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.

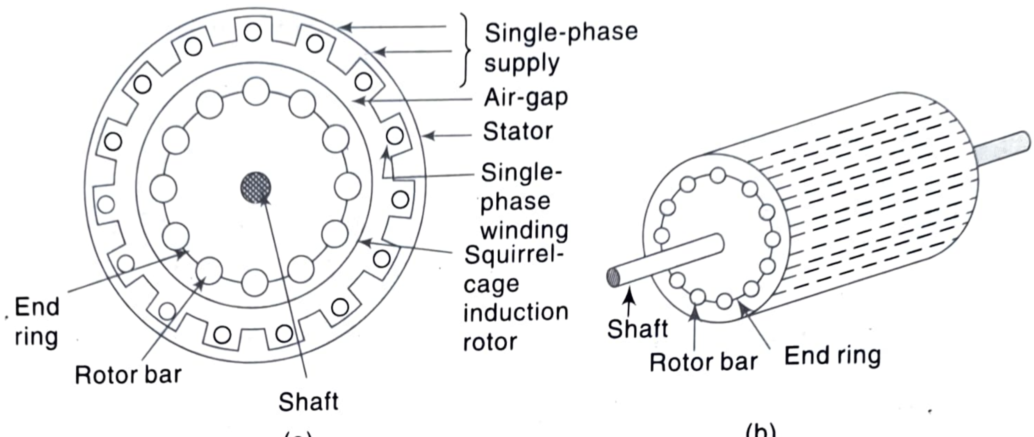


Fig. 5.36 Construction of a single-phase induction motor

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.

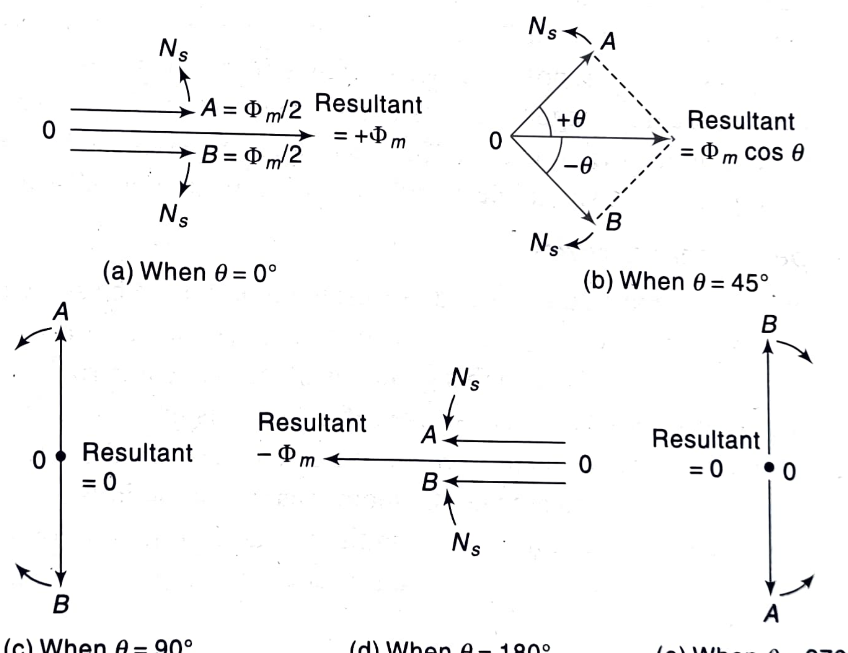


Fig. 5.37 Double-field revolving theory

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.

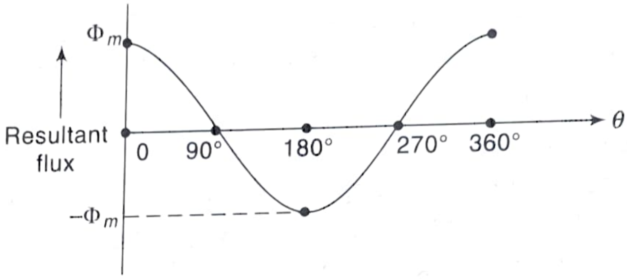


Fig. 5.38 Resultant flux

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.

