5.2.2 DC Motor

Working principle

The working of a dc motor is based on the principle that when a current-carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force, whose direction is given by Fleming's left hand rule and magnitude is given by

$$F = B\,I\,l\,\sin\theta \text{ newton}$$

where F = mechanical force experience by the conductor in N
B = flux density in Wb/m^2
l = active length of the conductor in m
I = current through the conductor in A
θ = angle between the direction of the current and the magnetic field

Consider a single conductor placed in a magnetic field produced by permanent magnets as shown in Fig. 5.5(a). If current is passed through the conductor in the direction shown in Fig. 5.5(b), i.e., into the plane, then according to the basic principle, the conductor will experience a mechanical force. If the force is sufficient, then the conductor will move in the direction of the force. By Fleming's left hand rule, it is observed that the direction of motion of the conductor or the force is towards the right direction (from left to right).

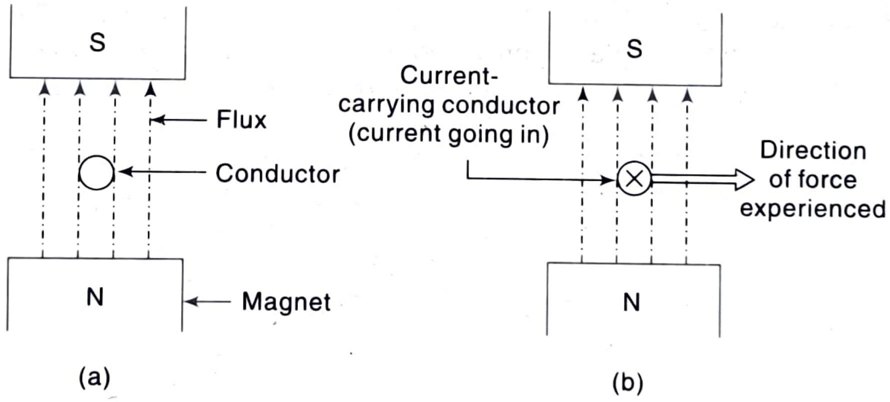


Fig. 5.5 Working principle of a dc motor

Fleming's left hand rule is as follows:

Outstretch the three fingers of left hand, namely thumb, index finger and middle finger, such that they are mutually perpendicular to each other. If the index finger is made to point in the direction of magnetic field, middle finger in the direction of the current, then the thumb gives the direction of the force experienced by the conductor.

Apply the above rule to verify the direction of force experienced by a single conductor placed in a magnetic field as shown in Figs 5.6 (a), (b), (c), and (d).

It can be seen that if the direction of magnetic field is reversed without changing the direction of current through the conductor, then the direction of force experienced also gets reversed [see Figs 5.6(a) and (c)]. Similarly, keeping the direction of magnetic field same, if the direction of current through the conductor is reversed, then also the direction of force experienced by the conductor gets

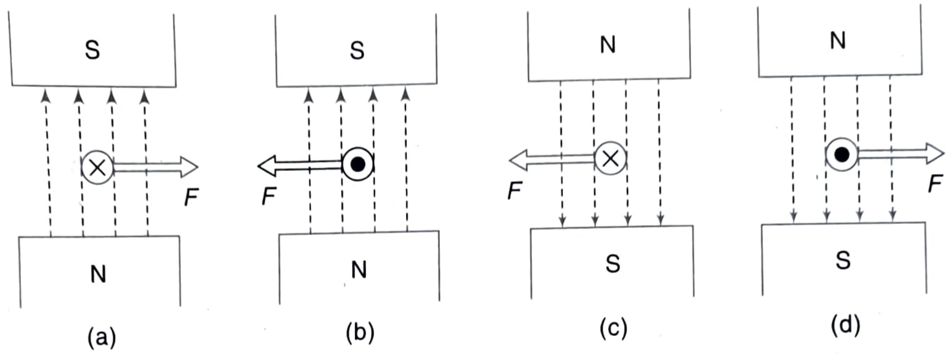


Fig. 5.6 A conductor placed in a magnetic field under different situations

reversed [see Figs 5.6(a) and (b)]. But if directions of both magnetic field and current through the conductor are reversed, then the direction of force experienced by the conductor remains unchanged [see Figs 5.6(a) and (d)].

Working

Figure 5.7 shows the schematic diagram of a simple dc motor consisting of a rectangular copper coil *ABCD* mounted on a shaft and placed in a magnetic field produced by permanent magnets. The coil has two identical conductors *AB* and *CD*. Two ends of the coil are connected permanently to two commutator segments R_1 and R_2 respectively. The commutator segments are well insulated from each other. The commutator is placed on the same shaft along with the coil. Two stationary carbon brushes B_1 and B_2 are pressed against the commutator.

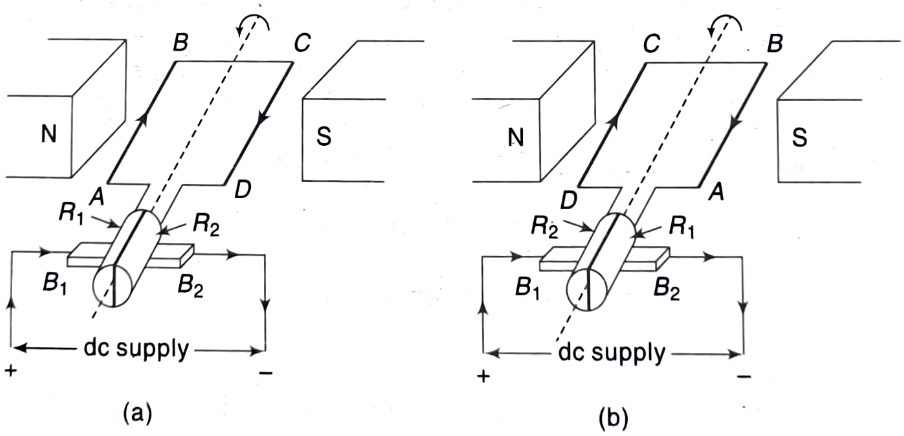


Fig. 5.7 Schematic diagram of a dc motor

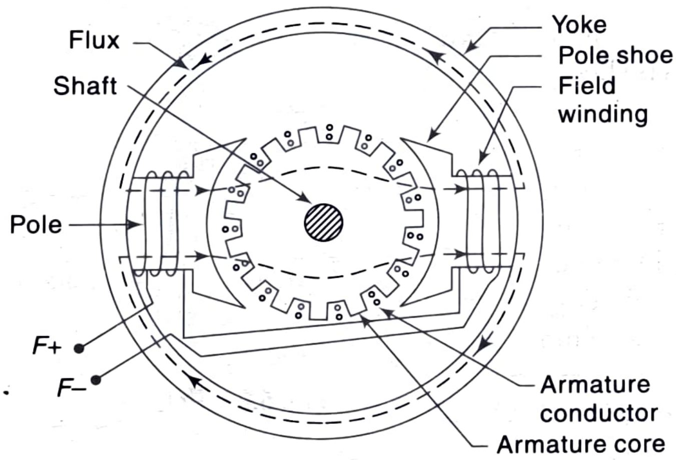
When the dc supply connected across the brushes B_1 and B_2 is switched on, current flows through the coil *ABCD* as shown in Fig. 5.7(a). As a result, each conductor of the coil experiences a mechanical force. By Fleming's left hand rule, the conductor *AB* experiences a force in downward direction, while the conductor *CD* experiences a force in upward direction. These forces collectively produce a torque, and the coil rotates about its own axis (shaft) in anticlockwise direction.

As soon as half a rotation of the coil is completed, segment R_1 of the commutator comes in contact with brush B_2 and segment R_2 with brush B_1, thereby reversing the direction of current in the coil as shown in Fig. 5.7(b). Since the position of the conductors *AB* and *CD* of the coil are also interchanged, the direction of rotation of the coil remains unchanged and the coil keeps on rotating in the same direction.

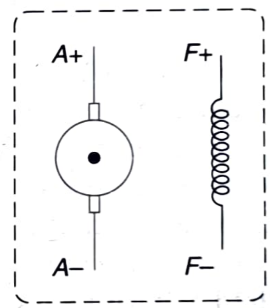
Thus, function of the commutator is to reverse the direction of the current in each conductor as it passes from one pole to another. It helps to develop a continuous and unidirectional torque.

5.3 Construction of DC Machine

Whether the dc machine is a generator or a motor, the basic construction remains the same. Figure 5.8(a) shows the cross-sectional view showing various parts of a two-pole dc machine. Figure 5.8(b) shows the equivalent circuit of the dc machine.



(a) Cross-sectional view



(b) Equivalent circuit

Fig. 5.8 DC machine

A dc machine consists of the following parts:

Stationary parts:

(i) Yoke
(ii) Pole
  (a) Pole shoes
  (b) Pole core
  (c) Field winding
(iii) Brushes

Rotating parts:

(i) Armature
  (a) Armature core
  (b) Armature winding
(ii) Commutator
(iii) Bearings

Yoke

It is the outer frame of the dc machine. It is normally made of a magnetic material such as cast iron. For large machines, rolled steel, cast steel, or silicon steel is used, which provides high permeability, i.e., low reluctance for the flux and gives good mechanical strength. Yoke generally serves two purposes:

(i) It provides mechanical support to the poles and acts as a protecting cover for the whole machine, so that the inner parts of the machine get protected from harmful atmospheric elements such as moisture, dust, and acidic fumes.

(ii) It forms a part of magnetic circuit and carries the magnetic flux produced by the poles. It provides the path of low reluctance for magnetic flux.

Poles

An even number of poles are bolted to the yoke. Each pole is divided into three parts, namely pole core, pole shoe, and field winding. This is shown in Fig. 5.9.

The poles of the machine are electromagnets. A winding is placed over the poles to excite them. This winding is called exciting winding or field winding or magnetizing winding. However, more commonly used name is **field winding**. As the poles are excited by the winding, they produce a magnetic field in the machine.

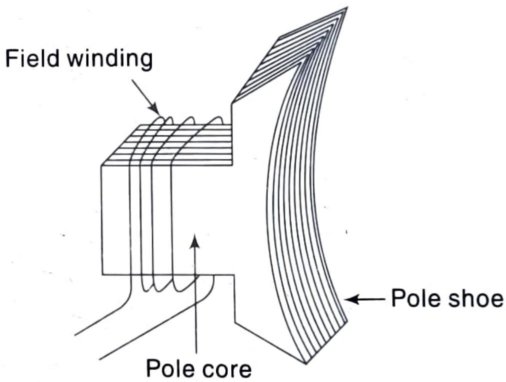


Fig. 5.9 Pole

The pole cores, which support the field windings, are mounted on the inside circumference of the yoke. The core is made of cast steel or sheet steel laminations of high permeability, so that it provides the low reluctance for the flux.

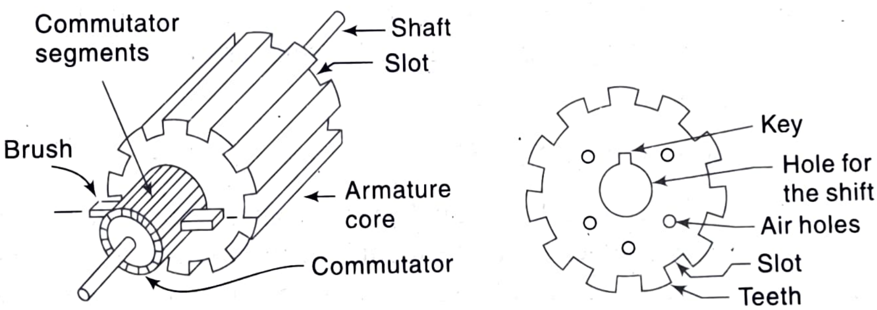
The pole faces are shaped to fit the curvature of the armature as shown in Fig. 5.8(a) and are known as the **shoes of the pole.** The pole shoes serve two purposes: (i) they spread out the flux in the air gap also, being of larger cross section, reduce the reluctance of the magnetic path and (ii) they support the exciting coils (or field coils).

The field coils, which consist of copper wire or strip, are former-wound for the correct dimension. Then the former is removed and the wound coil is put into the place over the core. These field coils are connected in series, so that finally we get the field winding having two terminals called **F+ and F–**. The field winding receives the current either from an external dc source or may be connected directly across the armature. When current flows through the field winding, magnetic flux lines are established in the yoke, pole pieces, air-gap and armature core as shown in Fig. 5.8(a).

Armature

It is further divided into two parts, namely armature core and armature winding.

The armature core is cylindrical in shape, mounted on the shaft as shown in Fig. 5.10(a) and rotates in the magnetic field. The outer surface is slotted to receive the armature conductors (winding). The armature core is made of laminations of sheet steel as shown in Fig. 5.10(b). The thickness of the laminations varies from 0.4 to 0.6 mm. The insulation between the core and the conductors is provided by placing thin sheets of solid insulation in the slots. The armature conductors connected in specific manner form the armature coils, which are called **armature winding.** The ends of the armature coils are brought to the commutator segments. The armature windings are made up copper and they form a closed circuit.



(a) Armature core (b) Armature lamination

Fig. 5.10 Armature

Commutator and brushes

As shown in Fig. 5.10(a), the commutator is a cylindrical drum mounted on the shaft, along with the armature drum. The surface of the drum is made of a large number of wedge-shaped segments of hard-drawn copper. The segments are insulated from one another by thin layer of mica. The armature winding is tapped at various points and these tapings are successively connected to various commutator segments.

The brushes generally are made to rest on the commutator by placing them in the brush holder against the action of spring whose tension can be adjusted as shown in Fig. 5.11.

