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

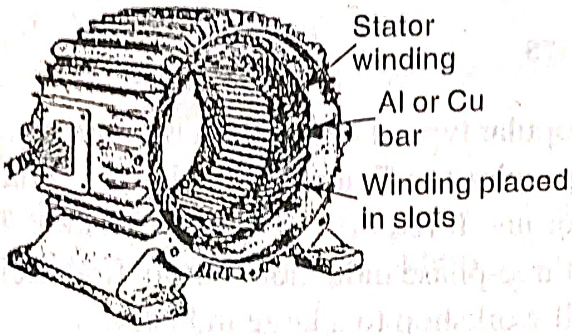
A three-phase induction motor consists of two parts: the stator and the rotor. The stator is the stationary part and the rotor is the rotating part.

Stator

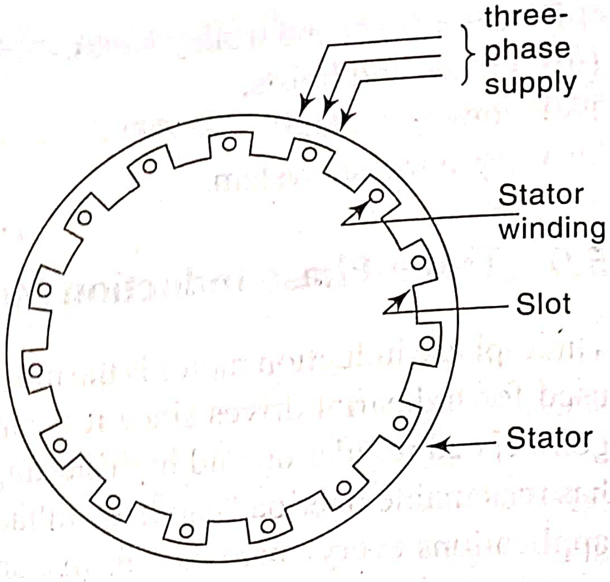
Stator is an outer 'stationary', hollow, cylindrical structure made of laminated sheet steel. The inner periphery of the stator is slotted to receive the windings. The stator carries the three-phase winding and is fed from a three-phase supply. It is wound for a definite number of poles, and the exact 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.



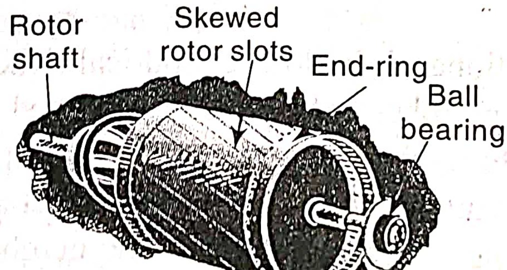
(a) Actual photograph



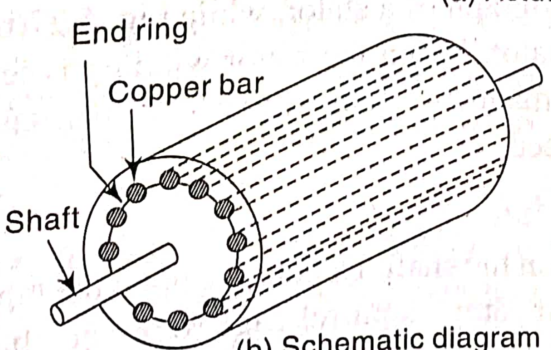
(b) Schematic diagram

Fig. 5.27 Stator

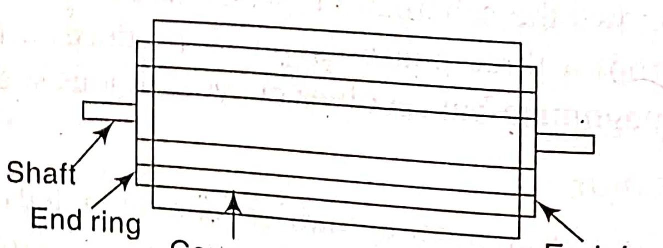
Squirrel-cage rotor This rotor has the simplest and most rugged construction. It consists of a cylindrical laminated core with slots parallel to the shaft axis. Each slot contains one bar conductor of aluminum or copper. At both the ends of the rotor, the bar conductors are short circuited by heavy end 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).

