eta V_{BB} + 0.5 \\ &= (0.63 \times 15) + 0.5 \\ &= 9.95 \text{ V} \end{aligned}$$

The frequency of the pulses from this circuit will depend on the time constant. The actual calculation of frequency can be complex, but if the standoff ratio is equal to, or near 0.63, the frequency may be determined from a simplified expression:

$$f = \frac{1}{RC}$$

where  $f$  = output frequency in hertz

$R$  = circuit resistance in ohms

$C$  = circuit capacitance in farads

### Example 16.3

In the circuit in Figure 16.30, determine the output frequency if the standoff ratio is 0.63, the value of  $RV_1$  is 10 kΩ and the capacitance is 0.1 μF.

$$\begin{aligned} f &= \frac{1}{RC} \\ &= \frac{1}{10 \times 10^3 \times 0.1 \times 10^{-6}} \\ &= 1000 \text{ Hz (or 1.0 kHz)} \end{aligned}$$

Determine the frequency if  $RV_1$  is set to 7.5 kΩ.

$$\begin{aligned} f &= \frac{1}{RC} \\ &= \frac{1}{7.5 \times 10^3 \times 0.1 \times 10^{-6}} \\ &= 1333.33 \text{ Hz (or 1.33 kHz)} \end{aligned}$$

It is worth noting that in most cases when a relaxation oscillator is used as a trigger circuit for thyristors, the calculation of frequency is not important. What is more important is the time delay from the start of a cycle to the point where a trigger pulse is delivered to the thyristor. This time delay will determine both the average value and the peak value of the voltage, and hence the heat power. The waveforms produced by the relaxation oscillator are shown in Figure 16.31.

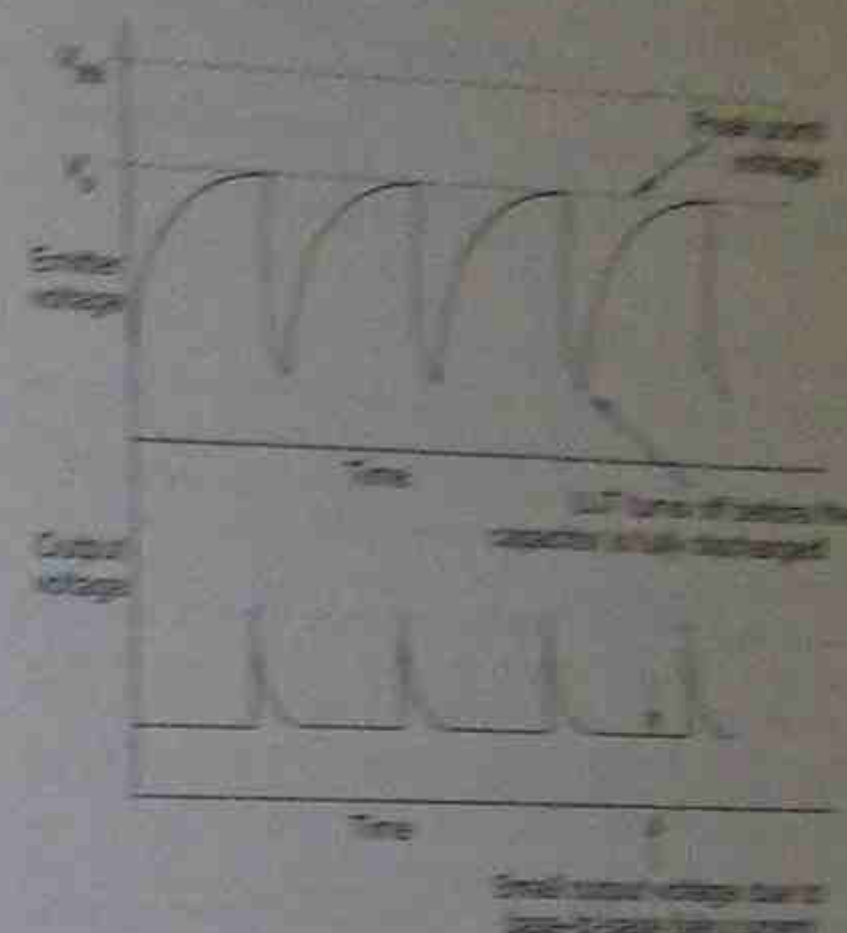


Figure 16.31 • Relaxation oscillator waveforms

The amount of energy in the output trigger pulses is an important consideration in the triggering of thyristors. The energy in the trigger pulse produced by a UJT relaxation oscillator may be increased by increasing the value of the capacitor in the RC timing circuit. However, there is a practical limit to the current that the UJT can carry. If the capacitance is too high, the UJT might be damaged.

The UJT relaxation oscillator has two major disadvantages:

- The standoff ratio is fixed and can only be changed by changing the UJT itself. However, this will produce only limited changes.
- The UJT might not be able to deliver sufficient energy to trigger large, high-current thyristors.

## 16.7 PROGRAMMABLE UNIJUNCTION TRANSISTOR (PUT)

The programmable unijunction transistor is a device that overcomes the major disadvantages of the UJT.

### 16.7.1 Construction

The PUT is a three-terminal two-layer device like the SCR, the difference being that the gate terminal is connected to the n-type layer near the anode. The PUT is not manufactured in the same high-current and voltage ratings as the



SCR. It is usually only available in smaller packages, similar to the very-low-current (1.0 A) SCRs.

The structure and the symbol are shown in Figure 16.32.

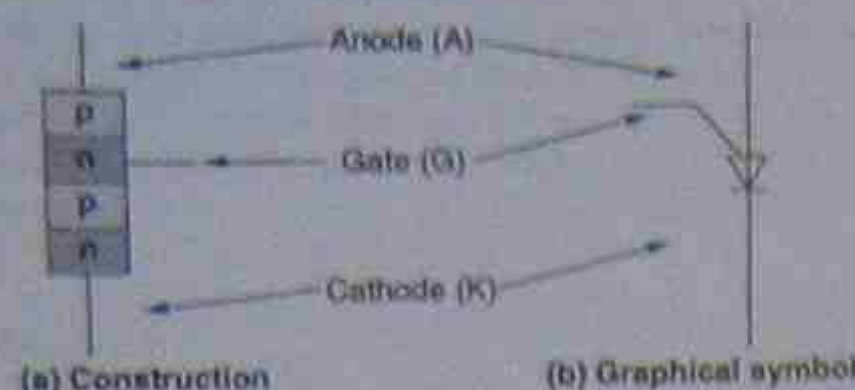


Figure 16.32 • PUT construction and symbol

### 16.7.2 Operation

A PUT is similar to a small SCR and operates in the same manner. It will block current until triggered on. When triggered it will latch on if the current is high enough and remain on until the anode current falls below the holding current.

To trigger the PUT into the on state, current is passed from the anode to the gate, therefore the anode-gate junction must be forward biased and the anode potential 0.6 V higher than the gate. The biasing and current directions in the PUT are shown in Figure 16.33.

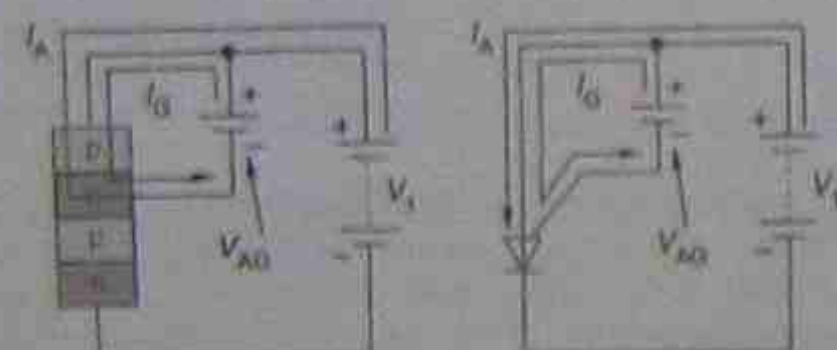


Figure 16.33 • PUT biasing and current flow

A feature of the PUT when compared with the UJT is that the on resistance is much lower and can carry much higher peak values of current. It can therefore provide higher levels of trigger energy.

### 16.7.3 Characteristic

The PUT characteristic is similar to that of the UJT, the major differences being that the reverse leakage current (gate to anode) is much lower, and the on resistance is much lower. The PUT characteristic is shown in Figure 16.34.

The transition from the off to the on state is also faster in the PUT than in the UJT.

The most significant advantage of the PUT over the UJT is that the standoff ratio is variable, externally programmable, and not determined by the structure or manufacture of the device. The peak point voltage may be varied by varying the potential on the gate of the PUT relative to the anode. This feature is examined in section 16.7.4.

### 16.7.4 PUT relaxation oscillator

The PUT is used in a relaxation oscillator circuit similarly to the UJT. The distinction is that the standoff ratio is

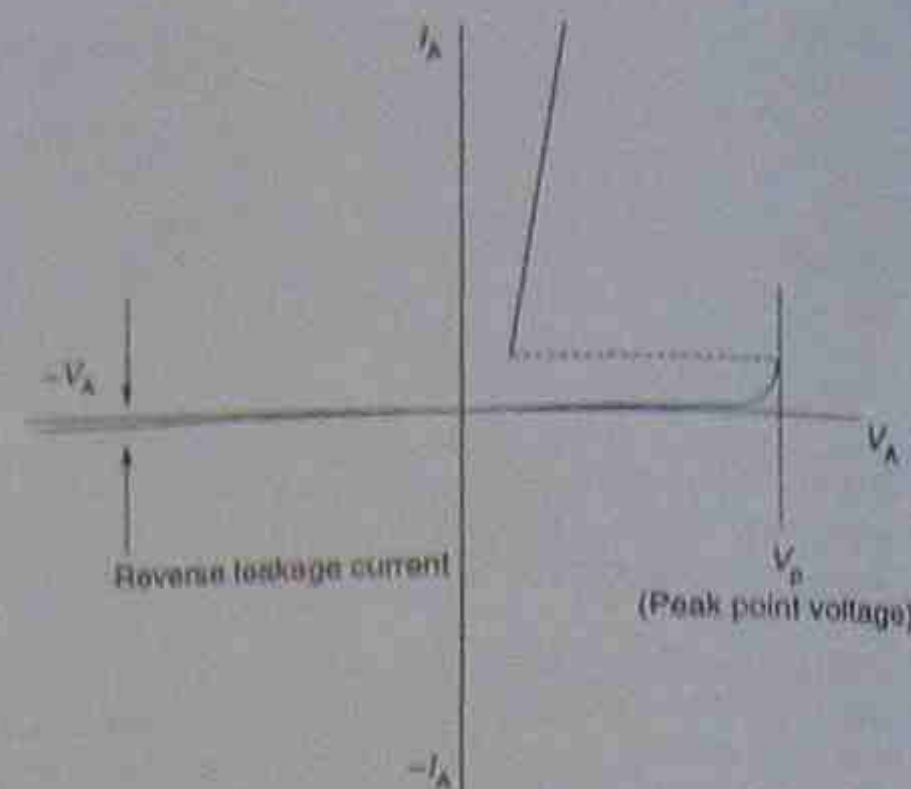


Figure 16.34 • PUT anode characteristic

programmable. Note that the PUT oscillator also employs an RC timing circuit like the UJT oscillator. The PUT oscillator circuit is shown in Figure 16.35.

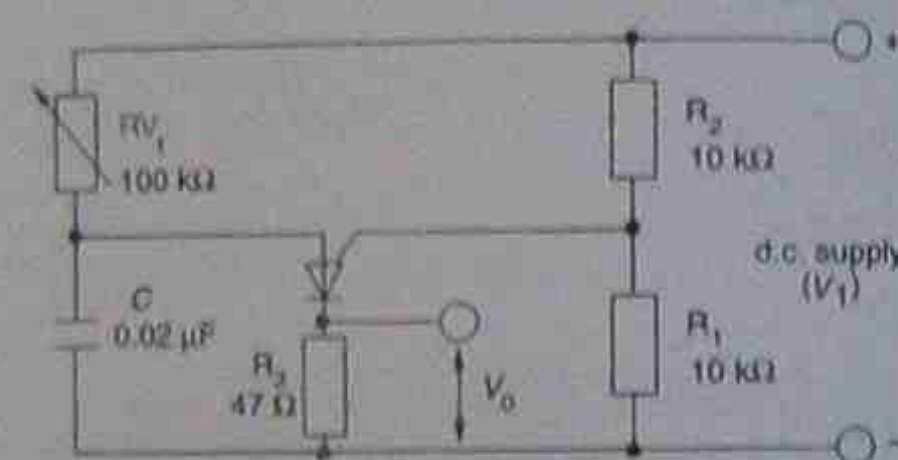


Figure 16.35 • PUT relaxation oscillator

The resistors  $R_1$  and  $R_2$  are called the *programming resistors*. It is these resistors that set the potential on the gate relative to the anode.

The PUT oscillator operates in a similar manner to the UJT oscillator. Its operation may be summarised as follows:

- Resistors  $R_1$  and  $R_2$  set up a bias voltage on the gate terminal of the PUT. The voltage is dependent on the supply voltage and the respective values of  $R_1$  and  $R_2$ . These resistors program the standoff ratio.
- When the supply is connected, the capacitor charges via  $RV_1$ . The rate at which it charges is fixed by the time constant of the RC circuit.
- When the anode voltage (the voltage across the capacitor) reaches a value 0.6 V above the gate voltage, the PUT turns on and latches on.
- When the PUT turns on, the capacitor discharges via the PUT and  $R_3$ . The resistance of this discharge path is very low, so the discharge time is very short.
- The resulting output pulse will have a high peak value with a very fast rise time, ideal for triggering an SCR or a triac.
- The oscillator relaxes back to the off state when the capacitor is discharged and the cycle recommences.

As discussed above, the voltage at the gate is fixed by the voltage divider and the voltage at the anode required to turn the PUT on is 0.6 V higher than this voltage. The anode voltage required to turn the PUT on is the peak point voltage  $V_P$ . This value is determined from:

$$V_P = V_1 \left( \frac{R_1}{R_1 + R_2} \right) + 0.6$$

where  $V_P$  = peak point voltage in volts  
 $V_1$  = d.c. supply voltage in volts

$R_1$  and  $R_2$  = value of the programming resistors in ohms.

It is not essential that the values of the programming resistors be expressed in ohms. What is essential is that both values must be in the same units;  $\Omega$ ,  $k\Omega$  or  $M\Omega$ .

This is similar to the expression used for the UJT, the difference being that in the case of the PUT, the standoff ratio is determined by the value of the external divider resistors. The PUT is therefore said to have a programmable *standoff ratio*—programmed by external resistors. The standoff ratio may therefore be any value between 0 and 1.0. This is a significant advantage when compared with the UJT oscillator.

### Example 16.4

Assume that the supply voltage in the circuit in Figure 16.35 is 20.0 V. Determine the standoff ratio and the peak point voltage.

$$\begin{aligned} \text{Standoff ratio } \eta &= \frac{R_1}{R_1 + R_2} \\ &= \frac{10.0}{10.0 + 10.0} \\ &= 0.5 \end{aligned}$$

$$\begin{aligned} V_P &= \eta V_1 + 0.6 \\ &= (0.5 \times 20) + 0.6 \\ &= 10.6 \text{ V} \end{aligned}$$

Assume that the programming resistors in Figure 16.35 are changed to  $R_1 = 6.8 k\Omega$  and  $R_2 = 12.0 k\Omega$ . Determine the standoff ratio and the peak point voltage.

$$\begin{aligned} \eta &= \frac{R_1}{R_1 + R_2} \\ &= \frac{6.8}{6.8 + 12.0} \\ &= 0.36 \end{aligned}$$

$$\begin{aligned} V_P &= \eta V_1 + 0.6 \\ &= (0.36 \times 20) + 0.6 \\ &= 7.8 \text{ V} \end{aligned}$$

The example illustrates that the peak point voltage can be altered without changing the actual trigger device or the supply voltage.

The waveforms produced by the PUT relaxation oscillator are shown in Figure 16.36. Note the similarity to the UJT oscillator waveforms.

Both oscillator circuits examined so far have been connected to a pure d.c. supply and the frequency of the pulses, or the time delay after the commencement of a

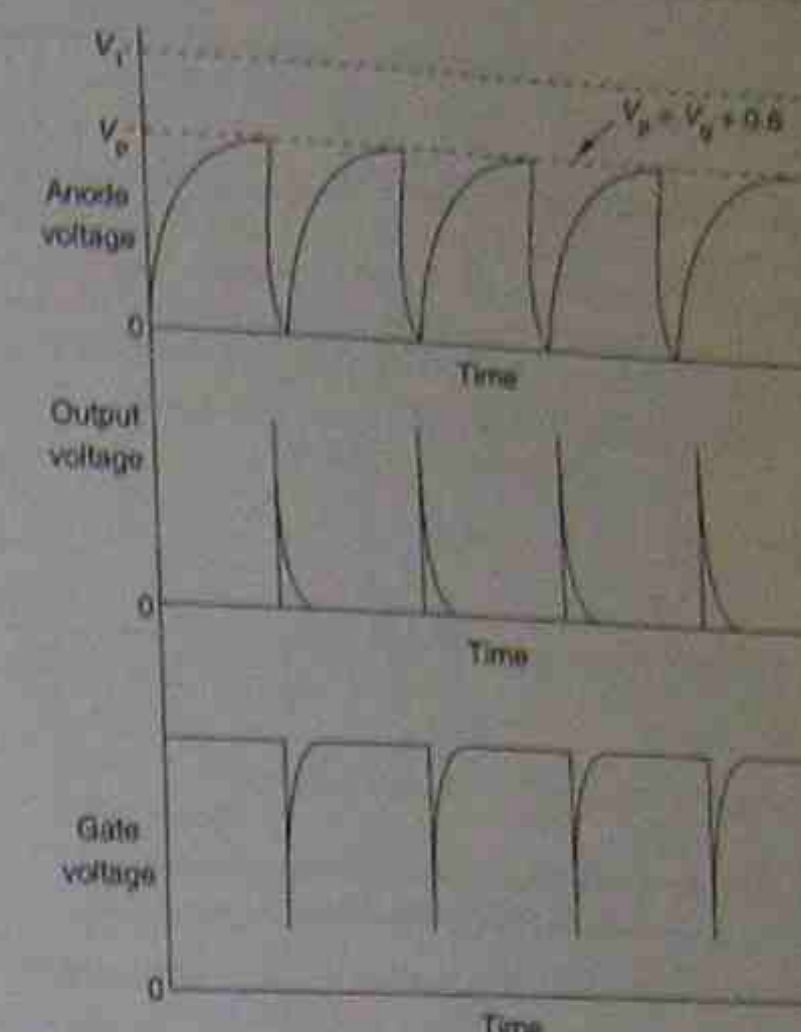


Figure 16.36 • PUT oscillator waveform

cycle, was varied. Where the thyristor is connected to an a.c. supply, the trigger pulses must be synchronised with the supply. The time delay after the start of a cycle is important and should be the same for each cycle or half-cycle. Synchronising a trigger circuit with the mains supply is examined in sections 16.9.1 and 16.11.

A feature of both UJT and PUT oscillator circuits is that they only produce output pulses of one polarity. In the case where a triac is to be triggered, pulses of alternate polarities may be better suited and an alternative device and trigger circuit is required.

## 16.8 DIACS

The diac is a two-terminal three-layer bi-directional trigger device. It is a thyristor device but does not have a gate terminal. The diac was developed specifically as a trigger device to provide bi-directional trigger pulses.

The construction of a diac is complex and beyond the scope of this book. The symbol is shown in Figure 16.37.



Figure 16.37 • Diac graphical symbol

Since the diac is a bi-directional device it has no terminal markings.

### 16.8.1 Operation

Like other thyristor devices, a diac will block current flow in either direction. It is switched to the on state by exceeding the blocking voltage in either direction.

The break-over voltage for a given diac is fixed. Usually this value is the same in either direction and will be in the range 28 to 36 V. Once the diac conducts, it will



remain in the on state until the current falls below the holding current.

### 16.8.2 Characteristics

From the V-I characteristics shown in Figure 16.38 it may be seen that the voltage drop across a conducting diac is much lower than the break-over voltage and is a relatively constant value. The on resistance of the diac is a very low value, like that of the PUT.

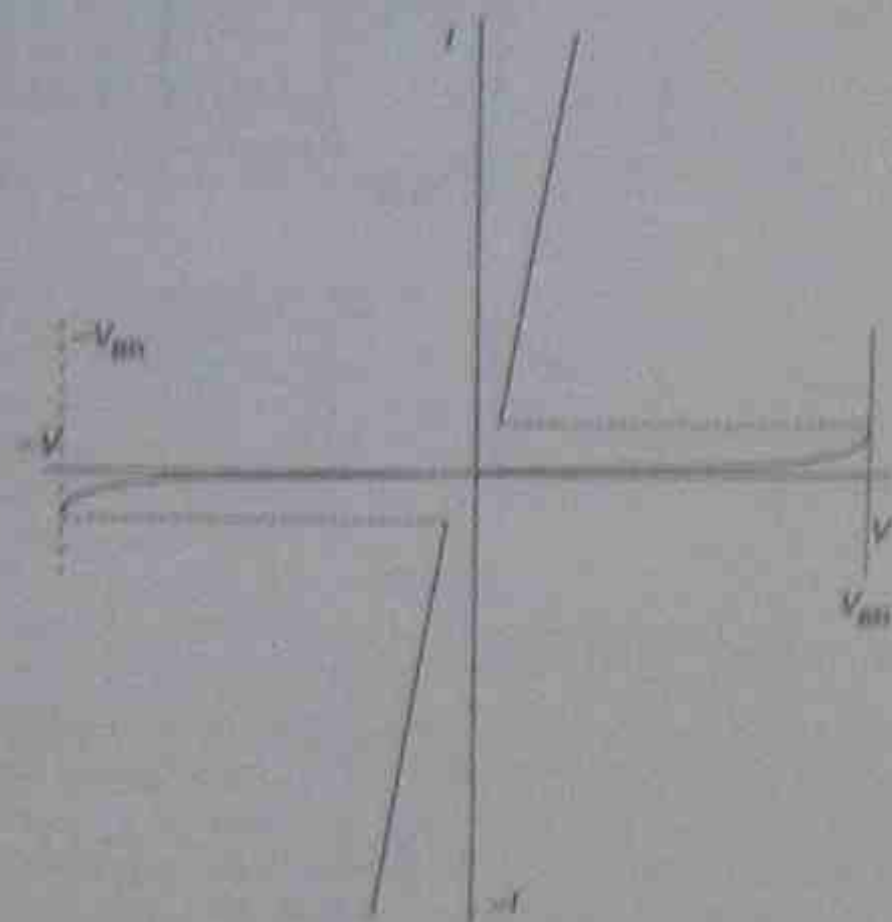


Figure 16.38 • Diac characteristics (symmetrical diac)

Diacs with the same break-over voltage in either direction are referred to as *symmetrical diacs*. The 512 diac is a symmetrical diac. In some cases a symmetrical diac results in asymmetric load voltages. For this reason, an *asymmetrical diac* has been developed. The break-over voltages are not the same in this case. In one direction the break-over voltage is in the range 7 to 9 V and in the opposite direction 14 to 18 V. The 514 is an asymmetrical diac.

### 16.8.3 Diac relaxation oscillator

The bi-directional nature of the diac allows trigger pulses of both polarities to be produced. This is achieved by connecting the diac to an RC timing circuit and to an a.c. supply.

The operation of the circuit in Figure 16.39 may be summarised as follows:

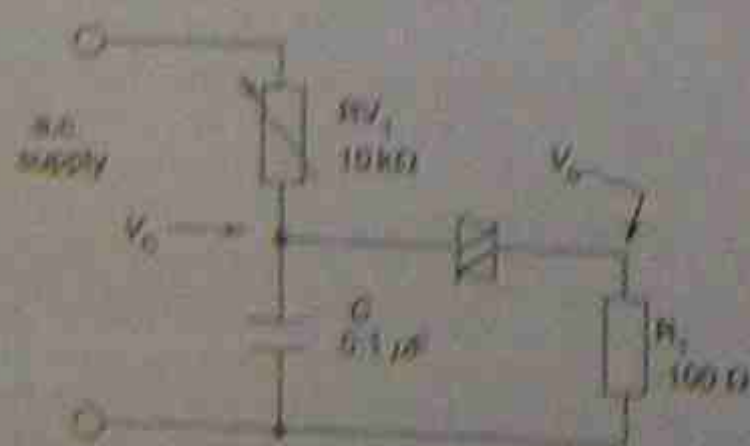


Figure 16.39 • Diac trigger circuit

- As one terminal of the supply becomes positive and increases in potential, the capacitor charges up.
- When the capacitor voltage is equal to the break-over voltage of the diac, the diac will turn on, allowing the capacitor to discharge through the load, which is usually the gate of a thyristor.
- The diac will turn off when the capacitor is almost fully discharged. The cycle then recommences. The rate at which the capacitor charges is determined by the value of the capacitor and  $RV_1$ .
- At the end of the cycle the supply will reverse and the circuit will operate in the same manner but with reverse polarity. This produces output pulses of the opposite polarity.
- With this circuit it may be possible to obtain multiple trigger pulses in each half of the a.c. cycle.

The waveforms produced by this circuit are shown in Figure 16.40.

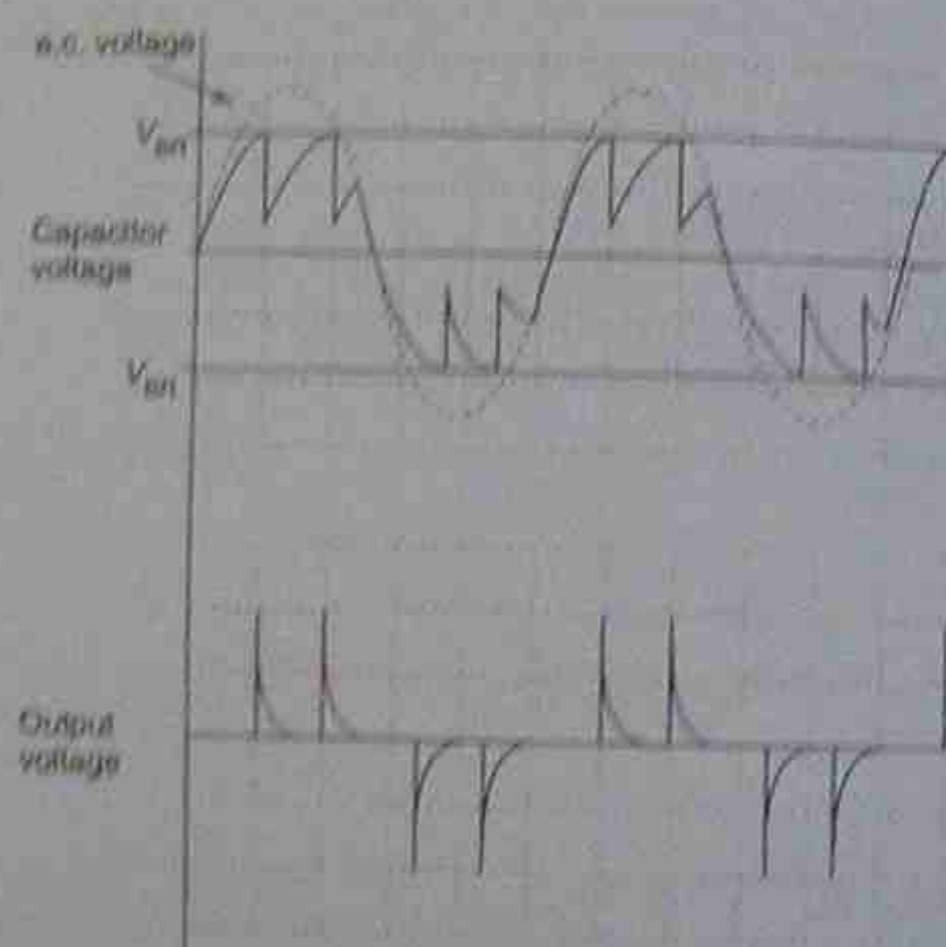


Figure 16.40 • Diac trigger circuit waveforms

The output pulses from the diac trigger circuit are much the same as the UJT and PUT trigger circuits. The major difference is that the pulses produced alternate in polarity, or are bi-directional. This makes the diac ideal for situations where bi-directional trigger pulses are required, as in many triac load-control circuits.

## 16.9 THYRISTOR PHASE CONTROL

Phase control is the most common technique employed in thyristor power control. Where phase-control techniques are employed, only part of an a.c. wave is used. The thyristor devices block conduction until they are triggered into the on state. Triggering of the thyristor may occur at any time in a given half-cycle. The longer triggering is delayed, the lower the load voltage will be.

Use of a thyristor such as an SCR, GTO thyristor or triac with a suitable triggering circuit will allow the load

voltage to be varied infinitely from zero to the maximum available value.

The load voltage is in effect controlled by the trigger angle  $\alpha$  of the thyristor. The trigger angle is an indication of the amount by which triggering is delayed and is measured in electrical degrees. When the load voltage is at its maximum the trigger angle is zero.

Phase-control techniques may be applied equally well to d.c. and a.c. loads supplied from an a.c. supply. In the case of d.c. loads the average load voltage is varied, while in the case of a.c. loads the r.m.s. load voltage is varied. In both cases this results in variations in the average load power.

Figure 16.41 displays typical load voltage waveforms for a controlled d.c. load where phase-control techniques are employed.