The brushes are usually made of carbon and can slide on the commutator with the rotation of the brush gears, so that they can be fixed at any desired position

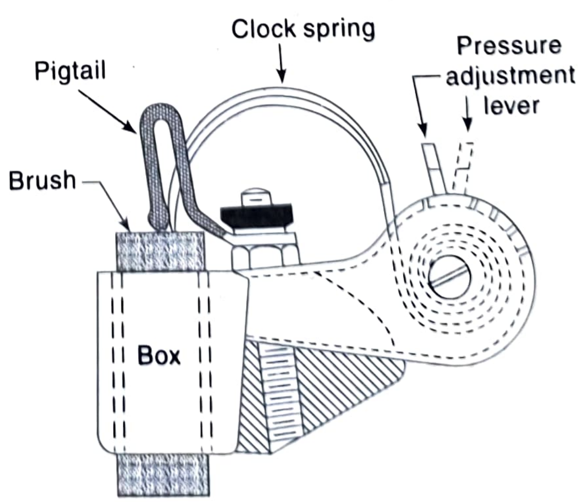


Fig. 5.11 Brush

on the surface of the commutator. A flexible copper pigtail mounted at the top of a brush carries the current. The brush holders, which are attached to the brush pieces together with the spring, hold the brushes in their position on the commutator. When a dc machine acts as a generator, the brushes are used to collect current from the commutator and supply it to the external circuit. When it acts as a motor, the brushes are used to send the current to the armature winding through commutator.

Bearings

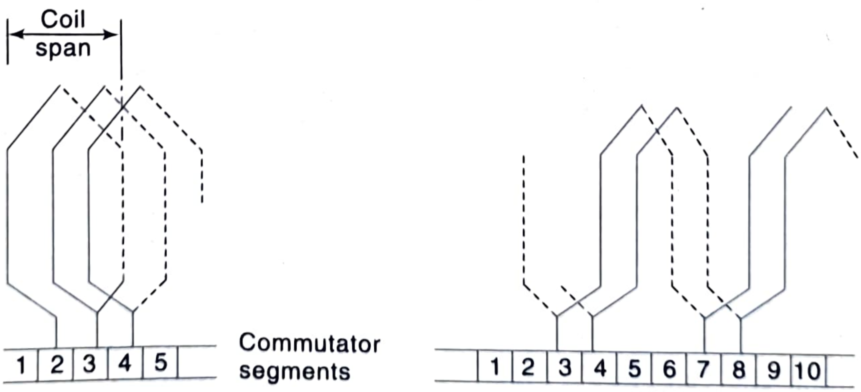
The bearings form an important part of all types of rotating machines. Their main function is to support the rotating part and allow its smooth motion with minimum friction. Ball and roller bearings are used for small- and medium-size dc machines. These bearings reduce the bearing losses to the great extent. For medium-size machines, roller bearings may be used at the driving end and ball bearings at the non-driving end (commutator end). Pedestal bearings are normally used for large dc machines.

5.3.1 Types of Armature Winding

In a dc machine, there are a large number of armature conductors, which are connected in specific manner as per the requirement. These are called **armature windings**. According to the way of connecting the conductors, armature winding are basically of two types, namely lap winding and wave winding.

Lap winding

In this type of winding, the armature conductors are divided into parallel paths, whose number equals the number of poles. In a simple lap winding, the connection is made from one commutator segment through the sides of the coil to the next commutator segment [see Fig. 5.12 (a)]. If an armature with lap winding has P poles and Z conductors, then the number of parallel paths will also be P, each consisting of Z/P conductors, connected in series between the positive and negative brushes. The current carried by each path is I_a/P, where I_a is the total armature



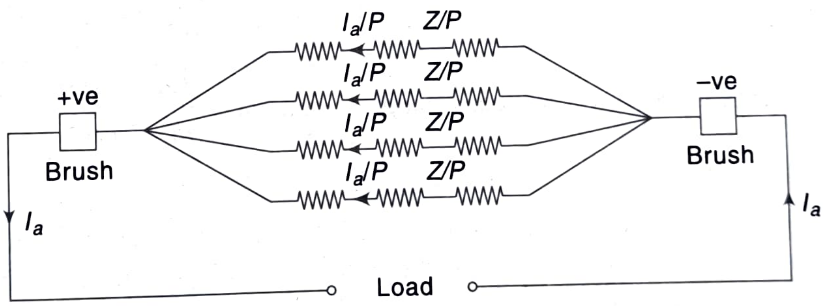
(a) Lap winding (b) Wave winding

Fig. 5.12 Types of armature winding

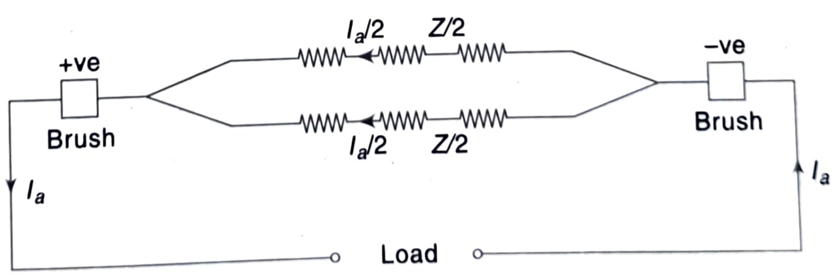
current. Due to the presence of a large number of parallel paths, lap winding is more suitable for generating large currents. Figure 5.13(a) shows the internal connections in armature of lap winding.

Wave winding

In this type of winding, the armature conductors are divided into two parallel paths. Thus, the armature current entering the negative brush finds two parallel paths while going to the positive brush. Hence, each parallel path carries a current of $I_a/2$, where I_a is the total armature current. In wave winding, the first conductor (say under N-pole) is connected directly to another conductor, which occupies a similar position, but under the opposite polarity pole (i.e., S-pole in the above example). The winding advances forward to the next N-pole and so on [see Fig. 5.12(b)]. This type of winding is so named because it travels like a progressive wave. As the number of parallel paths is less, it is preferable for low-current, high-voltage capacity generators. Figure 5.13(b) shows the internal connections in armature of wave winding.



(a) Lap winding



(b) Wave winding

Fig. 5.13 Internal connections in armature winding

5.4 EMF Equation of DC Generator

When field winding is excited, magnetic field is established in the dc machine. To use this machine as a generator, the armature is rotated with constant angular velocity with the help of prime mover. When the armature rotates, its conductors cut the magnetic flux lines and according to Faraday's law of electromagnetic induction, emf induced in the conductors. The equation of total induced emf in a dc generator can be calculated as follows.

Let P = Number of poles of generator
Φ = Flux produced by each pole in weber (Wb)
N = Speed of armature in rpm
Z = Total number of armature conductors
A = Number of parallel paths in which the total number of conductors are divided.

For lap type of winding, $A = P$
For wave type of winding, $A = 2$
According to Faraday's law of electromagnetic induction,

$$\text{Average value of emf induced in single conductor} = \frac{d\Phi}{dt} \qquad (\because N = 1)$$

Now, consider one revolution of a conductor. In one revolution, the conductor will cut the total flux produced by all the poles ($= P\Phi$).
Flux cut by the conductor in one revolution, $d\Phi = P\Phi$ weber

$$\text{Time required to complete one revolution, } dt = \frac{60}{N} \text{ sec}$$

$$\text{Hence, average value of emf induced in single conductor} = \frac{d\Phi}{dt} = \frac{P\Phi}{\left(\frac{60}{N}\right)} = \frac{P\Phi N}{60} \text{ volt}$$

This is the emf induced in one conductor. Now, the conductors in one parallel path are always in series. There are Z conductors with A parallel paths. Hence, Z/A number of conductors are always in series and emf remains same across all the parallel paths.
So, total emf can be expressed as

$$E_g = \frac{P\Phi N}{60} \times \frac{Z}{A} \text{ volt}$$

This equation is called emf equation of the dc generator.

We can also write $\boxed{E_g = \frac{\Phi Z N}{60} \times \frac{P}{A} \text{ volt}}$

where $A = P$ for lap winding
$A = 2$ for wave winding

5.5 Types of DC Generator

The symbolic representation of a dc generator is shown in Fig. 5.14. The armature is denoted by a circle with two brushes. The armature is driven by prime mover with speed N rpm. The two ends of the armature are denoted as $A+$ and $A-$. The field winding is shown near armature and the two ends are denoted by $F+$ and $F-$.

The poles of the machine are electromagnets. By passing the current through the field winding, the magnetic field is produced in the generator. Hence, this current is called **exciting current**. Depending on the way of deriving the field current or exiting current, dc generator is basically divided into two categories: (i) separately excited generator and (ii) self-excited generator. The self-excited generator is further classified depending upon the way of field winding connection with armature as (i) shunt generator, (ii) series generator, and (ii) compound generator.

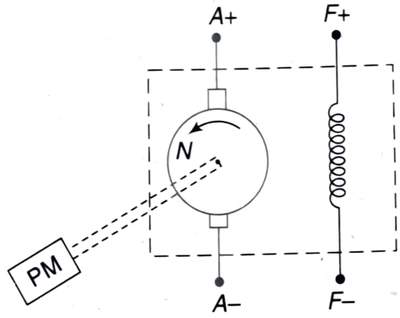


Fig. 5.14 Symbol of a dc generator

5.5.1 Separately Excited DC Generator

When the field winding is supplied from external, separate dc supply, i.e., excitation of the field winding is separate, the generator is called separately excited dc generator. Schematic representation of separately excited dc generator is shown in Fig. 5.15.

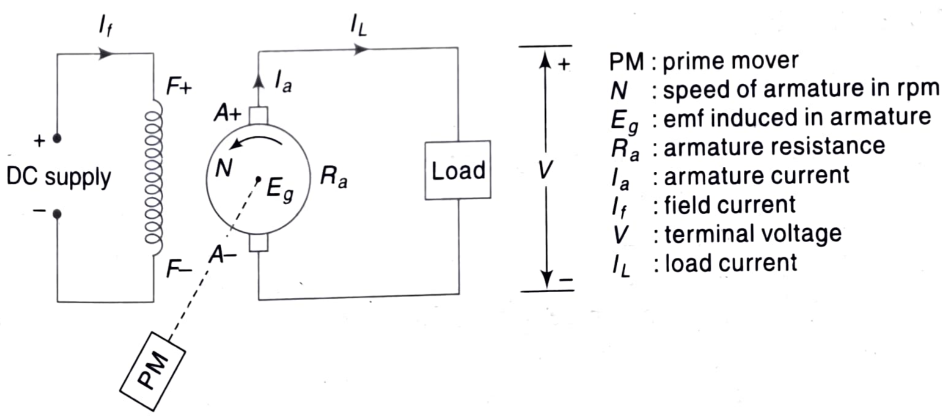


Fig. 5.15 Separately excited dc generator

Voltage and current relations

The prime mover rotates the armature at N rpm. The generator induces the emf E_g. Since the field winding is excited separately, the field current depends on supply voltage and resistance of the field winding. For armature side, we can see that it is supplying a load demanding a load current I_L at a voltage of V, which is called **terminal voltage**.

Now, $I_a = I_L$ (5.3)

Equation (5.3) is called **current equation**.

The internally induced emf E_g supplies the voltage to the load. Hence, terminal voltage V is a part of E_g. But it is not equal to V while supplying a load. This is because when armature current I_a flows through armature winding, due to armature winding resistance R_a ohm, there is a voltage drop across armature winding equal to I_aR_a volt. The induced emf has to supply this drop, along with the terminal voltage V. To keep I_aR_a drop to minimum, the resistance R_a is designed to be very small. In addition to this drop, there is some voltage drop at the contacts of the brush, called **brush contact drop**. But this drop is negligible and hence, generally neglected. When armature carries current I_a, it produces its own flux called armature flux. This flux has a tendency to disturb the pattern of main useful flux produced by field winding. This distortion produced by armature flux reacting with field flux is called **armature reaction**. Due to this armature reaction, there is a drop in voltage.

Hence, in all the induced emf, E_g has to overcome I_aR_a drop, brush contact drop and armature reaction drop to produce the terminal voltage V at the load. Thus, the voltage equation for the generator is

$$E_g = V + I_aR_a + V_{\text{brush}} + \text{Armature reaction drop} \tag{5.4}$$

Equation (5.4) is called **voltage equation.**

By using the voltage equation, induced emf E_g or terminal voltage V can be determined if other drops are known. The brush contact drop is generally specified as per brush drop. As there are two brushes, total brush drop is twice the drop per brush.

5.5.2 Self-excited DC Generator

Self-excited dc generator is one whose field windings are excited by the current produced by the generator itself. Now, without generated emf, field cannot be excited in such a generator and without excitation, there cannot be generated emf. So, one may obviously wonder how this type of generator works. The answer to this is residual magnetism possessed by the field poles under normal condition. This enables armature to develop small emf, which circulates current through field, which further increases the flux produced. Because of this cumulative process, the generator ultimately produces its rated voltage.

There are three types of self-excited generators named according to the manner in which their field windings are connected to the armature as: (i) shunt generator, (ii) series generator, and (iii) compound generator.

Shunt generator

When the field winding is connected across or in parallel with the armature, the generator is called shunt generator. Since the field winding has large number of turns of thin wire, it has high resistance compared to the armature winding. Let R_{sh} be the resistance of the field winding and I_{sh} be the current through the field winding. Schematic representation of shunt generator is shown in Fig. 5.16(a).

