6

Electrical Machines

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

LO 6.1 Explain construction of three phase induction motors
LO 6.2 Explain rotating magnetic field produced by three phase AC machines
LO 6.3 Discuss principle of operation of three phase induction motors
LO 6.4 Explain the concept of slip
LO 6.5 Explain construction and principle of operation of single phase induction motors
LO 6.6 Explain double field revolving theory in single phase induction motors
LO 6.7 Discuss types of single phase induction motors
LO 6.8 Explain concept of stepper motors, its types and principle of operation

AC

6.1 || THREE PHASE INDUCTION MOTORS

LO 6.1

Explain construction of three phase induction motors

6.1.1 Construction

A 3-phase induction motor has two main parts:

1. stator
2. rotor

1. Stator It consists of a steel frame which encloses a hollow cylindrical core made up of thin laminations of silicon steel. It is made up of number of stampings which are slotted to receive the windings. The stator carries a 3-phase winding and is fed from a 3-phase supply. When a 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

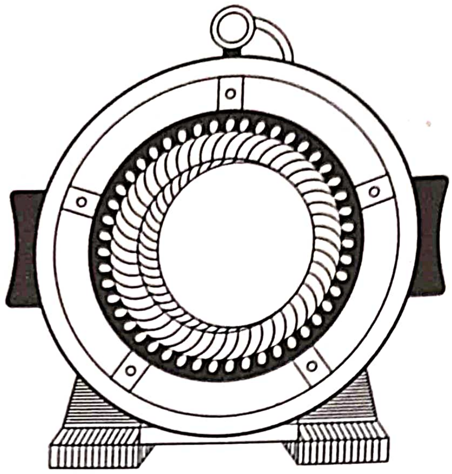

Fig. 6.1 *Stator*

2. Rotor The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The windings placed in these slots are one of the following two type:

(a) Squirrel cage

(b) Wound

(a) Squirrel cage rotor It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminium bar is placed in each slot. All these bars are joined at each end by metal rings called end rings. This forms a permanently short circuited winding. The entire construction resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator.

Since rotor bars are permanently short circuited, it is not possible to add any external resistance to the rotor circuit to have a large starting torque.

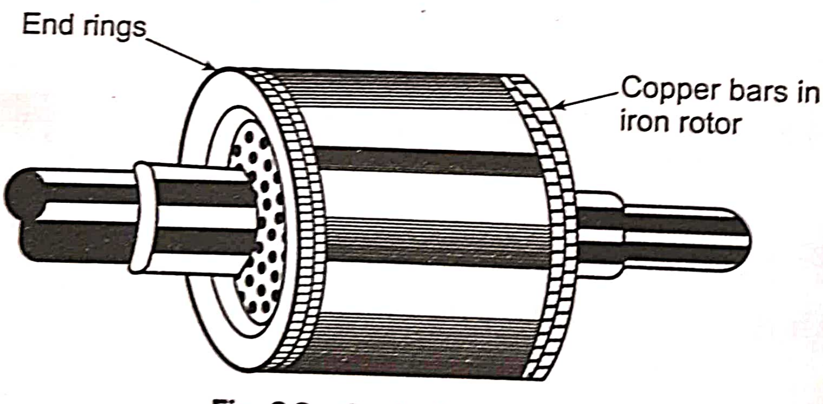

Fig. 6.2 *Squirrel cage rotor*

(b) Wound rotor It consists of a laminated cylindrical core and carries a 3-phase winding similar to one on the stator. The rotor winding is uniformly distributed in the slots and is usually star connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings are mounted on the rotor with one brush resting on each slip ring. The three brushes are connected to a 3-phase star connected rheostat. At starting, external resistances are included in the

rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed. When the motor attains normal speed, the three brushes are short circuited so that wound rotor runs like a squirrel cage rotor.