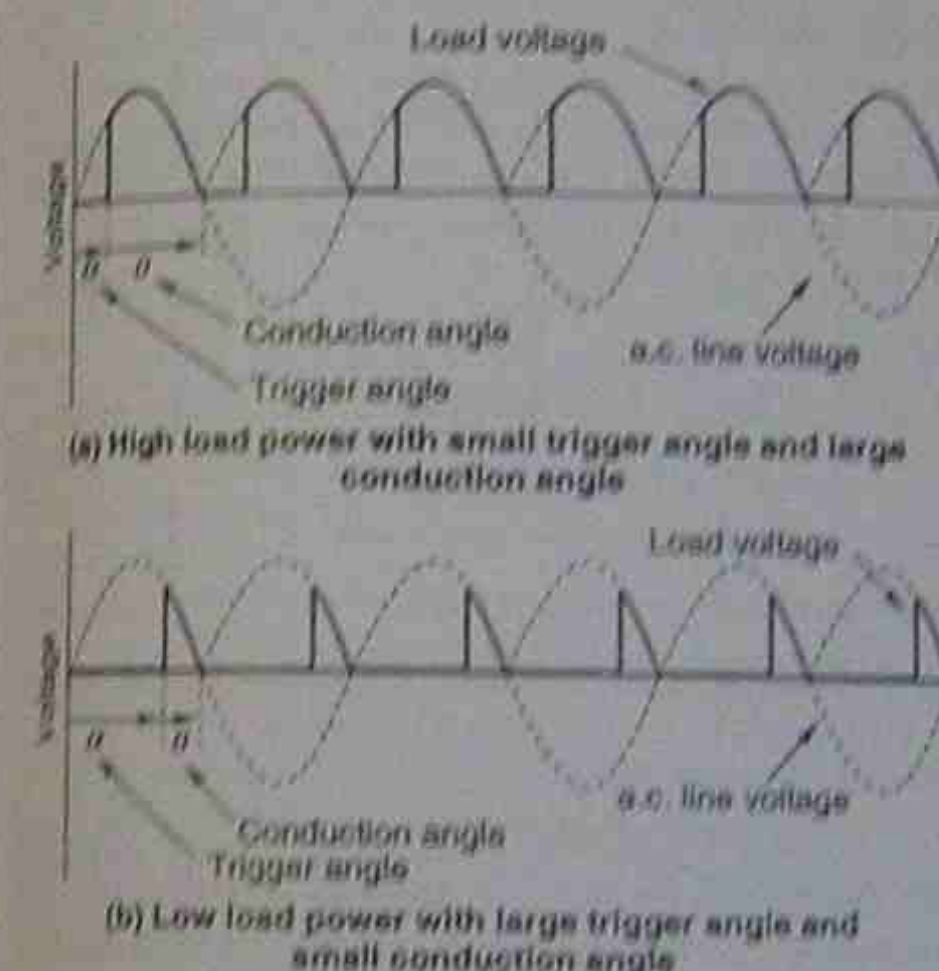


Figure 16.41 • Voltage waveforms for a d.c. load with phase control

From these waveforms, note that for high load power the trigger angle is small and the conduction angle  $\theta$ , the period in which the thyristor conducts, is large. For low load power,  $\alpha$  is large and  $\theta$  is small. As the trigger angle increases, the conduction angle decreases. For circuits where the supply is single phase and the load is resistive,

$$\alpha + \theta = 180^\circ$$

Therefore when  $\alpha = 45^\circ$ ,  $\theta = 135^\circ$ .

Figure 16.42 shows typical waveforms for a situation where phase-control techniques are employed to control the power in an a.c. load. The principles are identical to those of the d.c. application, the only difference being that the load current is bi-directional.

The advantages of phase control are:

- a wide range of applications, from very low to very high power loads
- high efficiency
- small size, compact equipment
- moderate cost.

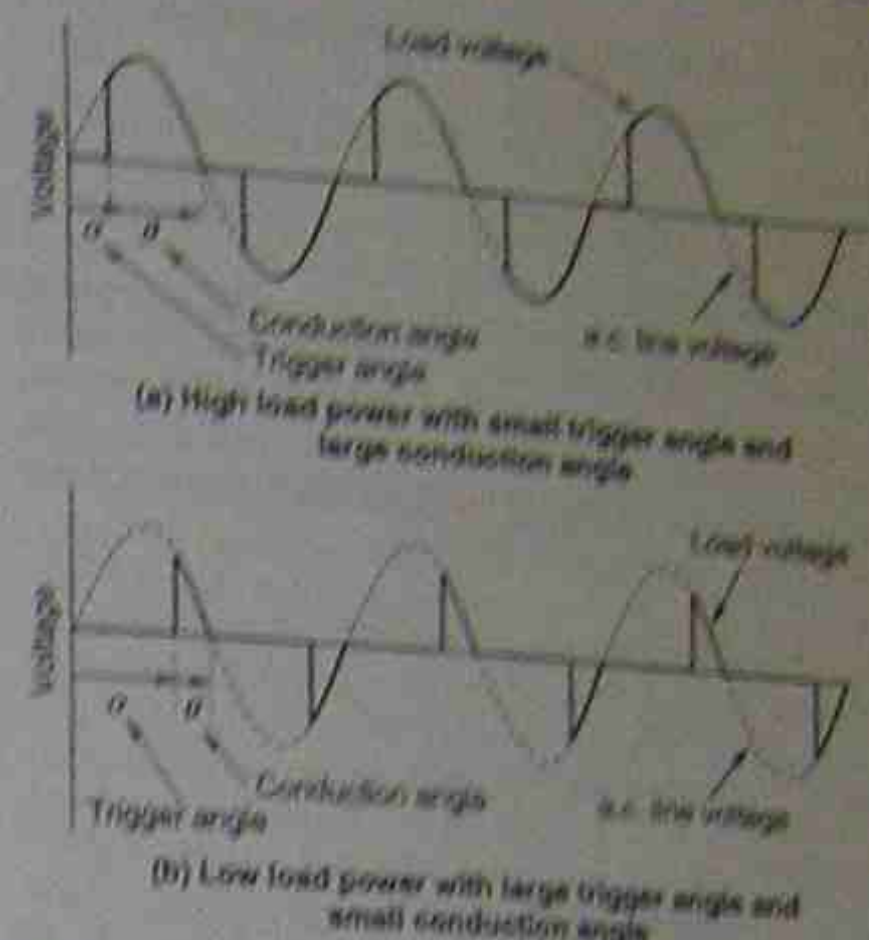


Figure 16.42 • Voltage waveforms for an a.c. load with phase control

Phase control has two major disadvantages:

- The 'chopped' waveform produces harmonics (multiples of the supply frequency) that reflect back into the supply system. These harmonics may in extreme cases interfere with other equipment.
- The rapid switching of the thyristor causes the load current to rise very quickly, producing high-frequency oscillations. The frequency of these oscillations is normally in the AM broadcast band and can cause interference to communications equipment operating at these frequencies. The oscillations, called radio-frequency interference (RFI), can radiate directly but can also penetrate the supply system. The RFI generated by thyristor circuits increases as the trigger angle approaches  $90^\circ$ . It is at a minimum when triggering occurs at  $0^\circ$  or  $180^\circ$ . The RFI may be prevented from getting back into the supply system by the use of RFI suppression circuits as shown in Figure 16.43.

At radio frequencies, the capacitor provides a low impedance path for RFI generated by the thyristor to return to the thyristor. For power line frequencies the capacitor has a high impedance and has no effect on the operation of electrical equipment.

The inductor offers a high impedance path to high frequency oscillations attempting to enter the supply. At power line frequencies it offers minimal impedance and does not affect the operation of the electrical equipment.

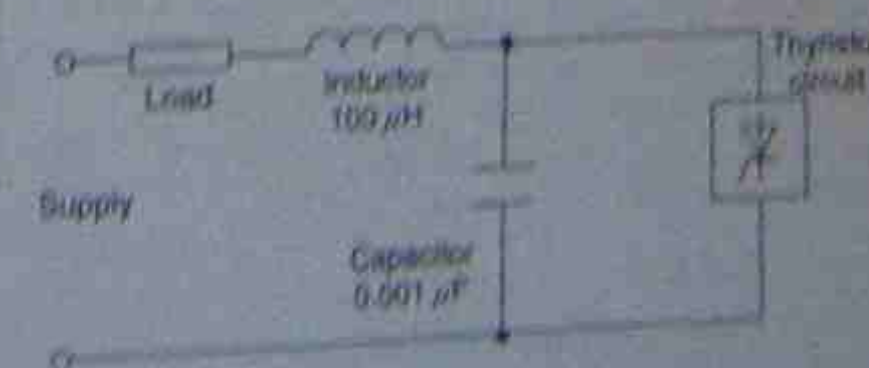


Figure 16.43 • RFI suppression



### 16.9.1 Half-wave controlled rectifier—single phase

The function of this circuit is to control the average value of power in a d.c. load supplied from an a.c. source. This is achieved by controlling the average value of load voltage using phase-control techniques.

The circuit configuration is similar to the single-phase half-wave rectifier described in Chapter 15, the major change being that the diode is replaced by an SCR. A trigger circuit must also be included to control the SCR. Many variations of the trigger circuit are possible. Only one trigger circuit will be discussed.

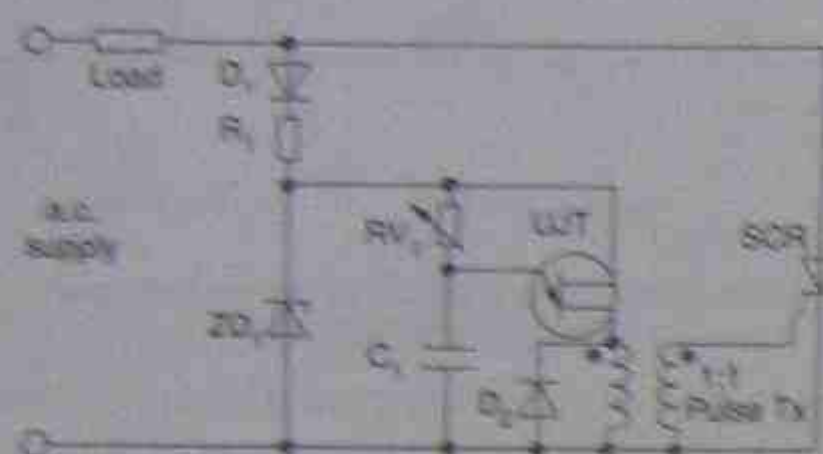


Figure 16.44 • Single-phase half-wave controlled rectifier

#### Operation

In a circuit of this type it is necessary to configure the trigger circuit so that the trigger pulses may be varied from the commencement of the positive half-cycle through to the end of the half-cycle. The pulses must be synchronised with the mains so that for a given setting on  $RV_1$ , the trigger delay is the same in every positive half-cycle.

In the circuit in Figure 16.44,  $D_1$ ,  $S_1$  and  $2D_1$  provide a regulated supply for the UJT trigger circuit. The trigger circuit is connected such that when the SCR is triggered on, the trigger circuit is effectively short-circuited, owing to the very low forward voltage drop across a conducting SCR. This results in:

- only one trigger pulse in each positive half-cycle
- the time taken for the capacitor to reach the peak point voltage and hence cause the UJT to trigger the SCR being the same in each positive half-cycle

As the time taken for the capacitor voltage to rise to the peak point voltage of the UJT increases, the triggering of the SCR is delayed further into each positive half-cycle, causing the average load voltage to be reduced. The trigger angle is controlled by the setting on  $RV_1$ . As  $RV_1$  is increased, the time constant in the trigger circuit increases, increasing the trigger angle. Similarly, if the setting on  $RV_1$  is reduced, the time constant and trigger angle decrease.

When  $RV_1$  is at its minimum value, the trigger angle will be zero and the load voltage will be at its maximum value.

In this case:

$$V_L = 0.45V_{ac}$$

where  $V_L$  = average load voltage in volts  
 $V_{ac}$  = a.c. input voltage

This value is identical to that obtained from an uncontrolled single-phase half-wave rectifier as discussed in Chapter 15.

When  $RV_1$  is set to its maximum value, the trigger angle will be  $180^\circ$  and the load voltage will be zero.

For trigger angles between  $0^\circ$  and  $180^\circ$ , the load voltage is determined from:

$$V_L = \frac{\sqrt{2}V_{ac}}{\pi} (1 + \cos \alpha)$$

where  $V_L$  = average load voltage in volts  
 $V_{ac}$  = a.c. input voltage  
 $\alpha$  = trigger angle in electrical degrees

#### Example 16.5

Determine the d.c. load voltage supplied from a single-phase half-wave controlled rectifier where the a.c. input voltage is 240 V and the trigger angle is set to  $60^\circ$ .

$$\begin{aligned} V_L &= \frac{\sqrt{2}V_{ac}}{\pi} (1 + \cos \alpha) \\ &= \frac{\sqrt{2} \times 240}{\pi} (1 + \cos 60^\circ) \\ &= 54.01 \times (1 + 0.5) \\ &= 81.02 \text{ V} \end{aligned}$$

The peak reverse voltage to which the SCR is subjected is also important and is found from:

$$PRV = \sqrt{2}V_{ac}$$

#### Example 16.6

In the previous circuit the a.c. input voltage was 240 V. Determine the required PRV rating of the SCR.

$$\begin{aligned} PRV &= \sqrt{2}V_{ac} \\ &= \sqrt{2} \times 240 \\ &= 339.4 \text{ V} \end{aligned}$$

The controlled single-phase half-wave rectifier has disadvantages similar to those of the uncontrolled single-phase half-wave rectifier. The most significant are:

- low d.c. output for a given a.c. input
- low ripple frequency and 'coarse' load voltage waveform
- saturation of the core of the supply transformer where the load current is high.

#### Waveforms

Figure 16.45 shows typical waveforms for the circuit in Figure 16.44 when the trigger angle is set to  $60^\circ$ .

Owing to the nature of the load voltage waveform and other disadvantages, the single-phase half-wave controlled rectifier finds few applications in industry. By contrast, polyphase half-wave controlled rectifiers are used extensively, but these circuits are beyond the scope of this book.

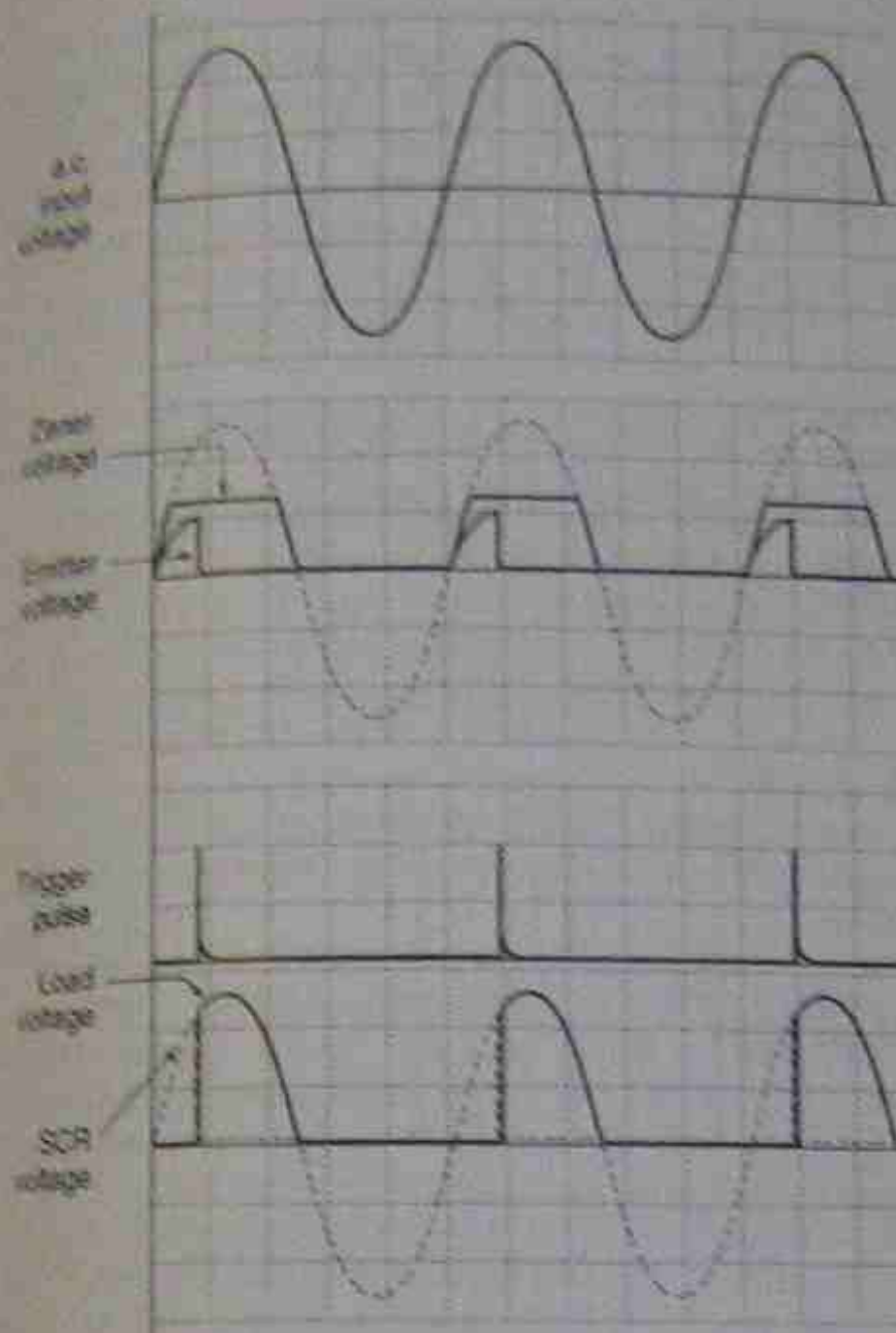


Figure 16.45 • Single-phase half-wave controlled rectifier waveforms ( $\alpha = 60^\circ$ )

### 16.9.2 Full-wave controlled rectifier—single phase

This rectifier circuit overcomes the major disadvantages of the half-wave controlled rectifier. The only way in which further improvements in performance may be obtained is to utilise polyphase rectifiers.

The single-phase full-wave controlled rectifier takes the form of a bridge rectifier, as discussed in section 15.4; however, it might take one of the following forms:

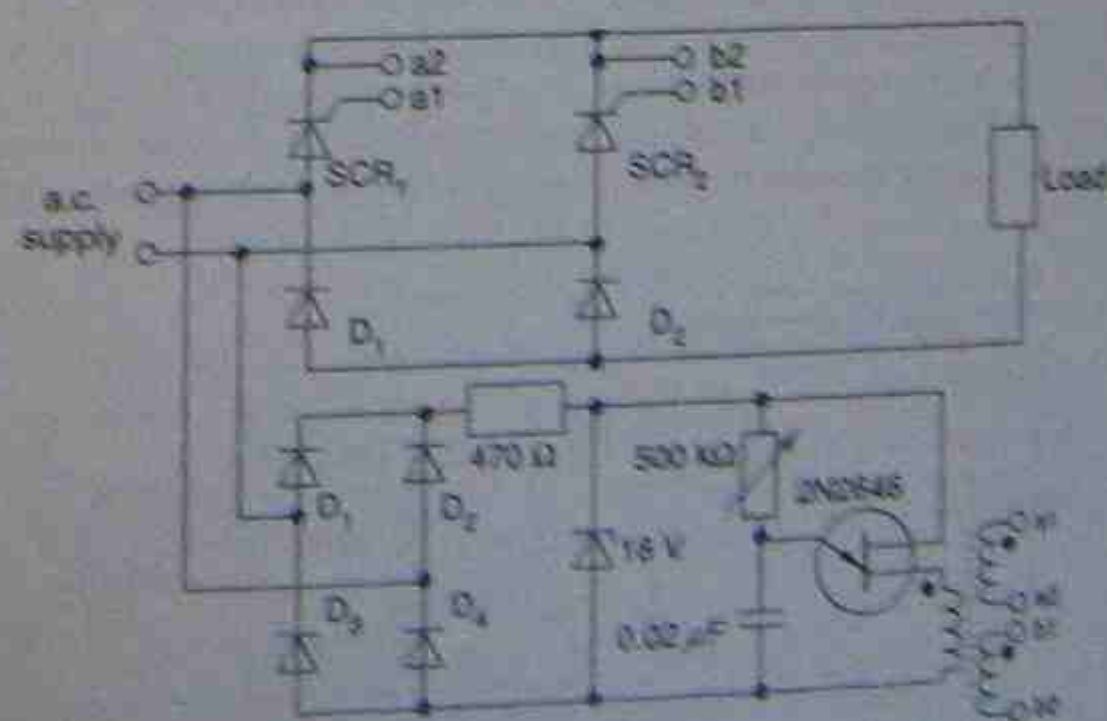


Figure 16.46 • Single-phase full-controlled bridge rectifier

- two SCRs and two diodes—a half-controlled bridge, or
- four SCRs—a fully controlled bridge.

Only the half-controlled bridge will be discussed in this book because a fully controlled bridge offers no advantages when supplying resistive loads, yet requires a more complex trigger circuit. Fully controlled bridges are used in applications such as d.c. motor speed control where regenerative braking is required.

### 16.9.3 Half-controlled bridge rectifier

A half-controlled bridge is shown in Figure 16.46.

In this circuit, load current in one half-cycle is supplied via  $SCR_1$  and  $D_2$  with  $SCR_2$  and  $D_1$  being reverse biased. In the next half-cycle, load current is supplied via  $SCR_3$  and  $D_4$  with  $SCR_4$  and  $D_3$  reverse biased. Load current cannot flow of course until the appropriate SCR is triggered into the on state.

The SCRs and diodes in this circuit operate on a 50 per cent duty cycle; that is, they conduct for only 50 per cent of the time. This fact may be taken into account, with some degree of caution, when selecting the current rating for the SCRs and diodes for a particular application.

The manner in which the trigger circuit is configured in this circuit is such that each SCR will receive multiple trigger pulses in each half-cycle. This does not normally present a problem, however, because a trigger pulse has no effect on a conducting SCR, nor on an SCR that is reverse biased.

Like the half-wave controlled rectifier, the output voltage from this circuit is controlled by the potentiometer in the trigger circuit.

When  $\alpha = 0^\circ$  the load voltage is a maximum, and

$$V_L = 0.9V_{ac}$$

where  $V_L$  = average load voltage in volts  
 $V_{ac}$  = a.c. input voltage

When  $\alpha = 180^\circ$ , the load voltage is zero. For trigger angles between  $0^\circ$  and  $180^\circ$  the load voltage may be determined from the following expression:

$$V_L = \frac{\sqrt{2}V_{ac}}{\pi} (1 + \cos \alpha)$$



where  $V_L$  = average load voltage in volts  
 $V_{in}$  = a.c. input voltage  
 $\alpha$  = trigger angle in electrical degrees

### Example 16.2

Determine the a.c. load voltage supplied with a single-phase half-controlled bridge rectifier where the a.c. input voltage is 240 V and the trigger angle is set to  $60^\circ$ .

$$V_L = \frac{\sqrt{2} V_{in}}{2} (1 + \cos \alpha)$$

$$= \frac{\sqrt{2} \times 240}{2} (1 + \cos 60^\circ)$$

$$= 162.4 \text{ V}$$

The  $\alpha$  and  $\cos \alpha$  in this circuit are subjected to the same PIV in the direction of single phase uncontrolled bridge rectifier as discussed in section 15.4, that is

$$\text{PIV} = \sqrt{2} V_{in}$$

### Example 16.3

In the circuit in Figure 16.46 the a.c. input voltage is 240 V. Determine the required PIV rating of the  $\text{SCR}$ s and diodes.

$$\text{PIV} = \sqrt{2} V_{in}$$

$$= \sqrt{2} \times 240$$

$$= 339.4 \text{ V}$$

Note that the output  $\text{SCR}$ s in this circuit is double that in the half-wave controlled rectifier for the same trigger angle. The controlled bridge rectifier is turned around  $90^\circ$  and is convenient used to supply low to medium power loads.

The circuit in Figure 16.46 can be modified to configure the trigger circuit so that only one trigger pulse is supplied in each half cycle as in Figure 16.47. Both  $\text{SCR}$ s are still triggered simultaneously; however, only the  $\text{SCR}$  that is forward biased will turn on.

#### Waveforms

Typical waveforms for a single-phase half-controlled bridge rectifier circuit are shown in Figure 16.48.

Comparing these waveforms, particularly the load current waveform, with those of Figure 16.45, it can be seen that better use is made of the supply waveform. Since

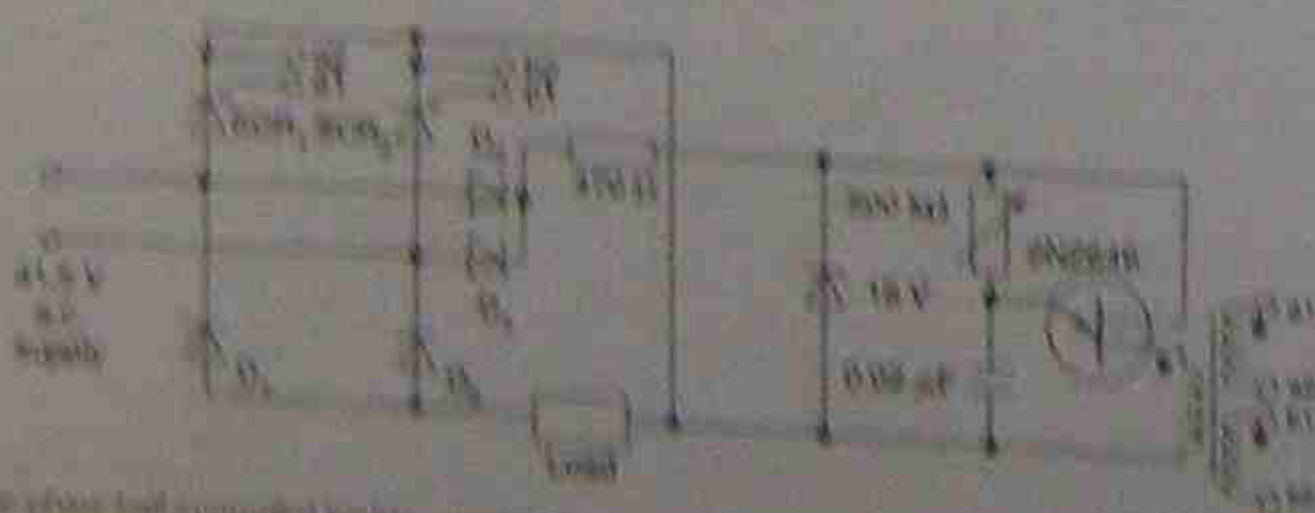


Figure 16.47 Single-phase half-controlled bridge – modified trigger circuit

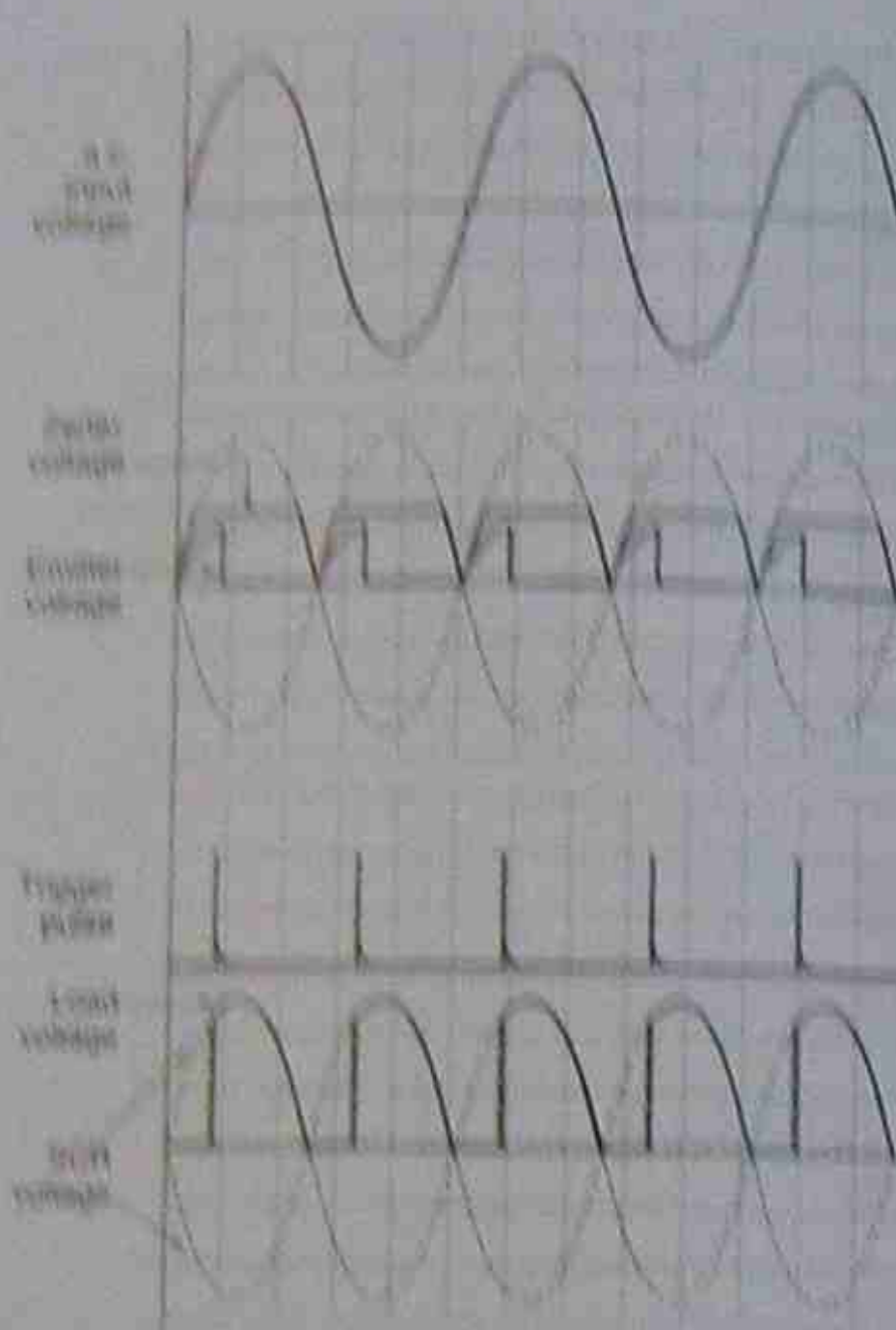


Figure 16.48 Single-phase half-controlled bridge waveforms ( $\alpha = 60^\circ$ )

both half cycles of the supply are utilized, the problem of the supply transformer saturating at high load currents is overcome. Also, since the periods between load voltage pulses are shorter (double the ripple frequency) the load power is smoother. This is particularly evident where the load is the armature of a d.c. motor, where the torque may be pulsating if the rectifier output is similar to the half-wave rectifier circuit.