Before loading a shunt generator, it is allowed to build up its voltage. Assume that the generator in Fig. 5.16(a) has no load connected to it and the armature is driven at a certain speed by a prime mover. Usually, there is always present some residual magnetism in the poles; hence, a small emf is produced initially. This emf circulates a small current in the field circuit, which increases the pole flux.

When flux is increased, generated emf is increased, which further increases the flux and so on. As shown in Fig. 5.16(b), 'E_1' is the induced emf due to residual magnetism, which appears across the field circuit and causes the field current 'I_{sh1}'to flow. This current aids residual flux and hence produces a larger induced emf 'E_2'. In turn, this increased emf 'E_2' causes an even larger current 'I_{sh2}', which creates more flux for a still larger emf and so on. This process of voltage build-up continues. The effect of magnetic saturation in the pole faces limits the terminal voltage of the generator to a steady state value (E_g).

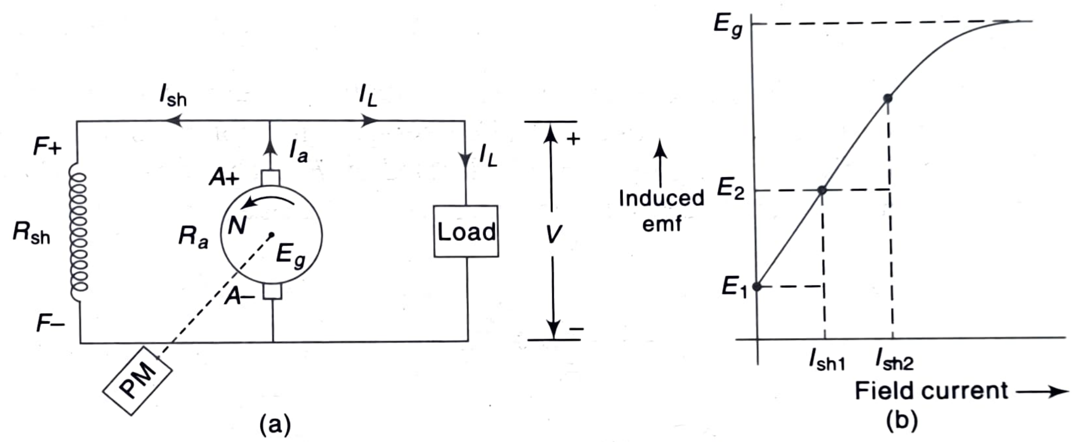


Fig. 5.16 Shunt generator and build-up of a generator

Voltage and current relations From the circuit shown in Fig. 5.16(a), we can write the current equation as

$$I_a = I_L + I_{sh} \tag{5.5}$$

Now, voltage across load is V, which is same across field winding as both are in parallel with each other.

So, $$I_{sh} = \frac{V}{R_{sh}}$$

While induced emf E_g still requires to supply voltage drop I_aR_a, brush contact drop and armature reaction drop. Thus, we get the voltage equation as

$$E_g = V + I_aR_a + V_{\text{brush}} + \text{Armature reaction drop} \tag{5.6}$$

Since the shunt field winding has large number of turns of thin copper, its cross-sectional area is small. Its resistance R_{sh} is high. This is because the load current should not disturb the field current I_{sh} and remains constant for the operation range of generator.

Load characteristics of shunt generator The relation between the terminal voltage V and the load current I_L is called load characteristics or performance characteristics of the generator.

From the voltage equation, we can see that as load current I_L increases, the armature current I_a increases to satisfy the load demand. Thus, the armature voltage drop I_aR_a also increases. Hence, the terminal voltage $V = E_g - I_aR_a$ decreases, neglecting other drops. But as R_a is very small, though I_L changes from no load to full load, the drop in the terminal voltage is very small. This is shown in Fig. 5.17. Hence, dc shunt generator is also called constant voltage generator.

Application of shunt generator Due to constant voltage characteristics, shunt generators are commonly used for battery charging, ordinary lighting and power supply purposes.

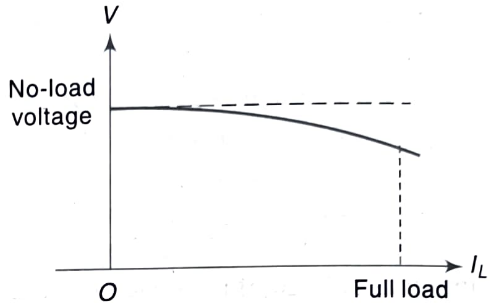


Fig. 5.17 Load current vs terminal voltage

Series generator

When the field winding is connected in series with the armature winding while supplying the load, the generator is called series generator. It is shown in Fig. 5.18. The field winding resistance is denoted by R_{se}. The resistance R_{se} is very small and hence, naturally it has less number of turns of a wire of thick cross section.

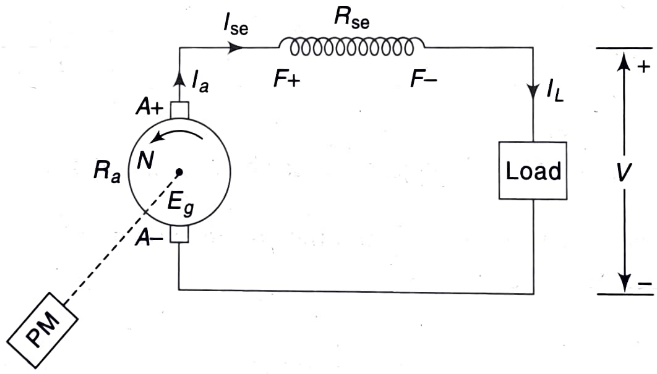


Fig. 5.18 Series generator

Voltage and current relations As armature, field winding and load, all are in series, they carry the same current. So, the current equation can be written as

$$I_a = I_{se} = I_L \tag{5.7}$$

where I_{se} = current through series field winding

Now, in addition to drop I_aR_a, induced emf has to supply voltage drop across series field winding too.

The voltage drop across series field winding = $I_{se}R_{se} = I_aR_{se}$ $(\because I_a = I_{se})$

Thus, voltage equation can be written as

$$E_g = V + I_aR_a + I_aR_{se} + V_{\text{brush}} + \text{Armature reaction drop}$$

or
$$E_g = V + I_a(R_a + R_{se}) + V_{\text{brush}} + \text{Armature reaction drop} \tag{5.8}$$

Load characteristics of series generator In series generator, as $I_a = I_{se} = I_L$, when I_L increases, I_{se} also increases. The flux Φ is directly proportional to I_{se}. So, the flux increases. As induced emf E_g is directly proportional to the flux, E_g also increases. For load characteristics, the drop $I_a(R_a + R_{se})$ increases as I_a increases. But this drop is small compared to increase in V due to increase in E_g, and so, graph of V versus I_L is rising in nature as shown in Fig. 5.19. On no load, there exists some voltage due to residual flux retained by the field winding, and the characteristics do not pass through origin.

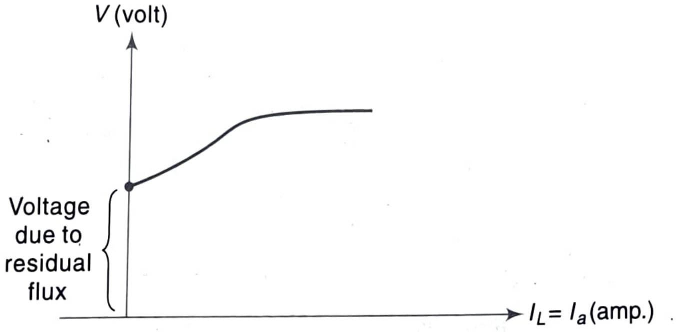


Fig. 5.19 Terminal voltage vs load current

Application of series generator Due to the rising characteristics, series generators are used as boosters on dc feeders and as constant current generators for welding generators and lamps.

Compound generator

In compound generator, the poles of the machine are excited by the two independent field windings, i.e., shunt field winding and series field winding. The shunt field winding is connected in parallel and the series field winding is connected in series, with the armature winding. The shunt field winding is stronger than the series field winding. If series field aids the shunt field, i.e., the magnetizing effect of the two windings is cumulative, the generator is called cumulative compound generator [see Fig. 5.20(a)]. If series field opposes the shunt field, the generator is said to be differential compound generator [see Fig. 5.20(b)].

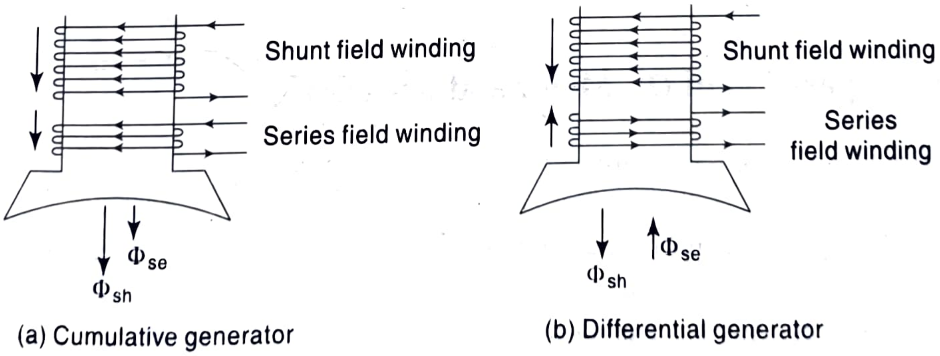


Fig. 5.20 Excitation of pole by shunt and series field windings

The compound generator can be either short shunt or long shunt as shown in Figs 5.21(a) and (b) respectively. So, the cumulative or differential compound generator can be either short shunt or long shunt.

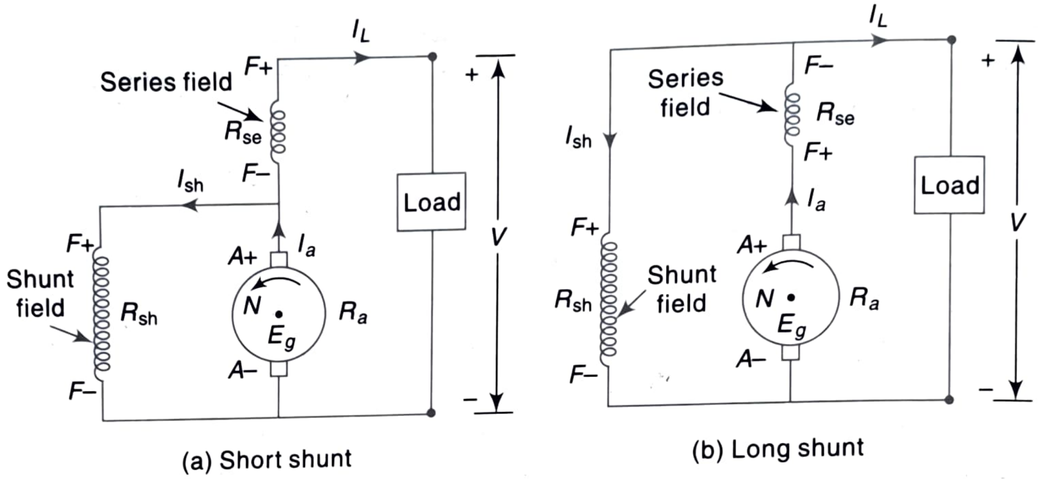


Fig. 5.21 Compound generator

Load characteristics In Fig. 5.21, if it is imagined that the series field winding is absent, it is simple-shunt generator and its load characteristics will be same as those shown in Fig. 5.17. These characteristics are of drooping nature. For the cumulative compound generator, series field aids the shunt field, and so, it gives characteristics of boosting nature. But for differential compound generator, as series field winding opposes the shunt field, it now gives negative boosting characteristics. The load characteristics of compound generator are shown in Fig. 5.22.

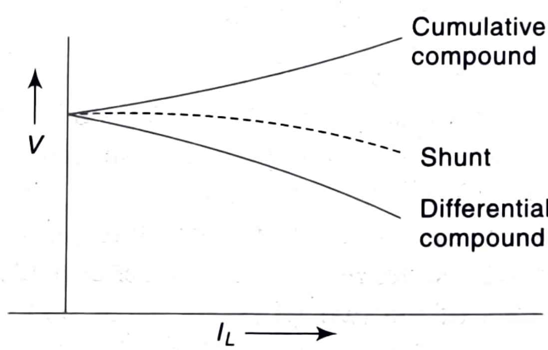


Fig. 5.22 Load characterstics of compound generator

5.6 Operation of DC Motor and Back EMF

We know that constructionally there is no basic difference between a dc generator and a dc motor. In fact, the same machine can be used interchangeably as a generator or as a motor.

Figure 5.23 shows the cross-sectional view of two-pole dc motor. When its field magnets are excited and dc voltage is applied to the motor, current flows through the armature conductors. Armature conductors under the N-pole are assumed to carry the current downwards (shown by crosses) and those under S-pole to carry current upwards (shown by dots).

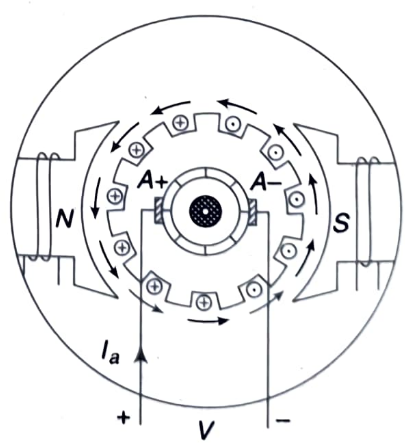


Fig. 5.23 Two-pole dc motor

By basic principle, each conductor will experience a mechanical force. According to Fleming's left hand rule, each conductor will experience a force in anticlockwise direction, which is shown by small arrows placed above each conductor. These forces collectively produce a driving torque, which sets the armature rotating in anticlockwise direction.