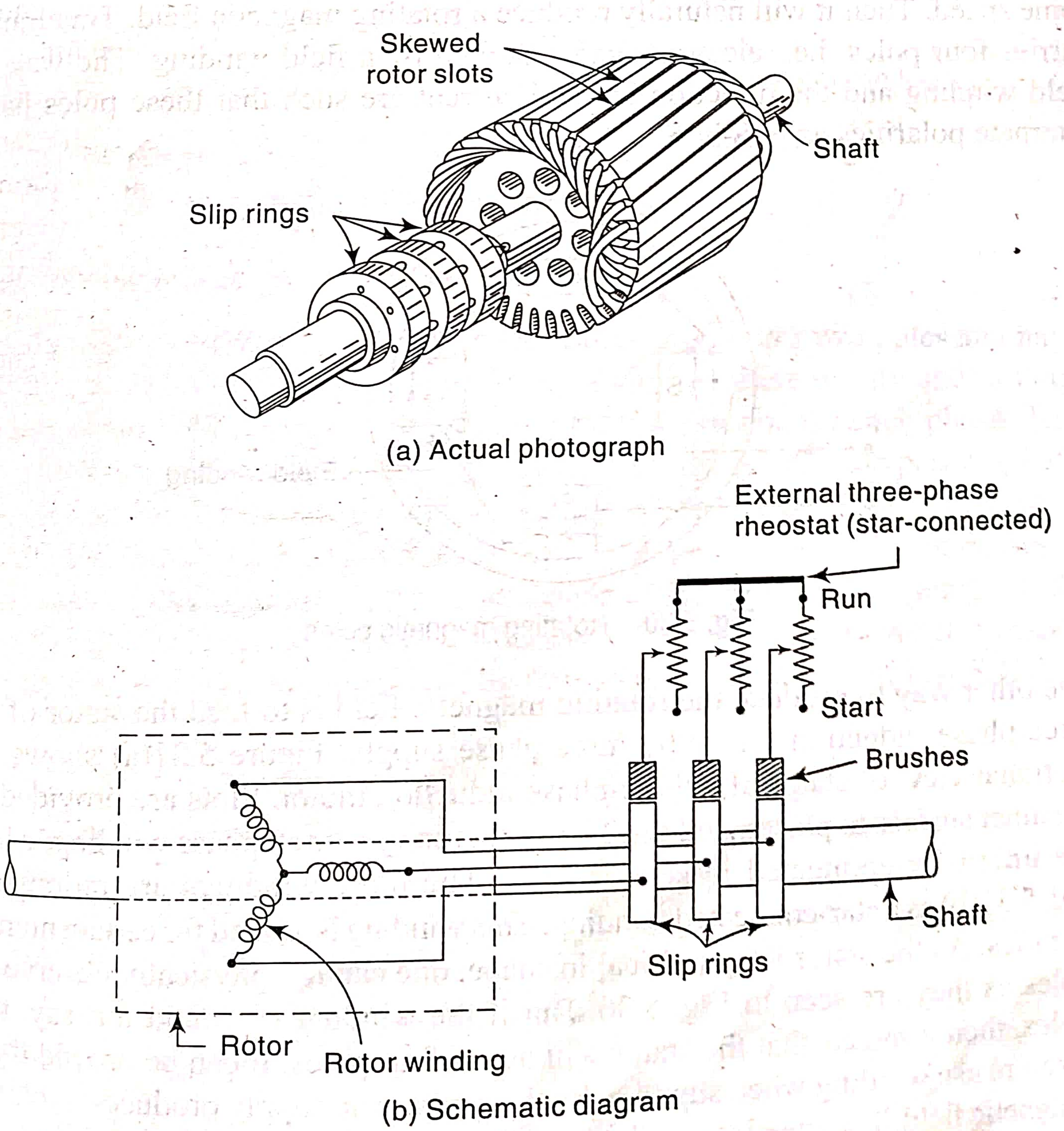


Fig. 5.29 Phase-wound rotor

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.