### 16.10 TRIGGER CIRCUIT ISOLATION

Note that in all three controlled rectifier circuits discussed to this point the trigger pulse is supplied to the  $\text{SCR}$  via a pulse transformer, which is a small transformer with a turns ratio of 1:1. It is sometimes an air-cored device and usually has one primary and two secondary windings.

The function of a pulse transformer is to isolate the trigger circuit from the  $\text{SCR}$ , or to isolate the main circuits of  $\text{SCR}$ s in the main circuit. This is essential in many cases, particularly where the supply and load voltages are medium to high values. Most trigger circuits operate only on extra-low voltage values.

Other techniques may be used to isolate trigger and power circuits, including that of optical isolation.

### 16.11 ALTERNATING CURRENT LOAD CONTROL WITH TRIACS

A fundamental principle of a.c. load control using thyristors is that a circuit must be established where it is possible to obtain a.c. current in the load. The current must be controlled using phase control techniques to achieve a wide range of load power variation.

The average load power is controlled by varying the peak value of the load voltage. This may be achieved by using inverse parallel connected  $\text{SCR}$ s, or by using a single triac.

Alternating current load control using triacs is the most common thyristor control method for low to moderately high power a.c. loads. The load power is controlled by controlling the r.m.s. value of the load voltage, which in turn is controlled by the trigger angle of the triac. This in turn controls the conduction time of the triac.

When the trigger angle  $\alpha$  is zero, the conduction angle  $\theta$  will be  $180^\circ$  and the load voltage will be a maximum and equal to the supply voltage. As the trigger angle is increased, the conduction angle will decrease and the load voltage will decrease. When  $\alpha$  is equal to  $180^\circ$ ,  $\theta$  will be zero and the load voltage will be zero.

The trigger circuit most commonly used with a triac to control a.c. loads is the diac trigger circuit shown in Figure 16.49.

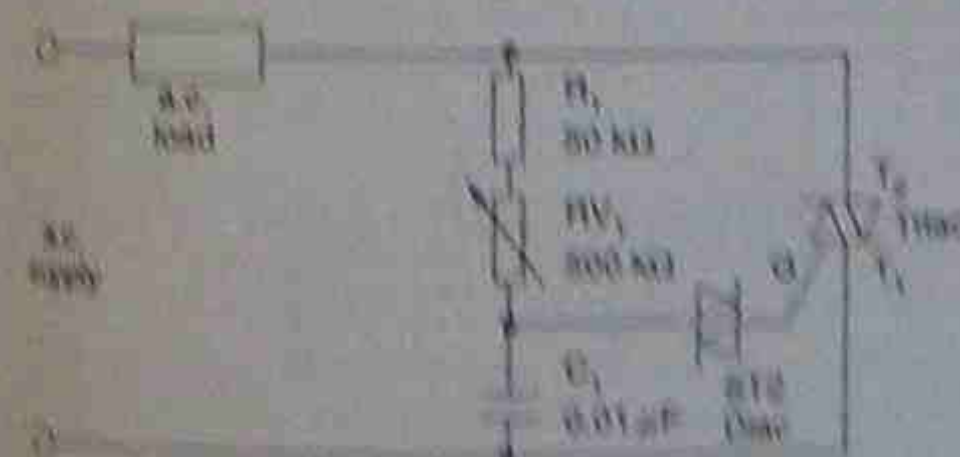


Figure 16.49 Diac control of a.c. loads

The trigger angle is controlled by varying the setting on the potentiometer  $RV_1$ . As this value is increased, the time taken for the capacitor to charge up to the break-over voltage of the diac will increase. This will delay the trigger angle and therefore reduce the conduction time. This in turn causes the load voltage to be reduced.

With the circuit arrangement above, the load may be controlled from full conduction through to almost zero; however, when the load voltage is increased again, a 'snap-on' effect is noticed. This is caused by a residual charge on the capacitor. The snap-on is evident because the current will suddenly increase from zero to some intermediate value.

The snap-on effect may be reduced by one or two methods:

- using an asymmetric diac (574) or
- introducing a second time delay in the trigger circuit, as shown in Figure 16.50.

In both circuits (Figs 16.49 and 16.50) the trigger circuit is not suited to extra-low voltage supplies. This is due to the relatively high break-over voltage of the diac, which is normally in the range 28 to 36 V.

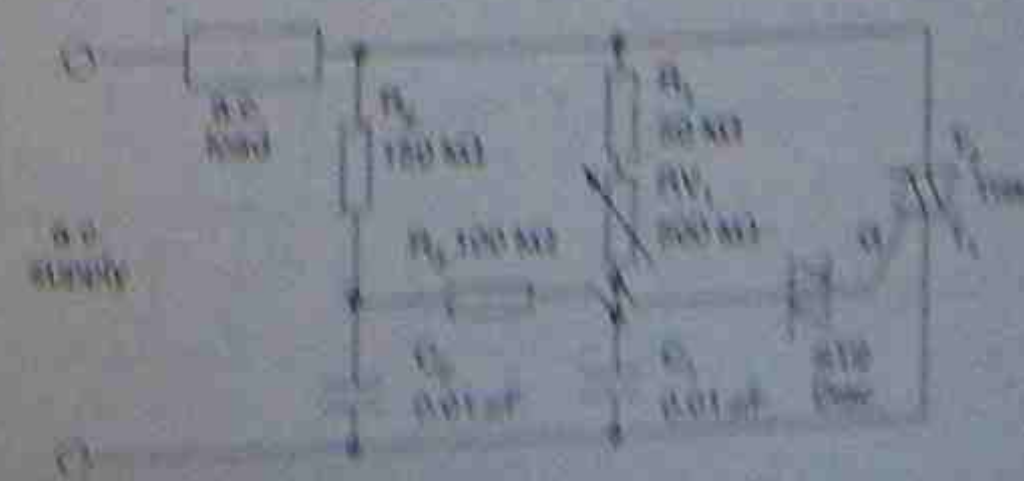
For example, if a diac has a break-over voltage of 30 V and is operating in a circuit connected to a 32 V supply, it will not be possible to trigger the diac until  $41^\circ$  into the cycle. The range of control is therefore very restricted. By contrast, if the supply is 240 V, the minimum trigger angle is  $3^\circ$ .

This problem may be overcome by using either a UJT or a PUT trigger circuit. With both circuits, the trigger angle may be controlled from almost  $0^\circ$  to  $180^\circ$ . A representative UJT circuit is shown in Figure 16.51.

Important points that should be noted for the UJT trigger circuit are:

- The trigger circuit is connected in such a way that it will be turned off when the triac is triggered. There will therefore be only one trigger pulse in each half cycle.
- Trigger pulses of one polarity only are available.
- The pulse transformer is connected in such a way that the triac will be triggered in modes 2 and 3, maximizing triggering sensitivity.

In terms of the output voltage and output current waveform, the only difference between the two circuits is that the UJT trigger circuit will provide a wider range of control when operating from an extra-low voltage supply. It is not unusual practice to use the diac trigger circuit when operating from an extra-low voltage supply.





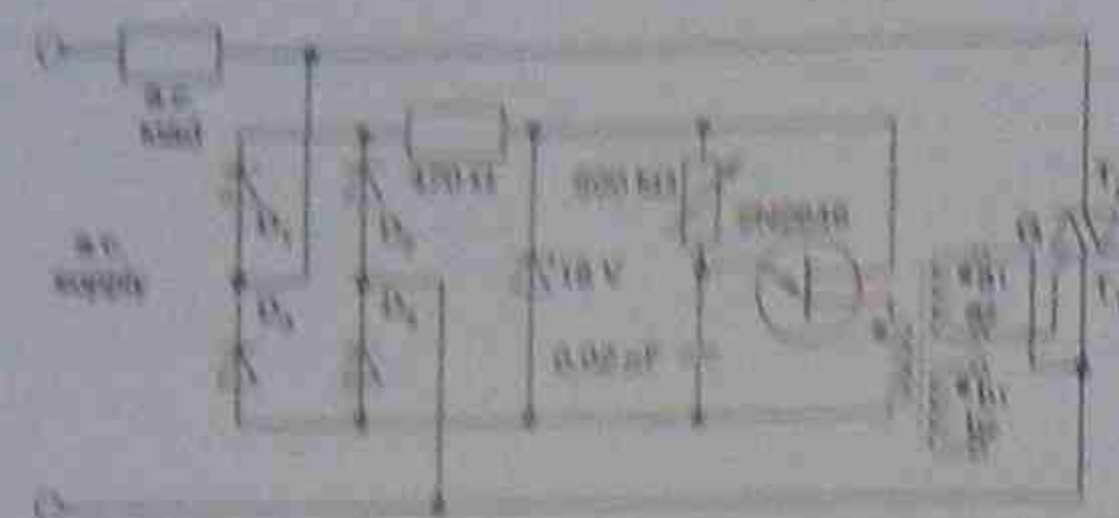


Figure 16.31 • Triac load control—UJT triggering

### 16.11.1 Output voltage

The load voltage may be determined from a circuit characteristic. The actual calculation of load voltage is complex and will not be used in this book. The circuit characteristic is shown in Figure 16.32.

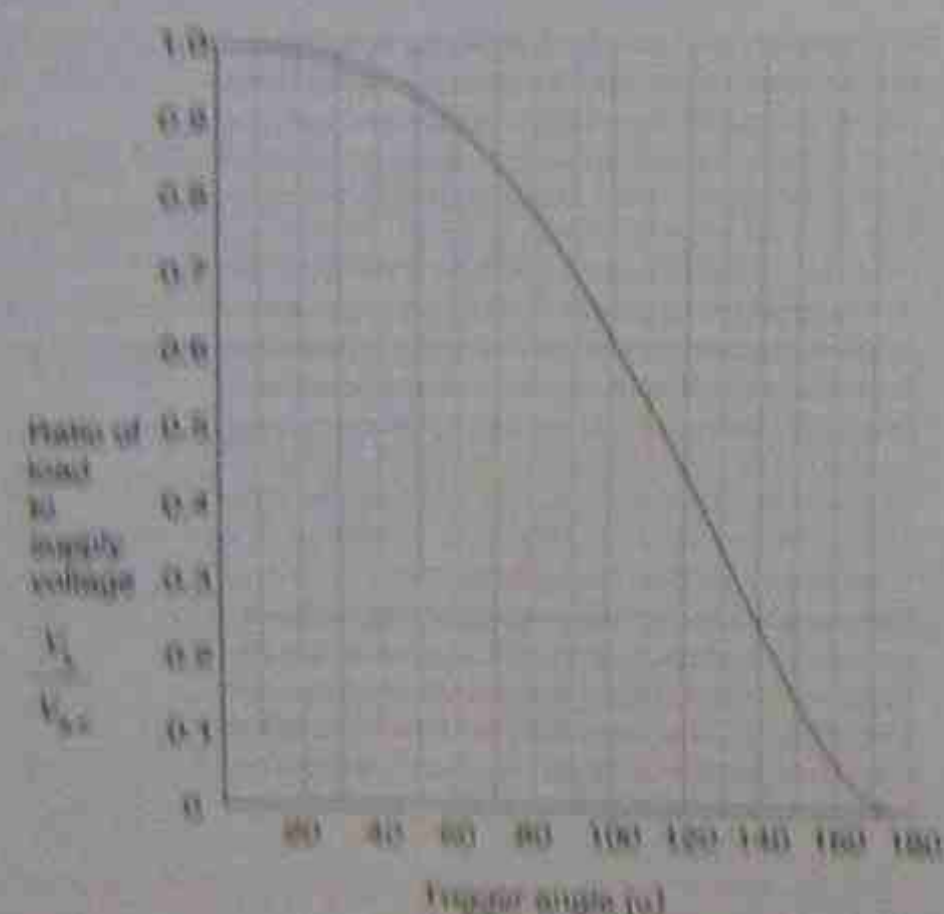


Figure 16.32 • Alternating current controller circuit characteristic

To obtain the load voltage for a particular trigger angle, project up from the horizontal axis at the appropriate trigger angle until the curve is intersected. Then project horizontally across to the vertical axis to obtain the ratio of load to supply voltage. The ratio is multiplied by the supply voltage to give the load voltage.

#### Example 16.9

A triac is used to control the power to an a.c. load with a supply voltage of 240 V. Determine, using the circuit characteristic, the load voltage when the trigger angle is 30°, 60°, 90°, 120° and 150°.

From the circuit characteristic, the ratio  $\frac{V_L}{V_S}$  is equal to

(a) When  $\alpha = 30^\circ$  (circuit char. = 0.98),  
 $V_L = 0.98 \times 240 = 235.2 \text{ V}$

(b) When  $\alpha = 60^\circ$  (circuit char. = 0.86),  
 $V_L = 0.86 \times 240 = 206.4 \text{ V}$

(c) When  $\alpha = 120^\circ$  (circuit char. = 0.44),

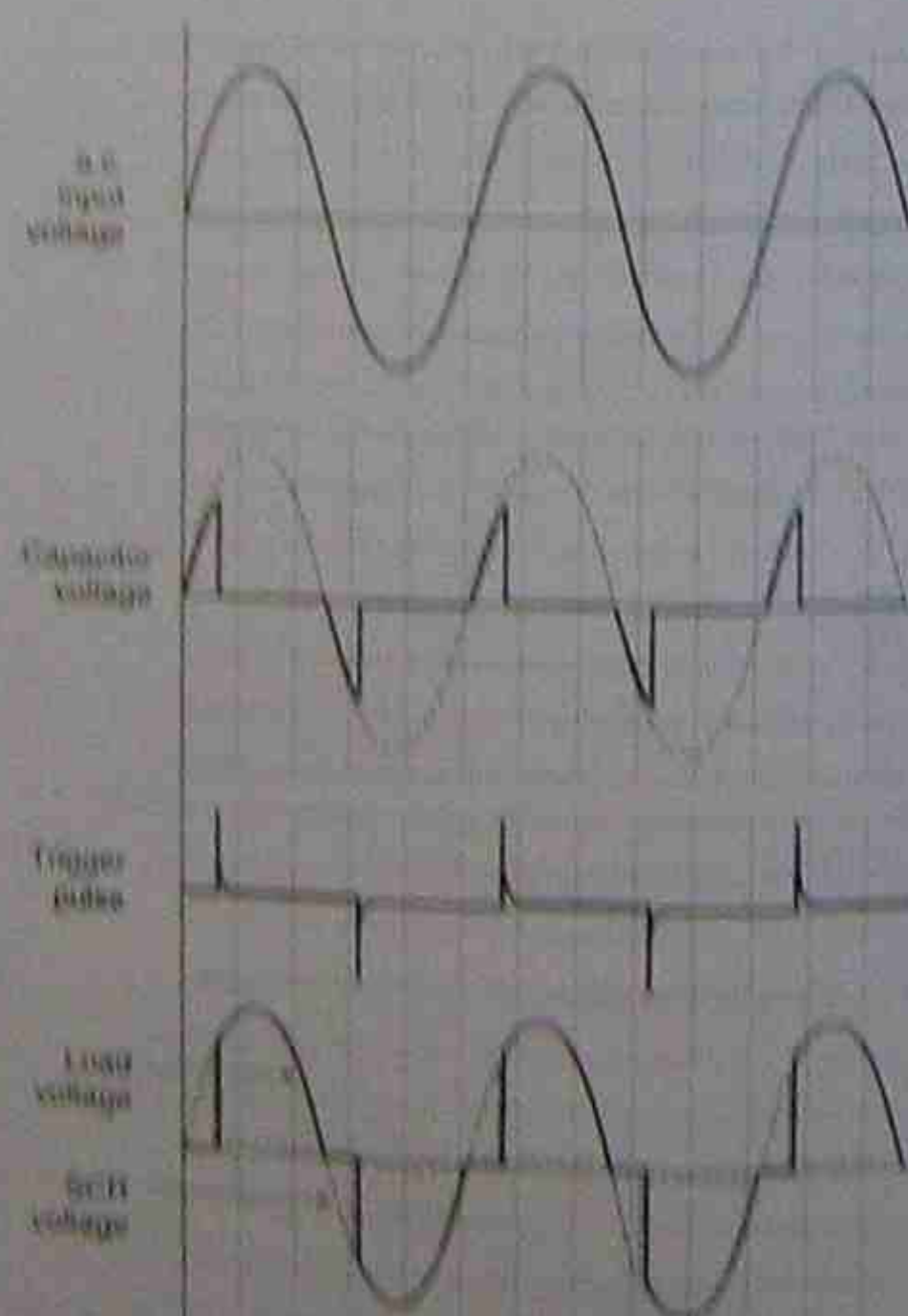
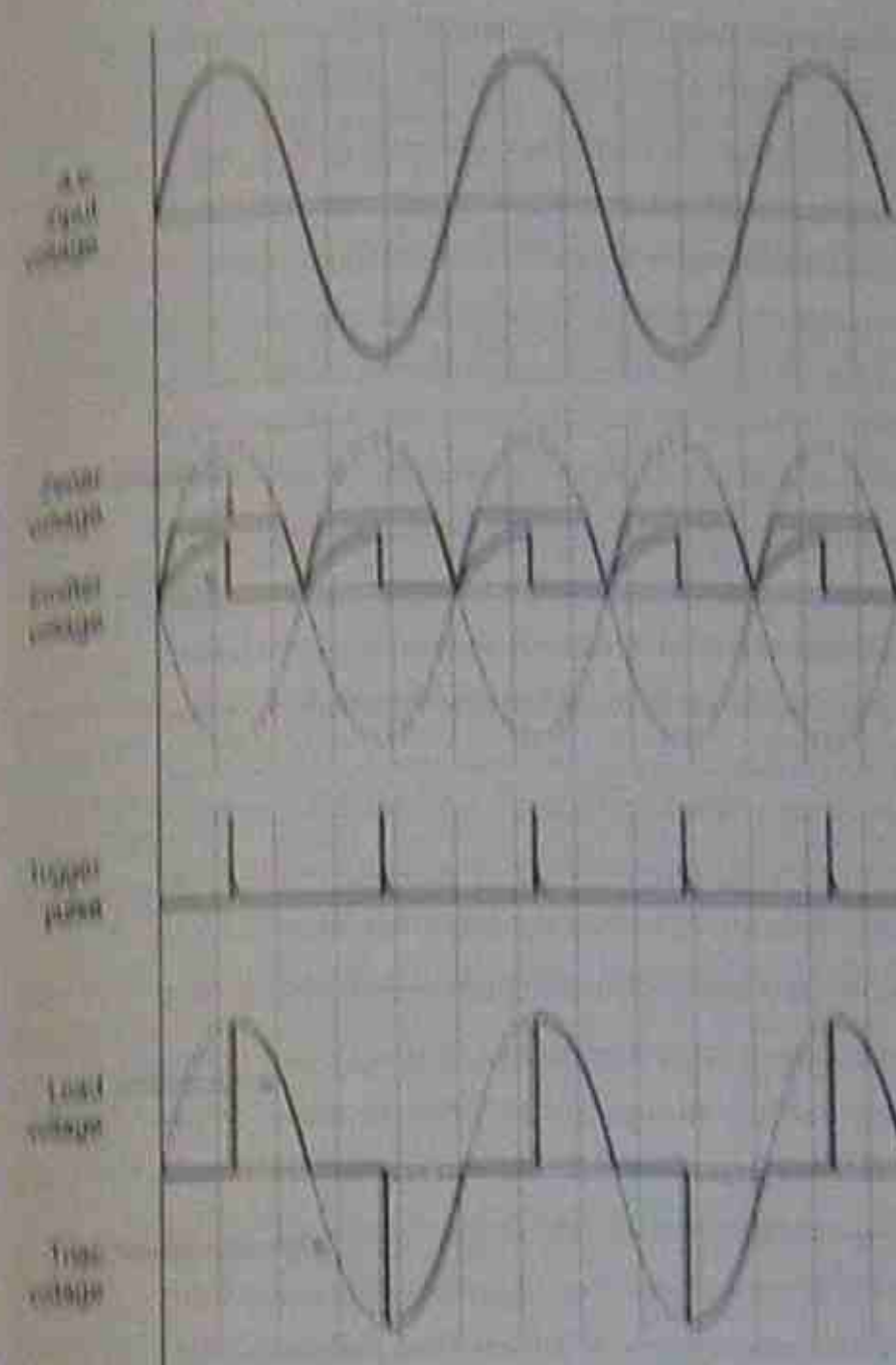
$$V_L = 0.44 \times 240 = 105.6 \text{ V}$$

### 16.11.2 Waveforms

The waveforms produced by a triac controlling a resistive a.c. load for a trigger angle of  $45^\circ$  with diac triggering, and  $90^\circ$  with UJT triggering, are shown in Figures 16.33 and 16.34 respectively.

The triac controller is used to control low to moderately high power loads. Some examples are:

- lamp illumination
- fan speed control (ceiling fans)

Figure 16.33 • Triac a.c. load controller—diac triggering (trigger angle  $45^\circ$ )Figure 16.34 • Triac a.c. load controller—UJT triggering (trigger angle  $90^\circ$ )

- motor speed control (limited to small motors)
  - heating elements in cooking and heating appliances.
- For higher current requirements, available triacs may not be capable of carrying the required load current. In such cases two SCRs connected in an inverse parallel configuration are used.

### 16.12 ALTERNATING CURRENT LOAD CONTROL WITH SCRs

A pair of inverse parallel-connected SCRs is equivalent to a triac. The SCRs provide controlled conduction in both directions, allowing alternating current in the load. In the circuit of Figure 16.35, both SCRs are triggered simultaneously.

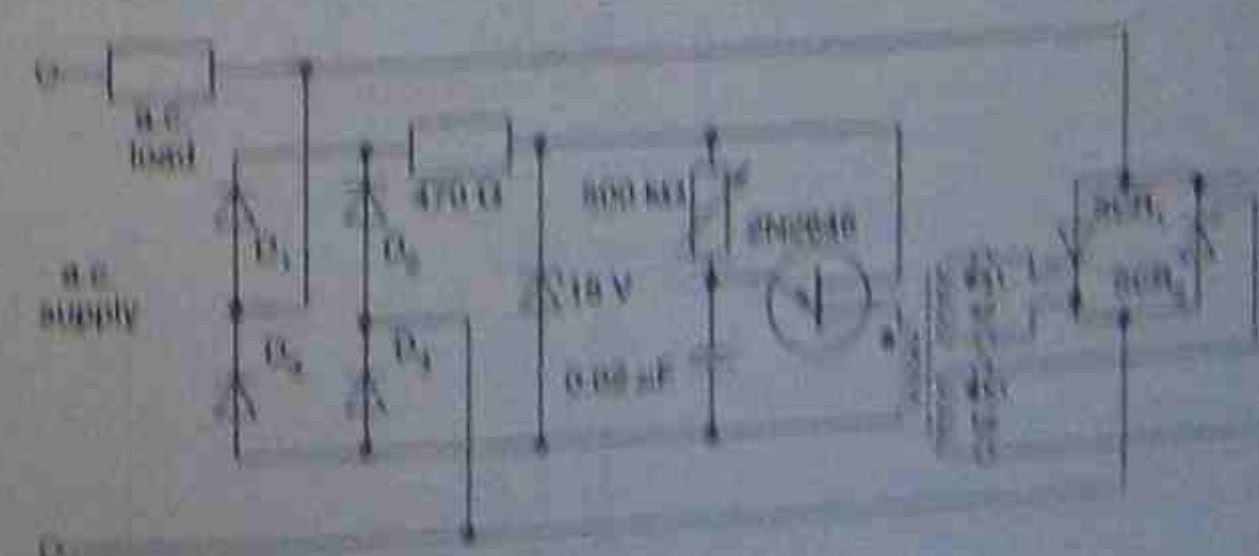


Figure 16.35 • Inverse parallel SCR load control—UJT triggering

ously, however, only the SCR that is forward biased will be turned on.

In situations where the load current exceeds values around 25 to 100 A, a pair of inverse parallel SCRs may be less expensive than the equivalent triac.

This circuit arrangement is common for medium to high-load power applications. The load voltage is controlled in exactly the same manner as a triac, that is, the load voltage will decrease as the trigger angle increases.

The waveforms produced by this circuit will be identical to those in Figure 16.33. The UJT trigger circuit may be replaced by a RFT trigger circuit. The operation of the SCRs will be identical, however, the meanings of the RFT trigger circuit is that the shutdown rate is programmable.

### 16.13 ZERO VOLTAGE SWITCHING (ZVS)

As discussed in section 16.9, a major disadvantage of phase control as a means of controlling load power is the RFI generated when the thyristors are triggered into the on state.

The RFI will both radiate into the surrounding atmosphere and propagate back into the supply system. The RFI generated is particularly bad where:

- the load current is high
- the trigger angle of the thyristors is around  $90^\circ$

Supply authorities usually require RFI suppression equipment to be installed. In cases where the load current is moderately high, only low cost components are required. In high load current situations, RFI suppression equipment can be expensive.

For some load types, such as illumination control, phase control is the only viable option to control the load power. Heating elements, however, are ideally suited to on/off type control. This is due to the high thermal inertia of heating elements, particularly elements in large heating appliances and equipment.

In section 16.2.1, this form of control was discussed in terms of thermostats and motor starters. An electronic version of these devices is the zero voltage switch (ZVS). The ZVS controls the load in a manner similar to the thermostat and motor starter but the relay action is measured in cycles.

The zero voltage switch is designed to always switch the thyristors (diacs or SCRs) as close as possible to the time when the supply voltage waveform crosses the zero line, in phases through zero. If a thyristor is triggered at the zero

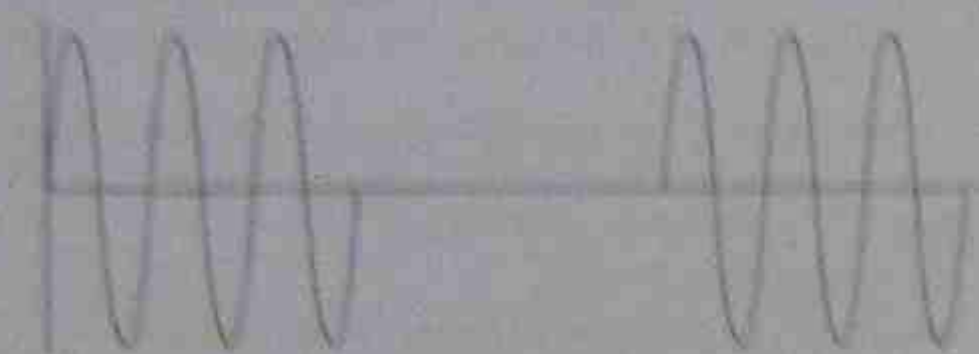


crossing, the RFI generated will be almost negligible and this particular disadvantage of phase control is overcome.

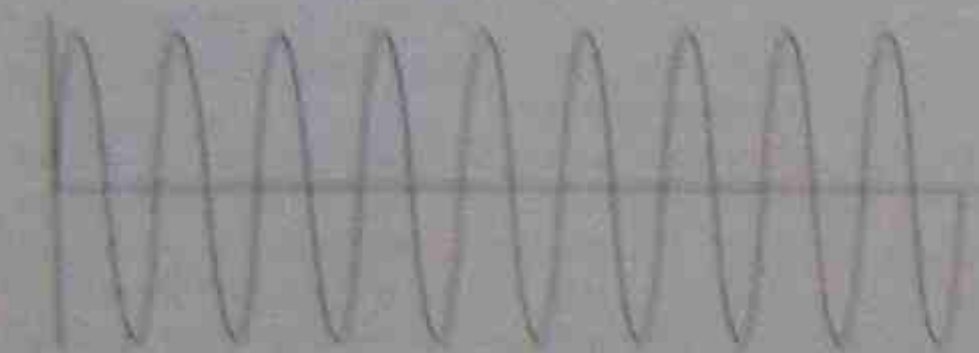
Control over average load power is achieved by switching the load on in bursts. For example a low level of load power may be achieved by switching the thyristor on for five cycles and off for twenty cycles. A medium level of power may be achieved by a cycle of on for ten cycles and off for ten cycles. This concept is displayed in the waveforms in Figure 16.56.



(a) Low load power



(b) Medium load power



(c) High, or maximum, load power

Figure 16.56 • Zero voltage switching load voltage waveforms

In each of the above cases, a trigger pulse must be supplied at precisely the time the supply voltage passes through zero, both in a positive and in a negative direction.

