# CHAPTER - 11
# THREE PHASE INDUCTION MOTOR

## 11.1 Introduction:

A three phase induction motor is an a.c. motor. Of all the a.c. motors available, it is extensively used, because of the following advantages:

1. Its construction is simple, rugged and almost unbreakable.
2. Its cost is low and is highly reliable.
3. Its efficiency is high.
4. It works with reasonably good power factor at rated load.
5. Its maintenance is less.
6. Induction motors are self-starting. Hence, motors of smaller ratings do not require a starter. The starting arrangements for larger motors are simple.

*The disadvantages are:*

1. It is essentially a constant speed motor and the speed cannot be changed easily. The speed variation can be done at the cost of efficiency.
2. The starting torque is inferior to that of a D.C. shunt motor.

## 11.2 Construction:

A three phase induction motor mainly consists of two parts. (i) *stator* and (ii) *rotor*. The rotor, which is the rotating part, is separated by the stator, which is the static part, by a small air gap, which usually varies from 0.4 mm to 4 mm, depending on the rating of the motor.

## 11.2 (a) Stator:

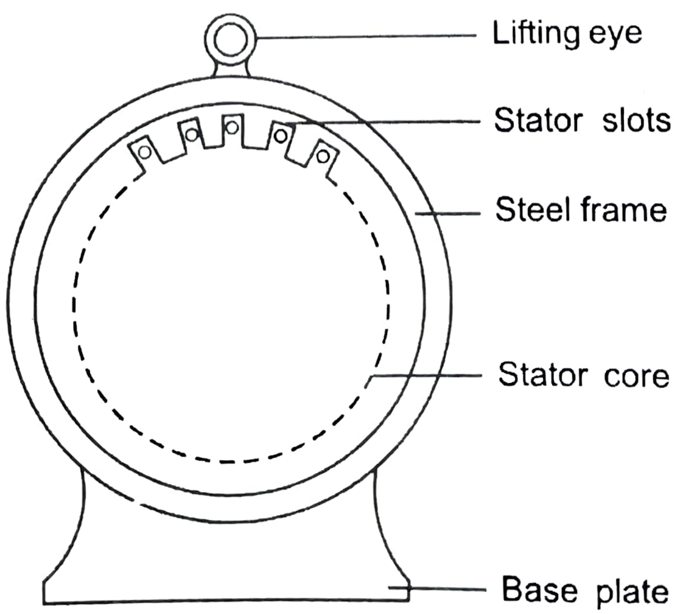



**Fig. 11.1**

Fig 11.1 shows the stator of the induction motor. It consists of a steel frame, which encloses a hollow, cylindrical core, made up of thin laminations of silicon steel to reduce eddy current loss and hysteresis loss. A large number of uniform slots are cut on the inner periphery of the core. The stator conductors are placed in these slots, which are insulated from one another and also from the slots. These conductors are connected as a balanced three phase star winding or delta winding. The windings are wound for a definite number of poles, depending on the requirement of speed. It is wound for more number of poles, if the speed required is less and vice-versa, according to the relation.

$$N_S = \frac{120\,f}{P} \qquad (11.1)$$

Where, $N_S$ = synchronous speed in r.p.m.

$f$ = frequency of the supply.

and $P$ = number of poles.

When a three phase supply is given to the stator winding, a magnetic field of constant magnitude and rotating at synchronous speed, given by the equation $N_S = 120\ f / P$ is produced. This rotating magnetic field is mainly responsible for producing the torque in the rotor, so that, it can rotate at its rated speed, which will be explained in detail in the later sections of this chapter.

## 11.2 (b) Rotor:

The rotor is the rotating part of the induction motor and is mounted on the shaft of the motor to which, any mechanical load can be connected. There are two types of rotors (i) *squirrel cage rotor* and (ii) *phase wound rotor*. According to the type of rotor used, three phase induction motors are classified as squirrel cage induction motors and phase wound or slip ring induction motors.

