Module 8

Three-phase Induction Motor

Lesson
34
Starting Methods for Single-phase Induction Motor

Instructional Objectives

- Why there is no starting torque in a single-phase induction motor with one (main) winding in the stator?
- Various starting methods used in the single-phase induction motors, with the introduction of additional features, like the addition of another winding in the stator, and/or capacitor in series with it.

Introduction

In the previous, i.e. fifth, lesson of this module, the direct-on-line (DOL) starter used in three-phase IM, along with the need for starters, has been described first. Two types of starters − star-delta, for motors with nominally delta-connected stator winding, and auto-transformer, used for cage rotor IM, are then presented, where both decrease in starting current and torque occur. Lastly, the rotor resistance starter for slip-ring (wound rotor) IM has been discussed, where starting current decreases along with increase in starting torque. In all such cases, additional cost is to be incurred. In the last (sixth) lesson of this module, firstly it is shown that there is no starting torque in a single-phase induction motor with only one (main) winding in the stator. Then, the various starting methods used for such motors, like, say, the addition of another (auxiliary) winding in the stator, and/or capacitor in series with it.

Keywords: Single-phase induction motor, starting torque, main and auxiliary windings, starting methods, split-phase, capacitor type, motor with capacitor start/run.

Single-phase Induction Motor

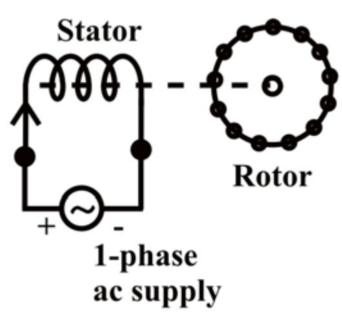


Fig. 34.1: Single Phase Induction Motor

The winding used normally in the stator (Fig. 34.1) of the single-phase induction motor (IM) is a distributed one. The rotor is of squirrel cage type, which is a cheap one, as the rating of this type of motor is low, unlike that for a three-phase IM. As the stator winding is fed from a single-phase supply, the flux in the air gap is alternating only, not a synchronously rotating one produced by a poly-phase (may be two- or three-) winding in the stator of IM. This type of alternating field cannot produce a torque ($(T_0)_{st} = 0.0$), if the rotor is stationery ($\omega_r = 0.0$). So, a single-phase IM is not self-starting, unlike a three-phase one. However, as shown later, if the rotor is initially given some torque in either direction ($\omega_r \neq 0.0$), then immediately a torque is produced in the motor. The motor then accelerates to its final speed, which is lower than its synchronous speed. This is now explained using double field revolving theory.

Double field revolving theory

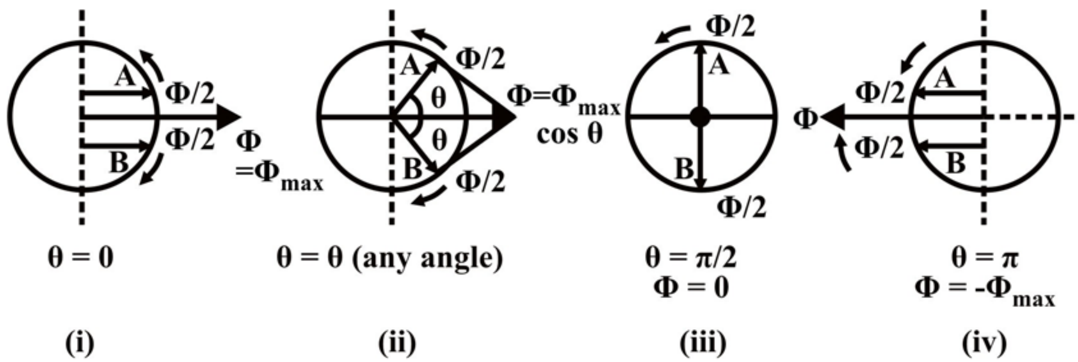


Fig. 34.2(a): Position of the pulsating and rotating in fluxes with change in angle (θ)