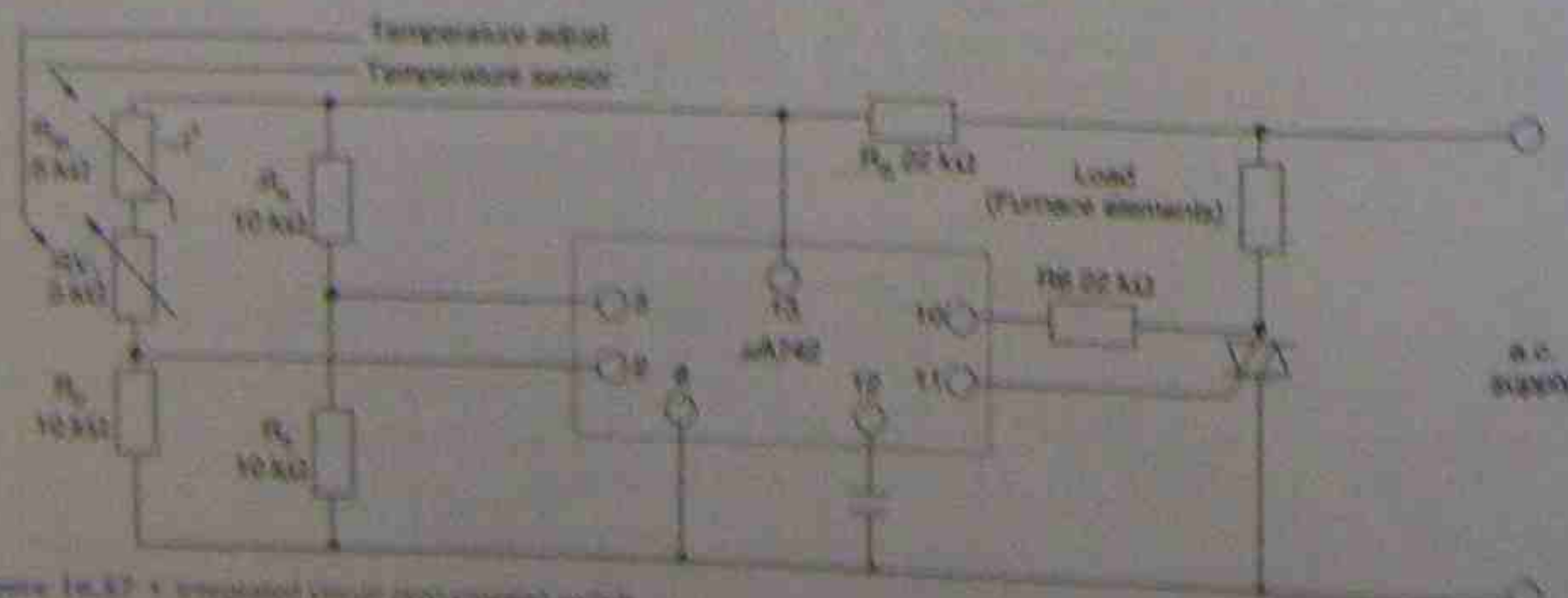


Figure 16.57 • Integrated circuit zero-crossing switch

A zero voltage switch consists of:

- an input, or control circuit. This is the circuit that actually controls the switching of the thyristors. It may consist of a simple on/off switch such as a thermostat or a resistance bridge, using thermistors to provide 'proportional' control over temperature.
  - a zero-crossing detector. This circuit determines the precise time at which the trigger pulses are delivered to the thyristors.
  - a pulse generator. This circuit actually generates the trigger pulse for the thyristor.
- Zero voltage switches may be made from:
- discrete components. The method is obsolete and now rarely used.
  - integrated circuits (ICs) specifically designed for this purpose.

The major application of ZVS is in the control of heating loads. Owing to the high thermal inertia of most heating elements, the burst firing of the thyristors controlling the load will have no adverse effect on the load.

A ZVS is not suited to applications such as motor speed control, owing to the pulsating nature of the motor torque at low speeds, or to illumination control, owing to the pulsating nature of the illumination output from lamps at low settings. In the case of incandescent lamps, this would appear as an annoying flicker in the lamps.

A ZVS can also be used in situations where simple on/off control is required. A device known as a solid state relay (SSR) has been developed for this purpose. An SSR consists of the main thyristor and the zero-crossing controller.

### 16.13.1 Integrated circuit zero-crossing switch

A number of integrated circuits have been developed to incorporate all the necessary features of a zero-crossing switch. One of the simpler ICs is the Fairchild  $\mu A742$ . A typical connection diagram is shown in Figure 16.57.

Resistors  $R_1$ ,  $R_2$  and  $R_3$ , together with  $RV_1$  and  $R_4$ , form a bridge circuit. The voltage at pin 3 is fixed and the voltage at pin 2 will vary as the temperature varies. If the voltage at pin 3 exceeds the voltage at pin 2, trigger pulses will be supplied to the triac. If the voltage at pin 3 is less than the voltage at pin 2, the trigger pulses will be inhibited and the load will not turn on.

The trigger pulses will be supplied to the triac as the supply voltage passes through zero. The thyristor is normally triggered on as the supply changes from negative to positive and will be retriggered in the next negative half-cycle. This ensures that the load is always supplied with complete cycles, rather than half-cycles that result in a d.c. component.

Resistor  $R_{NTC}$  is an NTC thermistor. Its resistance will decrease as temperature increases. This feature, and the setting on  $RV_1$ , provide the variation in voltage at pin 2. As temperature increases, this voltage increases. When the set temperature is reached, the voltage at pin 2 exceeds that at pin 3, and the triac turns on.

As the temperature then decreases, the resistance of  $R_{NTC}$  increases, causing the voltage at pin 2 to decrease. When this voltage is less than that at pin 3, the triac turns back at re-triggering the elements. This form of control is similar to a thermostat in that it is on/off control. The temperature variation or differential will be smaller than that provided by a thermostat. The actual on and off times for the thyristor, for a given temperature setting, will depend on the rate at which the measured temperature increases and decreases.

The manner in which temperature might vary is shown in Figure 16.58.

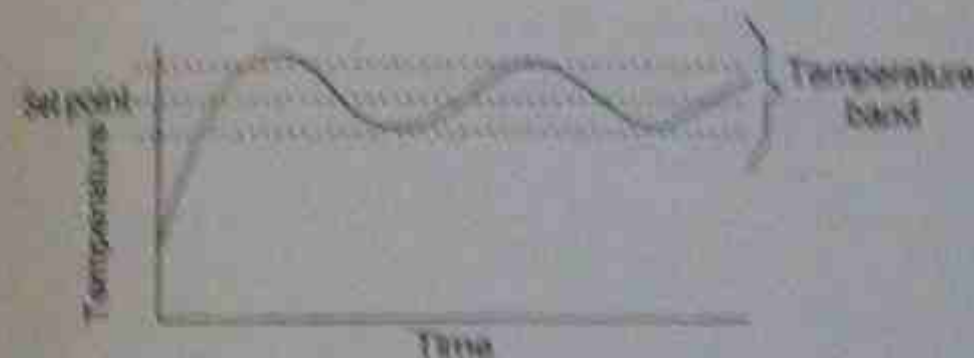


Figure 16.58 • Temperature variations—on/off control

In some applications the temperature should not vary from the set point by more than one or two degrees (or even less in some specialist applications). An example is a furnace used for case hardening or enamelling operations. In these cases 'proportional control' is used. This results in much greater accuracy, with the temperature varying within a much smaller band.

To achieve proportional control, an 'anticipatory' function is built into the control of the ZVS. This allows the controller to anticipate changes in temperature and actually switches the triac on or off sooner than is the case in the circuit in Figure 16.57. This anticipatory function could be achieved by modulating the voltage at pin 2. This modulation could be derived from a relaxation oscillator such as a PUT oscillator.

The manner in which the temperature varies in a proportional controller is shown in Figure 16.59.

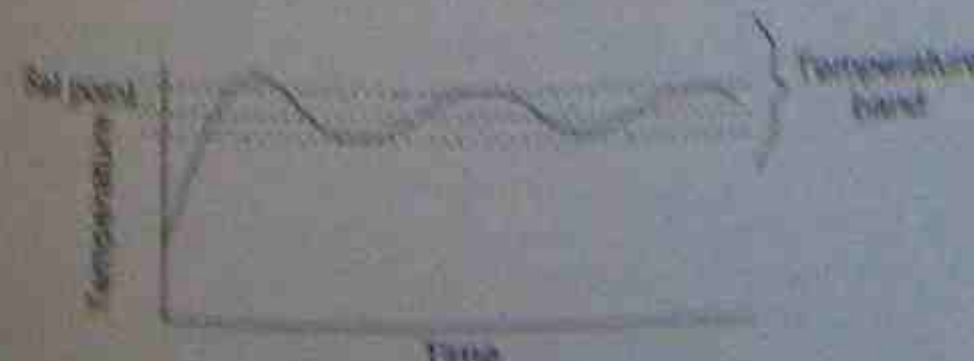


Figure 16.59 • Temperature variations—proportional control

## 16.14 SOLID STATE RELAYS (SSRs)

An integrated circuit has been developed that includes a thyristor (usually a triac) and a zero-voltage switch (ZVS). It is a four-terminal device and is known as a solid state relay (SSR). A typical SSR might be designed for a supply voltage of between 120 and 240 V a.c. with a control input of between 3 and 30 V d.c. Current ratings of up to 100 A are readily available.

The SSR is turned on by applying a d.c. voltage to the control terminals. The d.c. voltage may be derived from a simple switch or a more complex sensing circuit. A simplified example appears in Figure 16.60.

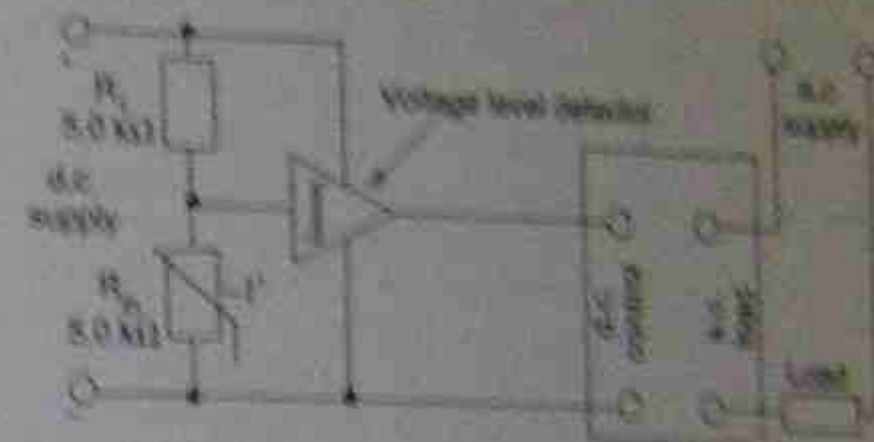


Figure 16.60 • Solid state relay load control

A major advantage of the SSR is its compactness. The four-terminal device can be adapted to suit a number of applications ranging from simple on/off control to more complex functions such as proportional control.

The SSR will turn the load on when a suitable d.c. voltage is applied to the control terminals. The relay will always turn on when the supply is at or near zero volts. Most SSRs are designed to be operated on a heat sink to prevent excessive junction temperature in the thyristor.

## 16.15 FAULT FINDING IN THYRISTOR CIRCUITS

It is essential that in the process of locating a fault in any electrical/electronic circuit, a systematic approach be adopted. Adopting a systematic approach will:

- save time. Many common faults are located easily by testing for some obvious problems, for example, the d.c. supply to a trigger circuit may have failed or a supply fuse may have blown.
- minimize the chances of making the fault, particularly where more than one fault exists in a circuit.

All individuals will develop their own procedure. It is not important that everyone use the same procedure, but it is important that a systematic approach be adopted. In fault finding, there is no substitute for practical experience.

As an example, the following procedure may serve as a model that may be developed and revised. It might also be advantageous to adopt slightly different procedures when confronted with different equipment or situations.

1. Clearly identify the equipment that is in physical location and all the interconnect points.
2. Obtain a copy of a circuit diagram. If this is not available, one might have to be developed. In some cases, previous experience or knowledge of the type of equipment and how it operates may suffice.



- Determine how the equipment is meant to operate, that is, specifically what it does.
- Determine how the circuit operates. This is achieved by studying the circuit diagram and relating it to what the equipment is meant to do. Writing a step-by-step procedure of the circuit operation may be an advantage at this point.
- Identify from the circuit diagram the components most likely to fail, and the common faults previously encountered in similar equipment. With the faults, identify the symptoms.
- Identify the symptoms displayed by the faulty equipment. This may allow the fault to be isolated to a particular section of the equipment, or a particular part of a circuit. For example, the thyristor or the trigger circuit.
- Using the information from steps 1 to 4, assess where the fault might be, test for this fault, and progressively narrow the possibilities. It is sometimes obvious that a component is faulty. It might show signs of stress such as burning. Do not assume that once a faulty component is located and replaced, that is all there is to do. That component might be

faulty because some other component in the circuit has failed or the faulty component that has been located and replaced might have caused other components to fail.

- check the faulty components have been replaced and the circuit to confirm its correct operation. It is important that the full range of functions or operating conditions be tested to eliminate any hidden or obscure faults.

This procedure might seem a little tedious, but with experience, many of the steps become automatic and very quick. It might also be necessary to run through the process several times before the fault is located if the first assumptions were incorrect.

Technicians should be prepared to verify this procedure and develop one that they are comfortable to work with. It is also worth noting that there is no real short cut to fault finding. There is also really no such thing as basic fault finding.

To be successful in this aspect of electronics, a technician or technician must be prepared to build a library of knowledge and experience and adapt to new situations and variations of basic circuits that will be encountered.

## SUMMARY

- Thyristor power control is used in preference to other traditional methods because of the high efficiency achieved.
- The thyristors used in power control applications are:
  - silicon controlled rectifiers (SCRs)
  - gate turn-off thyristors (GTO thyristors)
  - triacs.
- A silicon controlled rectifier is a three-terminal unilateral conducting device. In many respects it is similar to a p-n diode.
- The SCR blocks current when forward biased, unless:
  - the forward blocking voltage is exceeded
  - it is triggered on by a pulse of current from gate to cathode.
- SCRs are generally mounted on heat sinks to prevent excessive junction temperatures, which may destroy the SCR.
- The forward voltage drop across a conducting SCR is relatively constant and is a nominal 0.6 V. In practice this value will be nearer 1.0 to 2.0 V for higher current SCRs.
- SCRs must be protected against:
  - excessive currents (RMS, surge)
  - excessive rate of rise of anode current—series inductor
  - excessive rate of rise of off-state voltage—snubber circuit network.
- To turn an SCR on, the anode and gate must both be positive with respect to the cathode.
- For an SCR to turn on and remain on, the anode current must rise to a value above the latching current.
- If the anode current in a conducting SCR falls below the holding current, the SCR will turn off.
- The latching and holding currents have very small values when compared with the anode current rating of an SCR. The latching current is slightly higher than the holding current.
- The process of turning an SCR off is called commutation.
- An SCR may be commutated by:
  - reverse biasing the SCR with a charged capacitor
  - reverse biasing the SCR with an a.c. supply
  - injecting a pulse of current from cathode to anode.
- The gate pulse for an SCR, GTO thyristor and a triac should ideally have a very fast rise time. This pulse need only be of short duration ( $\mu$ s) but must contain sufficient energy to trigger the thyristor.
- The triggering sensitivity of thyristors increases with increases in temperature.
- As gate current increases, the break-over voltage required for a thyristor decreases.
- A GTO thyristor is similar to an SCR, the major difference being that it may be commutated by injecting a pulse of current from cathode to gate.
- The triac is a three-terminal bilateral conducting device.
- The triac operates in the same manner as an SCR, except that it can conduct current in both directions.
- A triac may be triggered by both positive and negative gate pulses.
- A triac may be triggered in one of four modes:
  - mode 1:  $T_1$  and gate positive with respect to  $T_2$
  - mode 2:  $T_1$  and gate both negative with respect to  $T_2$
  - mode 3:  $T_2$  positive and gate negative with respect to  $T_1$
  - mode 4:  $T_2$  negative and gate positive with respect to  $T_1$
- When triggering a triac:
  - mode 1 is the most sensitive
  - mode 2 and 3 are only slightly less sensitive
  - mode 4 is the least sensitive and is rarely used.
- Where trigger pulses of only one polarity are available, such as those from a UJT trigger circuit, negative pulses are used so that the triac is triggered in modes 2 and 3.

triacs are also mounted on heat sinks to prevent excessive junction temperatures.

Devices used to develop trigger pulses for thyristor devices are called trigger devices, the most common being:

- the unijunction transistor (UJT)
- the programmable unijunction transistor (PUT)
- the diac.

The UJT is a three-terminal device that has a high resistance from base 2 to base 1, typically 5 to 10 k $\Omega$ .

When the voltage applied to the emitter of the UJT is sufficiently high to overcome the internal voltage drop, plus the barrier potential across the emitter-base 1 junction, the emitter conducts heavily, releasing current carriers and causing the resistance between the emitter and base 1 to decrease to only a few hundred ohms.

The emitter voltage that causes conduction is called the peak point voltage. This value is dependent on the supply voltage and the intrinsic standoff ratio  $\eta$  of the UJT.

The UJT is used in conjunction with an RC timing circuit to produce a pulse to trigger thyristor devices. The circuit is called a UJT relaxation oscillator. The frequency, or time period, of the output pulses is controlled by the time constant of the RC timing circuit.

The major disadvantage of the UJT is that it is a low power device and cannot deliver sufficient energy to trigger thyristors with a high current rating.

The programmable unijunction transistor, developed to overcome the disadvantages of the UJT, is actually a three-terminal thyristor, similar to an SCR.

The PUT is triggered when current flows from anode to gate. This occurs when the anode is 0.5 V more positive than the gate.

The PUT is used in a similar manner to the UJT. The voltage on the gate is programmed by external resistors. The voltage fixes the peak point voltage, hence the term programmable unijunction transistor.

The standoff ratio of a PUT trigger circuit may be varied by changing the ratio of the programming resistors with respect to one another.

Like the UJT oscillator, the PUT oscillator is controlled by the time constant of the RC timing circuit.

The diac is a two-terminal bi-directional conducting device. The diac conducts when the break-over voltage is exceeded. This value will be:

- 20 to 30 V for symmetric devices such as the ST2 diac
- 7 to 9 V in one direction and 14 to 18 V in the other direction for asymmetric diacs such as the ST4 diac.

The diac is used in situations where bi-directional trigger pulses are required.

When used in conjunction with an RC timing circuit and connected to an a.c. supply, the diac produces bi-directional trigger pulses.

Due to the relatively high break-over voltages, diacs are not suited to extra-low voltage applications.

Phase control techniques are commonly used in thyristor

circuits to control load power. Control of load power is achieved by varying the average RMS voltage or RMS (a.c.) circuit load voltage.

When employing phase control techniques, load voltage is varied by chopping up the a.c. supply waveform with either a controlled rectifier or an a.c. controller.

Load voltage is controlled in phase control circuits by controlling the point at which the thyristor is triggered on. The triggering is delayed, later than triggering the thyristor at the start of a half-cycle. The angle of delay is called the *trigger angle*.

As the trigger angle is increased, the time through which the thyristor conducts is decreased and the RMS voltage, average or RMS, is decreased. The time through which the thyristor conducts is called the *conduction angle*.

For resistive loads, the trigger angle plus the conduction angle equals 180°.

Phase control circuits have the disadvantage that when the thyristors are triggered:

- harmonics may be generated that reflect back into the supply
- radio frequency interference (RFI) is generated.

Radio frequency interference (RFI) may be minimized by the use of suppression circuits.

For loads such as heating elements, load power may be controlled by using zero voltage switching (ZVS). This involves turning thyristors on only when the supply voltage is at or near zero volts.

When using ZVS, load power is controlled by turning thyristors on for a given number of cycles, then off for a given number. The average load power is controlled by varying the on to the off time (or cycles) of the thyristors.

When controlling a.c. loads, an integrated-circuit ZVS usually turns the thyristor on at the commencement of the positive half-cycle of the supply, and allows the full cycle to be completed to ensure a symmetrical load voltage.

Average power in a d.c. load may be controlled by using an a.c. supply and a controlled rectifier. The average load voltage is controlled by controlling the trigger angle of the thyristors.

Average power in an a.c. load, where a ZVS is not suitable, may be controlled by using an a.c. supply and an a.c. controller. The RMS load voltage is controlled by controlling the trigger angle of the thyristors.

Loads such as induction motors and fluorescent or neon tubes need a ZVS.

A solid state relay (SSR) is a combination of a thyristor, usually a triac, and a ZVS.

Fault finding in thyristor circuits is best achieved by following a logical systematic procedure and building up past experience.

Often an obvious fault in a thyristor circuit has been caused by some other fault. Thorough testing is essential to eliminate all faults in equipment.



1. Discuss the advantages and disadvantages of rheostat control.
2. Discuss the advantages and disadvantages of reactor control.
3. What are the disadvantages of using a tapped reactor for speed control compared with rheostat speed control?
4. Compare the relative advantages of zero-voltage switching and phase control.
5. What are the disadvantages of using variable semiconductor devices for high-power speed control?
6. What is the function of a trigger circuit in a thyristor converter?
7. With reference to thyristor power control, what is the main difference between phase control and zero-voltage switching?
8. Give two applications for a.c. power control.
9. Draw the standard symbol used for a phase-controlled rectifier (SCR) load at terminals.
10. What polarity conditions of the anode and gate must be met for an SCR to switch from the off state to the on state?
11. What is the function of a bias and return an SCR?
12. Draw the significance and the meaning of:
  - (a) the SCR latching current.
  - (b) the SCR holding current.
13. Draw a typical SCR commutation circuit.
14. Give two methods of commutating an SCR.
15. Describe the effect of gate current on the forward break-over current of an SCR.
16. Draw the standard symbol for a GTO thyristor and state its functions.
17. Draw the standard symbol for a triac and state its functions.
18. Explain the significance and the meaning of:
  - (a) the triac latching current.
  - (b) triac holding current.
19. Explain how a GTO thyristor is commutated.
20. Draw circuit diagrams for the two modes of operation of a triac: (a) forward and (b) reverse. Indicate which is the most efficient and which is the most sensitive.
21. Give two applications for a triac.
22. Draw the standard symbol for a triac with a bidirectional switching.
23. Explain how the frequency of the output pulse from the SCR is determined.

- 15.24 Explain the significance and meaning of:
  - (a) peak-to-peak voltage.
  - (b) average (average) value.
- 15.25 Explain what is meant by  $R_{TH}$  and how it is generated.
- 15.26 Draw a circuit diagram showing how  $R_{TH}$  may be suppressed and prevented from being reproduced in the supply system.
- 15.27 Discuss the advantages and disadvantages of phase control of an SCR to control load power.
- 15.28 Explain how the load voltage from a controlled rectifier is varied.
- 15.29 What is the relationship between the trigger angle and the conduction angle in the output of a controlled rectifier?
- 15.30 The diodes and SCRs in a half-bridge bridge rectifier are said to be in a 50 per cent duty cycle. Explain what this means and its significance.
- 15.31 If a half-bridge bridge is replaced by a fully-controlled bridge, what effect will this have on the output voltage for a given trigger angle?
- 15.32 Explain what is meant by the voltage effect of a triac-like a.c. controller and state briefly what causes the effect.
- 15.33 Draw a circuit diagram showing how a triac may be controlled by a full bridge in such a way that an a.c. load may be controlled.
- 15.34 Draw a circuit diagram showing how a triac trigger circuit may be modified to reduce the voltage drop.
- 15.35 Describe how the load voltage from an a.c. controller is varied.
- 15.36 Why is the triggering of a triac set up for modes 2 and 3 triggering when unidirectional pulses are used? Why are modes 1 and 4 not used?
- 15.37 What would be the advantages of using a pair of forward parallel SCRs in place of a triac in an a.c. controller?
- 15.38 Draw the relevant waveforms on sulphur paper for a triac controller with a GTO trigger circuit as shown in figure 15.11 for a trigger angle of  $120^\circ$ .
- 15.39 Explain what is meant by zero-voltage switching (ZVS).
- 15.40 Explain why zero-voltage switching is used in preference to phase control when using thyristors to control load power.
- 15.41 In what form of load is zero-voltage switching most useful?
- 15.42 Explain why zero-voltage switching is not useful in speed control of large motors.

SELF-TESTING PROBLEMS

- 15.43 For the circuit shown in figure 15.61, determine:
  - (a) the power in the load when the rheostat is set to  $10 \Omega$ .
  - (b) the power loss in the rheostat for this setting.
  - (c) the input power.
  - (d) the efficiency.

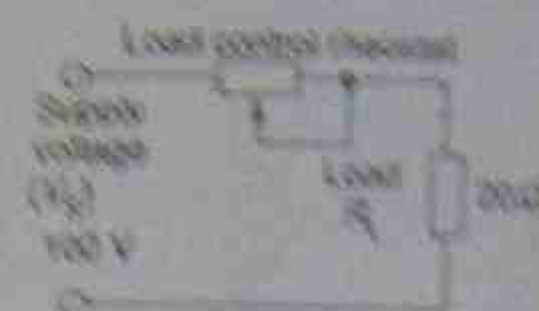


Figure 15.61 • Rheostat load control

- 15.44 For the circuit shown in figure 15.62, find:
  - (a) the power in the load.
  - (b) the efficiency.

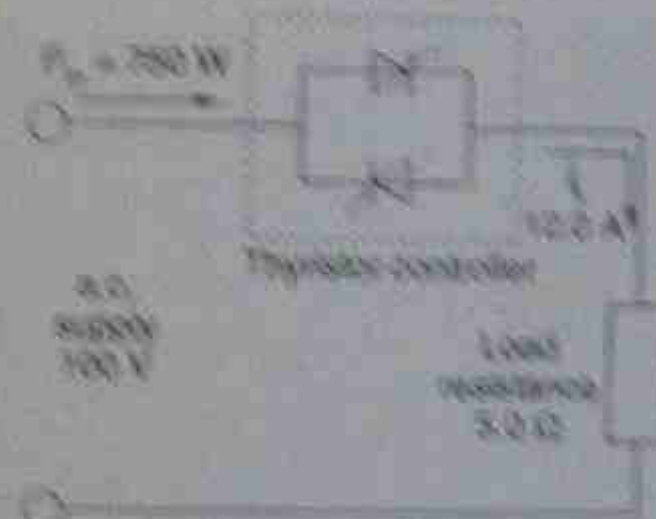


Figure 15.62 • Thyristor power control

- 15.45 A UJT oscillator circuit has a 15 V supply and a stand-off ratio of 0.7. Determine the peak-to-peak voltage.

- 15.46 For the UJT oscillator in figure 15.63, find:
  - (a) the stand-off ratio.
  - (b) the peak-to-peak voltage.
  - (c) the time constant of the RC circuit.
  - (d) the frequency of the output pulse.

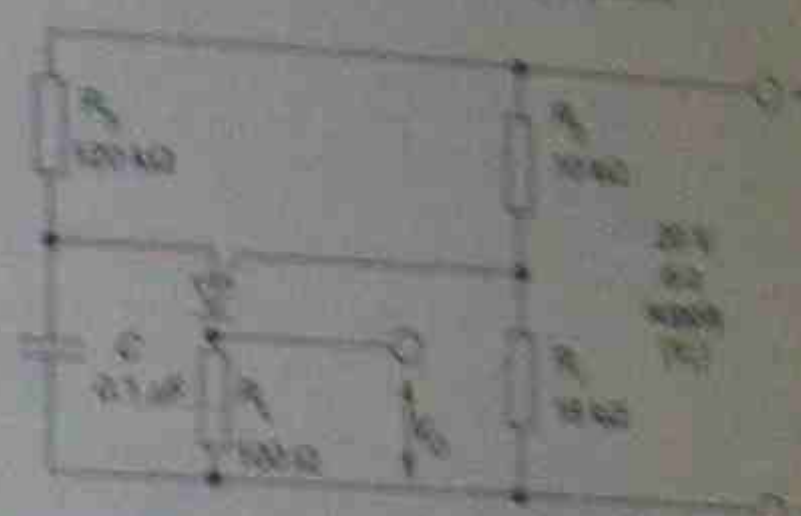


Figure 15.63 • UJT oscillator

- 15.47 A single-phase half-wave controlled rectifier is supplied from a 100 V a.c. source. Determine the load voltage for trigger angles of:
  - (a)  $30^\circ$ .
  - (b)  $150^\circ$ .
- 15.48 A single-phase half-bridge bridge rectifier is supplied from a 240 V source. Obtain the load voltage when the trigger angle is:
  - (a)  $60^\circ$ .
  - (b)  $150^\circ$ .
- 15.49 Calculate the minimum peak inverse voltage rating required for the circuit diodes and SCRs in question 15.48.
- 15.50 A single-phase a.c. triac controller is supplied from a 100 V a.c. source. Determine the load voltage at trigger angles of:
  - (a)  $30^\circ$ .
  - (b)  $150^\circ$ .



# Chapter 17

## Electrical drawing

### 17.1 INTRODUCTION

In previous chapters, electrical circuits have been introduced. In these circuits batteries, switches, lamps and resistors were depicted. All these devices were represented by symbols. Called *graphical symbols* they represent some object without any further explanation or written text. Graphical symbols are used in everyday life. Examples include the stylised figure of a man and a woman to represent male and female toilets. Graphical figures are seen on road signs, indicating bends or curves, or slippery conditions ahead.



Figure 17.1 • Easily recognised graphical symbols

Graphical symbols can be used and interpreted by people speaking different languages. This allows people who speak different languages both to draw and to read electrical circuit diagrams that are able to be understood by all.

Electrical schematic circuit diagrams are stylised graphical representations of components and the connections between components in an electrical circuit. They do not necessarily represent the appearance of the circuit. However, what they do show, in a formal and easy to interpret manner, is how a circuit operates.

Schematic circuit diagrams and diagram layouts have been refined over many years. Symbols representing circuit components have changed so that they are easier to both recognise and draw.

All electrical drawings should conform to the current AS/NZS 1102—*Graphical Symbols for Electrotechnology*. This is divided into various sections, each covering a specific group of symbols. When all drawings are carried out according to the relevant standard practice in the use of symbols, they become universally easier to read and understand.

The list of symbols in AS/NZS 1102 is extensive, and not all of them will be shown in this chapter. Electrical trades trainees should make themselves familiar with the relevant section of AS/NZS 1102, covering the symbols that they could use in their particular vocation.