### i) Squirrel cage rotor:

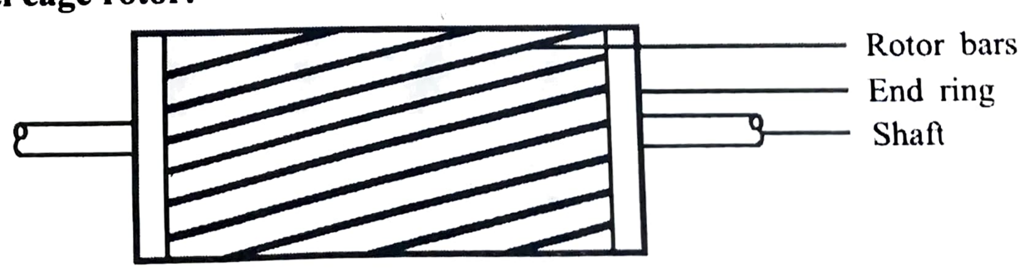



**Fig.11.2**

Nearly 90% of the induction motors are of squirrel cage type, as the rotor is simple and rugged in construction. This type of rotor, shown in Fig. 11.2, consists of a cylindrical laminated core with parallel slots, for carrying rotor conductors. The rotor conductors are heavy bars of copper or aluminium. One bar is placed in each slot. All the bars are brazed or welded at both ends to two copper end rings, thus short circuiting them at both ends. As the rotor bars are short circuited on themselves, it is not possible to add any external resistance in series with the rotor circuit during starting. The slots are slightly skewed, which helps in two ways (i) it reduces the noise due to magnetic hum and makes the rotor to run quietly and (ii) it reduces the locking tendency between the rotor and the stator.

### ii) Phase Wound Rotor:

This rotor is a laminated, cylindrical core having uniform slots on its outer periphery. A three phase winding, which is star connected is placed in these slots. The open ends of the star winding are brought out and connected to three insulated slip rings, mounted on the shaft of the motor, with carbon brushes resting on them.

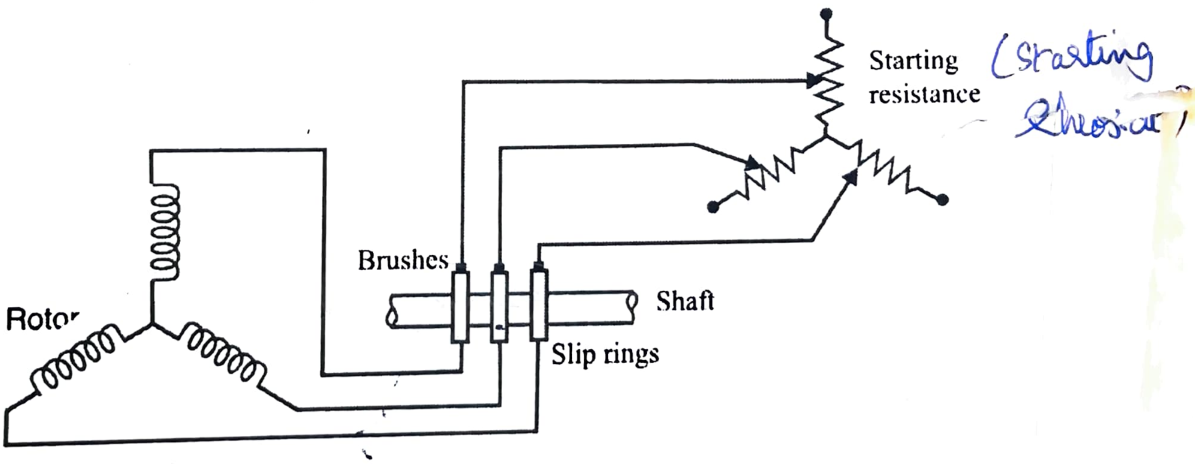



**Fig.11.3**

The three brushes are externally connected to a three phase star connected rheostat, which is used as a starter during the starting period. When running under normal conditions, the slip rings are automatically short circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip rings, to reduce the frictional losses, wear and tear. The equivalent circuit diagram of a phase wound induction motor along with the rotor connections to the starting resistance is as shown fig.11.3.