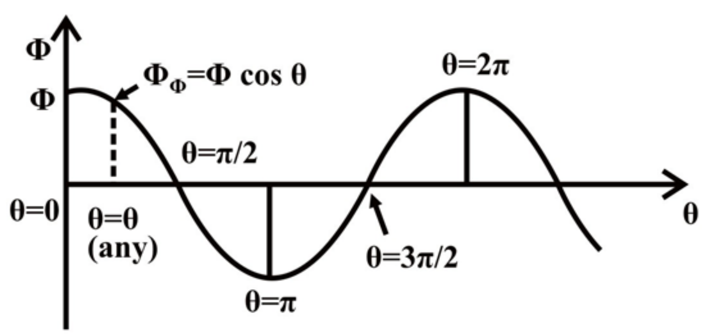


Fig. 34.2(b): Pulsating (sinusoidal) flux as a function of space angle (θ)

When the stator winding (distributed one as stated earlier) carries a sinusoidal current (being fed from a single-phase supply), a sinusoidal space distributed mmf, whose peak or maximum value pulsates (alternates) with time, is produced in the air gap. This sinusoidally varying flux (ϕ) is the sum of two rotating fluxes or fields, the magnitude of which is equal to half the value of the alternating flux ($\phi/2$), and both the fluxes rotating synchronously at the speed, ($n_s = (2 \cdot f)/P$) in opposite directions. This is shown in Fig. 34.2a. The first set of figures (Fig. 34.1a (i-iv)) show the resultant sum of the two rotating fluxes or fields, as the time axis (angle) is changing from $\theta = 0°$ to $\pi(180°)$. Fig. 34.2b shows the alternating or pulsating flux (resultant) varying with time or angle.

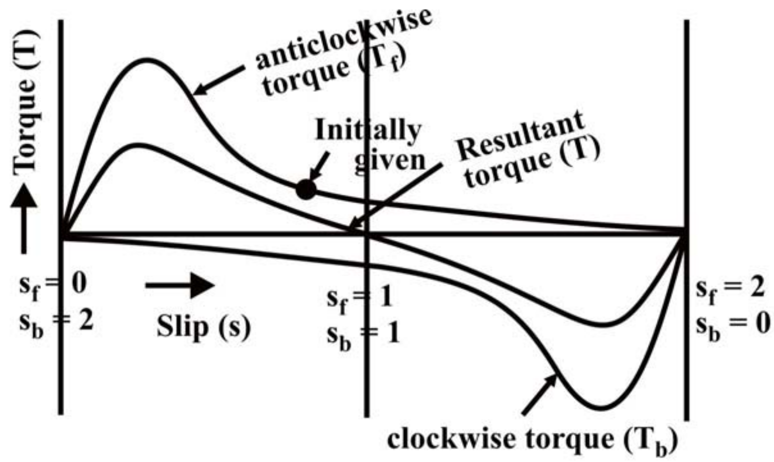


Fig. 34.3:Speed-torque characteristics of single phase induction motor

The flux or field rotating at synchronous speed, say, in the anticlockwise direction, i.e. the same direction, as that of the motor (rotor) taken as positive induces emf (voltage) in the rotor conductors. The rotor is a squirrel cage one, with bars short circuited via end rings. The current flows in the rotor conductors, and the electromagnetic torque is produced in the same direction as given above, which is termed as positive (+ve). The other part of flux or field rotates at the same speed in the opposite (clockwise) direction, taken as negative. So, the torque produced by this field is negative (-ve), as it is in the clockwise direction, same as that of the direction of rotation of this field. Two torques are in the opposite direction, and the resultant (total) torque is the difference of the two torques produced (Fig. 34.3). If the rotor is stationary ($\omega_r = 0.0$), the slip due to forward (anticlockwise) rotating field is $s_f = 1.0$. Similarly, the slip due to backward rotating field is also $s_b = 1.0$. The two torques are equal and opposite, and the resultant torque is 0.0 (zero). So, there is no starting torque in a single-phase IM.