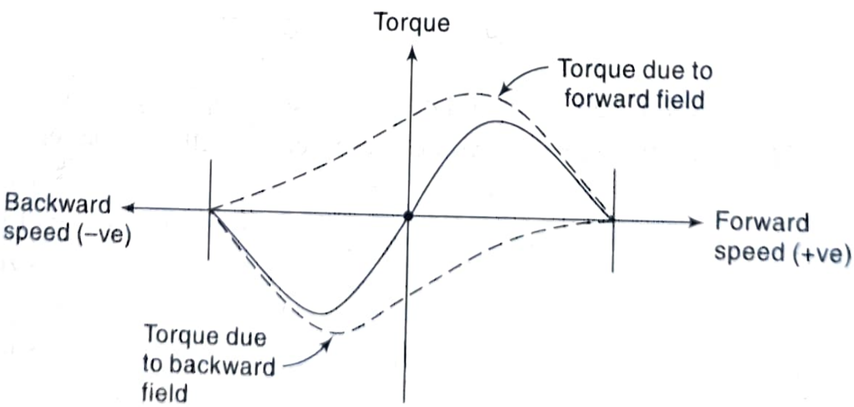


Fig. 5.39 Torque–speed characteristics

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.

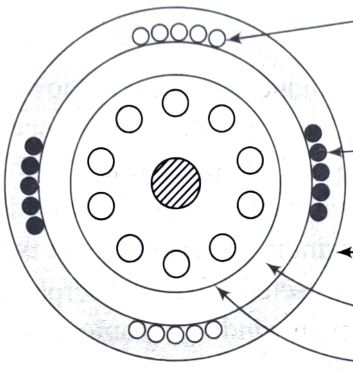


Fig. 5.40 Single-phase induction motor

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).

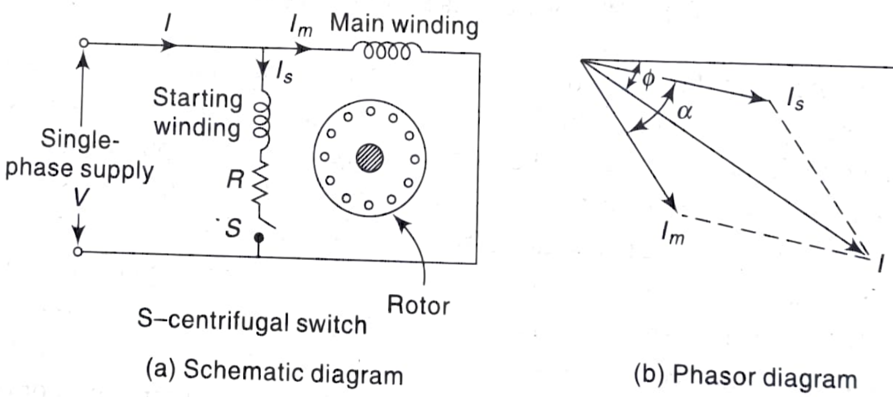


Fig. 5.41 Split-phase induction motor

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 sinα, 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.

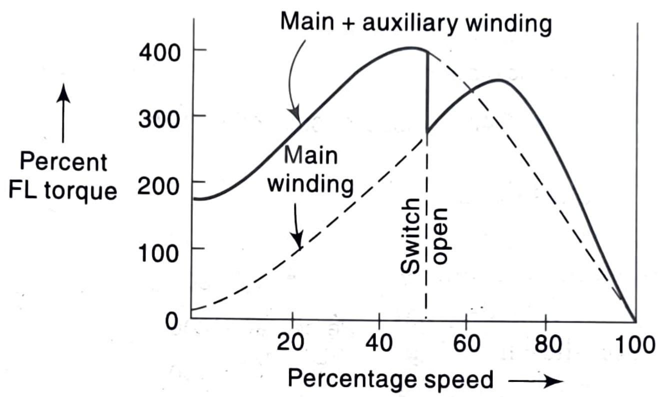


Fig. 5.42 Torque–speed characteristics

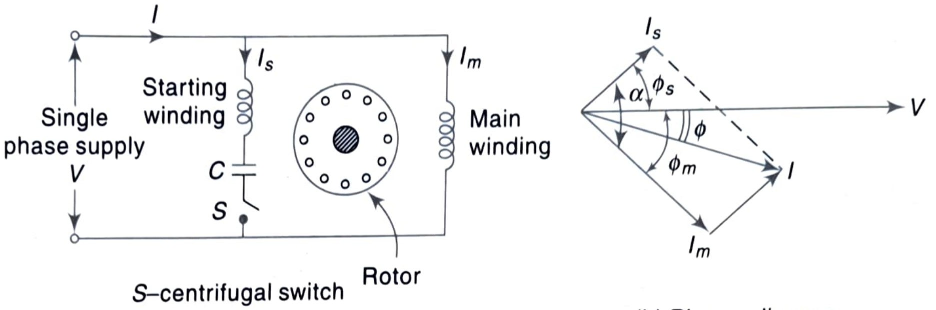
The direction of rotation of this motor can be reversed by reversing the terminals of either the main winding or the auxiliary winding. This changes the direction of the rotating magnetic field, which in turn changes the direction of rotation of the motor.