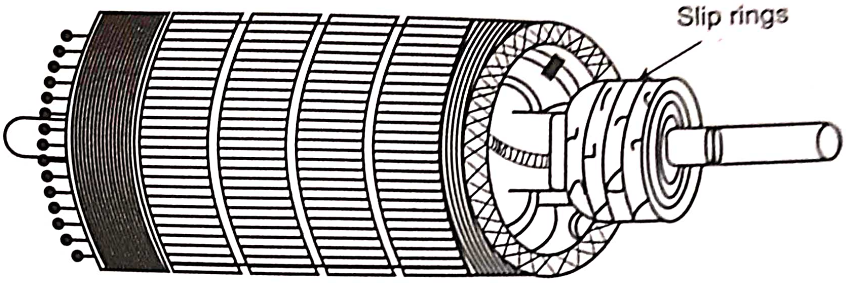

Fig. 6.3 *Wound rotor*

6.2 ROTATING MAGNETIC FIELD PRODUCED BY THREE PHASE AC MACHINES

LO 6.2

Explain rotating magnetic field produced by three phase AC machines

When 3-phase winding is fed from a 3-phase supply, a rotating magnetic field is produced which can be explained as follows:

The flux due to 3-phase winding is shown in Fig. 6.4.

$$\phi_1 = \phi_m \sin \theta$$
$$\phi_2 = \phi_m \sin (\theta - 120°)$$
$$\phi_3 = \phi_m \sin (\theta - 240°)$$

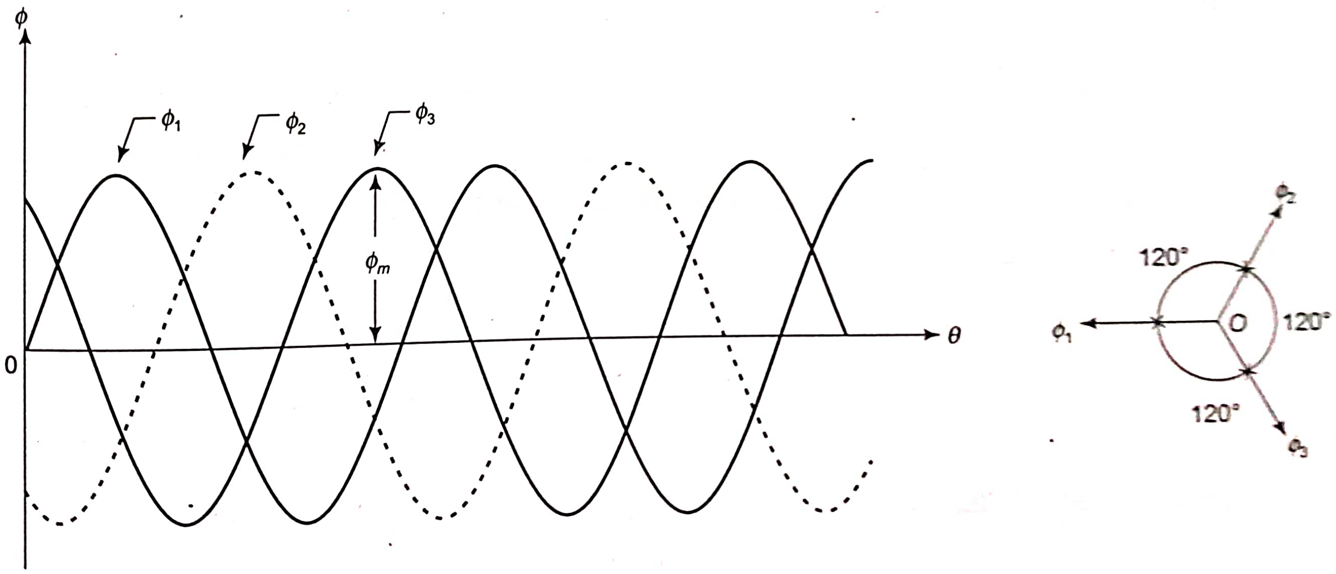

Fig. 6.4

Let the maximum value of flux due to any one of the three phases be ϕ_m. The resultant flux ϕ_r, at any instant, is given by the vector sum of the individual fluxes ϕ_1, ϕ_2 and ϕ_3 due to three phases.