### 17.2 CIRCUIT DIAGRAMS

When the notations of electrical circuits were first made in the 19th century, the representations were simply what the drawer saw, like a simple sketch. It was eventually realised that no matter how carefully and accurately they were drawn, the various connections were hard to see. To make them easier to follow the drawings were stylised. This meant that the wires and components were deliberately separated and drawn apart. This was done even though the drawing did not look exactly like the layout.

It was evident that this procedure did not give a really clear picture of all components and their connections. It was then decided to make all drawings in the one plane,

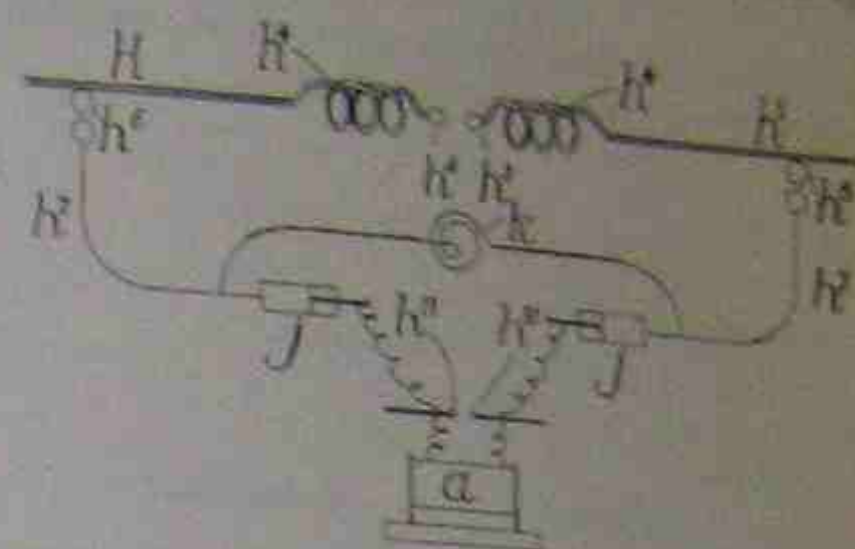


Figure 17.2 • Very early electrical circuit drawing (1897)

as if the viewer were looking down from above. Even this did not give a clear picture until the various styles and shapes of the one component, say a lamp or switch, were represented with a single symbol.

As the years passed, and circuits became more complex, many drawers of electrical circuits made up their own symbols to represent components. Quite often a key was given with the drawing, listing what the symbols represented. Eventually circuits in the one country tended to be drawn similarly. This then led to a national or standardised style of drawing.

Eventually an international body The International Electrotechnical Committee (IEC) formulated an international standard of graphical representation.

Some companies, and organisations in different countries, at first ignored the suggested standards and still produced their own versions of symbols. Most countries which adopted the metric standard of measurement then also adopted the IEC symbols. AS/NZS 1102 is very close to the IEC standard and practically all Australian organisations follow it.

### 17.3 CONVENTIONS IN LINE WORK

In actual circuits the components in the circuits are connected by conductors. These may be actual wires or copper tracks on a printed circuit board. In most normal circuits the conductors are considered to have negligible resistance, as far as that particular circuit is concerned. This is illustrated in Figure 17.3.

The conductors themselves are always represented by straight lines. These lines may join to the circuit components, or to other conductors. When conductors connect to other conductors, they are usually indicated by a distinctive dot at the join. This is shown in Figure 17.4(a). Conductors can be offset so that there can be no confusion, or they can be straight lines at right angles. The connection is indicated by the dot at the point of connection. It should be noted that if no dot is shown there is no

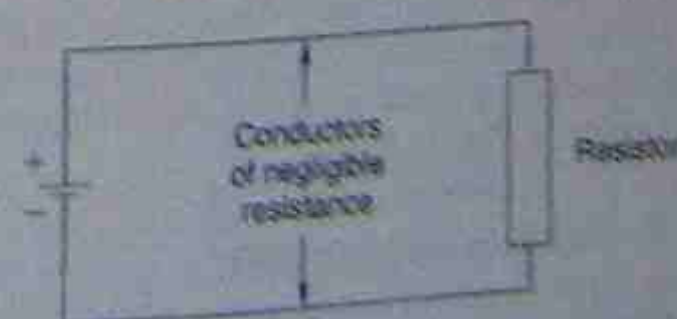


Figure 17.3 • Conductors between components in a circuit are considered to have negligible resistance



connection. See Figure 17.4(b), which shows conductors crossing but not connected to one another.

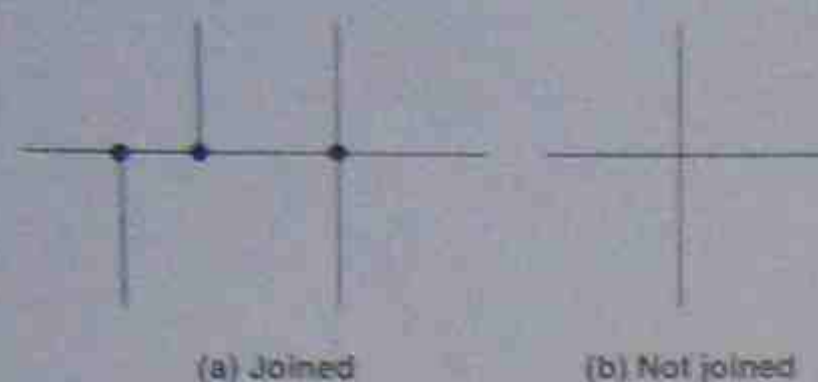


Figure 17.4 • Representation of conductors joining at (a) and not joining at (b)

When lines representing conductors must cross in a schematic circuit diagram, they should do so at right angles or as close to right angles as possible. There is no necessity to indicate in any way that crossing conductors are not joined and certainly no dot is shown at the point of crossing.

In some diagrams conductors both cross and join. To avoid any possible confusion the conductors are often offset, as shown in Figure 17.4(a). As an alternative to this method the ends of the lines representing the conductors are sometimes displaced sideways at 45° at a distance of about 3 mm. A dot is then placed at the point of each join.

## 17.4 SYMBOLS USED IN ELECTRICAL CIRCUIT DIAGRAMS

It is not possible to list all the AS/NZS 1102 symbols, but some of the more common are shown in Figure 17.5. There is no definite size for symbols but all symbols in the same drawing should be the same relative size and proportion. It is suggested that a 5 mm grid be used when determining the size and proportions of symbols.

## 17.5 PLACEMENT OF CIRCUIT COMPONENTS

### 17.5.1 Connections to symbols

Connections to circuit symbols in schematic circuit diagrams should be made at some distance (about 5 mm) from the circuit symbols and not on the symbols themselves. This is done so that the outlines of the symbols are not confused with closely drawn conductor lines.

### 17.5.2 Arrangement of components

Symbols should be placed symmetrically so that they are easy to see and interpret. They should also be placed in line, or in the same relative position, if they are similar. In the one drawing, symbols should be placed evenly across the diagram (see Fig. 17.6).

### 17.5.3 Parallel components

In electrical circuits, two components are often placed in parallel. If one symbol has more importance than another it is placed in the same line as the conductor and the parallel symbol is offset. If they both have the same importance, then they are placed evenly each side of the conductor line. Both these features can be seen in Figure 17.7.

allel symbol is offset. If they both have the same importance, then they are placed evenly each side of the conductor line. Both these features can be seen in Figure 17.7.

## 17.6 DRAWING SCHEMATIC CIRCUIT DIAGRAMS

To make schematic circuit diagrams easier to read, certain conventions are used in their layout. One is that the flow of energy, or flow of 'signal' and sequence of operation or events, is from left to right and top to bottom. At times it might be difficult to adhere exactly to this convention but it is followed as closely as possible.

Consider the simple schematic circuit diagram in Figure 17.6. The power supply is on the left and current flow is to the right through the main switch to operate the three loads. Load 1 and Switch 1 are to the left of Load 2 and Switch 2. Similarly Load 3 and Switch 3 are further to the right. When each is operated, current flows from top to bottom through each load. Note that both switches and loads are in line to make the diagram easier to read and understand.

The important thing to remember is that a schematic circuit diagram might have no resemblance to the actual physical components of the circuit. It must be emphasised that a schematic circuit diagram is a theoretical representation of the components and the connections to and between them. A circuit diagram is intended to show how an electrical circuit operates. Other forms of diagrams are used to show how a circuit is actually constructed.

To see something more complex, examine the schematic circuit diagram of the electric motor starter in Figure 17.8. There are special features in this circuit representation. Note the thicknesses of the lines. The left-hand part of the circuit is drawn in lines twice as thick as that on the right-hand side. This is because this section represents the *power circuit* of the motor starter. Power passes from the supply at the top to the motor beneath. The *starter* conducts current through either one of two contactors to the motor windings. One contactor allows the motor to rotate in one direction while the other allows reverse rotation by reversing the connections to two of the motor phase windings.

The *control circuit* is drawn in thinner lines because it takes no part in transferring energy to the motor and, in fact, the actual currents in the circuit may be only about 100 mA or so. The thinner lines emphasise this factor.

When the *start forward* push-button switch is pressed, current flows through the normally closed *stop* push-button through the normally closed interlock K2/5 to the relay K1/5. It then flows through the normally closed overload contact and back to line. When K1/5 is energised it open-circuits the interlock contact K1/5 and isolates the reversing contactor K2/5. The coils K1/5 and K2/5 are part of devices called *contactors*. When energised they operate all its associated switch contacts. The contactor called K1 and the figure 5 under the K1 signifies that it has 5 associated contacts. So when this coil is energised, all its associated switch contacts (K1.1, K1.2, K1.3, K1.4 and K1.5) operate. The first three switch contacts supply power to the motor. Contact K1.4 is part of the control circuit and, because it is in parallel with the *start* push-button

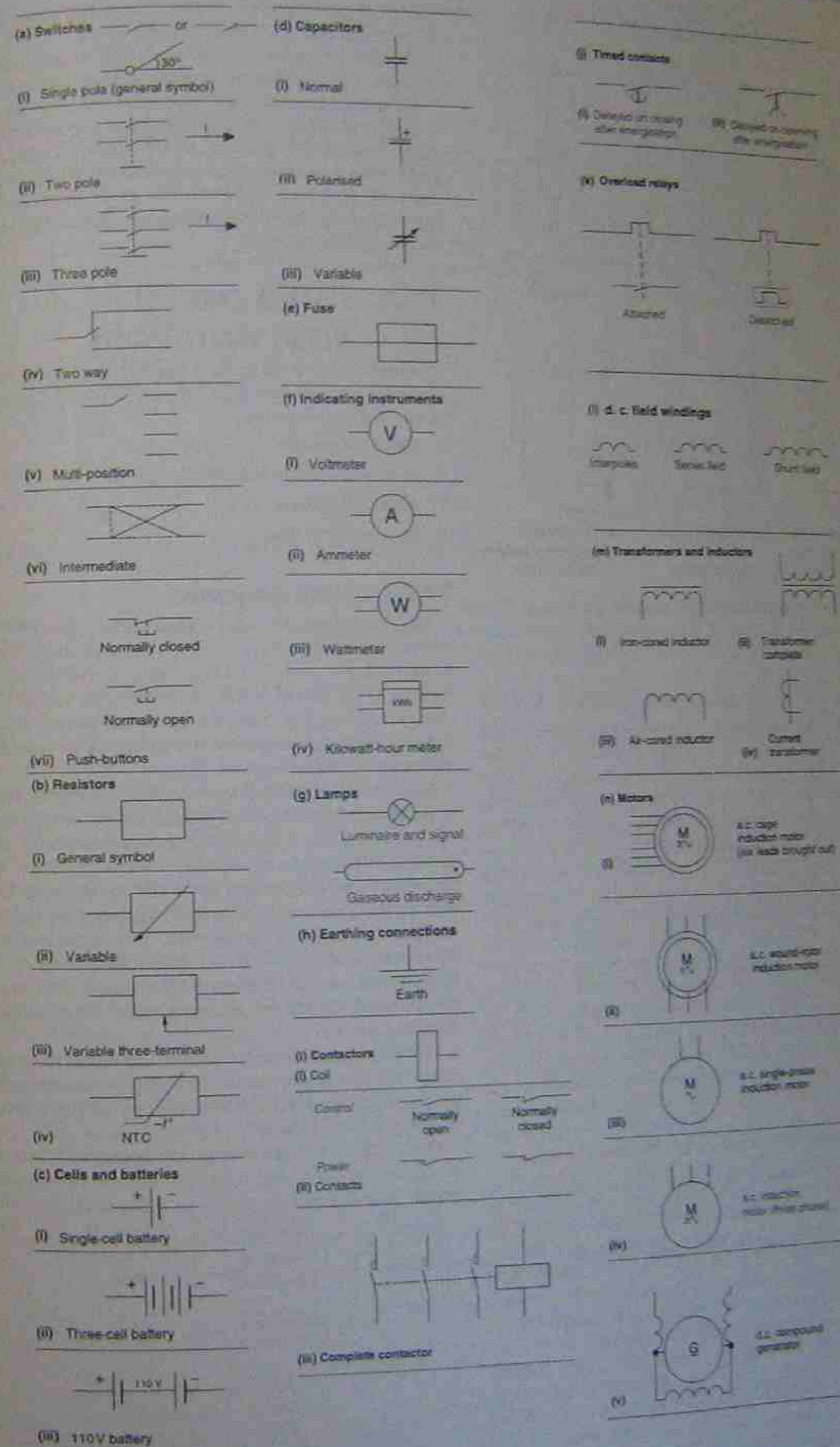


Figure 17.5 • Some commonly used electrical circuit symbols



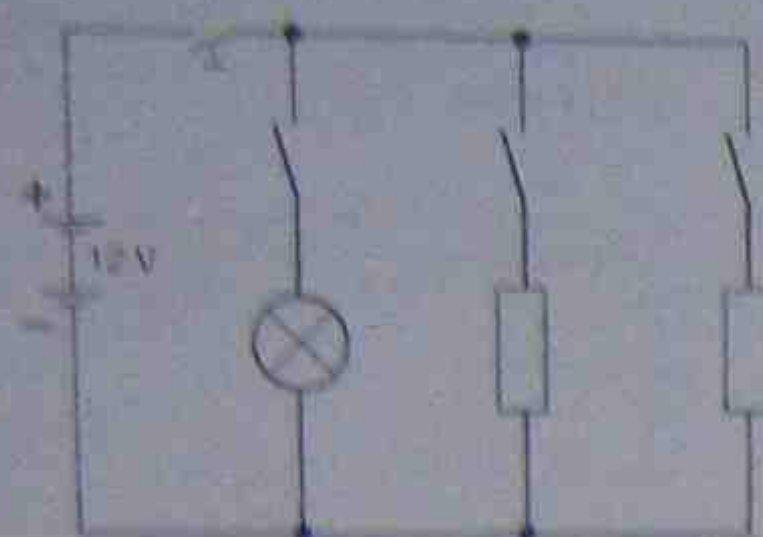


Figure 17.6 • Symbols placed symmetrically are easier to interpret

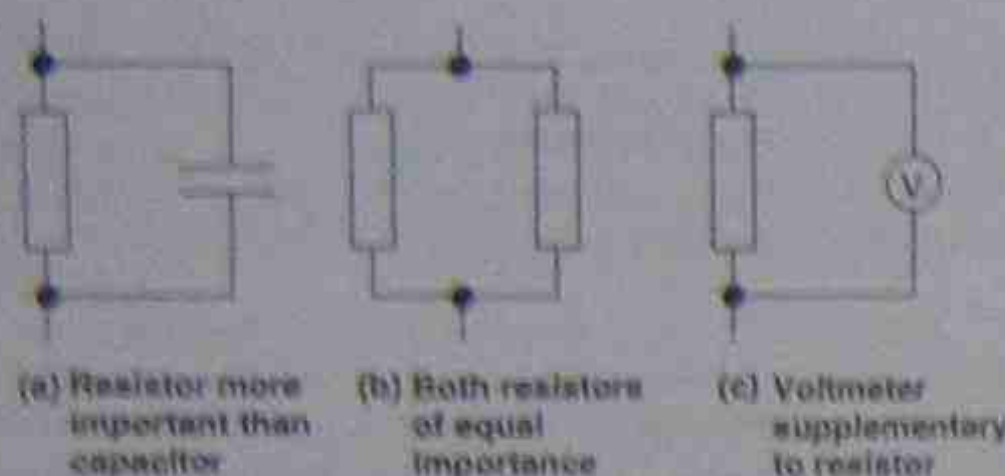


Figure 17.7 • Parallel connection of circuit components

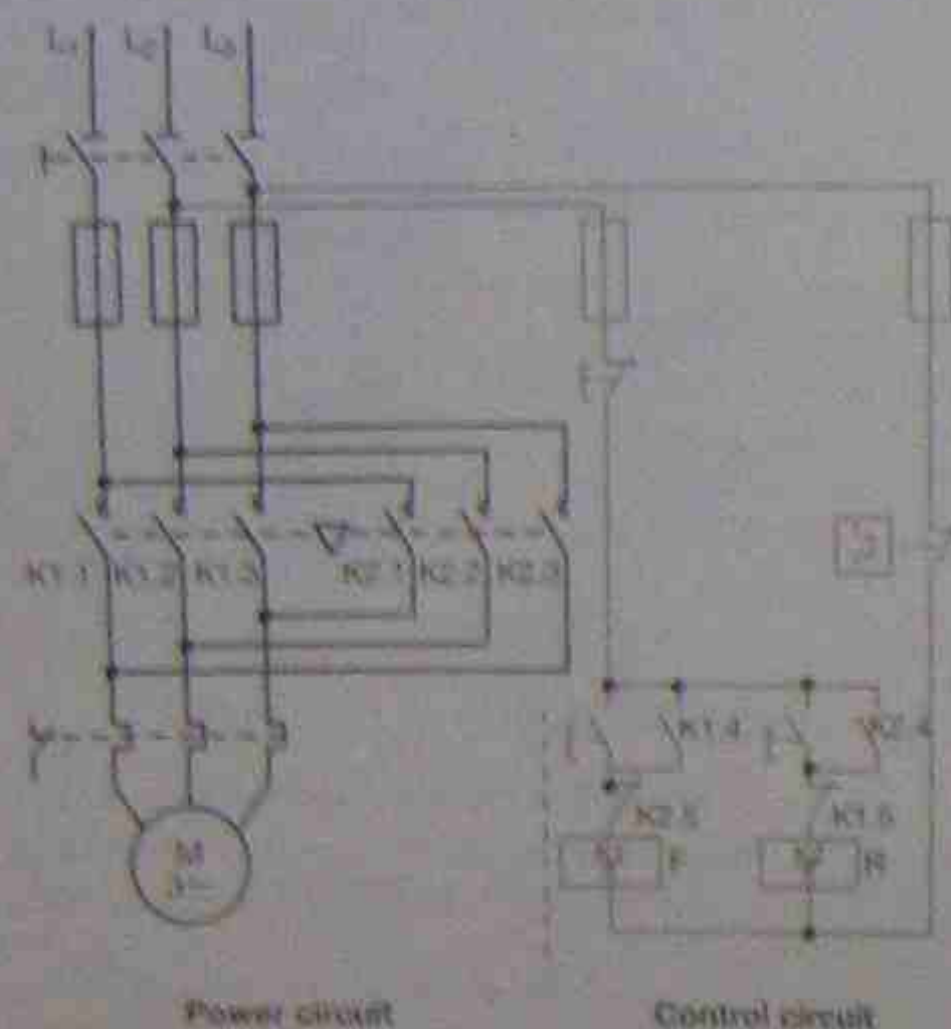


Figure 17.8 • Schematic circuit diagram of a motor starter

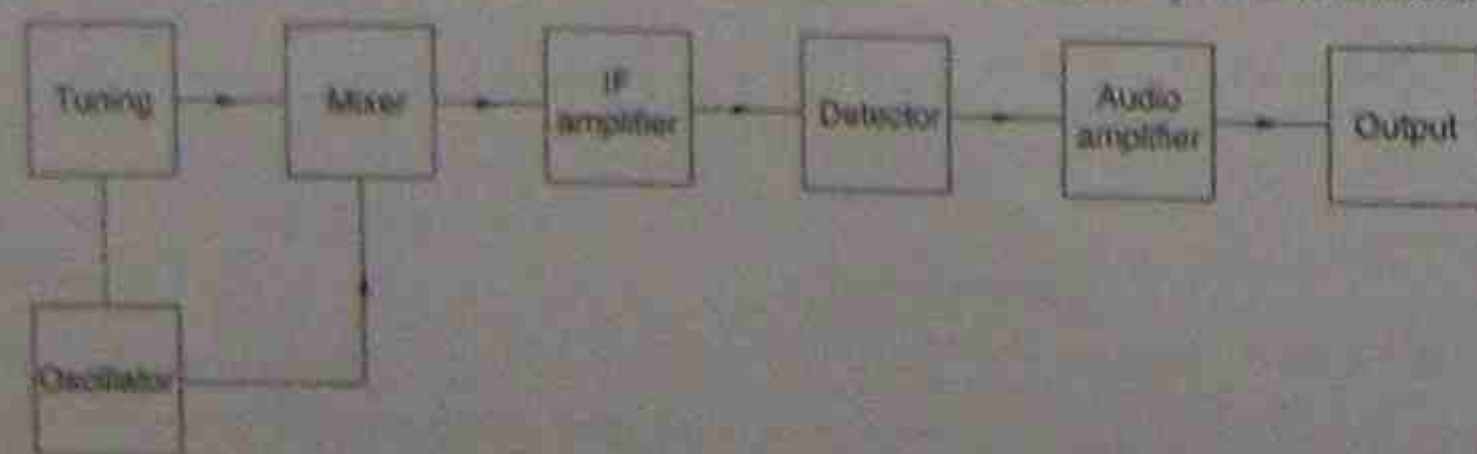


Figure 17.9 • Block diagram of an AM radio receiver

switch, it takes its place in the circuit. The start switch can be released and K1/5 remains energised.

To stop the motor the stop push-button switch is pressed and all coils and contacts return to their 'off' state.

Now, note how the flow of energy and the sequence of events was either from left to right or top to bottom. Also note that all the contacts of the switches are drawn in their normal or de-energised condition. When switch contacts are operated, either manually or from their associated coils, the line representing the operating part of the switch rotates clockwise.

## 17.7 OTHER CIRCUIT REPRESENTATIONS

Schematic circuit diagrams have been mentioned, but electrical circuits can also be represented in other ways. Some of these ways are:

- block diagrams
- single-line diagrams (dealt with in later work)
- wiring diagrams
- architectural diagrams.

### 17.7.1 Block diagrams

A block diagram shows what a circuit does, not how it works. It is an overall picture of why a particular circuit is used and the function of groups of components in a circuit. It is useful when a particular circuit is more complex. In many cases an electrical worker might first look at a block diagram of a circuit before reading the schematic circuit diagram.

Refer to Figure 17.9. It is a block diagram of a small AM transistor radio receiver. Although the actual circuit might appear complex, it is made from seven separate sections. The block diagram shows these seven sections. Without knowing exactly how the radio circuit operates, the function of the circuit can be easily explained from the block diagram. Compare this with the actual schematic diagram shown in Figure 17.10. This circuit is not for study purposes but is only an illustration showing how a complicated circuit can be represented by a simple block diagram.

Block diagrams usually do not show any power supply. They do not represent actual circuit connections but merely explain what the circuit does, so there is no need to include these details.

Figure 17.11 is a simpler block diagram. It represents a regulated supply connected to an electrical load. The input from the mains passes to a block on the left called

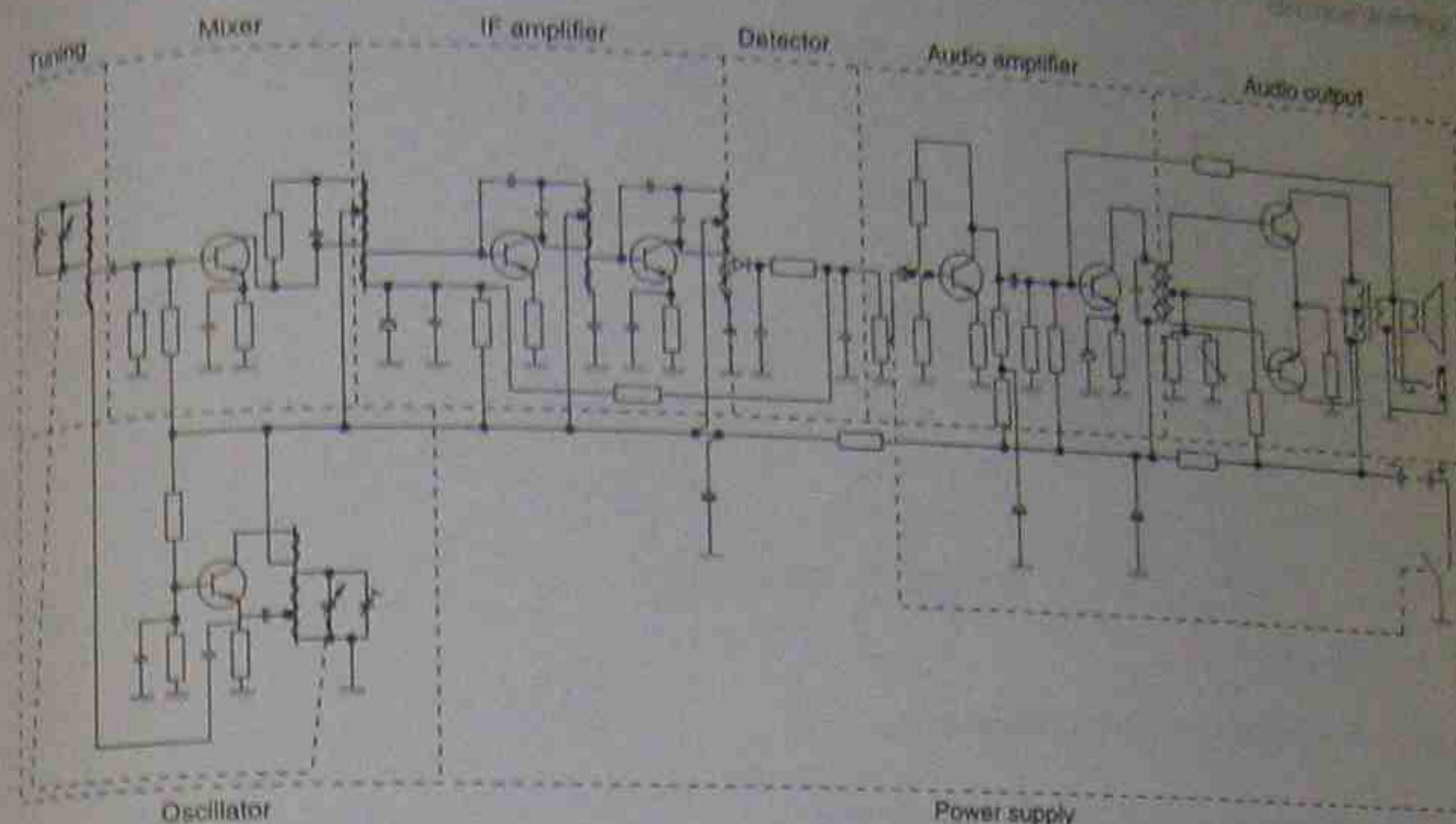


Figure 17.10 • Schematic circuit diagram of a small AM radio receiver

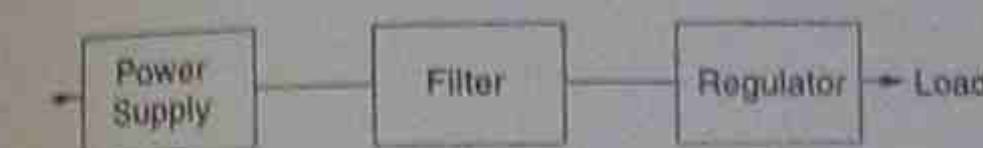


Figure 17.11 • Block diagram of a regulated power supply

the power supply. This could be an a.c. to d.c. rectifier unit. Its output then passes through another block called a filter to a block labelled regulator. This regulates the voltage to a predetermined value. The regulated voltage is then passed to the load.

Figure 17.12 is a block diagram of a motor starting circuit. The arrows on the lines indicate the sequence and purpose of each circuit block. The a.c. supply from the mains is connected to the line contactor. However, it cannot operate until allowed to do so by the control and timing circuit. When the control circuit is activated (usually by a push-button switch) the line contactor closes and supplies energy to the motor through the current-limiting starting resistors. The motor starts up and, after a predetermined time, when it is up to nearly full speed, the accelerating contactor closes and bypasses the starting resistors. Full supply is now provided to the motor, enabling it to develop full power. By operating a stop

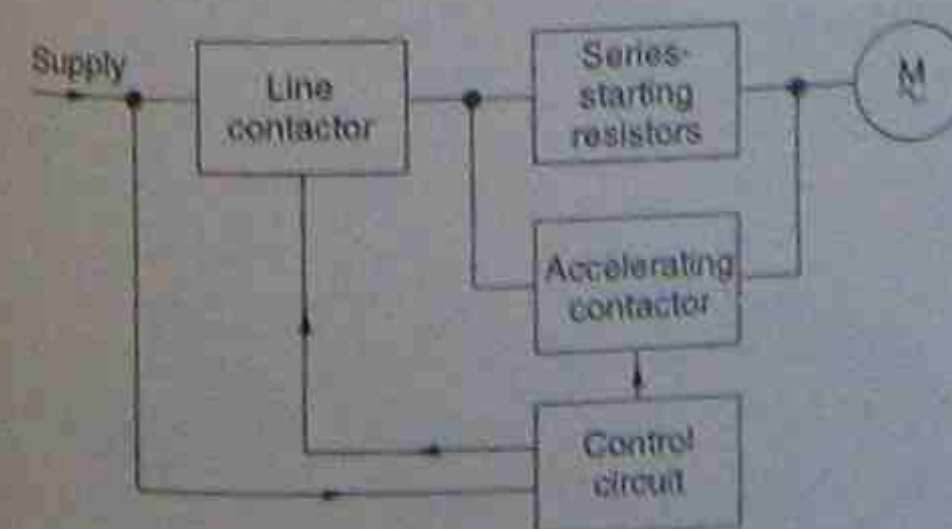


Figure 17.12 • Block diagram of a motor starting circuit

push-button switch, the control circuit opens all the contactors and the motor stops. Figure 17.14 shows a wiring diagram for this starter.