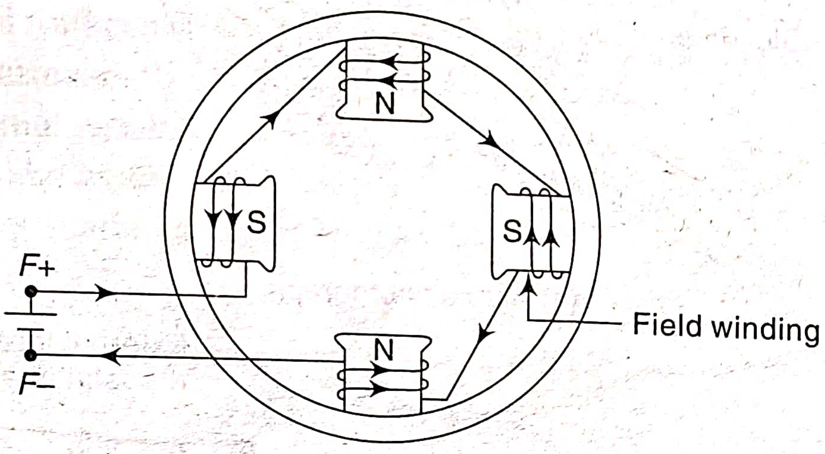


Fig. 5.30 Rotating magnetic poles

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

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

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.

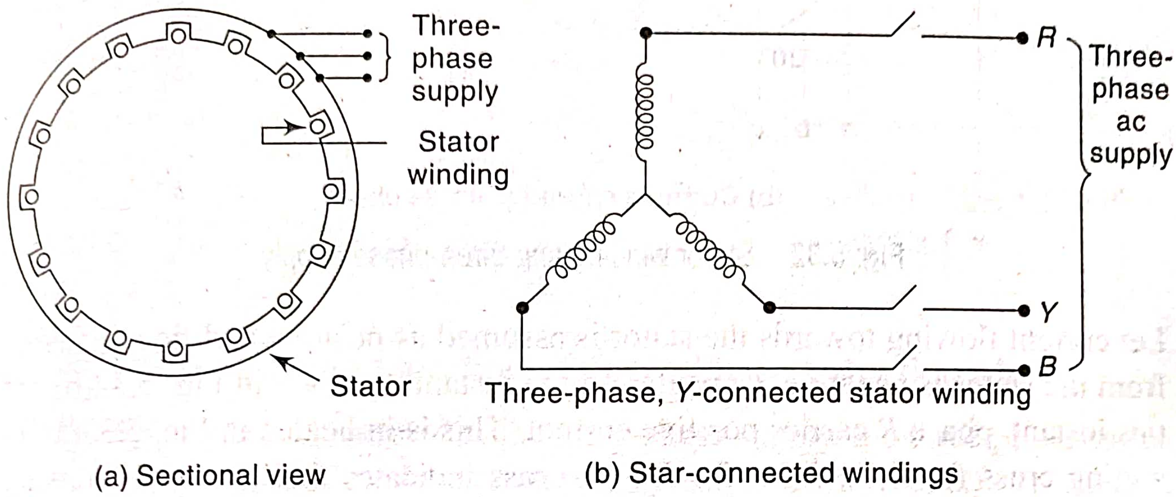
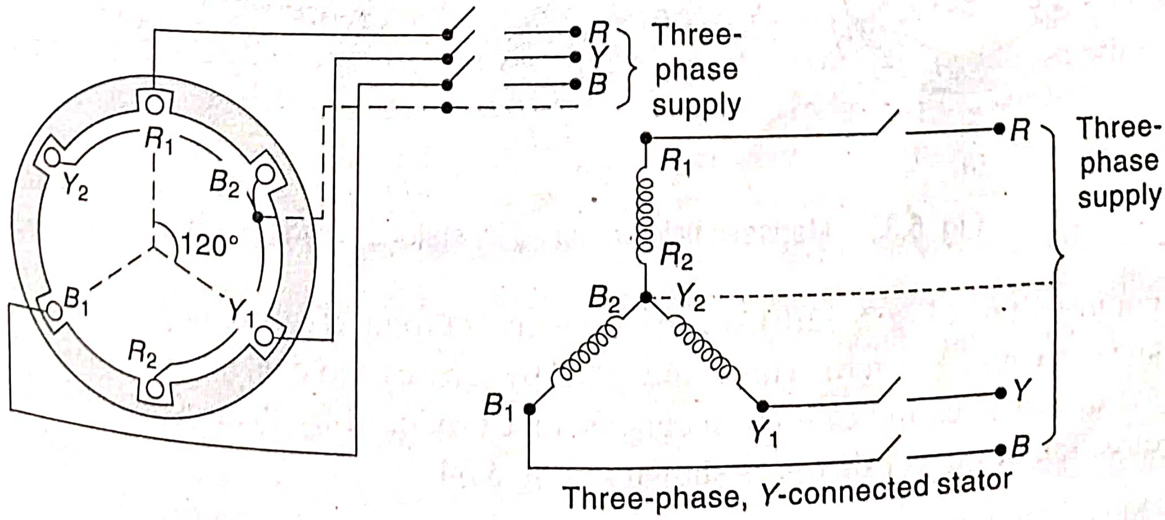