Case I: When $\theta = 0°$

$$\phi_1 = 0$$

$$\phi_2 = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_3 = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2}$$

$$= \sqrt{3} \times \frac{\sqrt{3}}{2}\phi_m$$

$$= \frac{3}{2}\phi_m$$

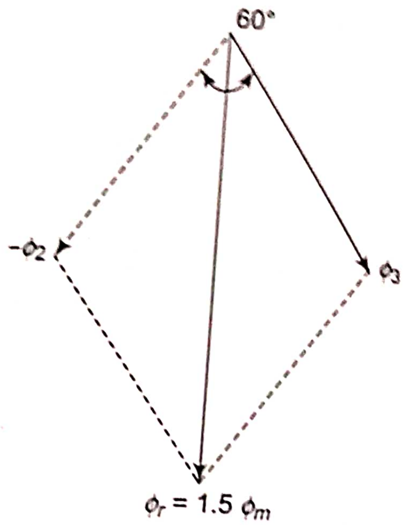

Fig. 6.5 $\theta = 0°$

Case II: When $\theta = 60°$

$$\phi_1 = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_2 = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_3 = 0$$

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos 30°$$

$$= \frac{3}{2}\phi_m$$

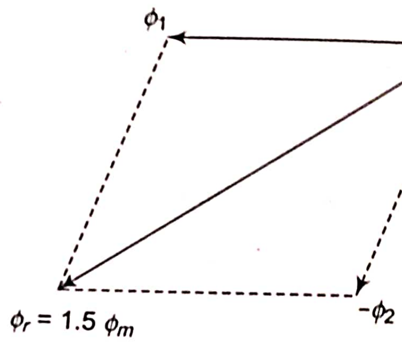

Fig. 6.6 $\theta = 60°$

Resultant flux is $\frac{3}{2}\phi_m$ but has rotated clockwise through an angle of 60°.

Case III: When $\theta = 120°$

$$\phi_1 = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_2 = 0$$

$$\phi_3 = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_r = \frac{3}{2}\phi_m$$

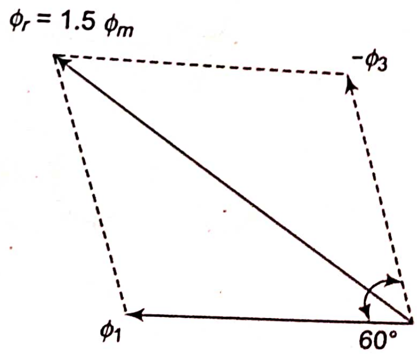

Fig. 6.7 $\theta = 120°$

esultant flux ϕ_r has further rotated clockwise through an angle of 60°.

Case IV: When $\theta = 180°$

$$\phi_1 = 0$$

$$\phi_2 = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_3 = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_r = \frac{3}{2}\phi_m$$

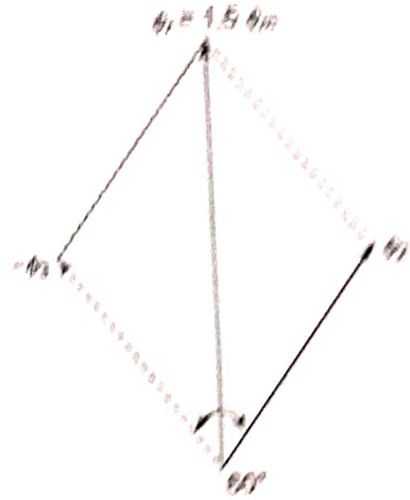

Fig. 6.8 $\theta = 180°$

Resultant flux ϕ_r has rotated clockwise through an additional angle of 60°.

Hence, the resultant flux is of constant value $\frac{3}{2}\phi_m$ but rotates around the stator at synchronous speed.

Synchronous Speed The speed at which the revolving flux rotates is called synchronous speed (N_S). Its value depends upon the number of poles and supply frequency.

$$N_S = \frac{120f}{P}$$

6.3 PRINCIPLE OF OPERATION OF THREE PHASE INDUCTION MOTORS

LO 6.3

Discuss principle of operation of three phase induction motors

When a 3-phase stator winding is fed from a 3-phase supply, a rotating magnetic field is set up. The rotating field passes through the air-gap and cuts the rotor conductors, which as yet, are stationary. Due to the relative speed between the rotating flux and the stationary rotor conductors, emfs are induced in the rotor conductors according to Faraday's laws of electromagnetic induction. Since the rotor circuit is short circuited, current starts flowing in the rotor conductors. The current carrying conductors are placed in the magnetic field produced by the stator. Hence mechanical force acts on the rotor conductors. This mechanical forces produces a torque which tends to move the rotor in the same direction as the rotating field.