### 17.7.2 Wiring diagrams

A wiring diagram is much closer to the real thing than a schematic circuit diagram. A wiring diagram is a stylised true representation of the components and wiring of an electrical circuit. It would be possible to take a photograph of the wiring of a circuit but it would be of little use if it was necessary to know exactly how all the connections are made. The problem is that the wires may be bunched together, or connections may be made in an area below or behind another object. This would make a photograph extremely difficult to follow.

In a wiring diagram, lines representing the conductors are drawn straight and separate. They are usually evenly spaced and are all connected to circles representing the terminals on the circuit components. In addition, where more than one conductor line terminates at a terminal, all lines are angled to the terminal circles, so there is a clear indication where each line (representing a conductor) starts and finishes.

A representation of the wiring of two lights can be seen in Figure 17.13. In this diagram the actual circuit components (switches and lampholders, in this case) are drawn in the same relative position they would be in an actual circuit. The terminals of the lampholders and switches have been emphasised to show exactly where each conductor connects. For clarity the lamps have been separated from the lampholders in this instance.

A wiring diagram is seldom drawn to scale but in some cases it may be in direct proportion to the shape of the object represented. In Figure 17.13, both the lamps and switches could be some distance apart. If it were drawn to scale, or even in proportion, the component parts would be too small to be of any use. What has been done is that



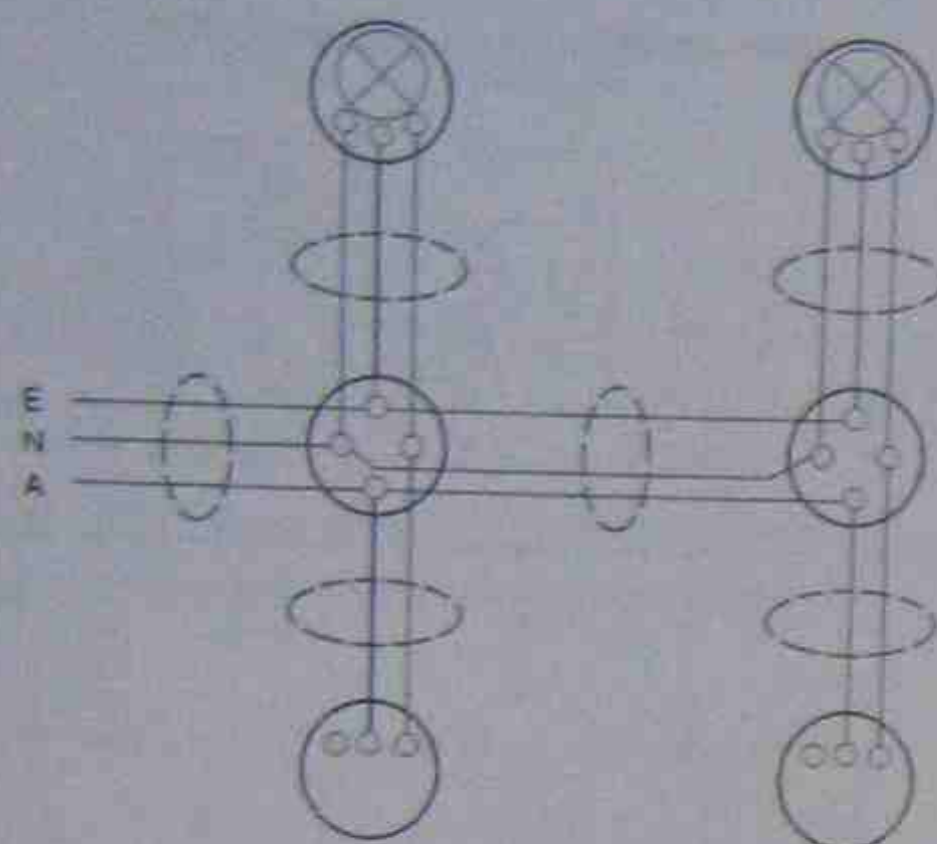


Figure 17.13 • Wiring diagram of a simple lighting circuit

all the lines representing the wires have been shortened so that their actual connections to the components are clear.

Another wiring diagram of the previous motor starter is shown in Figure 17.14. In this case all the components are in proportion, both in outline and position. It is a true representation of the motor starter but not drawn to any particular scale. Note that the outlines of all components are drawn as dashed lines. In addition, the schematic circuit diagram symbols have been inserted to show the actual operation of the circuit components. The greatest prominence is given to the lines representing the wiring conductors and the circles representing the terminals.

The main point to note about wiring diagrams is that the conductors are all separated and, as far as possible, equally spaced. Note also the manner in which many conductors have been angled as they connect to the terminals. In a wiring diagram, connections are only made at terminals. In a schematic circuit diagram, connections between conductors are made away from the components and may be shown at any point on a given conductor. Schematic circuit diagrams do not represent the actual physical circuit layout; wiring diagrams do.

Drawing a wiring diagram is, in effect, wiring up the circuit or apparatus on paper. Each conductor line drawn between terminals represents an actual insulated cable, cut to length, bared of insulation at the ends, and connected properly to each terminal. Because of this, a wiring diagram is invaluable for actually wiring up a piece of equipment or checking equipment when looking for a fault.

In many cases a designer of a piece of equipment may first produce a block diagram, then design a schematic circuit diagram, and finally produce a wiring diagram.

### 17.7.3 Architectural electrical diagrams

Architectural drawing and building construction is a large subject and cannot be covered in detail here. The following material will examine how electrical architectural designers indicate to those installing the appliances, switches and outlets the actual layout in the building they have designed.

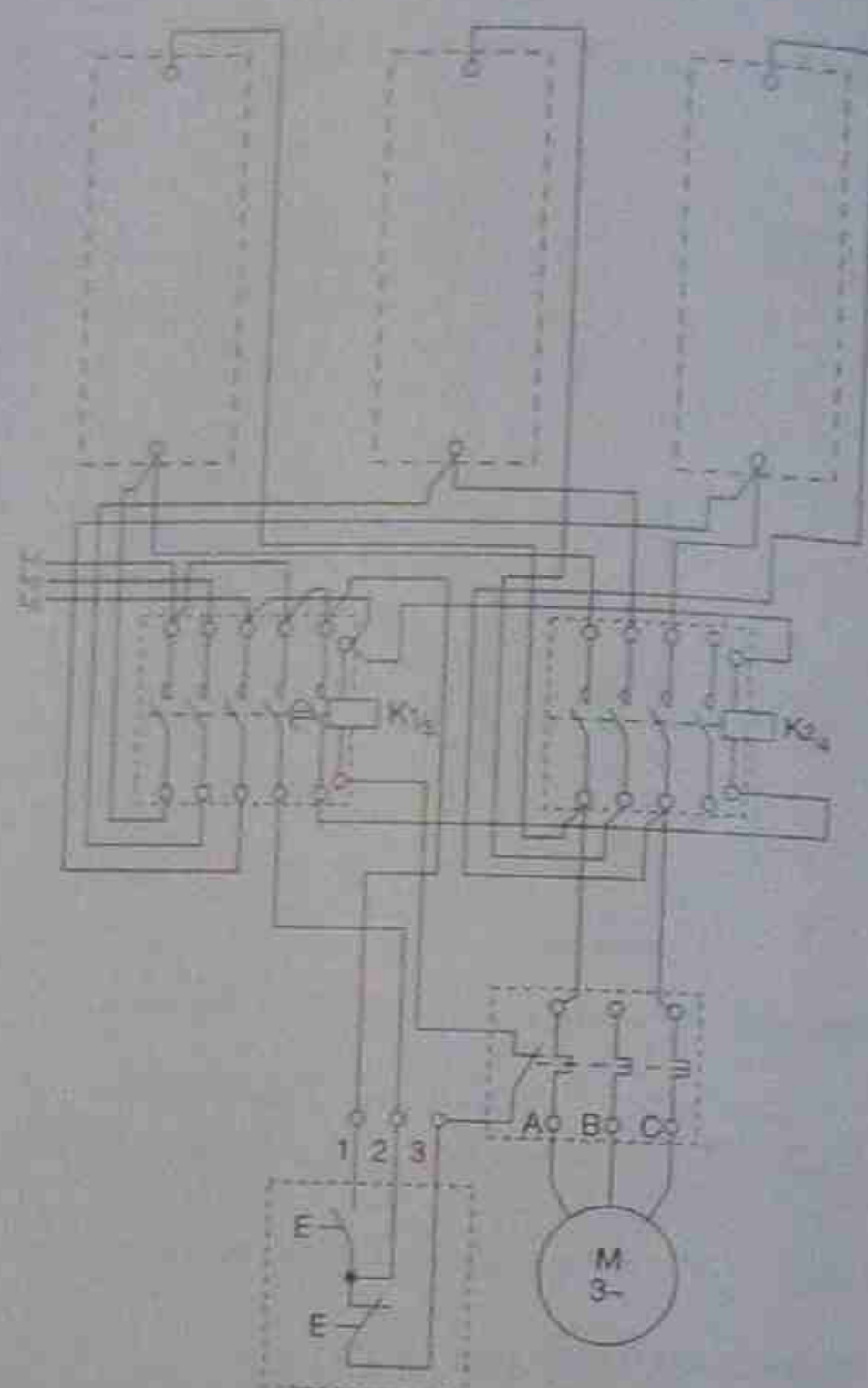


Figure 17.14 • Wiring diagram of an automatic motor starter

An architectural electrical drawing indicates to the installing electrician where the outlets are to be placed. It does not give any detail on how wiring and circuit connections are to be carried out.

In most cases the architectural electrical drawing is accompanied by a set of specifications and a schedule. These may give much more detail on the work to be done.

An electrical architectural drawing is a drawing of the floor plan of a building to which the electrical symbols have been added. A floor plan of a building is a view looking down on the building, imagining that the building had been cut through at a level of 1250 mm from the floor and the upper part removed. This can be seen in Figure 17.15 and the actual floor plan can be seen in Figure 17.16.

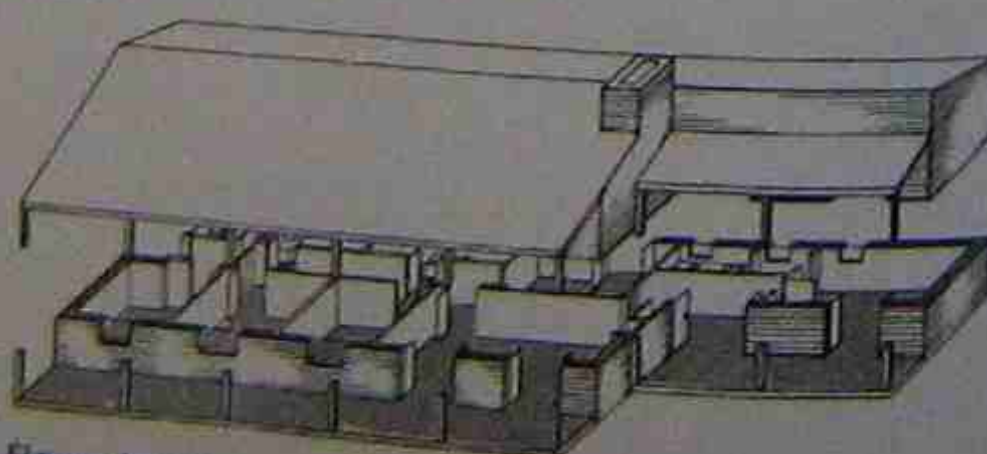


Figure 17.15 • How a floor plan is derived

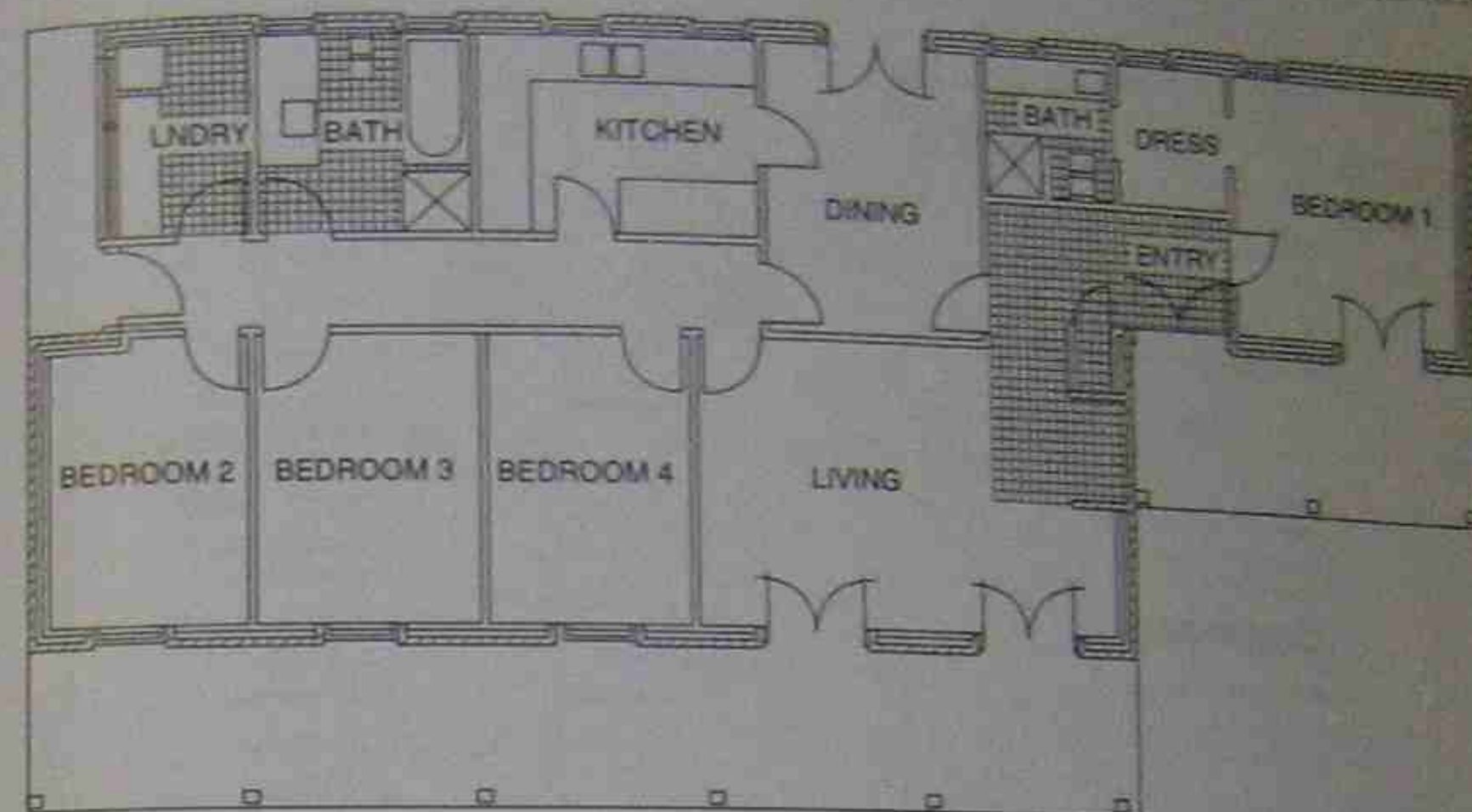


Figure 17.16 • Floor plan derived from a horizontal section of Figure 17.15

Note that the drawing of Figure 17.16 uses certain features that might not be familiar. Check these features with the representations shown in Figure 17.17. These are the most common representations found in domestic floor plans. The features of importance to the installing electrician are doors. The hinge side of the door is important because it is more practical to install light switches on the latch side of the door frame, rather than install it behind the door.

Electrical symbols are drawn on the floor plan to make the architectural electrical drawing. The symbols used on these diagrams are different to those used in either schematic circuit diagrams or wiring diagrams. They have been derived so that they are easy to draw, easy to recognise and distinctive. Examine the symbols illustrated in Figure 17.18.

Figure 17.19 is an architectural electrical plan of a small domestic dwelling. Refer to Figure 17.18 for an explanation of the symbols.

The main feature of the drawing in Figure 17.19 are the symbols representing the outlets (luminaires, general-purpose outlets and appliances) and the switches. Another feature is that there are dashed lines between all switches and luminaire outlets. (Luminaire is the correct technical term for 'lighting fitting'.) The dashed lines simply represent which switches control particular luminaires. They do not represent the path of the wiring; this is left to the installing electrician.

Note that some lights are controlled by more than one switch. These special switches, two-way or intermediate, are indicated on the plan. Also note that the bell push at the front door has a dashed line to the symbol representing the bell in the hall. This tells the electrician where to position the doorbell and that it is controlled from a bell push near the front door.

Note the position of the general-purpose outlets, the major appliances and the main switchboard. The drawing gives no details about how these outlets are to be wired and connected. This is also left to the skill of the installing electrician, who will follow any instructions given in the

specifications and will work within the requirements of Standard AS/NZS 3000.

## 17.8 CONTACTORS AND RELAYS

A relay is simply an electromagnetically operated switch. A contactor is also an electromagnetically operated switch that controls power to a load. A contactor actually is just a large relay and it is sometimes difficult to say whether a device should be called a relay or contactor in any given circuit application.

In effect, the two terms are the same. In this section the term contactor is generally used but reference could also be made to relay contacts and power contacts all operated from the same device.

### 17.8.1 Construction and operation of contactors

A contactor consists of three basic parts—the operating coil, the associated magnetic circuit, and the contacts that are actuated by the coil. Refer to Figure 17.20. This is a representation of a very old type of contactor. It clearly shows the coil, the operating part of the magnetic circuit, and a single contact. Modern contactors look like that shown in Figure 17.21, but the principle of operation is exactly the same as the representation in Figure 17.20. When the coil is energised a magnetic field is produced in the magnetic circuit. This attracts the hinged armature, against the tension of the spring, to complete the magnetic circuit. The movable contact attached to, but insulated from, the armature closes against the fixed contact. When the coil is de-energised the armature springs open and also opens the contact.

Contactors may have many contacts, but those in use in power work seldom have more than six. In most contactors there are at least three power contacts. These contacts are designed to carry the full rated current of the contactor. When used for motor starting duty they are designed to carry five times their rated current for a short time. The



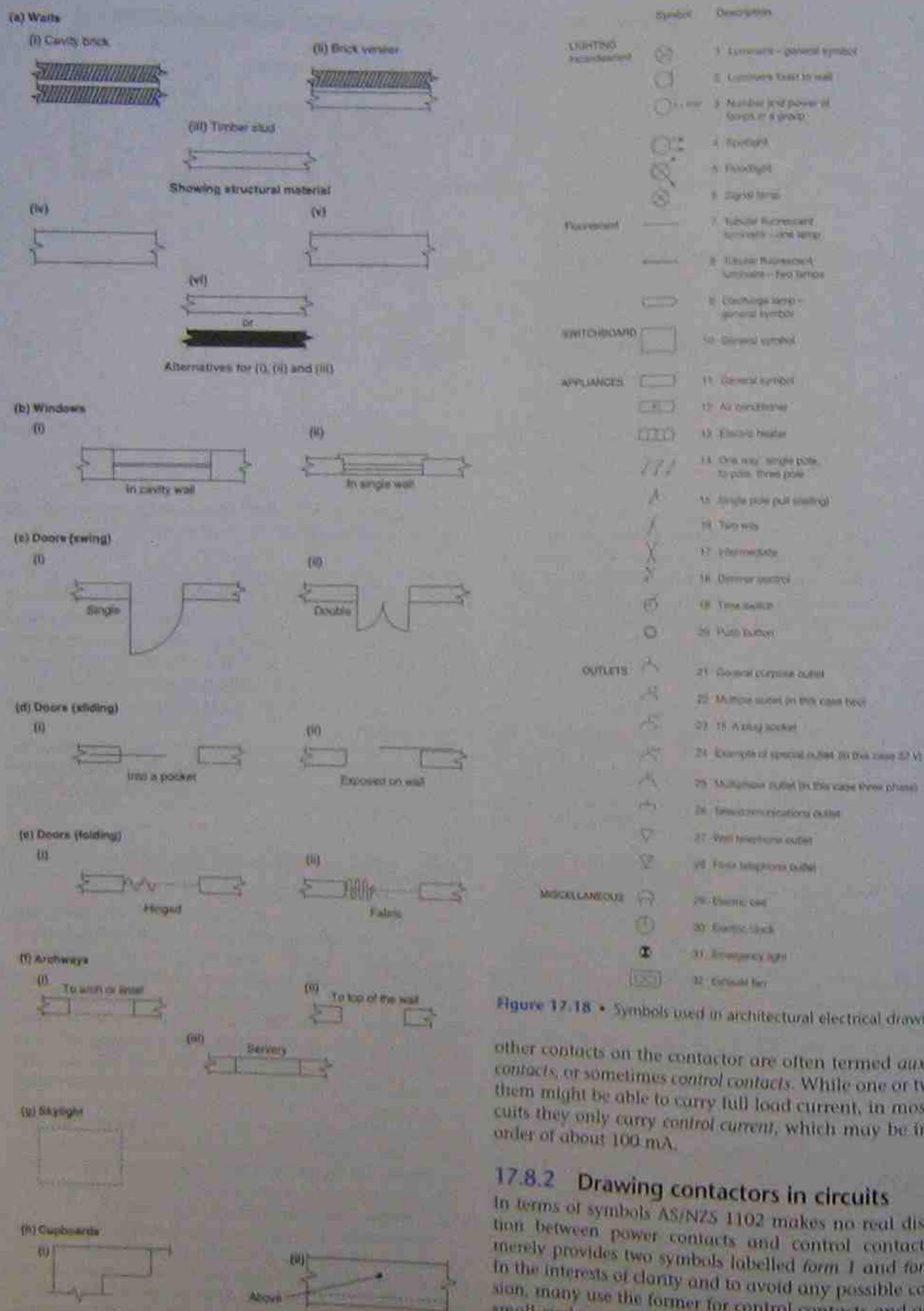


Figure 17.18 • Symbols used in architectural electrical drawings

other contacts on the contactor are often termed *auxiliary contacts*, or sometimes *control contacts*. While one or two of them might be able to carry full load current, in most circuits they only carry *control current*, which may be in the order of about 100 mA.

### 17.8.2 Drawing contactors in circuits

In terms of symbols AS/NZS 1102 makes no real distinction between power contacts and control contacts. It merely provides two symbols labelled *form 1* and *form 2*. In the interests of clarity and to avoid any possible confusion, many use the former for control contacts and add a small circle, as shown in Figure 17.22, with form 2 contacts for the power part of the circuit. Individuals have their own preferences and make their choice accordingly.

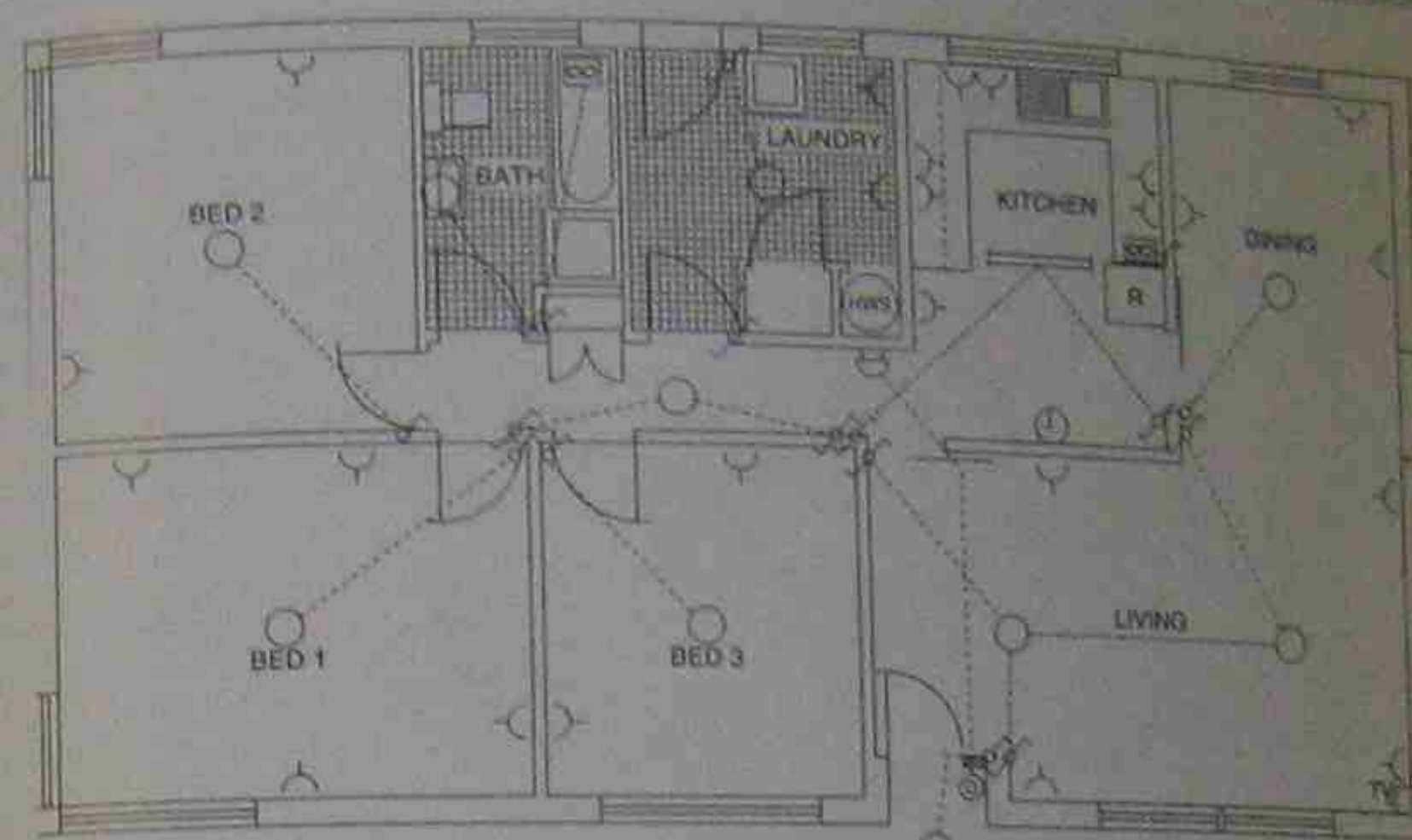


Figure 17.19 • Architectural electrical floor plan of a small domestic residence

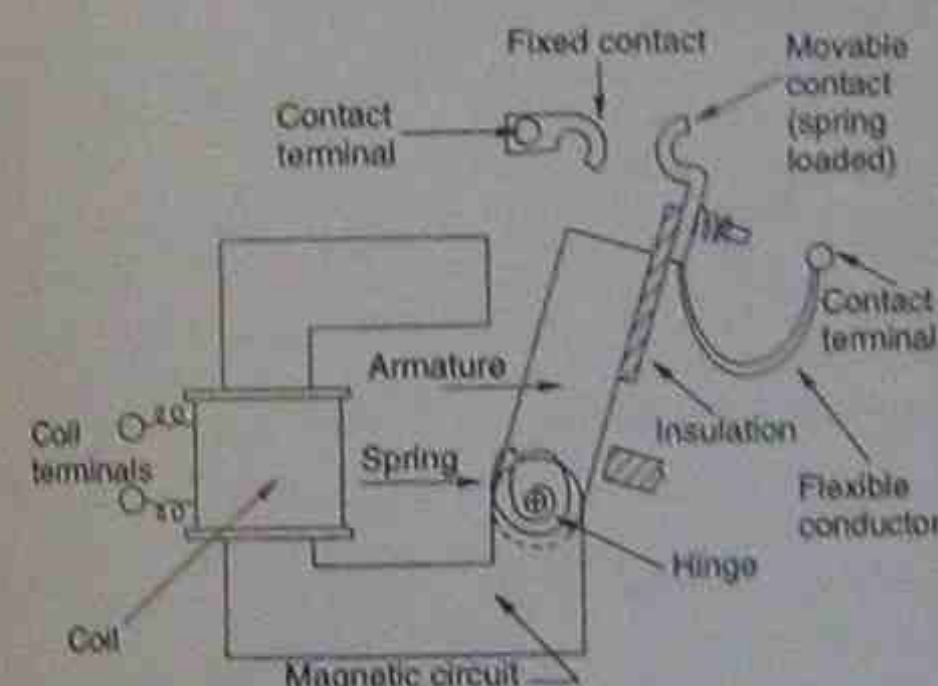


Figure 17.20 • Operating components of a contactor

Refer to Figure 17.22 to see the different types of contact symbols. Form 1 contacts and contactor symbols are used extensively throughout this material.

Both power and control contacts may be either *normally open* or *normally closed*. When using the word *normal* it is meant that the contactor is not energised (i.e. power is not applied to the coil). When the contactor coil is energised, the contacts change their state. Normally open contacts close, and normally closed contacts open. In drawings they are *always* drawn in the un-energised state. The operation of contact symbols is always considered to be clockwise.

Some contactors may have contacts that are *timed*. These timed contacts will close, or open, after a designated time (say, 5 s). The timing device may be mechanical or electrical. When electrically timed contacts are required, quite often a *timing relay* is used. Timing relays are often connected in parallel with the coil of a contactor and may be adjusted to open or close contacts. Any timed contacts are designated by a special symbol. This takes the form of a semicircle to indicate the contact is slowed down in

operation. Timed contact symbols of various forms are shown in Figure 17.23.