It should be noted that the function of commutator is to reverse the direction of current in each conductor as it passes from one pole to another. It helps to develop a continuous and unidirectional torque.

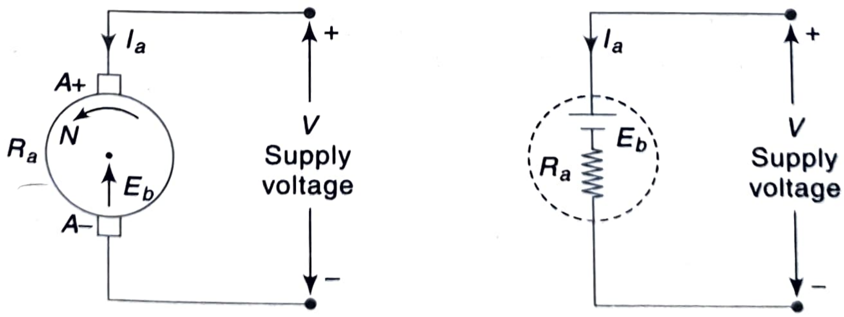
It is seen in the generator action that when an armature conductor cuts the lines of flux, emf gets induced in it. In a dc motor, after a motoring action, there exists a generator action. When the armature rotates, the conductor cuts the magnetic flux lines and according to Faraday's law of electromagnetic induction, emf gets induced in it. This induced emf in the armature always acts in the opposite direction of the supply voltage. This is according to Lenz's law, which states that the direction of induced emf is always so as to oppose the cause producing it. In a dc motor, electrical input, i.e., the supply voltage, is the cause and hence, this induced emf opposes the supply voltage. This emf tries to set up a current through the armature in the opposite direction, which supplies voltage forcing through the conductor.

So, as this emf always opposes the supply voltage, it is called **back emf** and denoted by E_b. Though it is denoted as E_b, basically it gets generated by the generating action that we have seen earlier. So, its magnitude can be determined by the emf equation derived earlier. Thus,

$$E_b = \frac{\Phi ZN}{60} \times \frac{P}{A} \text{ volt}$$

where all symbols carry the same meaning as in case of generators.

The back emf is shown schematically in Fig. 5.24(a). If V is the supply voltage and R_a is the value of the armature resistance, the equivalent circuit will be as shown in Fig. 5.24(b). In equivalent circuit, back emf is represented by a battery of emf E_b with polarity such that it opposes the supply voltage.



(a) Back emf (b) Equivalent circuit

Fig. 5.24 Armature circuit

Applying KVL to the equivalent circuit shown in Fig. 5.24(b), we get the voltage equation of the dc motor as

$$V = E_b + I_a R_a \tag{5.9}$$

Thus, in case of dc motor, supply voltage V has to overcome back emf E_b (which opposes V) and also armature resistance drop I_aR_a. In fact, the electrical work done in overcoming the back emf gets converted into the mechanical energy, developed in the armature.

The back emf is always less than the supply voltage. The net voltage across the armature is the difference between the supply voltage and the back emf, which decides the armature current. Hence, from the voltage equation, we can write

Armature current, $I_a = \dfrac{V - E_b}{R_a}$

Multiplying both sides of the voltage equation, Eq. (5.9), by I_a, we get

$$VI_a = E_bI_a + I_a^2R_a \tag{5.10}$$

where VI_a = Electrical power input to the armature
$I_a^2R_a$ = Power loss due to the armature resistance called armature copper loss
E_bI_a = Electrical equivalent of gross mechanical power developed in the armature

Equation (5.10) is called **power equation** of the dc motor.
Hence, some of the armature input is wasted in I^2R loss and rest is converted into mechanical power within the armature.

5.7 Torque Equation of a DC Motor

In general, torque is the turning or twisting movement of a force about an axis. The torque, angular speed and power are related as

Mechanical power developed, $P = T \times \omega$

where T = Torque in Nm
ω = Angular speed in rad/sec

In case of motor, each armature conductor experiences a force, and these forces collectively produce a torque (T_a).

Let T_a be the torque developed by the armature of the motor running at N rpm.
So, the mechanical power developed, $P = T_a \times \omega$ (5.11)
From Eq. (5.10) above (i.e., power equation of a motor), we know that
Mechanical power developed = E_bI_a (5.12)
Equating Eqs (5.11) and (5.12),

$$T_a \times \omega = E_bI_a$$

or $$T_a \times \frac{2\pi N}{60} = E_bI_a \qquad \left(\because \omega = \frac{2\pi N}{60}\right)$$

or $$T_a \times \frac{2\pi N}{60} = \left(\frac{\Phi ZN}{60} \times \frac{P}{A}\right) I_a \qquad \left(\because E_b = \frac{\Phi ZN}{60} \times \frac{P}{A}\right)$$

or $$T_a = \frac{1}{2\pi}\Phi ZI_a\left(\frac{P}{A}\right) \text{ Nm}$$

This is the **torque equation** of the dc motor. So, for a dc motor,

$$T_a \propto \Phi I_a$$

5.8 Types of DC Motor

Similar to the dc generators, the dc motors are classified depending upon the way of connecting the field winding with the armature winding as shunt motor and series motor.

5.8.1 Shunt Motor

In this type of dc motor, the field winding is connected across the armature winding and the combination is connected across the supply as shown in Fig. 5.25.

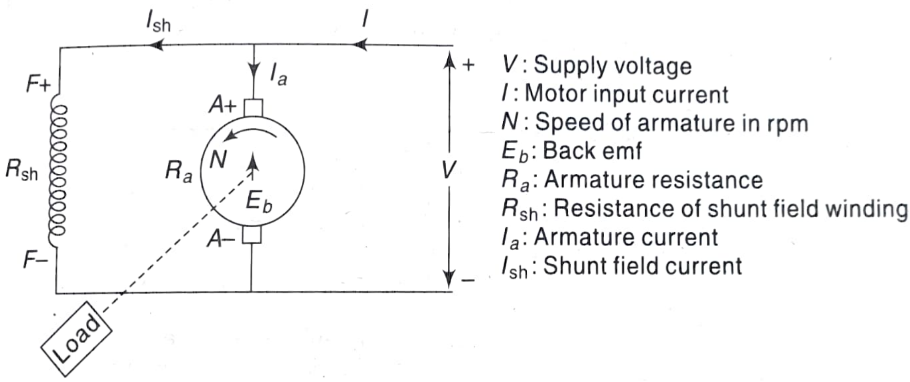


Fig. 5.25 Shunt motor

The value of R_a is very small while R_{sh} is quite large. Hence, shunt field winding has more number of turns with less cross-sectional area.

The voltage across the armature and the field winding is same—equal to the supply voltage V.

From circuit diagram, the total current drawn from the supply can be written as

$$I = I_a + I_{sh} \tag{5.13}$$

Equation (5.13) is called **current equation** of the shunt motor.

where shunt current, $I_{sh} = \dfrac{V}{R_{sh}}$

The supply voltage V has to overcome back emf E_b (which is opposing V) and also armature resistance drop I_aR_a. So, we get the voltage equation of shunt motor as

$$V = E_b + I_aR_a \tag{5.14}$$

Now, the flux produced by the field winding is proportional to the current passing through it, i.e.,

$$\Phi \propto I_{sh}$$

As long as the supply voltage is constant, which is generally so in practice, the flux produced is constant. Hence, dc shunt motor is also called **constant flux motor**.

Applications of shunt motor

Shunt motor is a constant speed motor having medium starting torque. The speed of a shunt motor can be adjusted over a wide range. Therefore, shunt motor can be used in

(i) various machine tools such as lathe machines, drilling machines, milling machines, etc.,
(ii) centrifugal and reciprocating pumps,
(iii) blowers and fans, and
(iv) printing machinery and paper machines.

5.8.2 Series Motor

In this type of dc motor, the series field winding is connected in series with the armature winding and the supply as shown in Fig. 5.26.

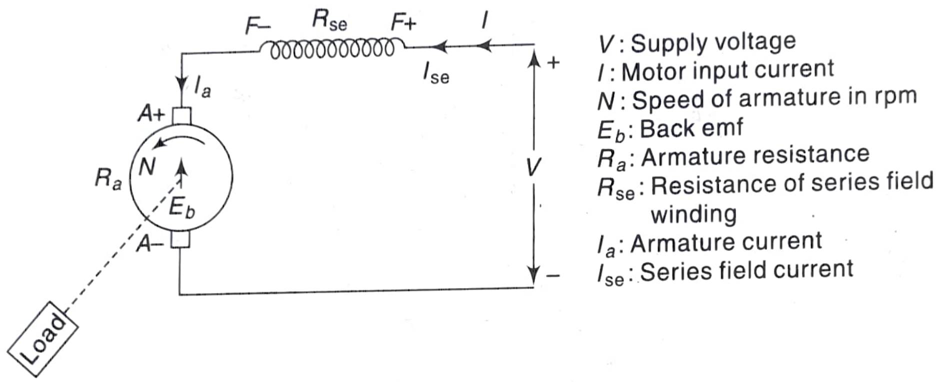


Fig. 5.26 Series motor

The value of R_{se} is very small and it is made of small number of turns having large cross-sectional area.

As all armature, field winding and supply are in series, they carry the same current. So, the current equation can be written as

$$I = I_{se} = I_a \tag{5.15}$$

where I_{se} = current through the series field winding

The supply voltage V has to overcome the drop across series field winding, in addition to the back emf E_b (which is opposing V) and the armature resistance drop I_aR_a. So, we get the voltage equation of series motor as

$$V = E_b + I_aR_a + I_aR_{se}$$

$$V = E_b + I_a(R_a + R_{se}) \tag{5.16}$$

In this motor, entire armature current is passing through the series field winding. So, flux produced is proportional to the armature current, i.e.,

$$\Phi \propto I_{se} \propto I_a$$

Applications of series motor

Series motor has very high starting torque and good accelerating torque. The speed is adjustable and varying. The motor has very low speed at high loads and dangerously high speed at low loads. Therefore, series motor can be used in

(i) electric trains,

(ii) trolley cars and trolley buses,
(iii) cranes and hoists,
(iv) conveyers, and
(v) rapid transit system.

5.9 Three-Phase Induction Motors

Three-phase induction motor is the most popular type of ac motor. It is commonly used for industrial drives since it is cheap, robust, efficient, and reliable. It has good speed regulation and high starting torque. It requires little maintenance. It has reasonable overload capacity. In fact, three-phase induction motors find their applications everywhere, i.e., from a small workshop to a large industry.

In motors, conversion of electrical power into mechanical power takes place in the rotating part of the motor, which is called **rotor**. In dc motors, electric power is conducted directly to the armature (i.e., rotating part) through brushes and commutator. Hence, in this case, a dc motor can be called a **conduction motor**. However, in ac motors, the rotor does not receive electrical power by conduction but receives it by induction in exactly the same way as the secondary of a transformer. That is why such motors are known as **induction motors**. In fact, an induction motor can be treated as a rotating transformer, i.e., one in which primary winding is stationary but the secondary is free to rotate.

5.9.1 Construction

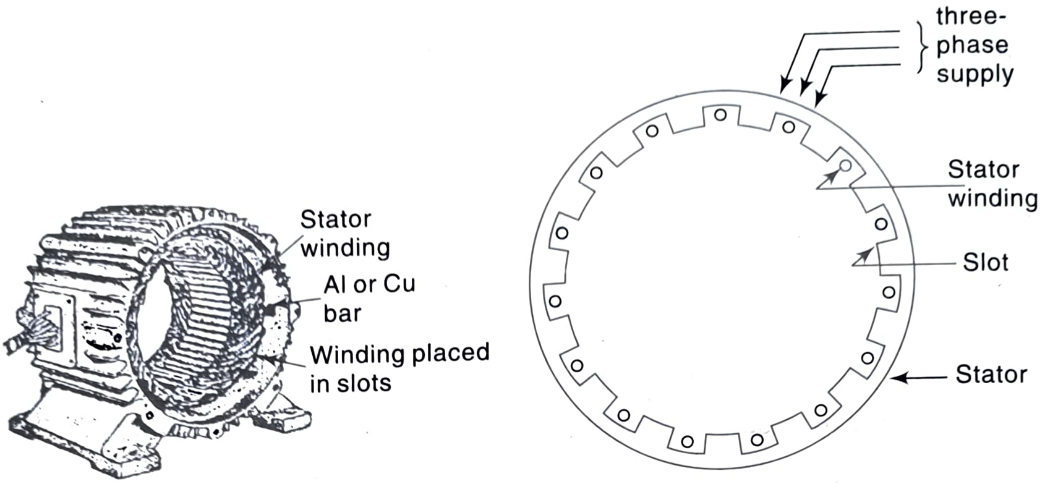
A three-phase induction motor consists of two parts: the stator and the rotor. The stator is the stationary part and the rotor is the rotating part.

Stator

Stator is an outer 'stationary', hollow, cylindrical structure made of laminated sheet steel. The inner periphery of the stator is slotted to receive the windings. The stator carries the three-phase winding and is fed from a three-phase supply. It is wound for a definite number of poles, and the exact number of poles is determined by the requirement of speed. Greater the number of poles, lesser is the speed and vice versa. The three-phase windings may be connected in star or delta. Figure 5.27(a) shows the actual photograph of a stator, while Fig. 5.27(b) shows the schematic representation of a stator. When the stator winding is fed from a three-phase supply, it produces a magnetic field, which is of constant magnitude but revolves at synchronous speed.