3φ Induction motors are self starting motors as rotating magnetic field is developed which causes 3φ motor

6.4 CONCEPT OF SLIP

LO 6.4

Explain the concept of slip

The rotor never succeeds up in catching up with the stator field. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore no torque to drive the rotor. Hence, the rotor speed (N) is always less than the stator field speed (N_S). This difference in speed depends upon load on the motor.

The difference between the synchronous speed N_S of the rotating stator field and the actual rotor speed N is called *slip*. It is usually expressed as a percentage of synchronous speed.

$$\% \text{ Slip } S = \frac{N_S - N}{N_S} \times 100$$

The quantity $N_S - N$ is sometimes called slip speed. When the rotor is stationary, i.e., $N = 0$, slip $S = 1$ or 100%.

6.5 || SINGLE PHASE INDUCTION MOTORS

LO 6.5

Explain construction and principle of operation of single phase induction motors

6.5.1 Construction

A single phase induction motor is very similar in construction to a 3-phase induction motor. It has a squirrel cage rotor identical to a 3-phase motor and a single phase winding on the stator. Single phase induction motors are classified according to the method employed to make them self starting into,

1. Split phase motors
2. Capacitor start motors
3. Shaded pole motors

6.6 || PRINCIPLE OF OPERATION OF SINGLE PHASE INDUCTION MOTORS

LO 6.5

When a single phase induction motor is fed from a single phase supply, its stator winding produces a magnetic field that is only alternating. The field polarity reverses after each cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel cage rotor. Hence, single phase induction motor is not self starting. However, if the rotor of a single phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation and rotor quickly accelerates to its final speed. Once the motor is running at his speed, it will continue to rotate even though single phase current is flowing through the stator winding. This typical behaviour of single phase induction motor can be explained with the help of ouble field revolving theory.

7 || DOUBLE FIELD REVOLVING THEORY

LO 6.6

Explain double field revolving theory in single phase induction motors

en a single phase inductor motor is fed from single phase supply, its or winding produces an alternating flux. According to double field olving theory, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of alternating flux and rotating synchronously $\left(N_S = \frac{120f}{P}\right)$ in opposite direction.

As shown in Fig. 6.9(a) let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each be equal to $\frac{\phi_m}{2}$ revolving in anticlockwise and clockwise directions respectively.

After some time, when A and B would have rotated through angle $+\theta$ and $-\theta$ as in Fig. 6.9(b), the resultant flux would be

$$\phi_r = 2 \times \frac{\phi_m}{2} \cos \frac{2\theta}{2} = \phi_m \cos\theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositely directed as shown in Fig. 6.9(c), so that the resultant flux would be zero.