Some contactors (or relays) are inherently timed by their construction. That is they close their contacts some time after they are energised. These relays are drawn with two diagonals in a rectangle on one end of their coil symbols. Some relays are slow to release after de-energisation and these are designated with a filled in rectangle on one end of their coil symbols. The symbols for the three types are shown in Figure 17.24. Normally this type only operates in d.c. circuits.

Schematic circuits may have no bearing on their actual physical placement or arrangement in a circuit. Contactors may be drawn in circuits in a number of ways. One way is shown in Figure 17.25(a), which shows a contactor with its operating coil and all its associated contacts. The broken line enclosing the components indicates that they are all part of the one assembly. This type of attached representation is seldom used in schematic circuits because it does not lend itself to a logical circuit arrangement.

A second method is to indicate by a dashed line that the contactor coil operates the contacts joined by the line. This method is sometimes seen in diagrams, especially when the components on the contactor are close together or in line, in a diagram. This method of semi-detached representation is illustrated in Figure 17.25(b).

The most common method is termed *detached representation*. In this convention the contactor coil is not only labelled with the contactor designation but also with the number of contacts it operates. This can be seen in Figure 17.26. The contactor is designated as K and, in the coil symbol, the KI/4 indicates that there are four associated contacts. Sometimes the coil designation is placed beside the coil symbol. In this case there are three normally open power contacts, and one normally open control contact. However, there could be more or less contacts, and some could be normally closed and some could be timed.

Figure 17.17 • Common floor-plan graphical features



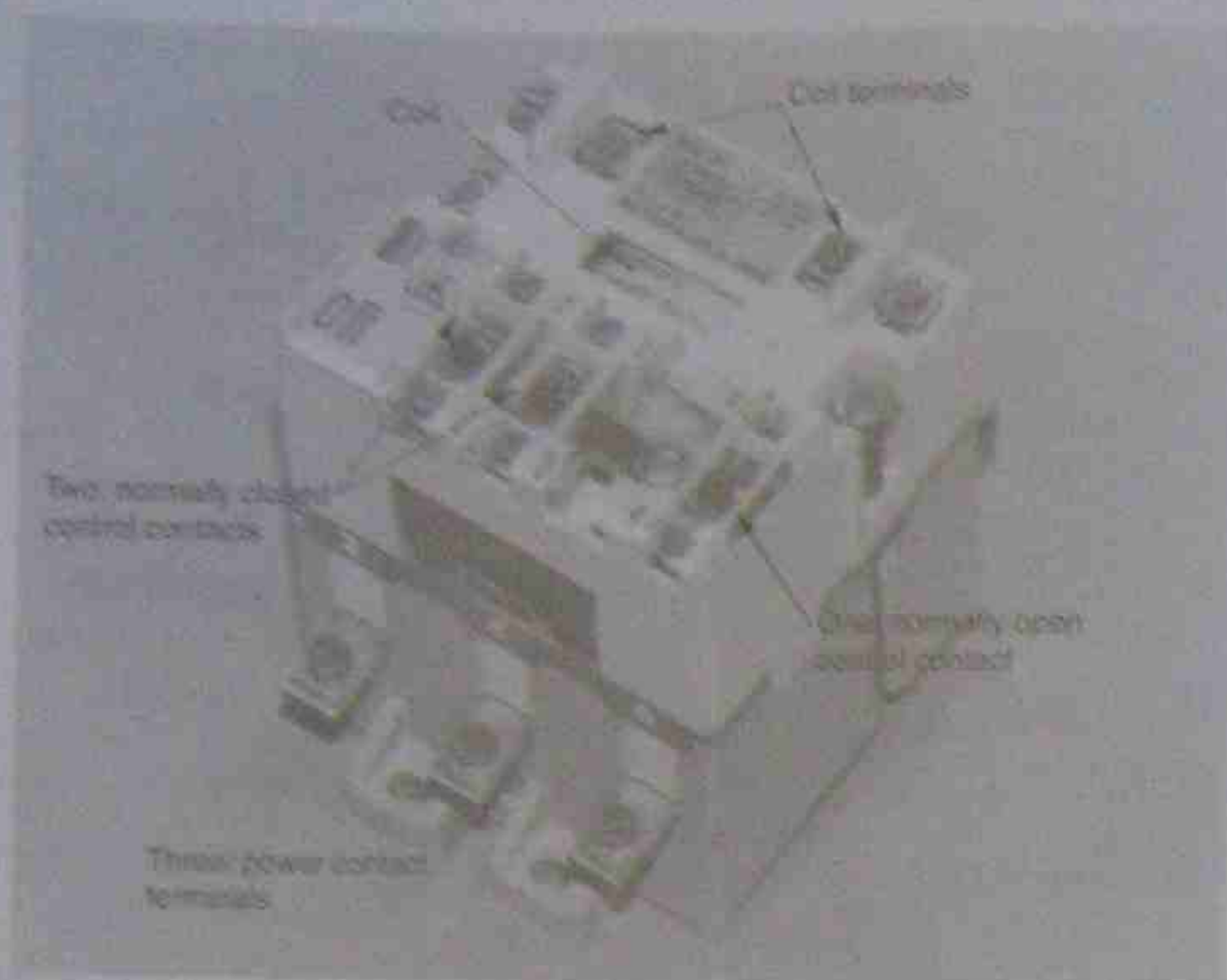


Figure 17.21 • Typical contactor

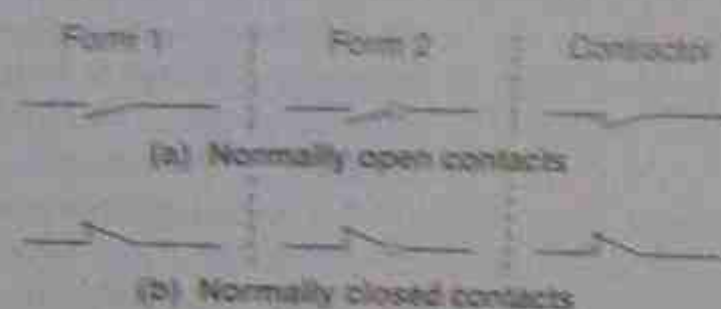


Figure 17.22 • Symbols for contacts and contactors



Figure 17.23 • Various timed contact symbols

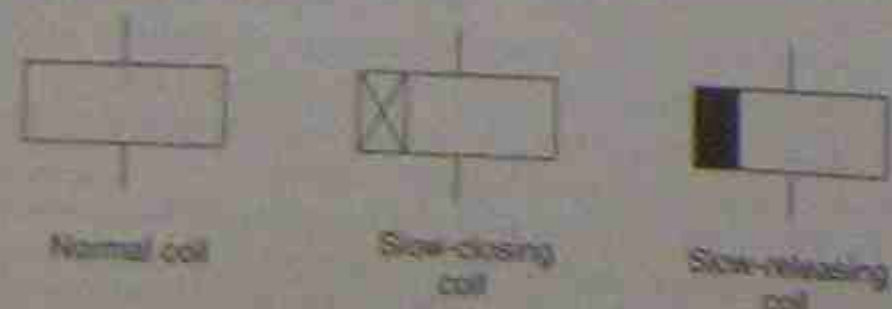


Figure 17.24 • Normal and timed relay coils

It can be seen that the detached representation makes the diagram easier to read. The broken line indicates that all three contacts close simultaneously. Power is supplied to the motor when the three power contacts, K1.1, K1.2, and K1.3 close. Also in the power circuit are three symbols indicating that they are thermal overload

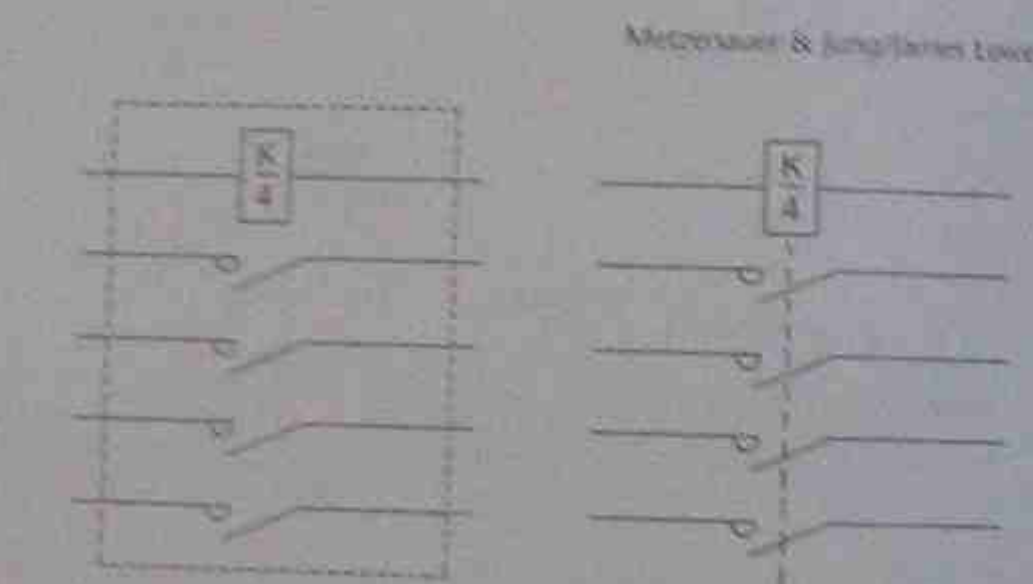


Figure 17.25 • Symbolic representation of coils and contactors

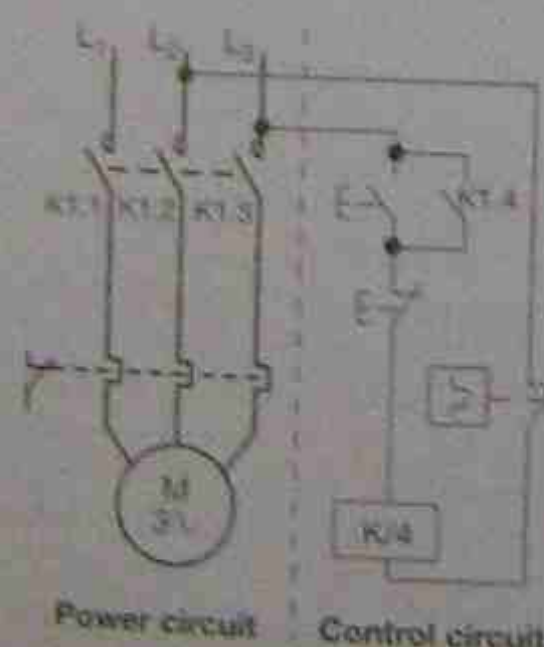


Figure 17.26 • Motor starter circuit—detached representation

detectors. If an overload occurs they will cause an associated contact to open. The lines representing the power conductor lines have been drawn thicker than the control power and control circuits. A broken line is shown here

separating the two parts of the circuit but it is not a regular practice.

Connected to two of the power lines are two control conductor lines. This circuit uses line voltage for the control circuit. To start the motor, press the start button. The symbol indicates that when the button is released, the switch contact will open again. Current passes to the coil through the normally closed stop push-button switch and energises the coil of the contactor, K1.4. It is not regular practice to designate the start and stop push-button switches unless there is a special need. Just the nature of the symbols is enough to show that a normally open push-button switch is a start switch and a normally closed one is a stop switch.

The moment the start switch is pressed, and K1.4 energised, all K1 contacts operate. In this case they are all normally open contacts so they all close. K1.1, K1.2 and K1.3 supply power to the motor and it starts up. K1.4 takes the place of the start push-button switch when the start push-button is released.

Pushing the stop push-button switch opens the circuit to coil K1.5 and all the associated contacts open. The motor then stops and cannot be re-started until the start push-button switch is again pressed.

If an overload condition occurs, the thermal overload detectors open the overload contact and again the motor will stop. Some thermal overload relays are self-setting, while others must be reset before the motor can be started. The circuit layout with the flow of energy and sequence of events moves from left to right and top to bottom. All components have been spaced across the drawing and kept in line as much as possible. Any drawing should be laid out in this manner, even if it is only a pencil sketch. It makes it much easier to read and interpret at a later date.

## 17.9 CONTROL CIRCUIT VARIATIONS

### 17.9.1 Two-position control

The stop and start push-button switches, in motor and other control circuits, are convenient ways to operate circuits. It is easier to press a button rather than operate a toggle or turn a handle. So far only circuits with one start and one stop push-button have been discussed. To provide extra start positions, all that is needed is to connect the extra start push-buttons in parallel with the first. To stop or de-energise the circuit, extra stop push-button switches are placed in series with the first. In Figure 17.27 there are two start and two stop push-button switches. As is usual, the start push-buttons are normally open and the stop push-buttons are normally closed. They have been labelled Start 1, Start 2, Stop 1 and Stop 2 for clarity.

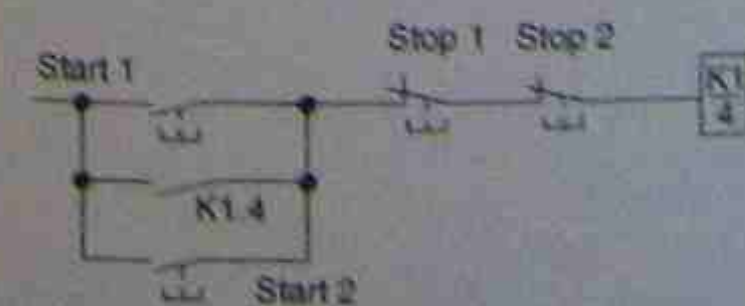


Figure 17.27 • Two start and stop control positions in a circuit

A variation on the control circuit in Figure 17.27 is the provision of only one start position with multiple stop positions. This can arise when a number of emergency stop positions might be required in a plant. Only one push-button switch will start the operation but if there is a malfunction in the plant it can be stopped by operators at any number of positions. It requires that all the stop push-button switches are connected in series, as in Figure 17.28.



Figure 17.28 • Multiple stop control positions

### 17.9.2 Local or remote operation

In some operations it may be necessary to start the operating position of the stop-start push-button switches. To avoid the possibility of someone operating the machine at the incorrect position, the circuit of Figure 17.29 is amended so that only one position at a time can be used. This is often referred to as local or remote operation. Figure 17.29 is a circuit representation of this type. On the left side of the diagram is a hand-operated changeover switch, which switches into circuit either the upper local or lower remote push-button switches. This type of circuit requires an extra contactor contact and only a simple changeover switch.

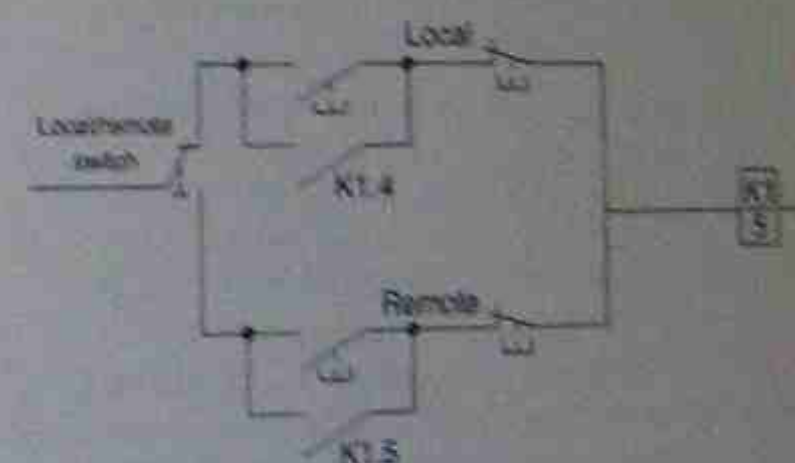


Figure 17.29 • Remote or local operation control

### 17.9.3 Two-wire control

Many motor control circuits use an automatic start control. This could be, for example, from a thermostat on a refrigerator, a float switch on a water tank or a pressure switch on an air compressor. Because there is no other stop-start control, and only two wires need to be run to the actuating device, it is usually referred to as two-wire control. Figure 17.30 is a simple two-wire control circuit. In this case the controlling device is a pressure switch, which is represented by the lower case p in the rectangle.



Figure 17.30 • Two-wire control by a pressure switch



### 17.9.4 Two-wire and push-button control

In some cases it might be necessary to start a motor controlled device using a push-button switch but allow another control to turn it off. This type of circuit is shown in Figure 17.31. It has normal stop-start control with a float switch connected in series with the stop push-button. This would enable a pump to be started and then switch off automatically when a tank is full. The motor could be stopped at any time while running but it could not be restarted after an automatic stop until the water level fell and the float switch closed again.



Figure 17.31 • Combined stop-start and automatic control

### 17.9.5 Jogging control

When a push-button switch is connected so that a circuit operates only while the switch is held depressed, it is called *jogging control*. It is sometimes necessary to jog a machine to a certain position, so that adjustments may be made. It would be possible to jog both start and stop push-buttons using two hands, but it is not good practice or reliable and could be dangerous. It is more efficient to install a special push-button for this function.

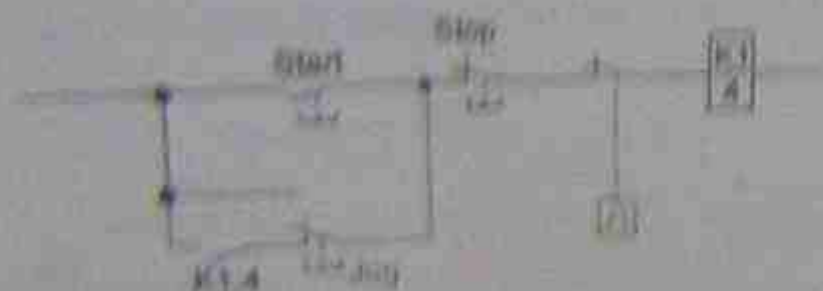


Figure 17.32 • Jogging push-button switch in a control circuit

In the schematic circuit diagram of Figure 17.32 the jogging push-button switch is a push-button changeover switch with a normally closed and a normally open position. In its normal position the circuit operates as a simple stop/start control. When the jogging button is pressed, the hold-in contact K1.4 is isolated and the stop push-button switch is bypassed. While the jogging button is pressed, coil K1.4 is energised. When the button is released, the circuit to the coil is opened and then remakes the normally closed contact so that normal operation is possible. The jogging push-button sometimes includes a small delay on returning to give the contactor time to open contact K1.4.

### 17.9.6 Reversing circuits

To reverse a three-phase motor, all that is necessary is to interchange two supply lines to the motor. This can be accomplished by using two contactors, as in the schematic circuit diagram in Figure 17.33. When either the F1.1, K1.2 and K1.3, or K1.1, K2.2 and K2.3 contacts close, the motor will operate either in a forward direction or in the reverse. Examination of the power circuit will show that two supply lines would be short-circuited if both contactors closed at the same time.

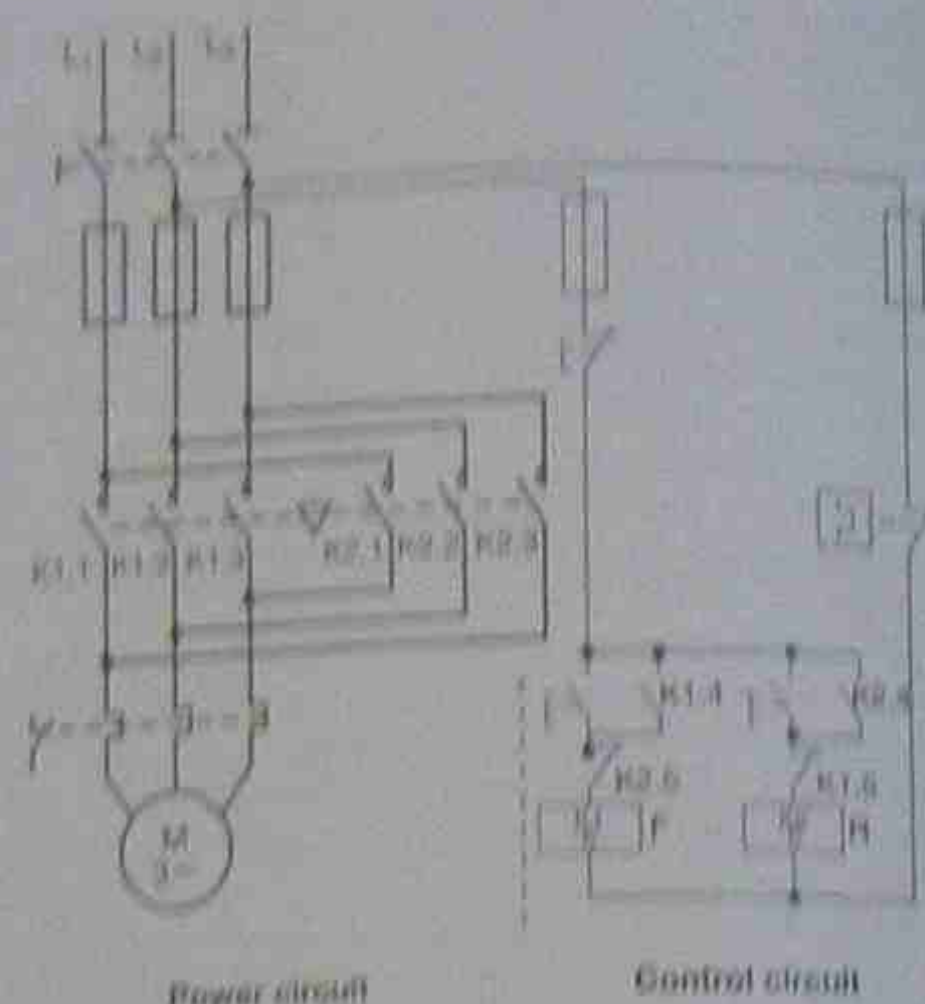


Figure 17.33 • Schematic circuit diagram of a reversing contactor

This can be prevented in two ways. The small equilateral triangle and the broken lines between the two sets of power contacts signify that the two contactors are *mechanically interlocked*. This means that if one contactor is closed it is mechanically impossible for the other to close.

The second method is to use *electrical interlocks* in each contactor coil circuit. This can be seen in Figure 17.33 where the normally closed contact K2.5 is in the forward coil circuit and the normally closed contact K1.5 is in the reverse coil circuit. This means that when contactor coil K1/5 is energised, contact K1.5 will open. Then, if the reverse push-button switch is pressed, coil K2/5 cannot be energised. The same applies to the reverse operation.

Only one stop push-button is used and the thermal overload contact is also in series with the stop button. By necessity, the stop push-button switch is ahead of the forward and reverse push-buttons so that it can control both.

### 17.9.7 Ladder diagrams

Control circuits in particular can be drawn as *ladder diagrams*. They are called that because the supply lines are drawn on each side and the circuit component parts are drawn across them so the result is that it looks like the sides of a ladder.

Ladder diagrams also follow the requirement that energy flow and sequence of events be from left to right and top to bottom whenever possible in a similar manner to common drawing practice in this country.

These diagrams are a step towards programming logic controllers and are mostly used with programming in mind. The control circuit of Figure 17.33 has been redrawn in a horizontal orientation and is shown in Figure 17.34. Symbols as recommended in AS/NZS 1102 are used. The circuit, however, is identical to that of the control circuit in Figure 17.33.

In other countries different standard symbols are often used. In the United States of America there are more than

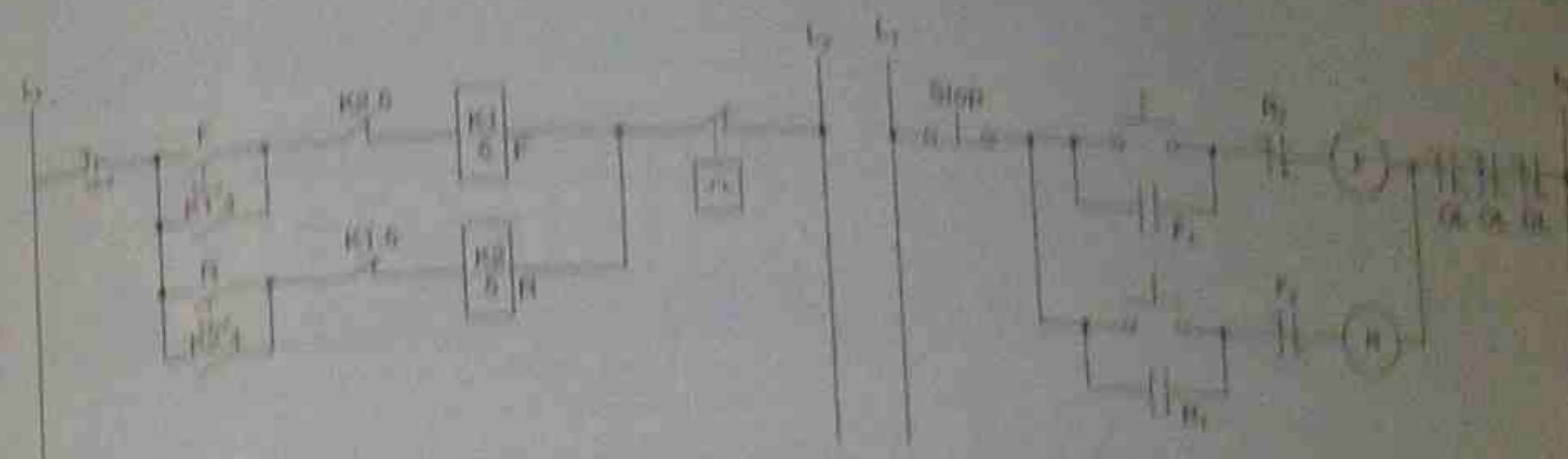


Figure 17.34 • Control circuit of Figure 17.33 drawn with a horizontal layout

one set of standards but one popular one is called the NEMA standard. The name is short for the National Electrical Manufacturers Association. The control circuit of Figure 17.34 is redrawn to NEMA standard and is shown in Figure 17.35. It is still the identical circuit except that now each overload is shown separately as three normally closed contacts.

Figure 17.35 • Reversing control circuit drawn to NEMA standard

Many of the programmable logic controllers in this country and others use this standard and the programmes are oriented towards this standard. Circuit diagrams supplied with the controllers are, more often than not, drawn to NEMA standards.

## SUMMARY

- Schematic circuit diagrams should:
  - show exactly how a circuit operates
  - be laid out in a neat and logical manner
  - show the sequence of events, energy flow, or signal flow from left to right and/or top to bottom if possible
  - be drawn from Standard AS 1102 symbols
- Block diagrams are useful because they:
  - show what the circuit does
  - provide an overview of a circuit
  - are an aid to understanding a circuit
  - could provide a design starting point for a circuit
- A good clear wiring diagram should have the following features:
  - Prominence should be given to the conductors and terminals
  - All conductors should be evenly spaced where possible
  - Where more than one conductor connects to a terminal, each conductor should be angled to the terminal
  - All changes of direction of conductors should be at right angles, if possible
- The features of an architectural electrical drawing are:
  - they use special architectural electrical symbols
  - they use a floor plan as a basis
  - they show the positions of luminaires and outlets
  - they show which switches control particular luminaires
  - they give no indication on how a building is to be wired
- Relays and contactors are both electromagnetically operated switches:
  - A contactor is used in a power circuit
  - A contactor can have both power and control contacts
  - Both contactors and relays consist of an operating coil, a magnetic circuit and associated contacts
- There are various types of contacts controlled by contactors and relays. Some of these are:
  - normally open
  - normally closed
  - timed on closing
  - timed on opening
  - timed on both closing and opening

- In motor control schematic circuit diagrams, the control circuit is drawn in lighter lines than the power circuit
- In detached representation in schematic circuit diagrams, the contactor coil is designated with both the contactor designation and the number of contacts it operates. The coil designation, for example K1.1, may be placed on or beside the coil symbol
- Each contact has the designation of the contactor and a number usually representing its importance or its order of operation, for example K1.1
- In push-button switch control:
  - extra start push-button switches are all placed in parallel
  - extra stop push-button switches are all placed in series
- Control by some automatically operated switches is termed two wire control
- When reversing contactors are used:
  - they are mechanically interlocked
  - they are also electrically interlocked in the control circuit
- A jogging control will allow the circuit to be energised only while it is held depressed
- When drawing schematic circuit diagrams, the top-to-bottom and left-to-right rule should be followed, when possible
- Control diagrams are usually drawn as ladder diagrams. In these:
  - the lighter sides are the supply lines
  - the ladder rungs are the control circuit lines



## EXERCISES

- 17.1 State the name and number of the Australian standard that deals with electrical drawing.
- 17.2 Draw the schematic circuit diagram symbols for the following:  
(a) a fuse  
(b) a 50 V battery  
(c) a normally closed push-button.
- 17.3 Draw two conductors crossing and joining in a schematic circuit diagram.
- 17.4 How do we show that when two components are in parallel, one is the more important one?
- 17.5 Draw a neat freehand sketch of the schematic circuit diagram of two lamps in parallel, controlled by the one switch.
- 17.6 Briefly state what a block diagram of an electrical circuit represents.
- 17.7 What part of a wiring diagram is given the greatest emphasis?
- 17.8 What is the main difference between a schematic circuit diagram and a wiring diagram?
- 17.9 Draw the following architectural electrical symbols:  
(a) a two-way switch  
(b) a general-purpose outlet  
(c) a main switchboard.
- 17.10 What is the meaning of a dashed line between a switch and a lighting outlet in an electrical architectural drawing?
- 17.11 Draw the following contacts:  
(a) changeover  
(b) normally closed, timed on reclosing.
- 17.12 Draw a detached diagram of a contactor with four normally open and one normally closed contacts.
- 17.13 Draw a control circuit with two start and three stop push-button switches.
- 17.14 Draw a thermal overload operating element and a contact it operates in detached representation.
- 17.15 Draw the schematic circuit diagram for a reversing motor controller. Include three stop push-button switches, and a thermal overload relay. Do not include pilot lights.

# Appendixes

## APPENDIX 1: POWER AND ENERGY METERS

### A1.1 Dynamometer instruments

The principle of operation of the dynamometer movement is the repulsion and attraction effect between two magnetic fields. These fields are produced by two sets of coils, one set being fixed in position and the other mounted on a spindle and free to rotate. Comparatively poor sensitivity restricts their use to power applications, of which the wattmeter is the most common.