Rotor

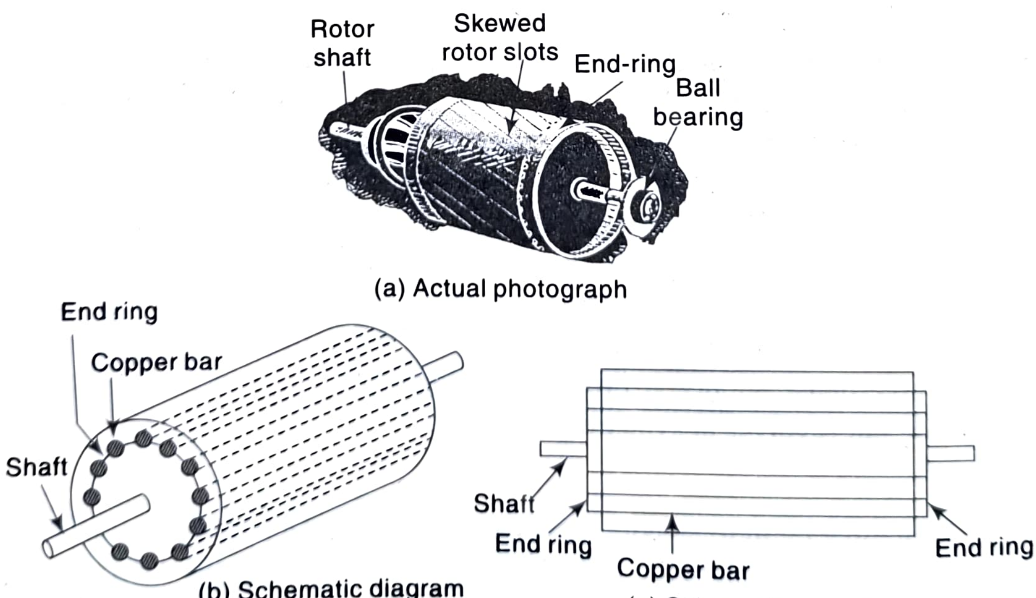
Rotor is an inner cylindrical core mounted on the shaft. Depending upon the type of the winding used, there are two types of rotors: squirrel-cage rotor and slip-ring (or phase-wound) rotor.



(a) Actual photograph (b) Schematic diagram

Fig. 5.27 Stator

Squirrel-cage rotor This rotor has the simplest and most rugged construction. It consists of a cylindrical laminated core with slots parallel to the shaft axis. Each slot contains one bar conductor of aluminum or copper. At both the ends of the rotor, the bar conductors are short circuited by heavy end rings of the same material. The bar conductors and end rings form a cage of the type that was once commonly used for keeping squirrels, hence its name. It should be noted that the rotor bars are permanently short circuited on themselves. Hence, it is not possible to add any external resistance in series with the rotor circuit for starting purposes. Figure 5.28(a) shows the actual photograph, while Figs 5.28(b) and (c) show schematic representation of squirrel-cage rotor.



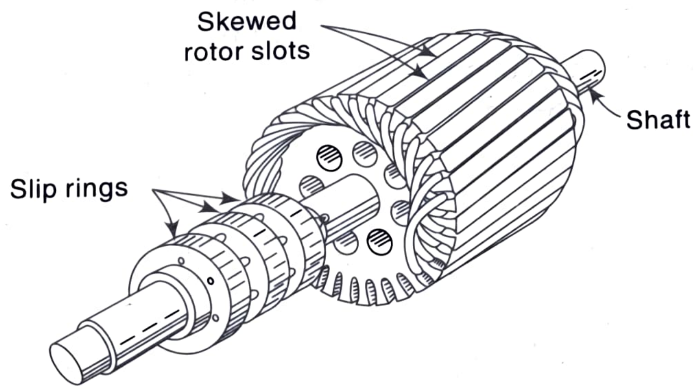
(a) Actual photograph

(b) Schematic diagram (c) Schematic diagram

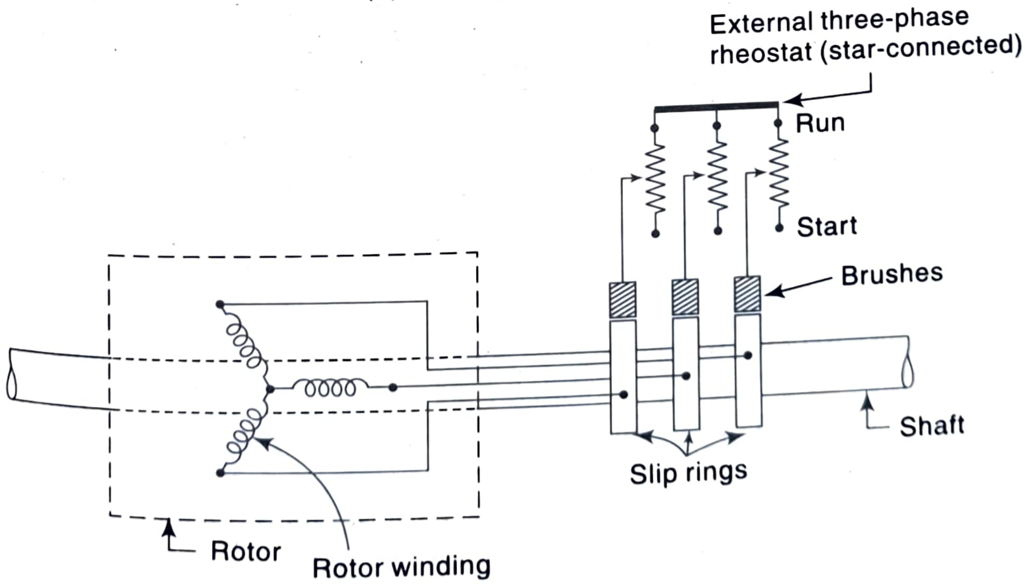
Fig. 5.28 Squirrel-cage rotor

The rotor slots are usually not quite parallel to the slot but are purposely given a slight skew. This is useful to reduce the magnetic hum and locking tendency of the rotor. During locking, the rotor and the stator teeth attract each other due to magnetic action.

Phase-wound rotor or slip-ring rotor This rotor consists of a slotted laminated core of sheet steel. A three-phase winding is placed in the rotor slots, having the same number of poles as the stator. The rotor winding is usually connected in star. The other three terminals are brought out and connected to three insulated slip rings mounted on the shaft with brushes resting on them as shown in Fig. 5.29(b).These three brushes are further externally connected to a three-phase star-connected rheostat. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor. Also by varying the external resistance, the speed of the motor can be controlled. A slip-ring induction rotor is shown in Fig. 5.29(a).



(a) Actual photograph



(b) Schematic diagram

Fig. 5.29 Phase-wound rotor

Table 5.1 Comparison of squirrel-cage rotor and slip-ring (phase-wound) rotor

Squirrel-cage rotor	Slip-ring (phase-wound) rotor
1. Cost of fabrication is low.	1. Cost of fabrication is high.
2. Construction is simple.	2. Construction is complicated.
3. Maintenance cost is very low.	3. Maintenance cost is high (due to the presence of brushes, brush gears, extra resistances, etc.).
4. Extra resistance can not be added in rotor circuit.	4. Extra resistance can be added in rotor circuit to enable the motor to develop the higher starting torque.
5. Nearly 95% of induction motors employ squirrel-cage rotor.	5. Only 5% of induction motors employ slip-ring (phase-wound) rotor.

5.9.2 Rotating Magnetic Field

There are two ways to produce a rotating magnetic field. The one way is to rotate a frame having magnetic poles as shown in Fig. 5.30 by some driving engine at some speed. Then it will naturally produce a rotating magnetic field. This frame carries four poles, i.e., electromagnets excited by a field winding. The way of field winding and the direction of field current are such that these poles have alternate polarities as N-S-N-S.

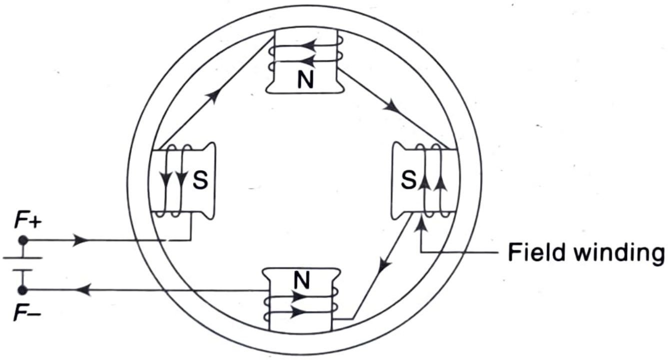


Fig. 5.30 Rotating magnetic poles

The other way to produce the rotating magnetic field is to feed the stator of the three-phase induction motor by three-phase supply. Figure 5.31(a) shows the sectional view of stator of a three-phase induction motor. Slots are provided on the inner surface to place winding. These slots carry a three-phase winding, which are internally connected in star or delta. The three windings are redrawn in Fig. 5.31(b) as a star-connected winding. This winding is wound for certain number of poles. As the stator is cylindrical in shape, one can not physically observe the poles as they are seen in Fig. 5.30. But if the winding is wound for, say, four poles, then it means that the stator will act as four poles. It can be proved that a three-phase winding when supplied by three-phase ac supply produces a rotating magnetic field. The speed at which magnetic field rotates is called the synchronous speed, denoted by N_s. If the winding is wound for P poles and f is the supply frequency in Hz, then

Synchronous speed, $N_s = \dfrac{120\,f}{P}$

Out of the two methods of producing rotating magnetic field explained above, the second method is used for production of rotating magnetic field. It may be noted that the stator shown in Fig. 5.31(a) is a stationary frame, and the winding placed in slots is also stationary, but the magnetic field produced is a rotating field. The following sub-section explains how a rotating field is generated.

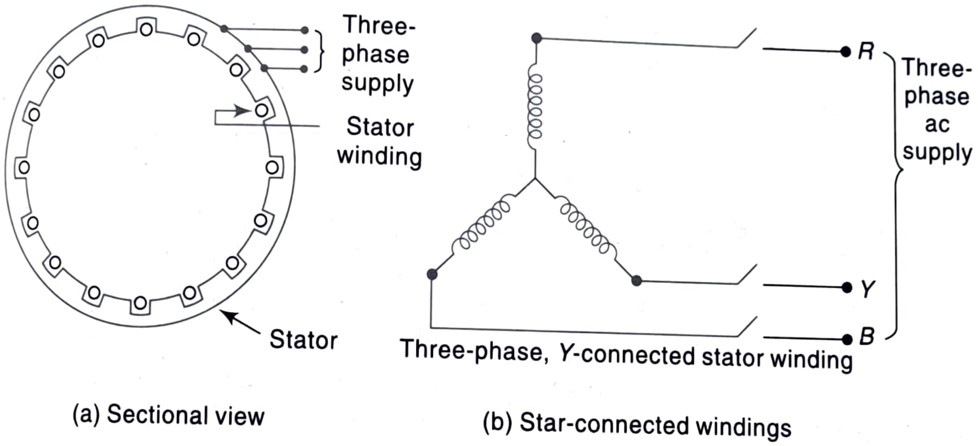
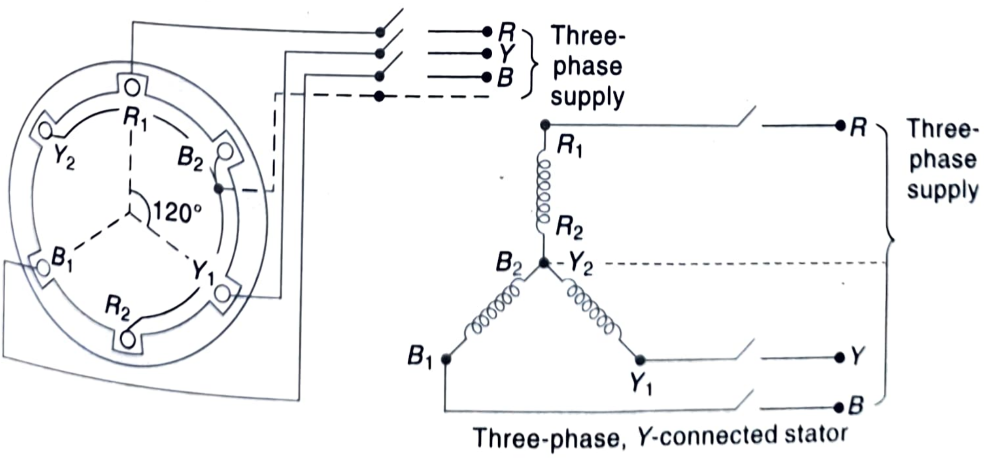


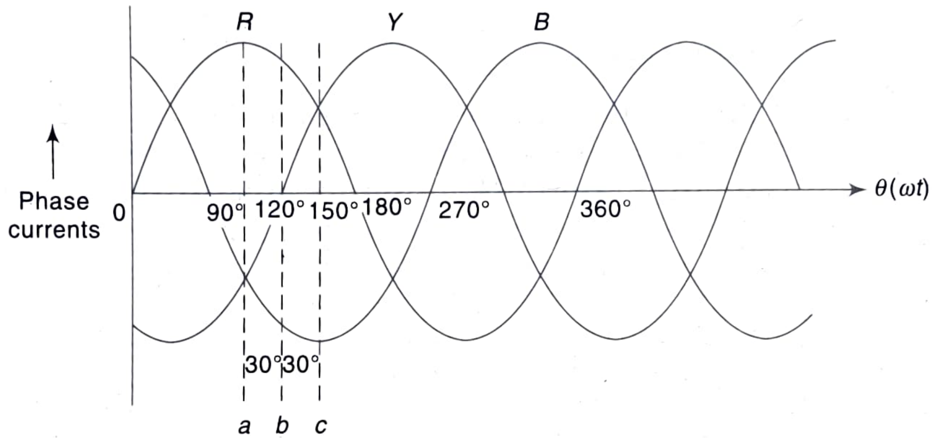
Fig. 5.31 Stator of a three-phase motor

5.9.3 Production of a Rotating Magnetic Field

Consider a stator of three-phase induction motor, wound for two poles and having only six slots as shown in Fig. 5.32(a). Obviously, there is only one slot per pole per phase. These slots will carry only three coils, one for each phase. The three windings (coils) are placed 120° apart from each other. Each phase (winding) coil has two terminals. R_1 and R_2 represent 'start' and 'finish' of phase R respectively. Similarly, Y_1, Y_2 and B_1, B_2 represent 'start' and 'finish' of phases Y and B respectively. The three phases are connected in star (i.e., finishing terminals are connected together). This star-connected winding is connected to three-phase ac supply. The currents carried by three phases are shown in Fig. 5.32(b).