## 11.2 (c) Squirrel Cage Induction Motor:

i) Advantages

...truction, rugged and can withstand rough handling.

4. A simple star-delta starter is sufficient to start the motor
5. It is explosion proof as there are no slip rings, brushes and their assembly.

ii) Disadvantages:

1. It has low starting torque.
2. The p.f. at starting is lower.
3. The starting current is high and it has no smooth running.

### 11.2 (d) Slip-ring Induction Motor:

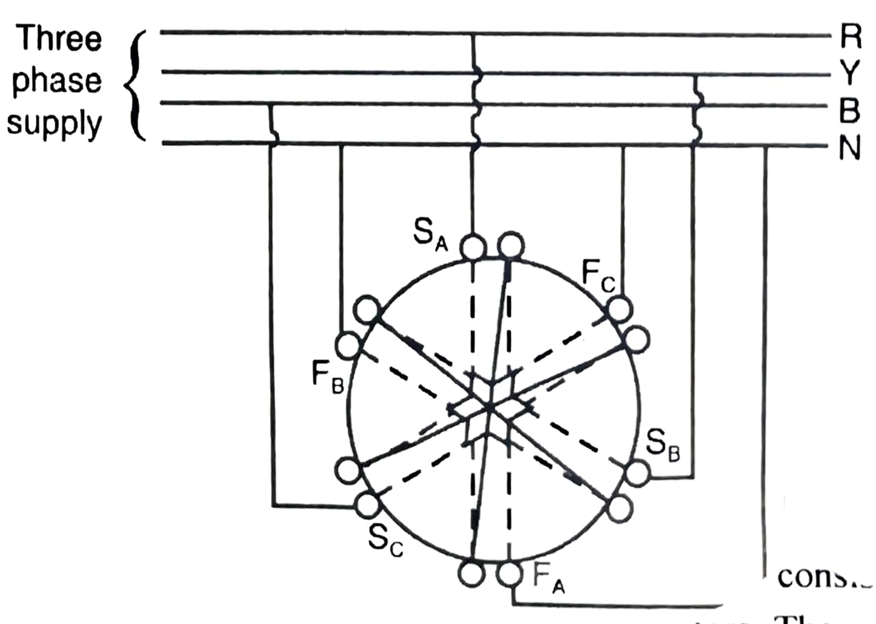
i) Advantages:

1. It has external resistance in the rotor circuit which can be used as a starter, especially with load, with higher starting torque and lower starting current.
2. The external resistance can be used to control the speed and also to improve the power factor.
3. The motor is smooth running.
4. Slip-ring induction motors of very high capacity can be built.

(ii) Disadvantages:

1. The size of the slip-ring induction motor of the same capacity is more than that of squirrel cage induction motor.
2. It is costlier as the construction is complicated.
3. The maintenance and repair costs are quite high.

### 11.3 Rotating Magnetic Field:

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When a three phase supply is given to the three phase winding of the stator, a rotating magnetic field of constant magnitude and rotating with synchronous speed is produced. This fact can be proved as follows.

The Fig. in 11.4, shows the three phase winding of the stator of an induction motor, which is connected to the three phase supply. The starting points of the windings $S_A$, $S_B$ and $S_C$ are connected to the three supply lines R, Y and B. The other three ends $F_A$, $F_B$ and $F_C$ are connected to the neutral N. When the supply is given, the fluxes produced in the three windings are as shown in Fig.11.5.