#### A1.1.1 Wattmeters

When the supply voltage is impressed across terminals  $V_1$  and  $V_2$ , a small current proportional to the voltage will flow through the voltage coil and produce a magnetic flux proportional to that voltage (see Fig. A1.1).

The fixed or current coils ( $C_1$ ,  $C_2$ ) are connected in series with the load, and a flux proportional to the load current is produced in these stationary coils. The torque produced (and the movement deflection) is proportional to the product of the two magnetic fluxes (i.e.  $T \propto \Phi_{\text{fixed}} \times \Phi_{\text{moving}}$ ), provided that the currents producing those fluxes are in phase with each other.

When used on d.c., both fluxes act constantly in the one direction at all times, but on a.c., this only occurs when the load is a resistive one (or when the power factor of the circuit being tested is unity). This means that the two fluxes

are at a maximum at the same instant of time and the movement produces the greatest torque. At other power factors, the maximum values of flux occur at different times and the torque is decreased. At zero power factor the two fluxes are at 90°E to each other, no torque is produced, and consequently there is no deflection. The wattmeter indicates true power consumed regardless of power factor.

The construction shown in Figure A1.1 limits the scale length available and to lengthen the scale an iron core is added (Fig. A1.2). In turn, however, the iron core limits the use to one frequency of a.c., owing to the reactance of the fixed and moving coils varying with different frequencies. At any other frequency than the one designed for the meter, the scale must be recalibrated.

The terminals of a wattmeter are designated in accordance with a standard method; the current coil is labelled M for the supply side and L for the side connected to the load, while the voltage coil is labelled  $V_+$  and  $V_-$ . Portable wattmeters are often fitted with a switch to short-circuit the M and L terminals. When used to find the power consumption of electric motors and other loads having a high initial starting current, the correct procedure is to short out the current coils during the starting sequence.

In specific applications where the load is higher than the rating of the meter, a CT should be used, as shown in Figure A1.3. Included in the diagram is a PT, which is required where the applied voltage is too high for the rated voltage of the meter.

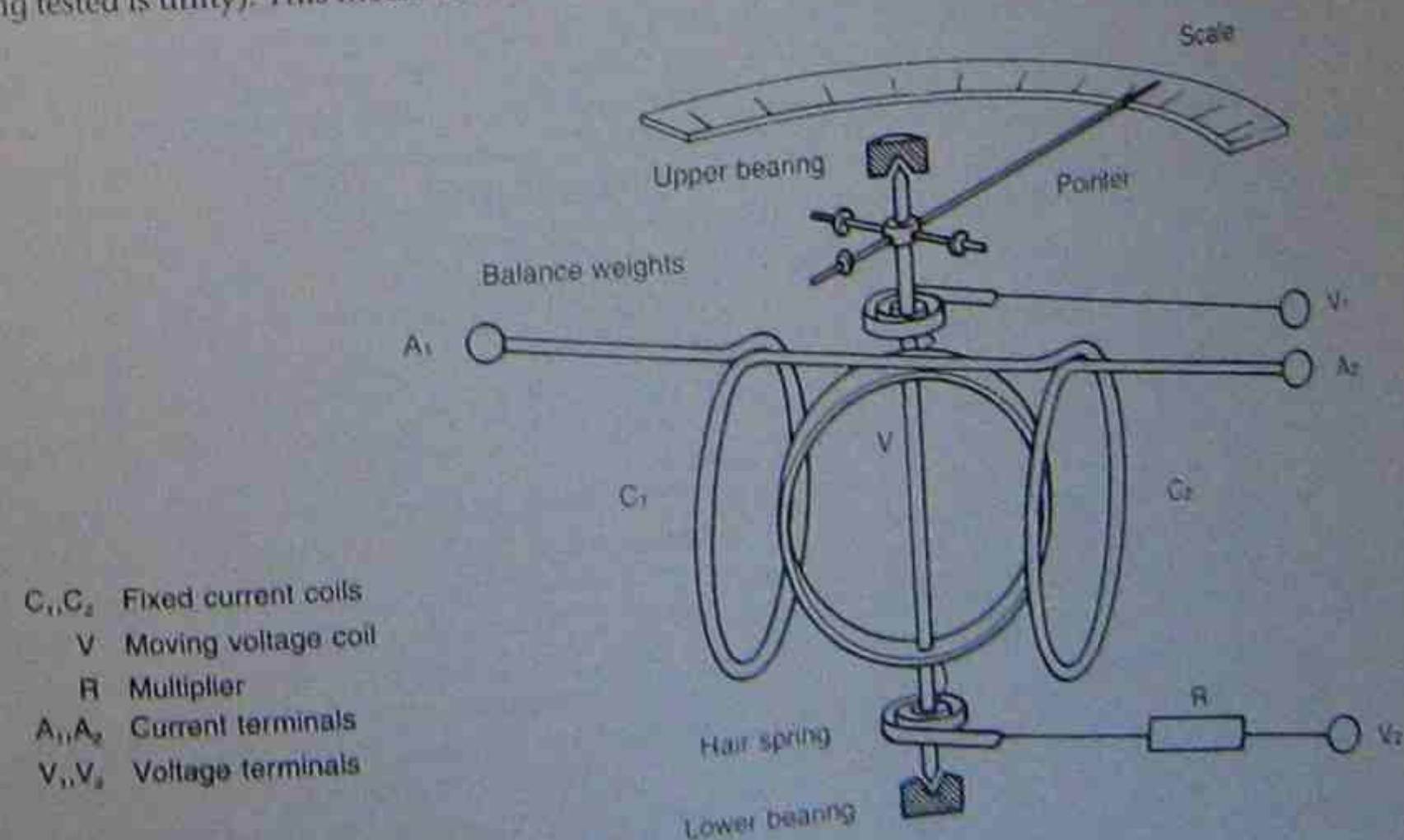


Figure A1.1 • Dynamometer wattmeter—air-core type



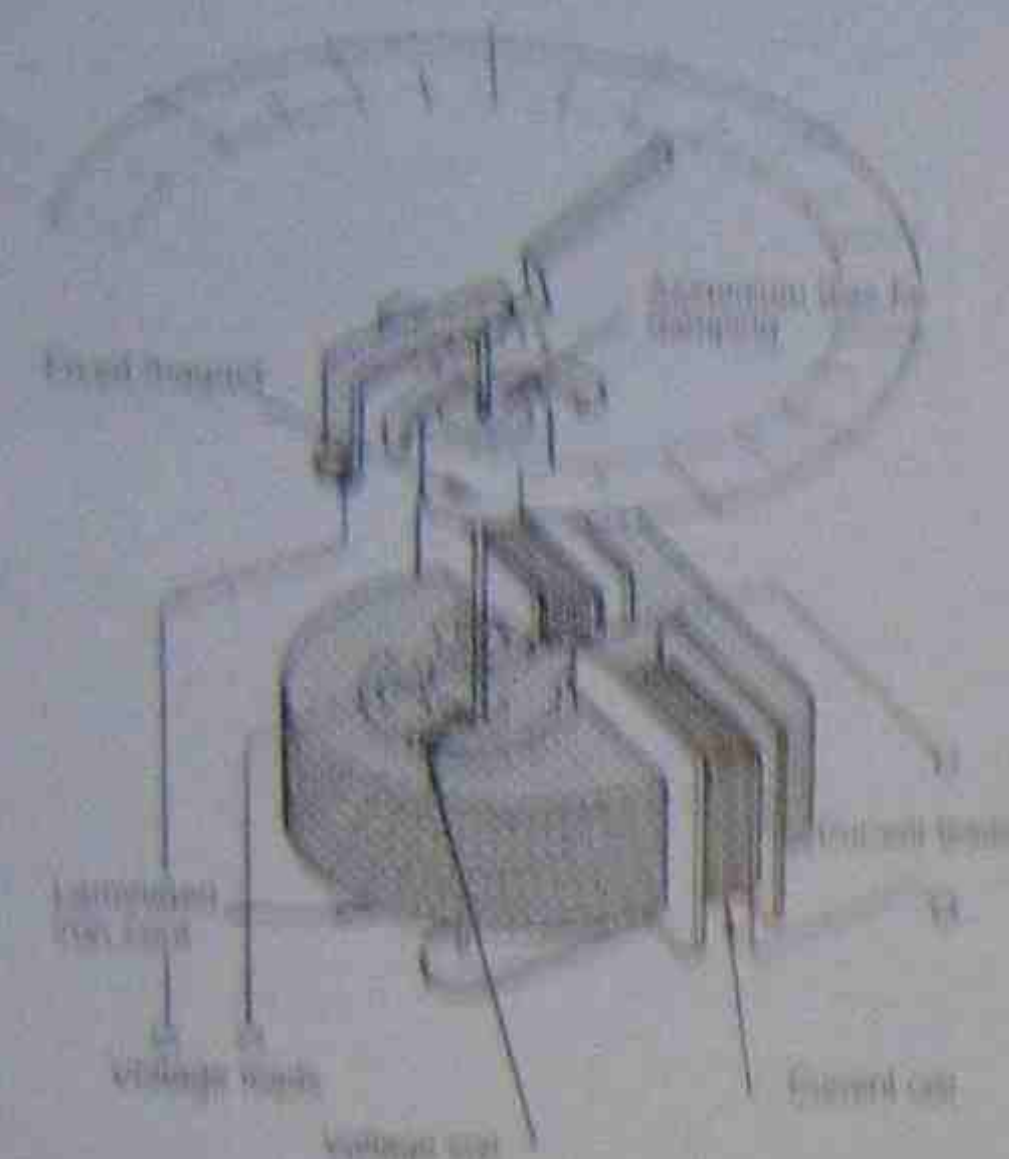


Figure A1.3 Thermocouple wattmeter—disc type

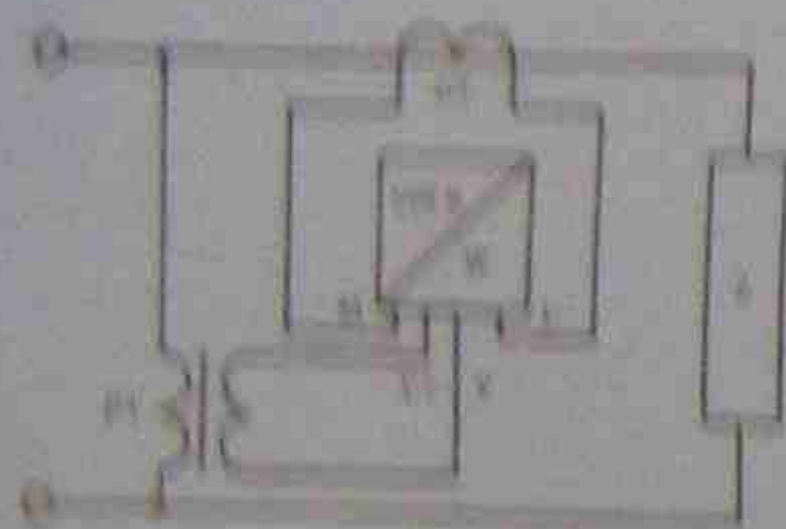


Figure A1.4 Use of thermocouple technology to extend the range

When a wattmeter is used to measure power, it is advisable to include an ammeter in the circuit so that the correct value of current flowing can be checked. The current coils in the meter have a definite maximum current rating and this value should not be exceeded. Within this power consumed by a load might be within the range of the wattmeter scale, giving in a low power meter the possibility of current overload and the meter current rating and so causing damage to the meter.

Consider a wattmeter with a scale calibrated to read a maximum of 1000 W on coil V with the meter current coil rated at 5 A. When connected to a load that dissipates 1000 W at unity power factor, the meter would indicate 1000 W and the current flowing would be  $I = 1000/240 = 4.17$  A.

Therefore, if the load had a power factor of 0.7, the meter would not indicate 1000 W, but then  $I = 4.17$  A but the current flowing would be  $1000/240 = 4.17 \times 0.7 = 2.92$  A.

Thus, it is critical to check the current coils of 10 per cent and can cause damage to the meter.

### A1.1.2 Power factor meters

The dynamometer principle can be applied to power factor measurement by adding another coil at right angles, fixed to the movable voltage coil. Figure A1.4 shows the arrangement of the coils and the connections of the meter.

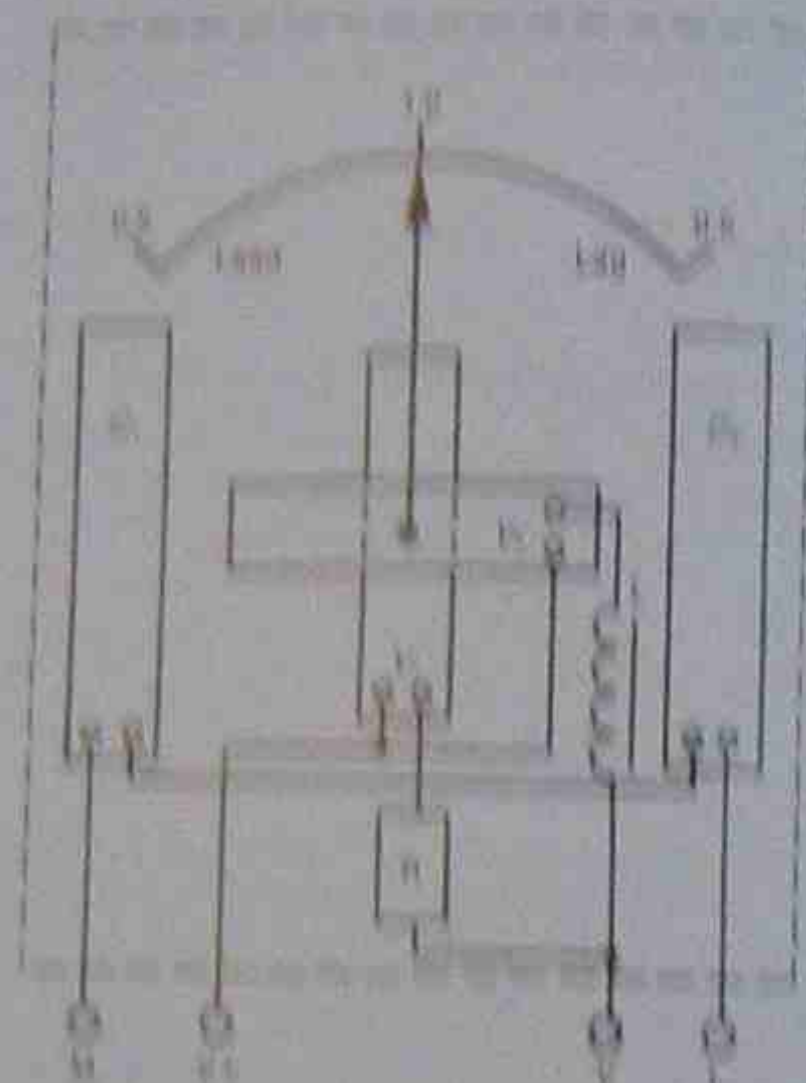


Figure A1.4 Internal construction of a power factor meter

As with the wattmeter, the moving coil  $V_1$  is largely resistive, but the additional coil  $V_2$  is made largely inductive by placing an inductor  $L$  in series with it. There are no hair springs connected to the moving element; instead, two flexible conductors are used to carry the current to and from coils  $V_1$  and  $V_2$ . When connected to the supply, the current in coil  $V_1$ , because of the resistive nature of its circuit, is virtually in phase with the supply voltage, while the current in  $V_2$  lags the supply voltage by almost 90°. When the load operates at unity power factor, the flux in the fixed current coils  $I_1$  and  $I_2$  and the flux in the moving voltage coil  $V_1$  reach their respective maximum values at the same instant. At the same time the flux in coil  $V_2$  will be zero because of its 90° lag. The torque created will be due to the interaction between the two fluxes in the fixed current coils and the voltage coil  $V_1$ , coil  $V_2$  having no effect. Coil  $V_1$  will rotate until its field lines up with the fixed field and the meter will indicate power factor (PF) = 1.

When the load power factor is zero, the load current is lagging the voltage by 90° and the fluxes of coils  $I_1$ ,  $I_2$  and  $V_1$  are in phase, and  $V_2$  has no effect on the torque produced. The moving system will then rotate until the two fields line up and the meter indicates PF = 0.

At intermediate values of power factor, both  $V_1$  and  $V_2$  will have some effect and the meter will indicate some value of PF between 0 and 1. The accuracy of the meter depends on the scale length is limited. To increase the scale length, a moving iron instrument is available with

all 360° rotation. This type is identified from the dial markings set out in four quadrants of 'lead' and 'lag'. The moving system has a pair of iron vanes mounted on a spindle with no electrical connections to it.

Both types of meter are subject to some inaccuracies and both types have their own advantages. The meter indicated in figure A1.4 is probably more accurate at low loads than the four-quadrant type. The latter load currents within the meter meter burden is usually greater with the four-quadrant type and this also leads to increased error at light loads. The four-quadrant type, however, indicates the direction of the reactive component of power and reads values of power factor below 0.5. In both cases the power factor can only be read with some uncertainty to the first significant figure; that is, the power factor is 0.5 or 0.7. Figures such as 0.521 for power factor read from a meter are unrealistic.

### A1.2 Induction disc instruments

#### A1.2.1 Wattmeters

Suitable for a.c. use only, the construction of an induction disc wattmeter is shown in Figure A1.5. It consists of a single voltage coil and two current coils, all wound on a specially shaped iron core. Between them is suspended an aluminium disc, which is free to rotate against a restraining hair spring.

When the load power factor is unity, the voltage and current are in phase with each other, but the fluxes produced in the meter are effectively 90° out of phase, owing to the inductance of the voltage coil. These two fluxes acting through the disc produce a rotating field, and eddy currents are induced in the disc. The disc then operates in a similar fashion to the meter in an induction meter and the torque produced moves it against the restraining force of the hair spring. A pointer attached to the disc reads the amount against a scale calibrated directly in watts. At power factors other than unity, the flux displacement is less than 90° and a lesser torque is produced, so leading to a lesser movement of the disc.

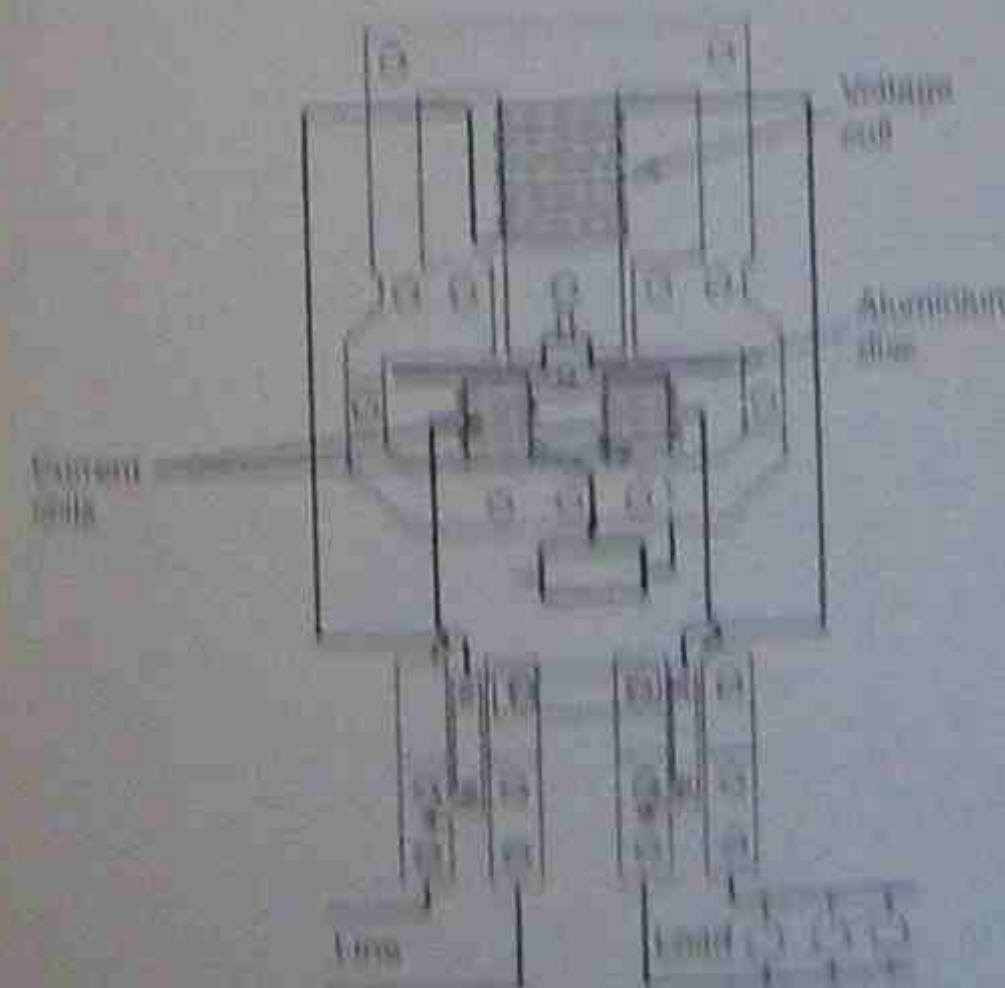


Figure A1.5 Induction disc wattmeter

### A1.2.2 Energy meters (kWh meters)

The induction disc wattmeter operates on the same principle as the induction disc wattmeter. The construction is similar, but no restraining torque hair spring is used. Instead, the disc is completely free to rotate and a worm wheel is provided at one end of the shaft. This is then driven by gear train attached to pointers rotating around calibrated scale. Energy is defined as power (watt) multiplied by time, and an energy meter must use both of these factors in obtaining an indication. To measure power the induction disc principle is used. The time during which the power is consumed is obtained by turning the disc and the gear train, and in measuring the pointer. The higher the value of power being consumed, the greater will be the number of revolutions of the disc in any unit of time and consequently the higher will be the reading on the calibrated scale. The construction for an energy meter is as for the induction disc wattmeter shown in Figure A1.5. For extension of voltage and current ranges beyond the ratings of the meter, potential and current transformers can be used, as shown in Figure A1.1.

#### Calculating power consumed

In many situations where an energy meter is installed without current or voltage transformers, the power being consumed can be calculated from:

$$\text{power in kW} = \frac{\text{revolutions of disc}}{\text{time in seconds}} \times \frac{3600}{\text{rev/kWh}}$$

For example, if a meter is rated on its identification plate as rotating 360 revolutions for each kilowatt hour, and if particular load turns the disc through 3 revolutions in 48 seconds, then the power consumed is:

$$P = \frac{3}{48} \times \frac{3600}{1} \\ = 0.5 \text{ kW} = 500 \text{ W}$$

### A1.2.3 Thermocouple wattmeters

Another type of wattmeter is the thermocouple wattmeter. Normally used in conjunction with both potential and current transformers, the output from the transformers supply power to two identical heaters. The heaters are used to heat opposite ends of a bank of thermocouples, as shown in Figure A1.6. The output is a low value direct current, which may be amplified to transmission level and fed to a remote reading meter.

The current from the potential transformer supplies current to the two heaters in series and a cable is heat both equally. The I output also supplies current to the heaters through the secondary of the CT. At the output end, the current divides equally and half flows through each heater on the return path to the CT. In Figure A1.6 both outputs from the transformers flow through heater 1 in the same direction and both cause the heater to produce heat at the upper thermocouple junction.

In the lower half, however, the two currents flow in opposite directions and tend to cancel each other out. The degree depending on the phase shift between the two currents and the relative value of the two currents. Effectively, there is a lesser heating effect at the lower



heater. The lower junctions of the thermocouples are heated less, and an output is produced by the thermocouples.

Assuming that the power factor of the circuit being tested is zero, the two currents are flowing at 90°E to each other and producing an identical situation in the upper half of the circuit. Because both junctions of the thermocouples are being heated equally, there is no relative output voltage, and the meter would read zero.

With a lagging power factor, one heater will produce more heat than the other and the meter will register a value. With a leading power factor the opposite heater produces more heat and the thermocouple output will be of the opposite polarity.

Because the wattmeter works on the principle of producing relative amounts of heat, it is a true r.m.s. reading meter, takes into account the relative power factor of the circuit and produces an output with a polarity to indicate a lagging or leading power factor. The meter is tolerant of some changes in frequency and waveform without affecting its accuracy. Its upper frequency limit is somewhat restricted, owing to the types of core in the instrument transformers used.

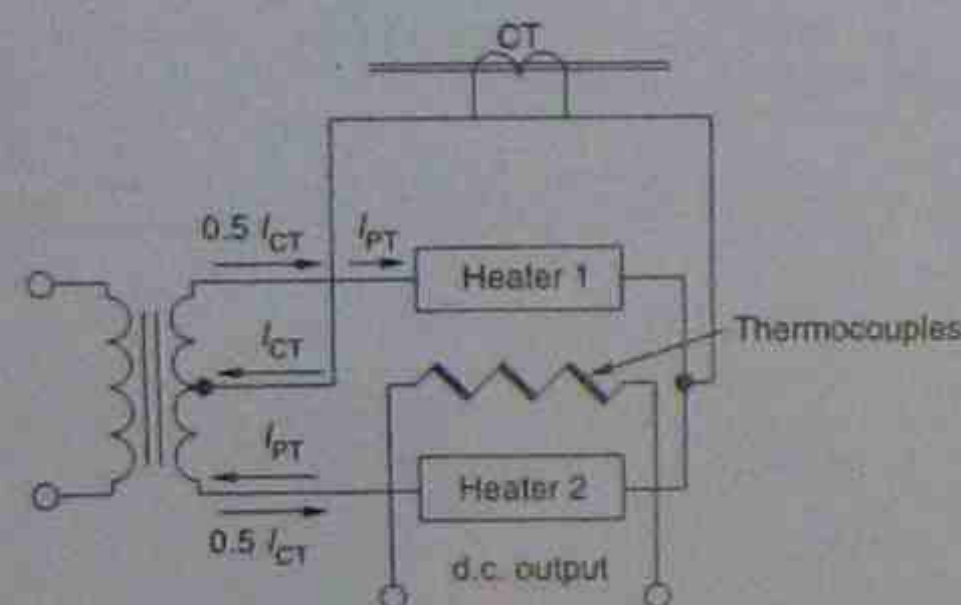


Figure A1.6 • Thermocouple wattmeter

## APPENDIX 2: GREEK LETTERS USED IN THE TEXT

$\alpha$	alpha	torque angle, trigger angle
$\Delta$	delta	difference
$\epsilon$	epsilon	permittivity
$\eta$	eta	efficiency, stand-off ratio
$\theta$	theta	angle of rotation, conduction angle
$\lambda$	lambda	power factor (= $\cos \phi$ for sinusoidal waveforms)
$\mu$	mu	permeability
$\rho$	rho	resistivity
$\tau$	tau	time constant
$\Phi$	phi	magnetic flux
$\phi$	phi	angle between phasors
$\Omega$	omega	resistance
$\omega$	omega	angular frequency
$\pi$	pi	a constant (= 3.1416)

## APPENDIX 3: LIST OF THE ELEMENTS

1	H	Hydrogen	53	I	Iodine
2	He	Helium	54	Xe	Xenon
3	Li	Lithium	55	Cs	Cesium
4	Be	Beryllium	56	Ba	Barium
5	B	Boron	57	La	Lanthanum
6	C	Carbon	58	Ce	Cerium
7	N	Nitrogen	59	Pr	Praseodymium
8	O	Oxygen	60	Nd	Neodymium
9	F	Fluorine	61	Pm	Promethium
10	Ne	Neon	62	Sm	Samarium
11	Na	Sodium	63	Eu	Europium
12	Mg	Magnesium	64	Gd	Gadolinium
13	Al	Aluminium	65	Tb	Terbium
14	Si	Silicon	66	Dy	Dysprosium
15	P	Phosphorus	67	Ho	Holmium
16	S	Sulphur	68	Er	Erbium
17	Cl	Chlorine	69	Tm	Thulium
18	Ar	Argon	70	Yb	Ytterbium
19	K	Potassium	71	Lu	Lutetium
20	Ca	Calcium	72	Hf	Hafnium
21	Sc	Scandium	73	Ta	Tantalum
22	Ti	Titanium	74	W	Tungsten
23	V	Vanadium	75	Re	Rhenium
24	Cr	Chromium	76	Os	Osmium
25	Mn	Manganese	77	Ir	Iridium
26	Fe	Iron	78	Pt	Platinum
27	Co	Cobalt	79	Au	Gold
28	Ni	Nickel	80	Hg	Mercury
29	Cu	Copper	81	Tl	Thallium
30	Zn	Zinc	82	Pb	Lead
31	Ga	Gallium	83	Bi	Bismuth
32	Ge	Germanium	84	Po	Polonium
33	As	Arsenic	85	At	Astatine
34	Se	Selenium	86	Rn	Radon
35	Br	Bromine	87	Fr	Francium
36	Kr	Krypton	88	Ra	Radium
37	Rb	Rubidium	89	Ac	Actinium
38	Sr	Strontium	90	Th	Thorium
39	Y	Yttrium	91	Pa	Protactinium
40	Zr	Zirconium	92	U	Uranium
41	Nb	Niobium	93	Np	Neptunium
42	Mo	Molybdenum	94	Pu	Plutonium
43	Tc	Technetium	95	Am	Americium
44	Ru	Ruthenium	96	Cm	Curium
45	Rh	Rhodium	97	Bk	Berkelium
46	Pd	Palladium	98	Cf	Californium
47	Ag	Silver	99	Es	Einsteinium
48	Cd	Cadmium	100	Fm	Fermium
49	In	Indium	101	Md	Mendelevium
50	Sn	Tin	102	No	Nobelium
51	Sb	Antimony	103	Lr	Lawrencium
52	Te	Tellurium			



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