(a)



(b) Currents carried by three phases

Fig. 5.32 Stator winding and three-phase supply

Let current flowing towards the stator is assumed as positive and flowing away from the stator is negative. Consider a time instant *a* shown in Fig. 5.32(b). At this instant, phase *R* carries positive current. This is indicated in Fig. 5.33(a) by putting cross for R_1 and dot for R_2. (A cross indicates that current is flowing inwards, perpendicular to the plane of the paper, whereas a dot indicates that it is flowing outwards.) At this instant, *Y* and *B* carry negative currents. This is indicated by showing Y_2, B_2 with crosses and Y_1, B_1 with dots. According to the right hand screw rule, the magnetic fluxes produced will be as shown by dotted lines [see Fig. 5.33(a)]. It is obvious that all the three coils together produce a net magnetic flux in a particular direction, as shown in Fig. 5.34.

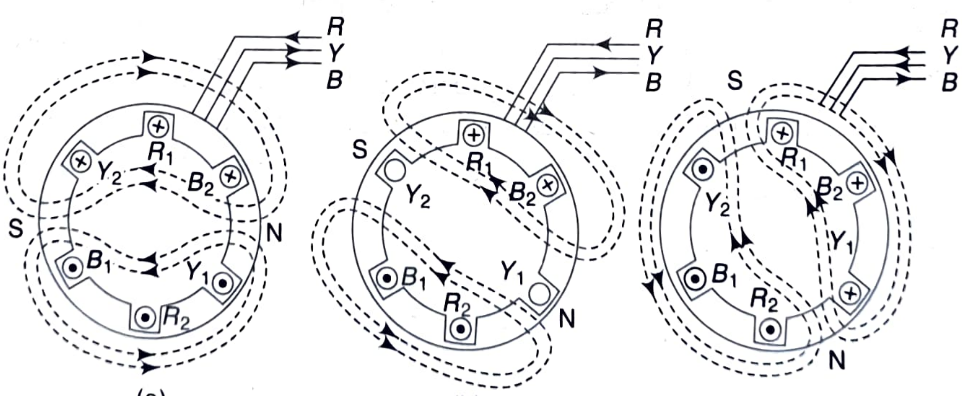


Fig. 5.33 Magnetic field produced by stator at various instants

For instant *b* of Fig. 5.32(b), *R* carries positive current, *B* carries negative current, and current in *Y* is zero. This is indicated by crosses and dots in Fig. 5.33(b) and the dotted lines indicate the magnetic flux produced by them. Obviously, the direction of the net flux is as shown in Fig. 5.34.

Similarly, for instant c of Fig. 5.32 (b), dot-cross position is shown in Fig. 5.33(c) and Fig. 5.34 shows the direction of the net flux.

It can be concluded that for the instants a, b and c having 30° intervals, the axis of the net magnetic flux also shifts by 30°. If various instants over one complete cycle are considered, it is obvious that the axis of the net magnetic flux will go through one complete rotation of 360°. Therefore, a three-phase stationary winding, carrying three-phase currents produces a rotating magnetic field.

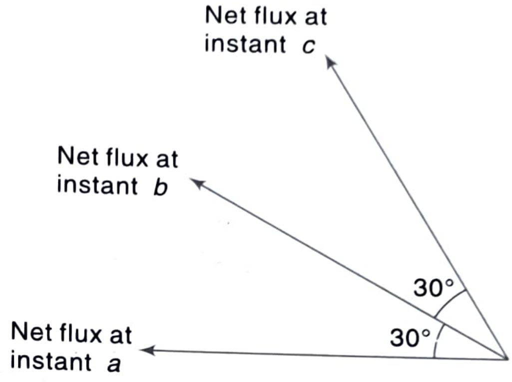


Fig. 5.34 Shifting of the axis of the net magnetic flux

5.9.4 Principle of Operation of Three-Phase Induction Motor

When the stator is connected to the three-phase supply, the three-phase currents in the stator winding produce a rotating magnetic field (or flux), which rotates round the stator at synchronous speed (N_s). This rotating flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors, which, as yet, are stationary. Due to the relative speed between the rotating flux and the stationary conductors, an emf is induced in the rotor conductors. The frequency of the induced emf is same as the supply frequency when the rotor is stationary. Since the rotor conductor's circuit is closed, the induced emf produces the rotor current, which starts flowing in the rotor conductors. The direction of the rotor current, as given by Lenz's law, is so as to oppose the very cause producing it. In this case, the cause that produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux.

The setting up of the torque for rotating the rotor is explained below.

Let us consider one conductor on the stationary rotor as shown in Fig. 5.35(a). Let this conductor be subjected to the rotating magnetic field produced when a three-phase supply is connected to the three-phase winding of the stator.

Let the rotation of the magnetic field be clockwise. A magnetic field moving clockwise has the same effect as a conductor moving anticlockwise in a stationary field. By Faraday's law of electromagnetic induction, a voltage will be induced in the conductor. Since the rotor circuit is closed, the induced voltage causes a current to flow in the rotor conductor. By right hand rule, we can determine the direction of the induced current in the conductor. Since the magnetic field is rotating clockwise and the conductor is stationary, we can assume that the conductor is in motion in the anticlockwise direction with respect to the magnetic field. By right hand rule, the direction of the induced current is outward (shown

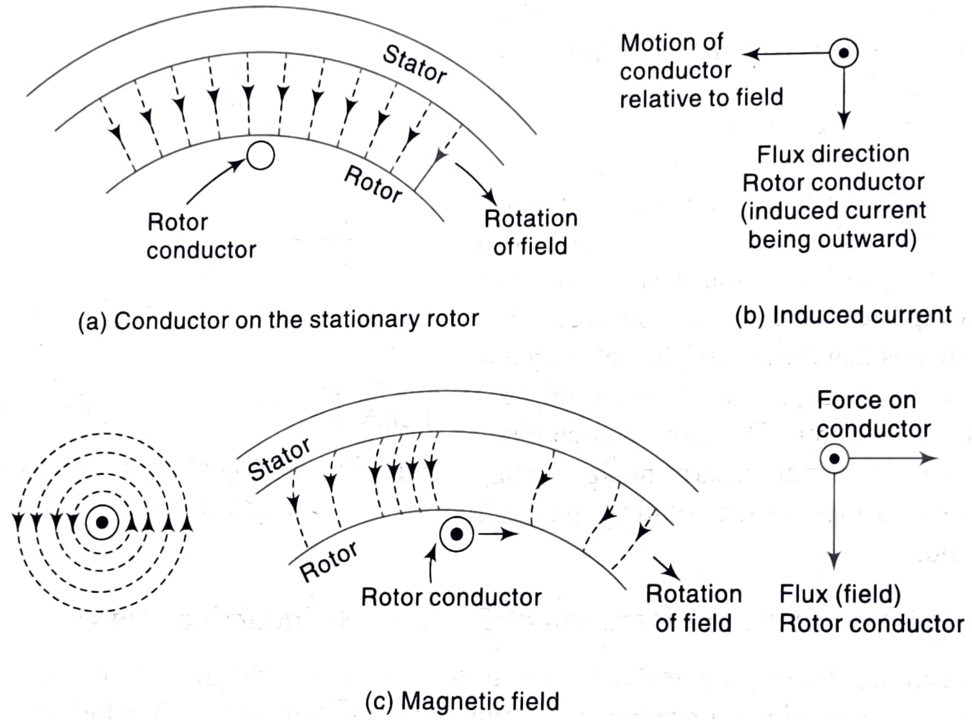


Fig. 5.35 Operation of three-phase induction motor

by dot) as shown in Fig. 5.35(b).The current in the rotor conductor produces its own magnetic field [Fig. 5.35(c)].

We know that when a current-carrying conductor is placed in a magnetic field, a force is produced on it. Thus, a force is produced on the rotor conductor. The direction of force can be found by left hand rule [Fig. 5.35(d)]. It is seen that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field. Similarly, each rotor conductor will experience a force. These forces collectively produce the driving torque and the rotor starts rotating in the same direction as the rotating magnetic field. Thus, a three-phase induction motor is self-starting.

5.9.5 Slip

An induction motor can not run at synchronous speed. Let us consider for a moment that a rotor is rotating at synchronous speed. Under this condition, there would be no cutting of flux by the rotor conductors, and there would be no generated voltage, no current and no torque. The rotor speed is, therefore, slightly less than the synchronous speed. An induction motor may be called asynchronous motor as it does not run at synchronous speed.

The difference between the synchronous speed of the magnetic field and the actual rotor speed is called the **slip speed.**

If N_s = Synchronous speed in rpm

and N = Actual rotor speed in rpm,

then slip speed = $(N_s - N)$ rpm

The slip speed is expressed as a fraction of the synchronous speed and this percentage slip is usually called the **slip**. It is denoted by s.

$$\% \text{ slip}, s = \frac{N_s - N}{N_s} \times 100$$

The slip at full load varies from about 5% for small motors to about 2% for large motors.

5.10 Single-Phase Induction Motors

Single-phase induction motors are small-size motors of fractional kilowatt ratings, which find wide domestic, commercial and industrial applications. Domestic appliances such as fans, hair driers, washing machines, vacuum cleaners, mixers, refrigerators, food processors and other kitchen equipment employ these motors. These motors also find applications in office machinery, small power tools, air-conditioning fans, blowers, dairy machinery, etc. Single-phase induction motors have less satisfactory operating characteristics as compared to polyphase motors of same rating. The major drawback of single-phase motors is that they do not have inherent self-starting torque. The other drawbacks are reduced efficiency and reduced power factor as compared to polyphase motors. Hence, in case of single-phase induction motors, various means and devices need to be used to start the motor. As such, there are many types of single-phase induction motors, depending upon the starting arrangement provided with the rotor. Some common types are split phase, capacitor start, capacitor run, and shaded pole. The following sub-sections explain the construction, working principle and various types of single-phase induction motors.

5.10.1 Construction

Single-phase induction motor has basically two main parts, one rotating and other stationary. The stationary part is called stator while the rotating part is called rotor. A single-phase induction motor is similar in construction to a three-phase squirrel-cage induction motor except that stator in a single-phase motor is provided with distributed single-phase winding. Figure 5.36(a) schematically represents a single-phase induction motor.

The stator has laminated construction, made up of stampings. The stampings are slotted on its inner periphery to carry the winding called stator winding or main winding. This is excited by a single-phase ac supply. The laminated construction keeps iron losses to minimum. The stampings are made up of material like silicon steel that minimizes the hysteresis loss. The stator winding is wound for certain definite number of poles, i.e., when excited by single-phase ac supply, the stator produces the magnetic field that creates the effect of certain definite number of poles. The number of poles for which the stator winding is wound, decides the synchronous speed of the motor. The synchronous speed is denoted by N_s and it has a fixed relation with supply frequency f and number of poles P.

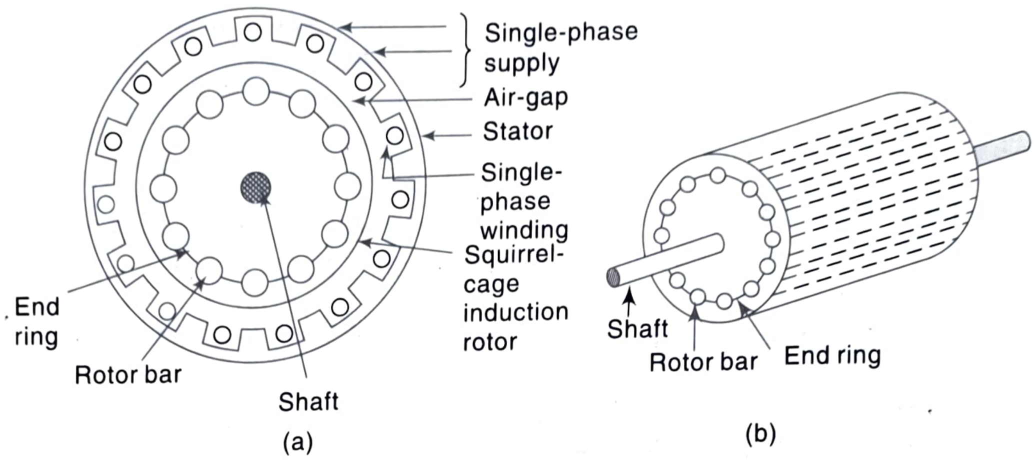


Fig. 5.36 Construction of a single-phase induction motor

The relation is given by

$$N_s = \frac{120\,f}{P}$$

The induction motor never rotates with the synchronous speed but rotates at a speed slightly less than the synchronous speed. The rotor construction is of squirrel-cage type. This type of rotor consists of copper or aluminum bars placed in the slots. The bars are permanently shorted at both the ends with the help of conducting rings called **end rings**. The entire structure looks like a cage, hence called squirrel-cage rotor. The air-gap between the stator and the rotor is kept uniform and as small as possible. Figure 5.36(b) shows the schematic representation of a squirrel-cage rotor.