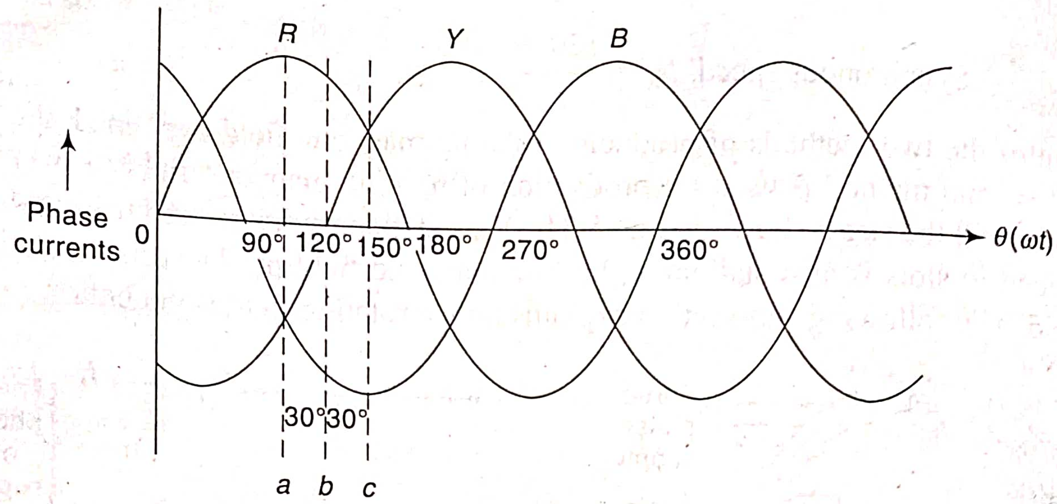
Fig. 5.31 Stator of a three-phase motor

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.

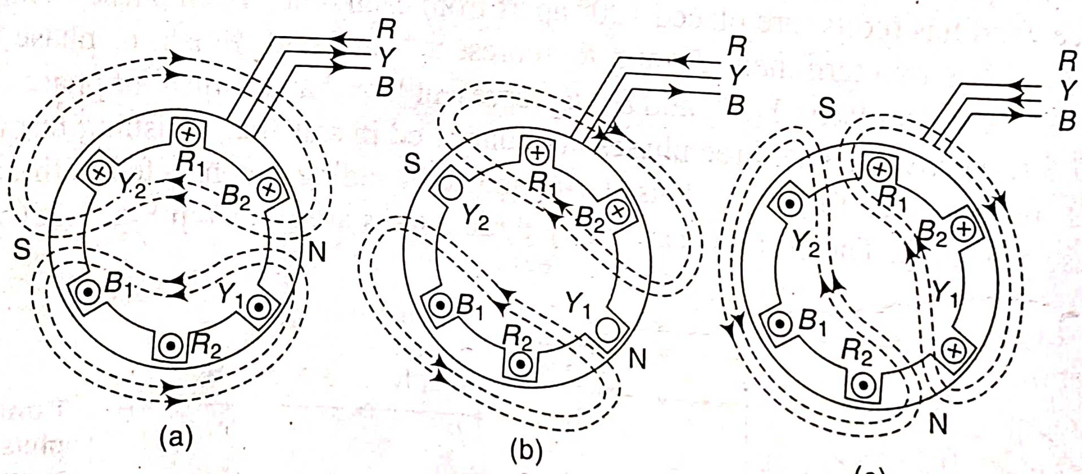


Fig. 5.33 Magnetic field produced by stator at various instants

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.