But, if the motor (rotor) is started or rotated somehow, say in the anticlockwise (forward) direction, the forward torque is more than the backward torque, with the resultant torque now being positive. The motor accelerates in the forward direction, with the forward torque being more than the backward torque. The resultant torque is thus positive as the motor rotates in the forward direction. The motor speed is decided by the load torque supplied, including the losses (specially mechanical loss).

Mathematically, the mmf, which is distributed sinusoidally in space, with its peak value pulsating with time, is described as $F = F_{peak} \cos\theta$, θ (space angle) measured from the winding axis. Now, $F_{peak} = F_{\max} \cos\omega t$. So, the mmf is distributed both in space and time, i.e. $F = F_{\max} \cos\theta \cdot \cos\omega t$. This can be expressed as,

$$F = (F_{\max}/2)\cdot\cos(\theta - \omega t) + (F_{\max}/2)\cdot\cos(\theta + \omega t),$$

which shows that a pulsating field can be considered as the sum of two synchronously rotating fields ($\omega_s = 2\pi\, n_s$). The forward rotating field is, $F_f = (F_{\max}/2)\cdot\cos(\theta - \omega t)$, and the backward rotating field is, $F_b = (F_{\max}/2)\cdot\cos(\theta + \omega t)$. Both the fields have the same amplitude equal to $(F_{\max}/2)$, where $F_{\max}$ is the maximum value of the pulsating mmf along the axis of the winding.

When the motor rotates in the forward (anticlockwise) direction with angular speed $(\omega_r = 2\pi n_r)$, the slip due to the forward rotating field is,

$s_f = (\omega_s - \omega_r)/\omega_s = 1 - (\omega_r/\omega_s)$, or $\omega_r = (1 - s_f)\omega_s$.

Similarly, the slip due to the backward rotating field, the speed of which is $(-\omega_s)$, is,

$s_b = (\omega_s + \omega_r)/\omega_s = 1 + (\omega_r/\omega_s) = 2 - s_b$,.

The torques produced by the two fields are in opposite direction. The resultant torque is,

$T = T_f - T_b$

It was earlier shown that, when the rotor is stationary, $T_f = T_b$, with both $s_f = s_b = 1.0$, as $\omega_r = 0.0$ or $n_r = 0.0$. Therefore, the resultant torque at start is 0.0 (zero).

Starting Methods

The single-phase IM has no starting torque, but has resultant torque, when it rotates at any other speed, except synchronous speed. It is also known that, in a balanced two-phase IM having two windings, each having equal number of turns and placed at a space angle of $90°$ (electrical), and are fed from a balanced two-phase supply, with two voltages equal in magnitude, at an angle of $90°$, the rotating magnetic fields are produced, as in a three-phase IM. The torque-speed characteristic is same as that of a three-phase one, having both starting and also running torque as shown earlier. So, in a single-phase IM, if an auxiliary winding is introduced in the stator, in addition to the main winding, but placed at a space angle of $90°$ (electrical), starting torque is produced. The currents in the two (main and auxiliary) stator windings also must be at an angle of $90°$, to produce maximum starting torque, as shown in a balanced two-phase stator. Thus, rotating magnetic field is produced in such motor, giving rise to starting torque. The various starting methods used in a single-phase IM are described here.