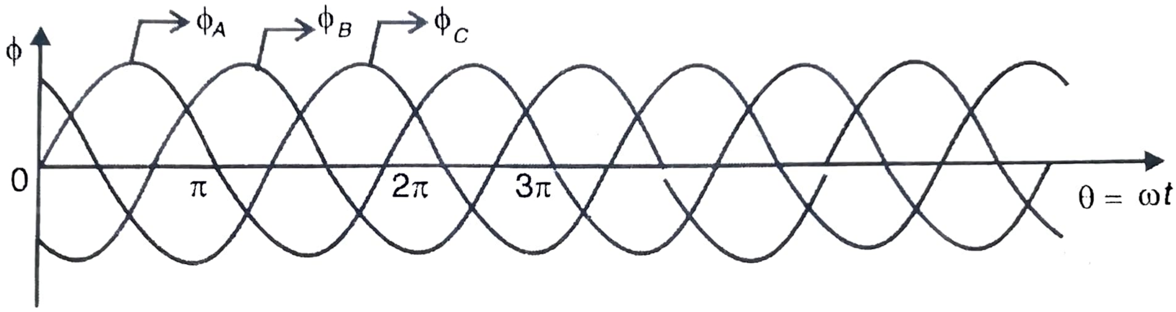



**Fig.11.5**

The assumed positive directions of fluxes are as shown in Fig. 11.6.

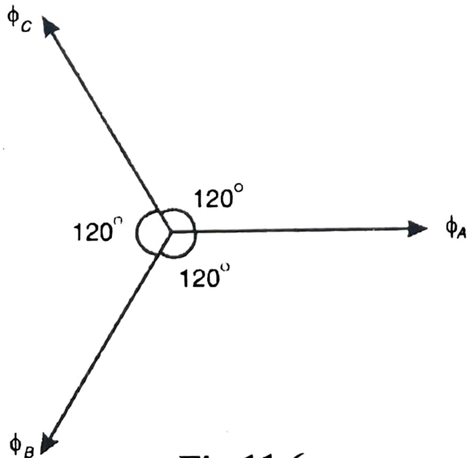



**Fig.11.6**

The equations for the three fluxes are:

$\phi_A = \phi_m \sin \omega t$

$\phi_B = \phi_m \sin (\omega t - 120°)$ and

$\phi_C = \phi_m \sin (\omega t - 240°)$

The resultant flux of these three fluxes at any instant, is given by the vector sum of the individual fluxes $\phi_A$, $\phi_B$ and $\phi_C$.

(i) When $\theta = 0°$, we find from the wave diagram of the fluxes, shown in Fig. 11.5 that

$\phi_A = 0$

$\phi_B = \phi_m \sin (-120°) = -\dfrac{\sqrt{3}}{2}\phi_m$  – sin (90+30)

– cos 30

$\phi_C = \phi_m \sin (-240°) = \dfrac{\sqrt{3}}{2}\phi_m$

These values of fluxes at this instant and their resultant are shown in Fig. 11.7. The vector $\phi_B$ is written opposite to its assumed positive direction, as it is negative. The resultant flux $\phi_r$ lies along Y–axis and its magnitude is given by,

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos 30° = \frac{3}{2}\phi_m = 1.5\ \phi_m$$