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.



(a) Schematic diagram (b) Phasor diagram

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.

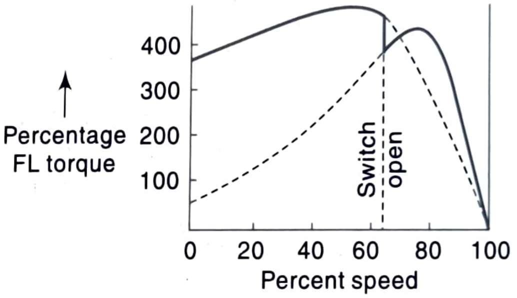
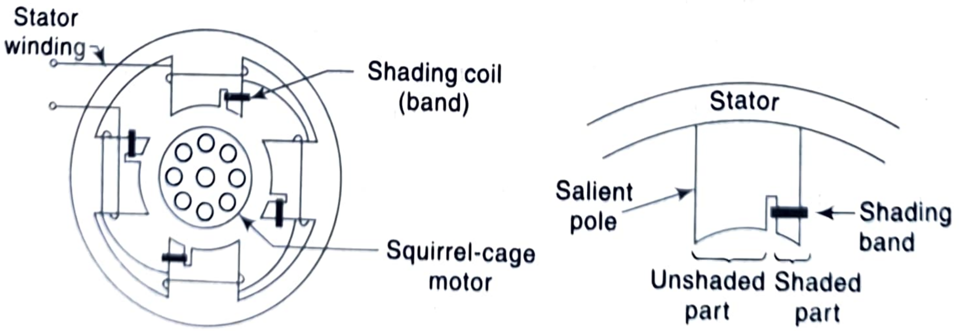


Fig. 5.44 Torque–speed characteristics

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



(a) Construction (b) Pole

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).

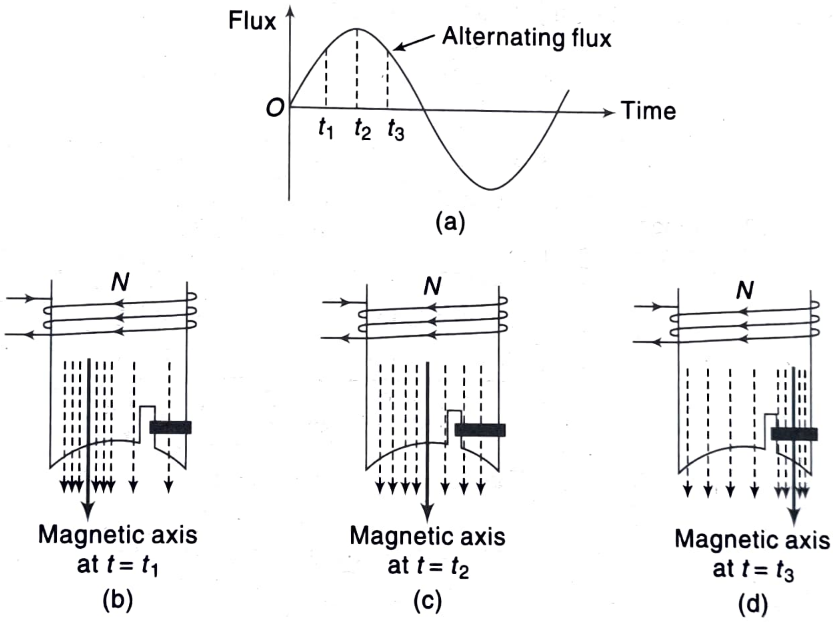


Fig. 5.46 Shifting of magnetic axis

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.

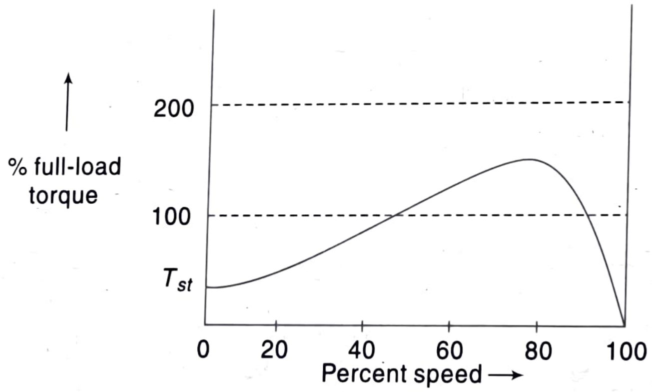


Fig. 5.47 Torque–speed characteristics

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?