Resistance Split-phase Motor

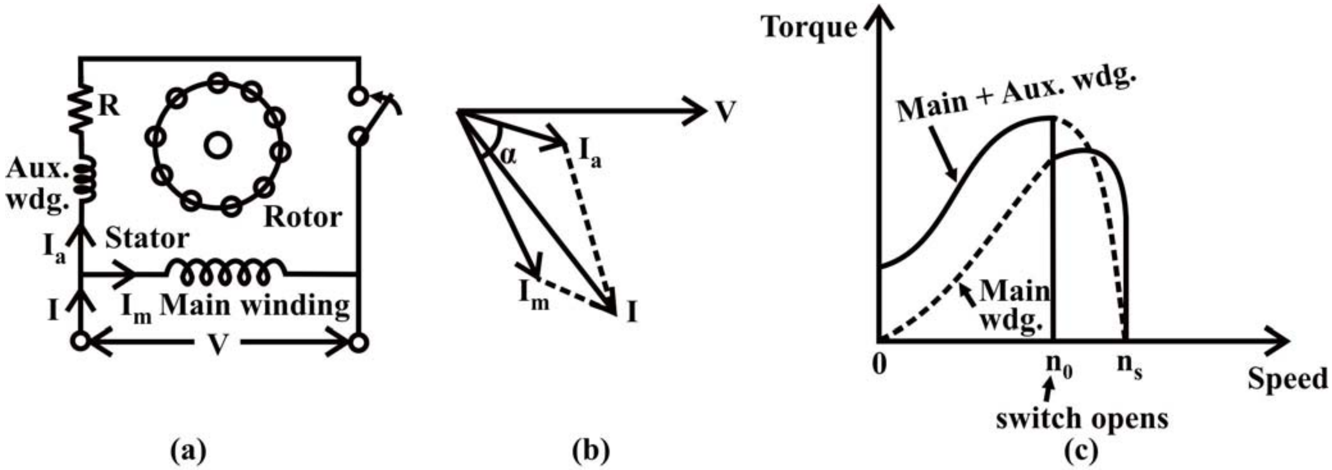


Fig. 34.4: Resistance Split-phase Induction Motor
(a) Schematic Diagram
(b) Phasor Diagram
(c) Torque-Speed characteristic

The schematic (circuit) diagram of this motor is given in Fig. 34.4a. As detailed earlier, another (auxiliary) winding with a high resistance in series is to be added along with the main winding in the stator. This winding has higher resistance to reactance (R_a / X_a) ratio as compared to that in the main winding, and is placed at a space angle of $90°$ from the main winding as given earlier. The phasor diagram of the currents in two windings and the input voltage is shown in Fig. 34.4b. The current (I_a) in the auxiliary winding lags the voltage (V) by an angle, ϕ_a, which is small, whereas the current (I_m) in the main winding lags the voltage (V) by an angle, ϕ_m, which is nearly $90°$. The phase angle between the two currents is ($90° - \phi_a$), which should be at least $30°$. This results in a small amount of starting torque. The switch, S (centrifugal switch) is in series with the auxiliary winding. It automatically cuts out the auxiliary or starting winding, when the motor attains a speed close to full load speed. The motor has a starting torque of 100−200% of full load torque, with the starting current as 5-7 times the full load current. The torque-speed characteristics of the motor with/without auxiliary winding are shown in Fig. 34.4c. The change over occurs, when the auxiliary winding is switched off as given earlier. The direction of rotation is reversed by reversing the terminals of any one of two windings, but not both, before connecting the motor to the supply terminals. This motor is used in applications, such as fan, saw, small lathe, centrifugal pump, blower, office equipment, washing machine, etc.

Capacitor Split-phase Motor

The motor described earlier, is a simple one, requiring only second (auxiliary) winding placed at a space angle of $90°$ from the main winding, which is there in nearly all such motors as discussed here. It does not need any other thing, except for centrifugal switch, as the auxiliary winding is used as a starting winding. But the main problem is low starting torque in the motor, as this torque is a function of, or related to the phase difference (angle) between the currents in the two windings. To get high starting torque, the phase difference required is 90° (Fig. 34.5b), when the starting torque will be proportional to the product of the magnitudes of two currents. As the current in the main winding is lagging by ϕ_m, the current in the auxiliary winding has to lead the input voltage by ϕ_a, with ($\phi_m + \phi_a = 90°$). ϕ_a is taken as negative (-ve), while ϕ_m is positive (+ve). This can be can be achieved by having a capacitor in series with the auxiliary winding, which results in additional cost, with the increase in starting torque, The two types of such motors are described here.