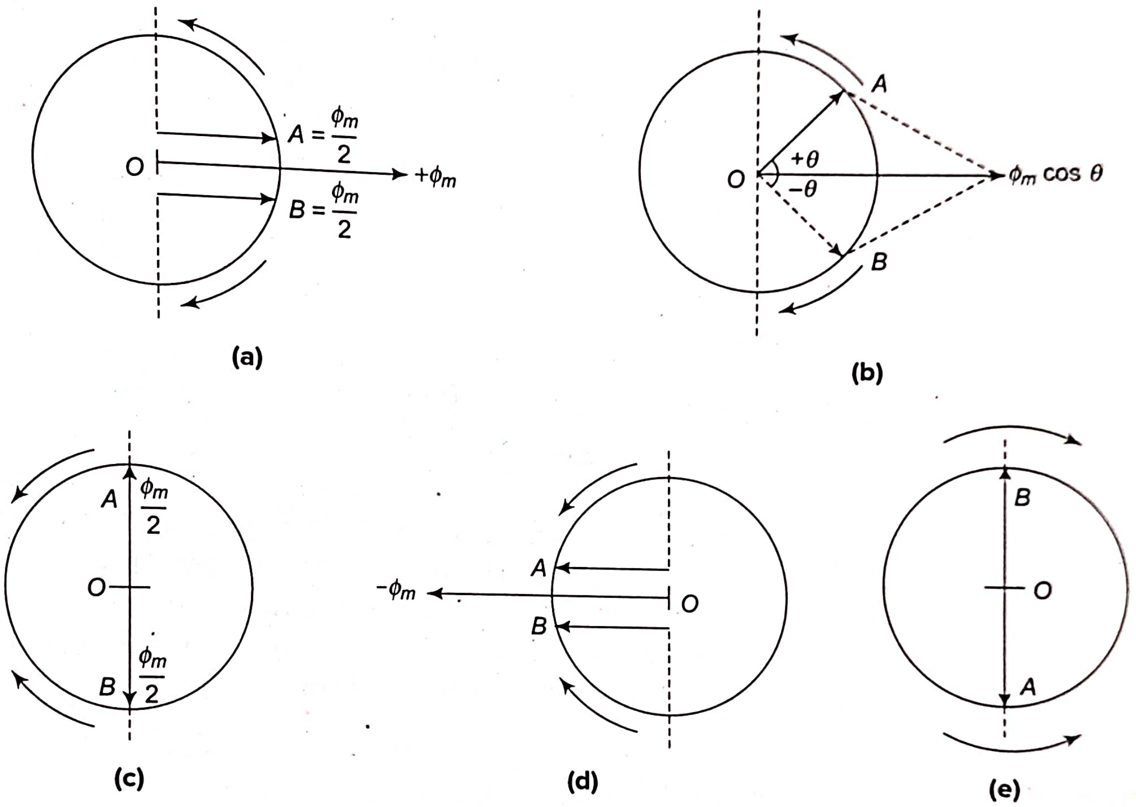

Fig. 6.9

After half a cycle, fluxes A and B will have a resultant $-2 \times \frac{\phi_m}{2} = -\phi_m$.

After three-quarters of a cycle, again the resultant is zero, as shown in Fig. 6.9(e) and so on.

When values of the resultant flux against θ is plotted, a sinusoidal curve is obtained as shown in Fig. 6.10.

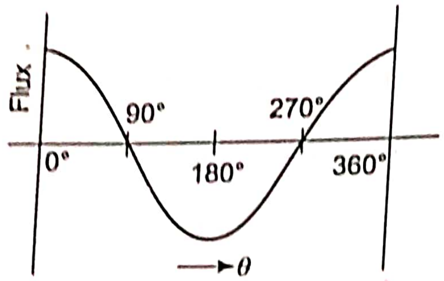

Fig. 6.10

Each of the component of revolving flux produces a torque in opposite directions. The total torque developed by the motor is given by the resultant of these two torques. The torque-speed characteristics is shown in Fig. 6.11.

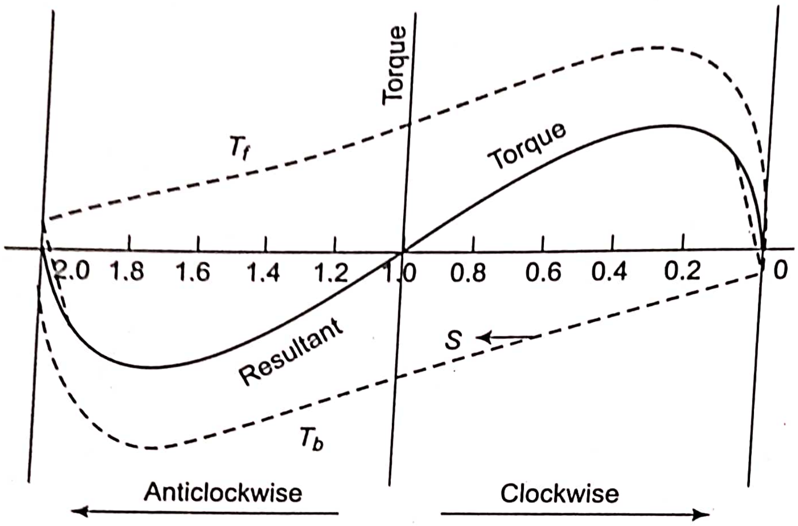

Fig. 6.11

At starting when the rotor is at standstill, the torques developed by two component of revolving fluxes are equal and opposite. Therefore, torque developed by the motor is zero. However, if the rotor is started somehow, say, in the clockwise direction, the clockwise torque starts increasing, and at the same time, the anticlockwise torque starts decreasing. Hence, there is certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

6.8 TYPES OF SINGLE PHASE INDUCTION MOTORS

LO 6.7

Discuss types of single phase induction motors

6.8.1 Split Phase Motor

To make single phase induction motor self starting, it is temporarily converted into a two phase motor during starting period. For this purpose, the stator of a single phase motor is provided with an extra winding, known as starting (or auxiliary) winding, in addition to the main (or running) winding. The two windings are spaced 90° electrical apart and are connected in parallel across the single phase supply as shown in Fig. 6.12. It is so arranged that the phase difference between the currents in the two stator windings is very large. Hence, the motor behaves like a two phase motor. These two currents produce a revolving flux and hence, make the motor self starting.