5.10.2 Double-Field Revolving Theory

The stator of single-phase induction motor is provided with distributed single-phase winding. When single-phase supply is connected to the stator, a flux (or field) is produced, which is alternating, i.e., one which alternates along one space axis only. It is not a synchronously revolving (or rotating) flux, as in case of a two-phase or a three-phase stator winding fed from a two- or three-phase supply. The alternating or pulsating flux acting on a stationary squirrel-cage rotor can not produce rotation (only a revolving flux can produce a rotation).That is why a single-phase motor is not self-starting. However, if the rotor of such a machine is given an initial start by hand in either direction, then immediately a torque arises and the motor accelerates to its final speed. This peculiar behaviour of the motor can be explained by double-field revolving theory.

According to the double-field revolving theory, any alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously in opposite direction.

When the alternating supply is fed to the stator winding, an alternating flux is developed and at any instant, its magnitude is given by

$$\Phi = \Phi_m \sin \omega t$$

where Φ_m is the maximum flux developed in the motor. According to the double-field revolving theory, the alternating flux Φ can be resolved into two components A and B, each equal to $\Phi_m/2$ and revolving synchronously in anticlockwise and clockwise directions respectively as shown in Fig. 5.37(a). It can be proved that the resultant of these two components at any instant gives the instantaneous value of the stator flux at that instant. So, resultant of these two is the original stator flux.

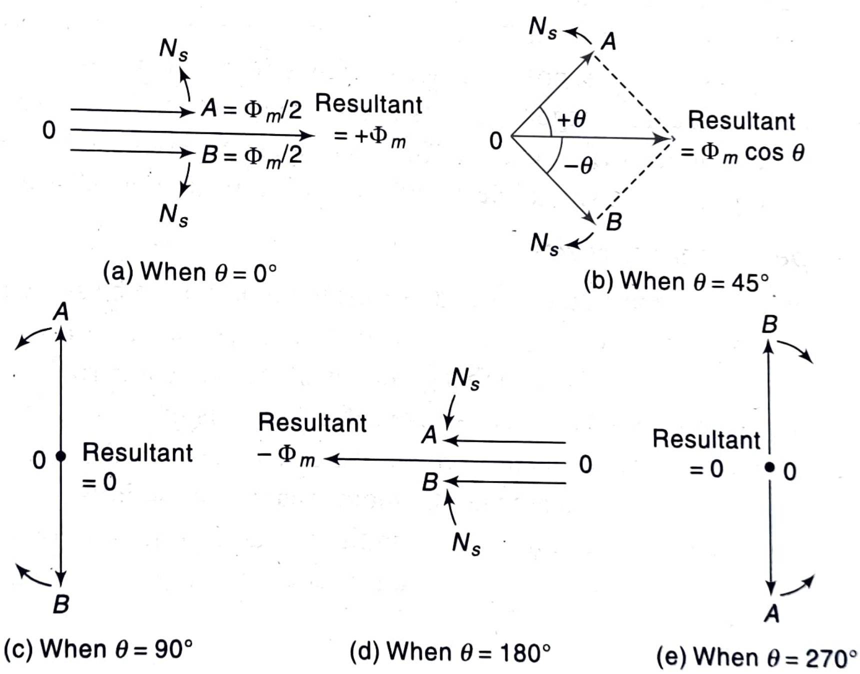


Fig. 5.37 Double-field revolving theory

After some time, when A and B would have rotated through angles $+\theta$ and $-\theta$, as in Fig. 5.37(b), the resultant flux would be $\Phi_m \cos \theta$. After a quarter cycle of rotation, fluxes A and B will be oppositely directed as shown in Fig. 5.37(c). So, the resultant flux will be zero. After half a cycle, fluxes A and B will have a resultant of $-\Phi_m$. After three-quarters of a cycle, again the resultant is zero, as shown in Fig. 5.37(e) and so on. If we plot the value of resultant flux against θ between the limits $\theta = 0°$ to $\theta = 360°$, then a curve similar to one shown in Fig. 5.38 is obtained. That is why alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously in opposite directions.

Both the components are rotating and hence are cut by the rotor conductors. Due to cutting of flux, emf gets induced in rotor, which circulates rotor current.

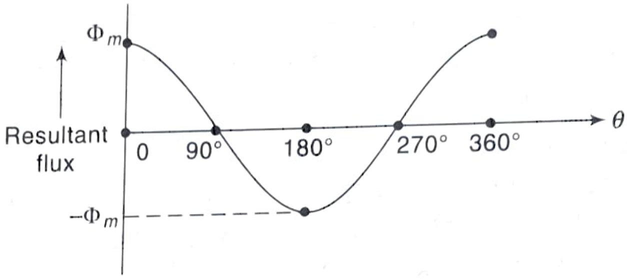


Fig. 5.38 Resultant flux

The rotor current produces rotor flux. This flux interacts with one component *A* to produce a torque in one particular direction, say anticlockwise direction, while it interacts with other component *B* to produce a torque in the clockwise direction. So, if anticlockwise torque is positive, then clockwise torque is negative. At start, these torques are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus, net torque experienced by the rotor is zero at start. Hence, the single-phase induction motors are not self-stating.

Torque–speed characteristics

The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque–speed characteristics. It is shown in Fig. 5.39. It can be seen that at start $N = 0$ and at that point, resultant torque is zero. So, single-phase motors are not self-starting. However, if the rotor is given an initial rotation in any direction, the resultant average torque increases in the direction in which the rotor is initially rotated and the motor starts rotating in that direction. But in practice, it is not possible to give initial torque to rotor externally, and hence, some modifications are done in construction of single-phase induction motors to make them self-starting.

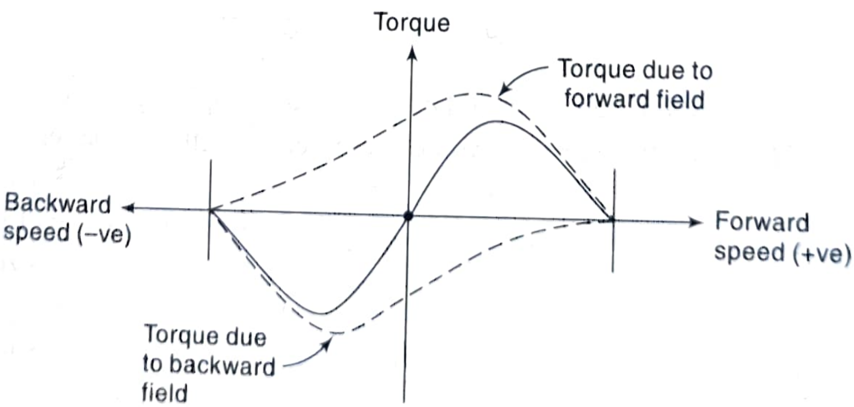


Fig. 5.39 Torque–speed characteristics

5.10.3 Working Principle

We have seen that a single-phase motor has an alternating field and not a rotating field. Therefore, it is not self-starting. To overcome this drawback and make the motor self-starting, it is temporarily converted into a two-phase motor during starting period. For this purpose, the stator of the single-phase motor is provided with an extra winding, known as starting winding or auxiliary winding, in addition to main or running winding. The two windings are spaced 90° electrically apart and are connected in parallel across the single-phase supply as shown in Fig. 5.40.

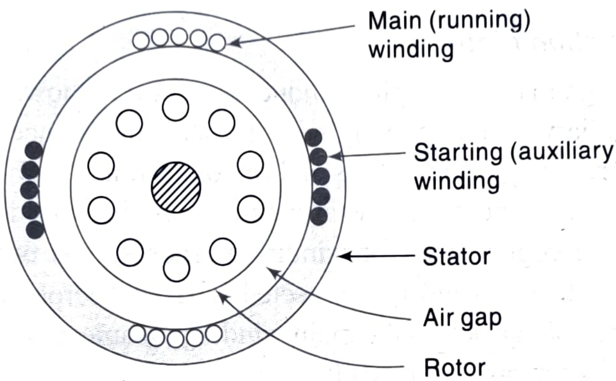


Fig. 5.40 Single-phase induction motor

It is so arranged that the phase difference between the currents in the two stator windings is very large (ideal value being 90°). Hence, when single-phase ac supply is given to the stator winding, the motor behaves like a two-phase motor and produces a rotating magnetic field (or flux), which rotates round the stator at synchronous speed (N_s). This rotating flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors, which, as yet, are stationary. Due to the relative speed between the rotating flux and the stationary conductors, an emf is induced in the rotor conductors. Since the rotor circuit is closed, so induced emf produces the rotor current, which starts flowing in the rotor conductors. The direction of the rotor current, as given by Lenz's law, is such as to oppose the very cause producing it. In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux. A centrifugal switch is connected in series with the starting winding and is located inside the motor. Once the motor speed reaches at 70 to 80% of the synchronous speed, the starting or auxiliary winding is disconnected from the supply with the help of centrifugal switch.

5.10.4 Types of Single-Phase Induction Motors

We have seen that a single-phase induction motor is not self-starting. To make the motor self-starting, a stator of the single-phase motor is provided with an extra winding, known as starting winding or auxiliary winding, so that initially the motor will behave like a two-phase motor. In order to make the motor behave as a two-phase motor, the two currents flowing through the two windings should have large phase difference. Thus, depending upon the methods of producing the necessary phase difference between the two currents, the single-phase induction motors are classified as follows:

(i) Spilt-phase induction motor
(ii) Capacitor-start induction motor
(iii) Shaded-pole induction motor

Split-phase induction motor

The schematic diagram of a split-phase induction motor is shown in Fig. 5.41(a). The starting (auxiliary) winding along with the series resistance R is connected across the main (running) winding. Instead of connecting a high resistance R in series with a starting winding, its resistance may be increased by choosing a high-resistance fine copper wire for winding purposes. The two windings are spaced 90° electrically apart and are connected in parallel across the single-phase supply. Hence, the voltage across the main winding is same as across the starting winding, equal to the supply voltage (V).

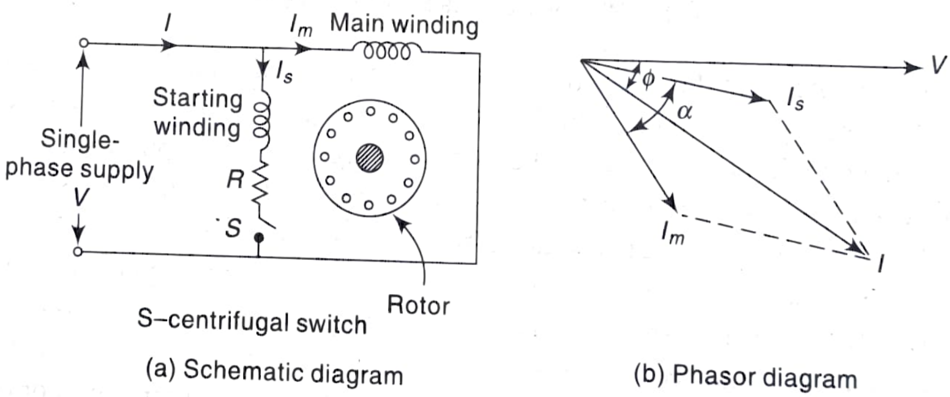


Fig. 5.41 Split-phase induction motor

Let I_m = Current through main winding
I_s = Current through auxiliary winding
I = Motor input current
V = Supply voltage

The main winding has low resistance but high reactance, whereas the starting winding has high resistance but low reactance. Hence, as shown in Fig. 5.41(b), the current I_s lags behind the applied voltage V by a small angle, whereas the current I_m lags behind V by a very large angle. Phase angle between I_m and I_s is made as large as possible because the starting torque is proportional to $\sin\alpha$, i.e., more the phase difference angle α, more is the starting torque produced.

The auxiliary winding has a centrifugal switch in series with it. When the motor gathers a speed up to 75 to 80% of synchronous speed, centrifugal switch gets opened mechanically and in running condition, auxiliary winding remains out of the circuit. So, the motor runs only on the stator winding. As the currents I_m and I_s split from each other by angle α at start, the motor is commonly called split-phase motor.

The torque–speed characteristics of split-phase motors is shown in Fig. 5.42. The split-phase motor gives poor starting torque, which is 150 to 200% of the full-load torque.

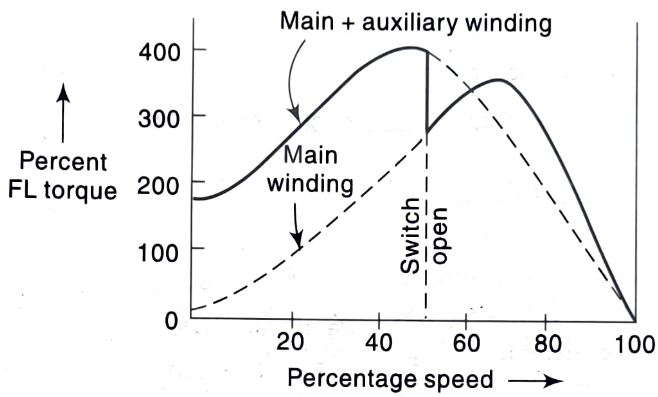


Fig. 5.42 Torque–speed characteristics

The direction of rotation of this motor can be reversed by reversing the terminals of either the main winding or the auxiliary winding. This changes the direction of the rotating magnetic field, which in turn changes the direction of rotation of the motor.