Capacitor-start Motor

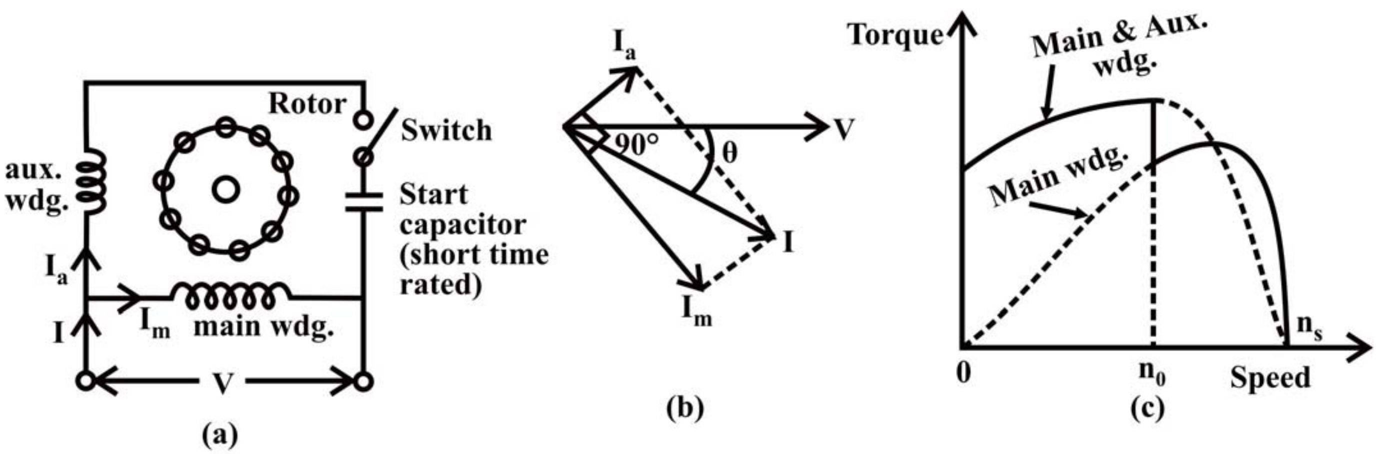
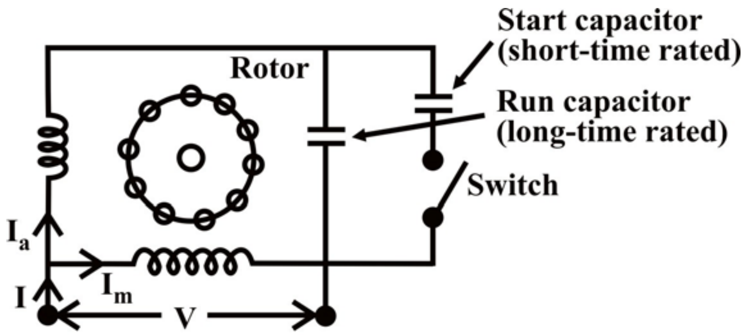


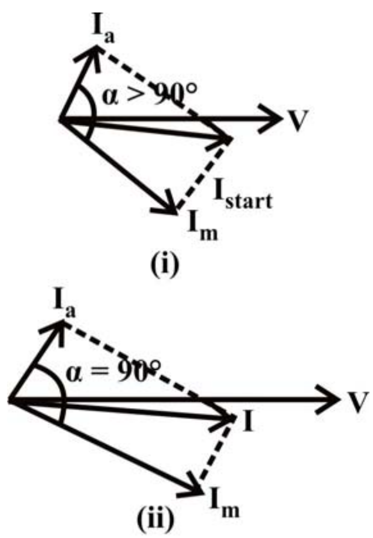
Fig. 34.5: Capacitor-Start Induction Motor
(a) Schematic Diagram
(b) Phasor Diagram
(c) Torque-Speed characteristic