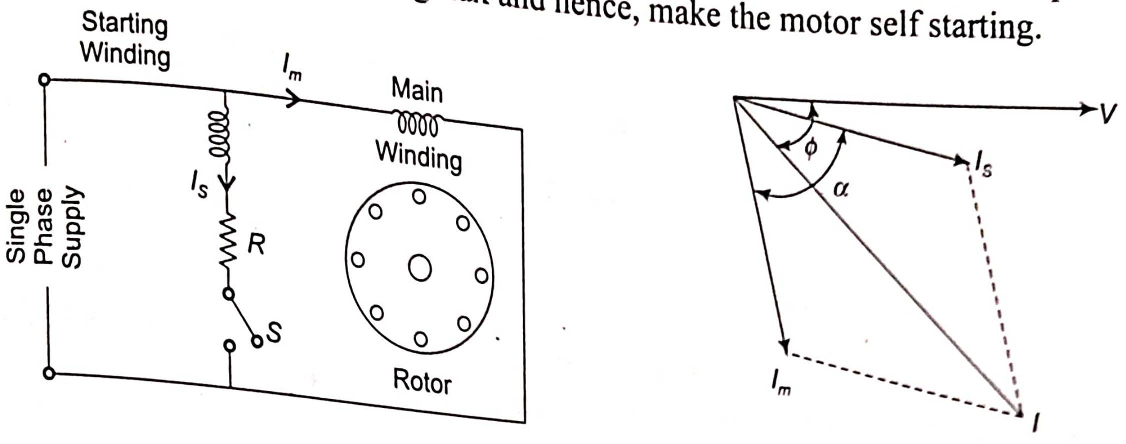

Fig. 6.12

In split phase induction motor, the main winding has low resistance but high reactance whereas the starting winding has a high resistance but low reactance. The resistance of the starting winding may be increased either by connecting a high resistance R in series with it or by choosing a high resistance fine copper wire for winding purpose. Hence, the current I_s drawn by the starting winding lags behind the applied voltage V by a small angle whereas current I_m taken by the main winding lags behind V by a very large angle. Phase angle between I_s and I_m is made as large as possible because the starting torque of a split phase motor is proportional to sin α. When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding. The motor then operates as a single phase induction motor and continues to accelerate till it reaches the normal speed.

6.8.2 Capacitor Start Motor

The capacitor start motor is identical to a split phase motor except that a capacitor C is connected in series with the starting winding as shown in Fig. 6.13. When the motor reaches about 75% of synchronous speed, the centrifugal switch opens and cuts out both the starting winding and the capacitor from the supply. The motor then operates as a single phase induction motor and continues to accelerate till it reaches normal speed. As shown in Fig. 6.13, current I_m drawn by the main winding lags the supply voltage V by a large angle whereas current I_s leads voltage V by a certain angle. The two currents are out of phase with each other by about 80° as compared to nearly 30° for a split phase motor. Since the torque developed by a split phase motor is proportional to the sine of the angle between I_s and I_m, the increase in angle (from 30° to 80°) alone increases the starting torque to nearly twice the value developed by a split phase induction motor.