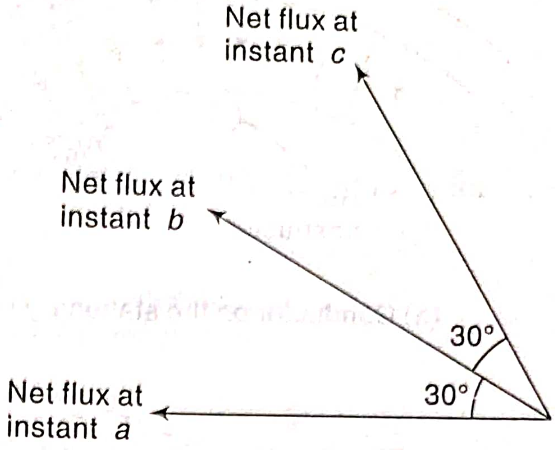


Fig. 5.34 Shifting of the axis of the net magnetic flux

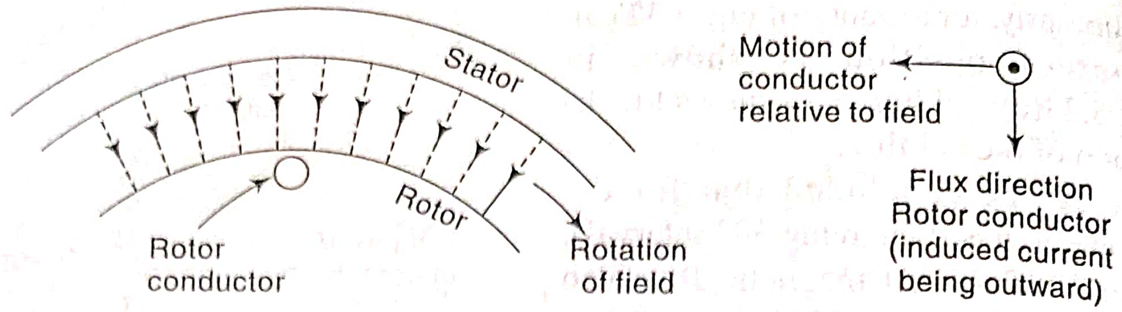
5.9.4 Principle of Operation of Three-Phase Induction Motor

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.

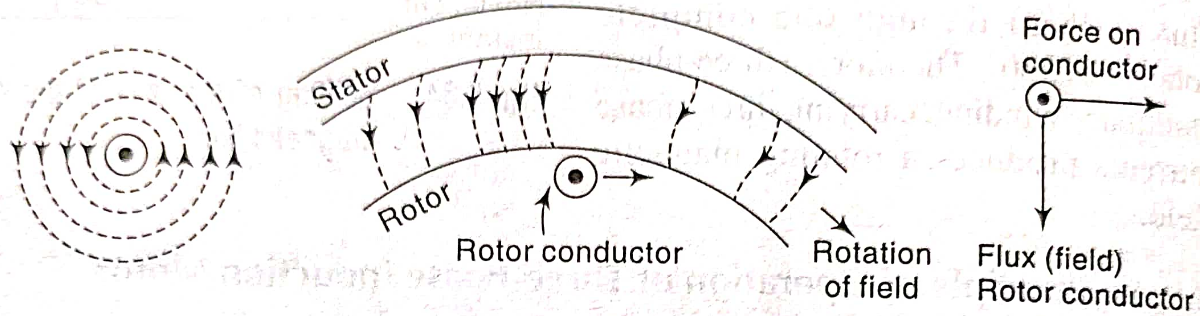
Let us consider one conductor on the stationary rotor as shown in Fig. 5.35(a). Let this conductor be subjected to the rotating magnetic field produced when a three-phase supply is connected to the three-phase winding of the stator.

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



(a) Conductor on the stationary rotor

(b) Induced current



(c) Magnetic field

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.