The schematic (circuit) diagram of this motor is given in Fig. 34.5a. It may be observed that a capacitor along with a centrifugal switch is connected in series with the auxiliary winding, which is being used here as a starting winding. The capacitor may be rated only for intermittent duty, the cost of which decreases, as it is used only at the time of starting. The function of the centrifugal switch has been described earlier. The phasor diagram of two currents as described earlier, and the torque-speed characteristics of the motor with/without auxiliary winding, are shown in Fig. 34.5b and Fig. 34.5c respectively. This motor is used in applications, such as compressor, conveyor, machine tool drive, refrigeration and air-conditioning equipment, etc.

Capacitor-start and Capacitor-run Motor



(a)



(b)

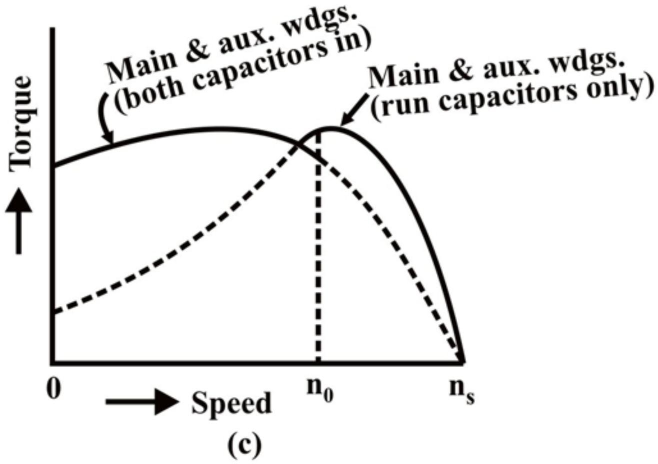


Fig. 34.6: Capacitor-Start and Capacitor-run Induction Motor
(a) Schematic Diagram
(b) Phasor Diagrams
(c) Torque-Speed characteristics

In this motor (Fig. 34.6a), two capacitors $-C_s$ for starting, and C_r for running, are used. The first capacitor is rated for intermittent duty, as described earlier, being used only for starting. A centrifugal switch is also needed here. The second one is to be rated for continuous duty, as it is used for running. The phasor diagram of two currents in both cases, and the torque-speed characteristics with two windings having different values of capacitors, are shown in Fig. 34.6b and Fig. 34.6c respectively. The phase difference between the two currents is ($\phi_m + \phi_a > 90°$) in the first case (starting), while it is $90°$ for second case (running). In the second case, the motor is a balanced two phase one, the two windings having same number of turns and other conditions as given earlier, are also satisfied. So, only the forward rotating field is present, and the no backward rotating field exists. The efficiency of the motor under this condition is higher. Hence, using two capacitors, the performance of the motor improves both at the time of starting and then running. This motor is used in applications, such as compressor, refrigerator, etc.

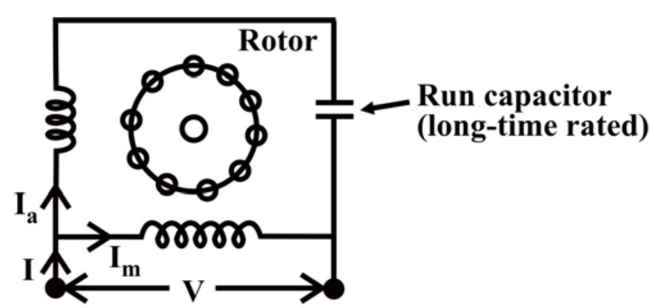


Fig. 34.7: Schematic Diagram of Capacitor-run Induction Motor

Beside the above two types of motors, a Permanent Capacitor Motor (Fig. 34.7) with the same capacitor being utilised for both starting and running, is also used. The power factor of this motor, when it is operating (running), is high. The operation is also quiet and smooth. This motor is used in applications, such as ceiling fans, air circulator, blower, etc.