Applications These motors have low starting current and moderate starting torque. These are used for easily started loads such as fans, blowers, grinders, centrifugal pumps, washing machines, oil burners, offices equipment, etc. These are available in the range of 1/20 to 1/12 kW.

Capacitor-start induction motor

The schematic diagram of a capacitor-start induction motor is shown in Fig. 5.43(a). The construction of this type of motor is similar to that of resistance split-phase type. The difference is that the capacitor is connected in series with the auxiliary winding. The capacitive circuit draws a leading current. This feature is used in this type of motor to increase the split-phase angle α between the two currents I_m and I_s. The capacitor is generally of electrolytic type and is usually mounted on the outside of the motor as a separate unit.

As shown in Fig. 5.43(b), the current I_m lags behind the voltage V by angle ϕ_m while due to capacitor, the current I_s leads the voltage by angle ϕ_s. Hence, there exists a large phase difference (α) between the two currents, which is almost 80° as compared to nearly 30° for a split-phase motor. The starting torque is proportional to α and hence, such motors produce very high starting torque, nearly twice the value developed by a standard split-phase induction motor. When the speed approaches 75 to 80% of the synchronous speed, the starting winding gets disconnected due to operation of the centrifugal switch. The capacitor remains in the circuit only at start, and hence, it is called capacitor-start motor.

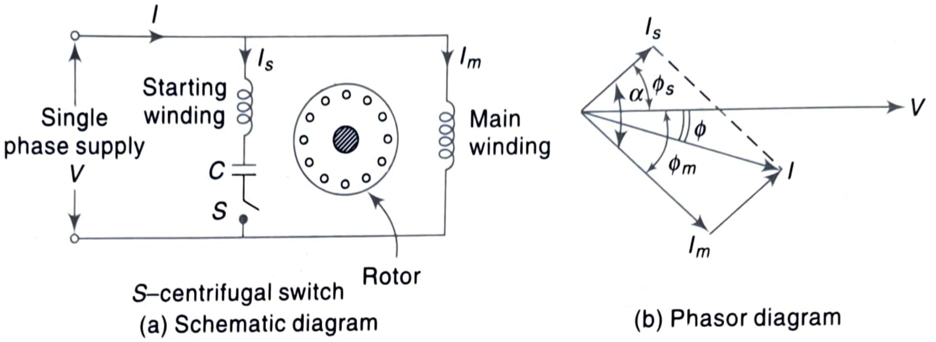


Fig. 5.43 Capacitor-start induction motor

The direction of rotation can be changed by interchanging the connections of main winding or auxiliary winding. The torque–speed characteristics are shown in Fig. 5.44. The capacitor value can be selected as per the requirement of starting torque, and the starting torque can be as high as 350 to 400% of full-load torque.

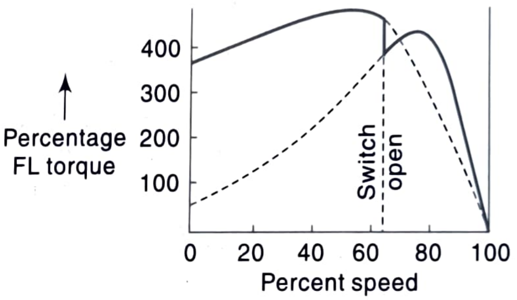


Fig. 5.44 Torque–speed characteristics

Applications These motors have high starting torque and hence are used for hard starting loads. These are used for compressors, conveyors, grinders, fans, blowers, refrigerators, air conditioners, etc. These are most commonly used motors..

Shaded-pole induction motor

A shaded-pole induction motor is a simple type of self-starting single-phase induction motor. It consists of a stator and squirrel-cage type rotor. The stator consists of salient poles, i.e., projected poles as shown in Fig. 5.45(a). One pole of such a motor is shown separately in Fig. 5.45(b). The laminated pole has a slot cut across the laminations approximately one-third distance from one edge. Around

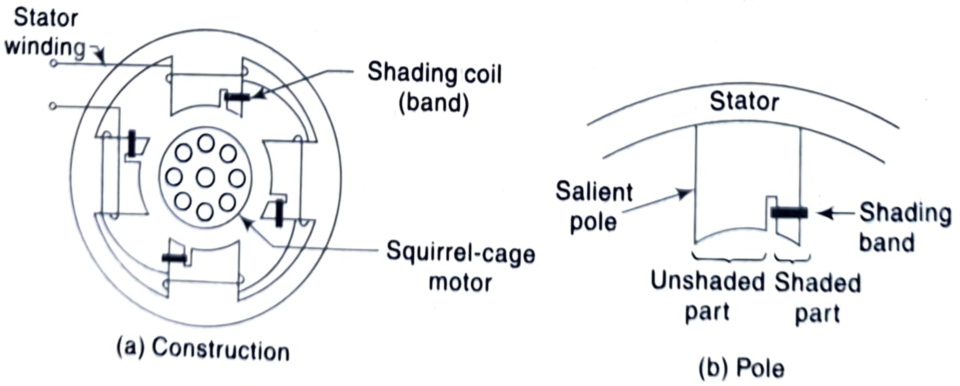


Fig. 5.45 Shaded-pole induction motor

the small part of the pole is placed a short-circuited copper coil known as shading coil or shading band. This part of the pole is known as shaded part and the other as unshaded part.

When single-phase ac supply is given to the stator winding, an alternating current flows through the exciting (or field) winding surrounding the whole pole, and the axis of the pole shifts from the unshaded part to the shaded part. This is equivalent to the production of rotating magnetic field. This can be explained as follows.

The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in Fig. 5.46(a). The distribution of this flux in the pole area is greatly influenced by the role of copper shading band. Consider the three instants, say t_1, t_2, t_3, during first half cycle of the flux as shown in Fig. 5.46(a).

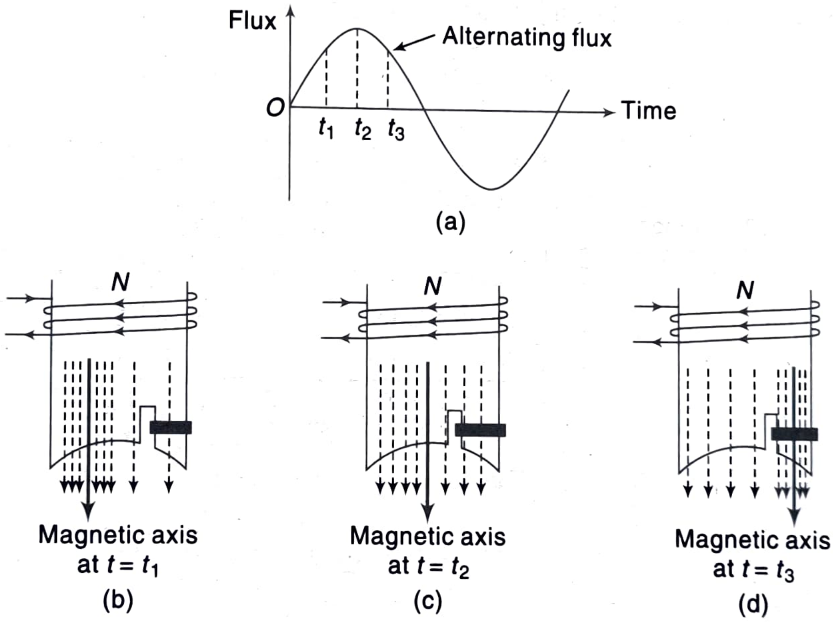


Fig. 5.46 Shifting of magnetic axis

At instant $t = t_1$, the rate of rise of current and, hence, the flux are very high. Due to the transformer action, a large emf gets induced in the copper shading band. This circulates current through shading band as it is short circuited, producing its own flux. According to Lenz's law, the direction of this current is so as to oppose the cause, i.e., rise in the current. Hence, the shading ring flux is opposing to the main flux, and there is crowding of the flux in unshaded part while weakening of the flux in shaded part. Overall magnetic axis shifts in unshaded part as shown in Fig. 5.46(b).

At instant $t = t_2$, the rate of rise of current and, hence, the rate of change of flux are almost zero as the flux almost reaches to its maximum value. So, the rate of change of the flux ($d\Phi$) is nearly zero. Hence, there is vary little induced emf in the shading ring. The shading ring flux is also negligible, hardly affecting the distribution of the main flux. Thus, the main flux distribution is uniform and the magnetic axis lies at the centre of the pole face as shown in Fig. 5.46(c).

At instant $t = t_3$, both the current and the flux are decreasing, and the rate of decrease is high, which again induces a very large emf in the shading ring. This circulates current through the ring, which produces its own flux. Now, direction of the flux produced by the shaded ring current is so as to oppose the cause, which is decrease in the flux. It means that the direction is same as that of the main flux, strengthening it. So, there is crowding of the flux in the shaded part as compared to the non-shaded part. Due to this, the magnetic axis shifts to middle of the shaded part of the pole. This is shown in Fig. 5.46(d).

This sequence keeps on repeating for negative half cycle too. Consequently, this produces an effect of rotating magnetic field, the direction of which is from the non-shaded part of the pole to the shaded part of the pole. Due to this, the motor produces the starting torque and starts rotating. The starting torque is low, which is about 40 to 50% of the full-load torque for this type of motor. The torque–speed characteristics are shown in Fig. 5.47.

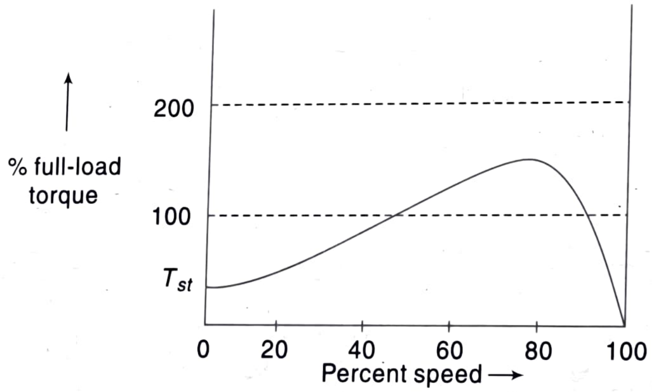


Fig. 5.47 Torque–speed characteristics

Due to absence of centrifugal switch, the construction is simple and robust, but this type of motor has a lot of limitations as given below:

(i) Low starting torque and low power factor
(ii) High I^2R (copper) losses in the shading ring
(iii) Low efficiency
(iv) Difficult speed reversal
(v) Small size and power rating (1/300 to 1/20 kW)

Applications These motors are cheap but have low starting torque, power factor and efficiency. These motors are commonly used for small fans, toy motors, advertising displays, film projectors, record players, hair dryers, photocopying machines, etc.

EXERCISES

1. What is the basic nature of induced emf in a dc generator? What is the function of commutator in a dc generator?
2. What is the difference between a generator and a motor?

3. Explain with a neat sketch the construction of a dc machine.
4. Which parts of a dc machine are laminated and why?
5. What is the difference between lap-type and wave-type armature windings?
6. What is the basic principle of a dc generator?
7. Derive from first principles, an expression for induced emf in a dc generator.
8. State different types of dc generator and state applications of each type.
9. Sketch and explain the load characteristics of the following types of generator:
   (i) DC shunt generator
   (ii) DC series generator
   (iii) DC compound generator
10. State various applications of dc generators.
11. Explain the principle of working of a dc motor. What is the function of commutator in a dc motor?
12. State voltage and power equations of a dc motor explaining the importance of each term.
13. What is back emf? Explain the significance of back emf.
14. Derive the expression for the electromagnetic torque developed in a dc motor.
15. Explain why a dc series motor should not be started on no load.
16. What are applications of dc shunt motor?
17. What are applications of dc series motor?
18. Describe with neat sketches the construction of a three-phase squirrel-cage type induction motor.
19. Describe with neat sketches the construction of a three-phase slip-ring (phase-wound) type induction motor.
20. Compare squirrel-cage and phase-wound three-phase induction motors with reference to construction, performance and applications.
21. Explain the principle of operation of a three-phase induction motor.
22. What are advantages of three-phase induction motors?
23. What is meant by slip in induction motor?
24. Explain why an induction motor can not run at synchronous speed.
25. Explain how the rotating magnetic field is generated when stator winding is connected to a three-phase supply.
26. Explain the general construction of a single-phase induction motor.
27. Explain the working principle of a single-phase induction motor.
28. Why are single-phase induction motors not self-starting?
29. Explain the double-field revolving theory.
30. State various types of single-phase induction motors.
31. Why is starting torque in capacitor-start induction motor more than resistance split-phase induction motor?
32. How is the direction of a single-phase induction motor changed?

33. Explain the construction, working principle, torque–speed characteristics and applications of the following types of motor:
    (i) Split-phase induction motor
    (ii) Capacitor-start induction motor
    (iii) Shaded-pole induction motor
34. What are the limitations of shaded-pole induction motor?
35. Is it possible to reverse direction of rotation in case of a shaded-pole induction motor? If yes, explain how.
36. Differentiate between single-phase and three-phase induction motors.