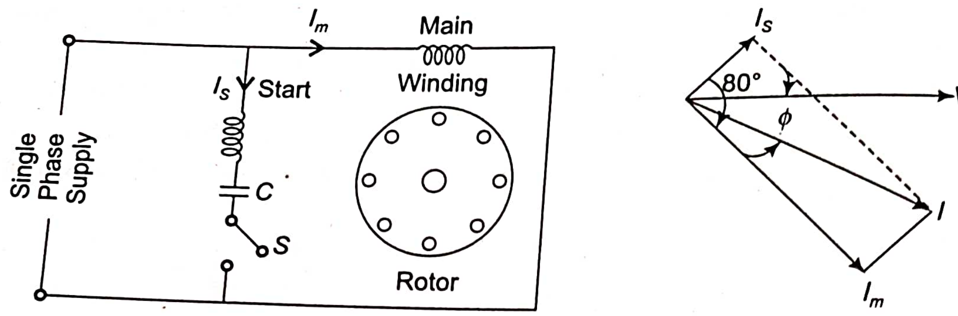

Fig. 6.13

6.8.3 Shaded Pole Motor

In shaded pole motor, the necessary phase splitting is produced by induction. These motors have salient poles on the stator and a squirrel cage rotor as shown in Fig. 6.14.

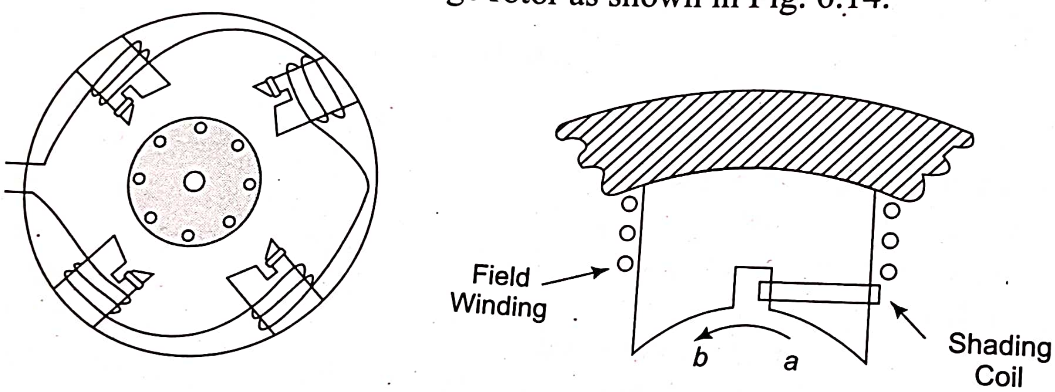

Fig. 6.14

ortion of each pole is surrounded by a short circuited turn of copper strip called shading coil. s part of the pole is known as shaded part and the other as unshaded part.

en an alternating current is passed through the field winding, alternating flux is produced. This is cut by shading coil, an emf is induced in the shading coil and current is circulated.

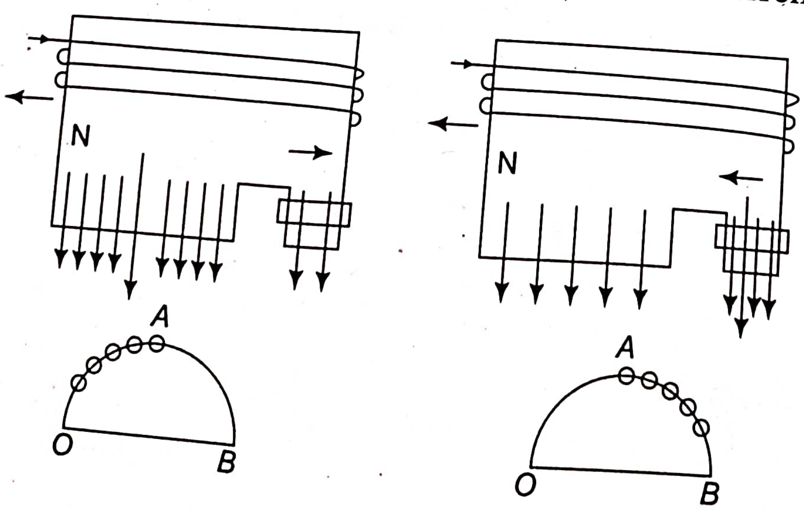

Fig. 6.15

When alternating flux is increasing along OA, on emf is induced in the shading coil and curren set up. This current has a direction such as to oppose increase in flux. Flux density in shaded p decreases and in unshaded part increases. Hence, magnetic axis lies in unshaded part.

When alternating flux is decreasing along AB induced current opposes decrease in flux. Flux dens in shaded part increases. Hence, magnetic axis shift in shaded part.

This shift in flux may be considered to be a partially rotating field and is sufficient to produc small starting torque. Hence, the motor runs in the direction of the shift in the flux.

LO 6.8