Shaded-pole Motor

A typical shaded-pole motor with a cage rotor is shown in Fig. 34.8a. This is a single-phase induction motor, with main winding in the stator. A small portion of each pole is covered with a short-circuited, single-turn copper coil called the shading coil. The sinusoidally varying flux created by ac (single-phase) excitation of the main winding induces emf in the shading coil. As a result, induced currents flow in the shading coil producing their own flux in the shaded portion of the pole.

Let the main winding flux be $\phi_m = \phi_{\max} \sin \omega t$

where

$\phi_m = \phi_m^{sc}$ (flux component linking shading coil)

$+ \ \phi'_m$ (flux component passing down the air-gap of the rest of the pole)

The emf induced in the shading coil is given by

$$e_{sc} = \frac{d\phi_m^{sc}}{dt} \text{ (since single-turn coil) } = \phi_{\max}^{sc} \ \omega \ \cos \omega t$$

Let the impedance of the shading coil be $Z_{sc} \angle \theta_{sc} = R_{sc} + j \, X_{sc}$

The current in the shading coil can then be expressed as

$$i_{sc} = \left[\left(\phi_{\max}^{sc} \ \omega \right) / Z_{sc} \right] \cos(\omega t - \theta_{sc})$$

The flux produced by i_{sc} is

$$\phi_{sc} = \frac{1 \times i_{sc}}{R} = \frac{\omega \ \phi_{\max}^{sc}}{Z_{sc} \ R} \cos(\omega t - \theta_{sc})$$

where $R =$ reluctance of the path of ϕ_{sc}

As per the above equations, the shading coil current (I_{sc}) and flux (ϕ_{sc}) phasors lag behind the induced emf (E_{sc}) by angle θ_{sc} ; while the flux phasor leads the induced emf (E_{sc}) by 90°. Obviously the phasor ϕ'_m is in phase with ϕ_m^{sc}. The resultant flux in the shaded pole is given by the phasor sum

$$\phi_{sp} = \phi_m^{sc} + \phi_{sc}$$

as shown in Fig. 34.8b and lags the flux ϕ'_m of the remaining pole by the angle α. The two sinusoidally varying fluxes ϕ'_m and ϕ'_{sp} are displaced in space as well as have a time phase difference (α), thereby producing forward and backward rotating fields, which produce a net torque. It may be noted that the motor is self-starting unlike a single-phase single-winding motor.

It is seen from the phasor diagram (Fig. 34.8b) that the net flux in the shaded portion of the pole (ϕ_{sp}) lags the flux (ϕ'_m) in the unshaded portion of the pole resulting in a net torque, which causes the rotor to rotate from the unshaded to the shaded portion of the pole. The motor thus has a definite direction of rotation, which cannot be reversed.

The reversal of the direction of rotation, where desired, can be achieved by providing two shading coils, one on each end of every pole, and by open-circuiting one set of shading coils and by short-circuiting the other set.

The fact that the shaded-pole motor is single-winding (no auxiliary winding) self-starting one, makes it less costly and results in rugged construction. The motor has low efficiency and is usually available in a range of 1/300 to 1/20 kW. It is used for domestic fans, record players and tape recorders, humidifiers, slide projectors, small business machines, etc. The shaded-pole principle is used in starting electric clocks and other single-phase synchronous timing motors.

In this lesson − the sixth and last one of this module, firstly, it is shown that, no starting torque is produced in the single-phase induction motor with only one (main) stator winding, as the flux produced is a pulsating one, with the winding being fed from single phase supply. Using double revolving field theory, the torque-speed characteristics of this type of motor are described, and it is also shown that, if the motor is initially given some torque in either direction, the motor accelerates in that direction, and also the torque is produced in that direction. Then, the various types of single phase induction motors, along with the starting methods used in each one are presented. Two stator windings − main and auxiliary, are needed to produce the starting torque. The merits and demerits of each type, along with their application area, are presented. The process of production of starting torque in shade-pole motor is also described in brief. In the next module consisting of seven lessons, the construction and also operation of dc machines, both as generator and motor, will be discussed.

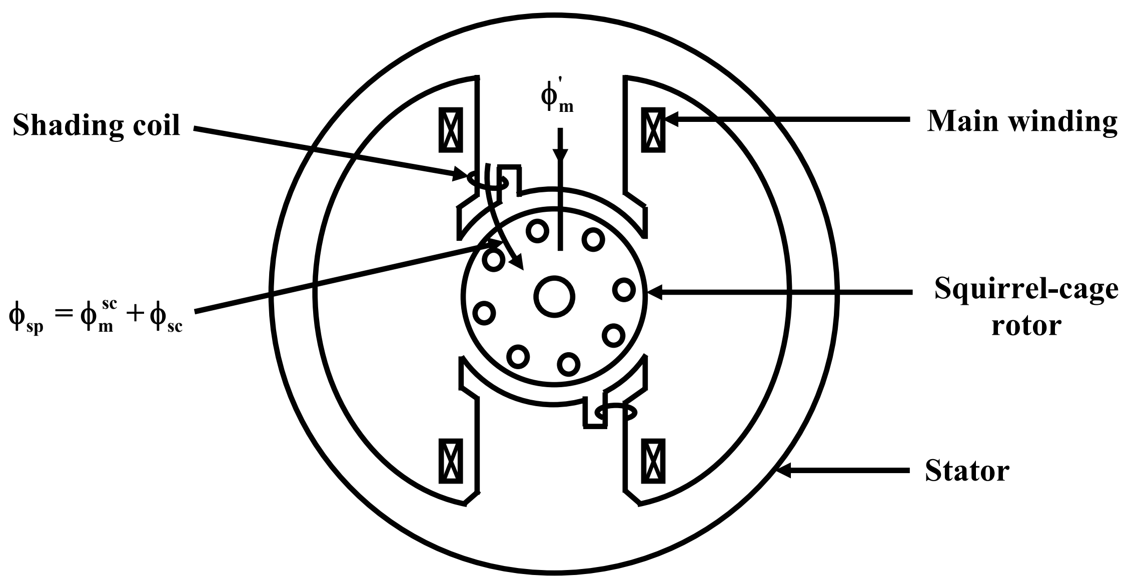


Fig. 34.8(a): Shaded-pole motor (single-phase induction type)

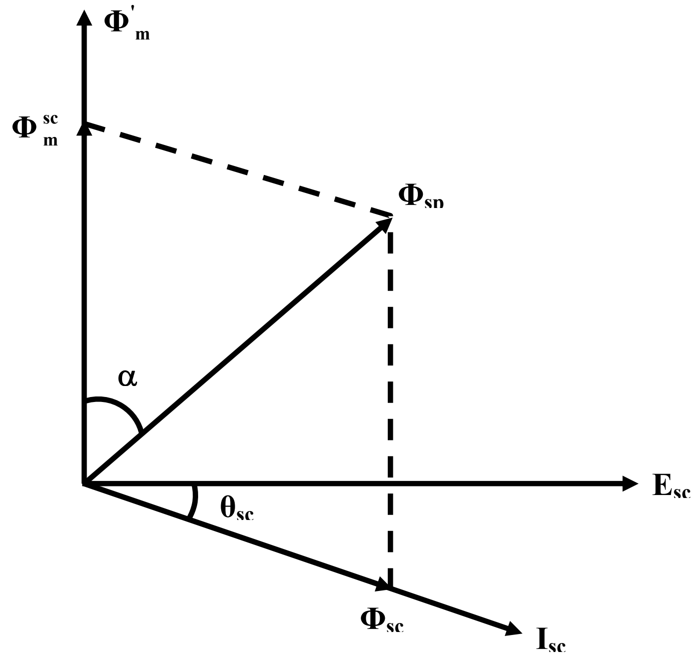


Fig. 34.8(b): Phasor diagram of the fluxes in shaded=pole motor