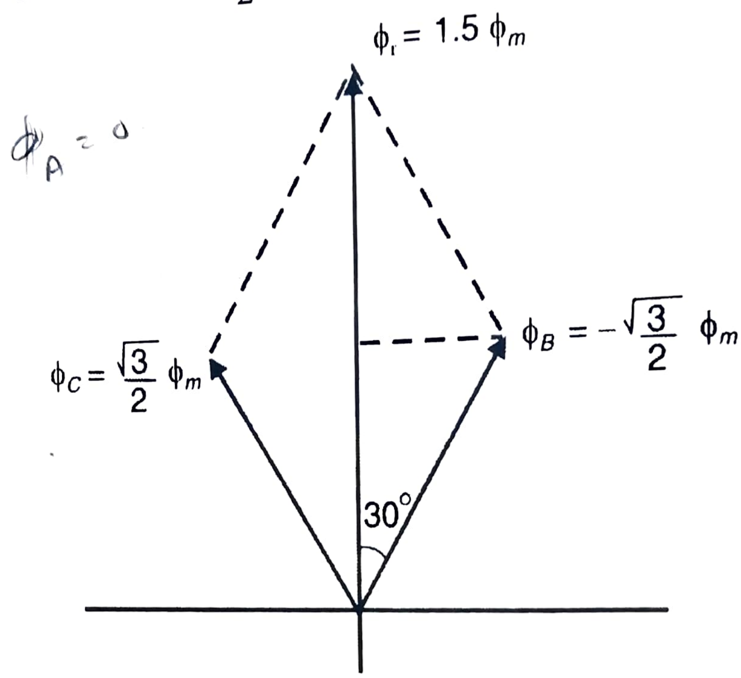



**Fig. 11.7**

ii) When $\theta = 60°$, the values of the three fluxes are,

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

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

$$\phi_C = 0$$

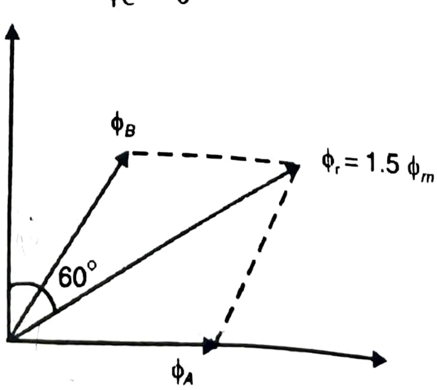



**Fig.11.8**

The three fluxes at this instant and their resultant are shown in Fig. 11.8. It is observed that, the resultant flux has rotated by 60° in the clockwise direction and its magnitude is 1.5 $\phi_m$.

iii) When $\theta = 120°$, the values of the three fluxes are,

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

$$\phi_B = 0 \quad \text{and} \quad \phi_C = -\frac{\sqrt{3}}{2}\phi_m$$

The three fluxes at this instant and their resultant are shown in Fig. 11.9. It is observed that the resultant flux has rotated by another 60° i.e. through 120°, from its original position and its magnitude is 1.5 $\phi_m$.

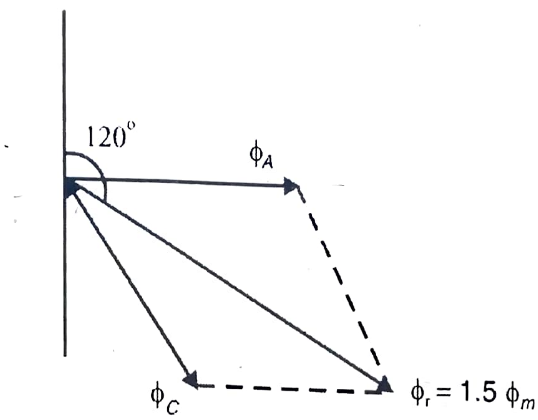
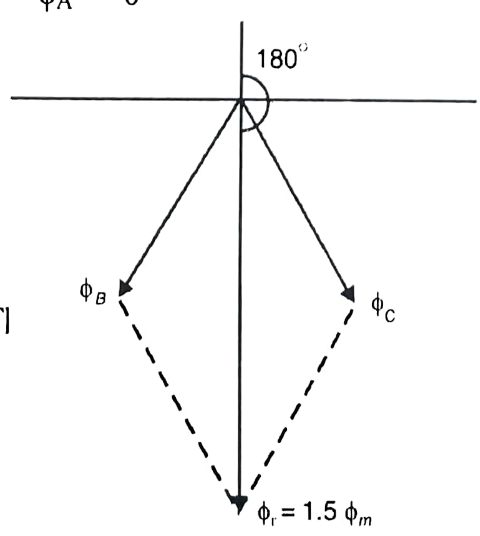



**Fig. 11.9**

iv) When $\theta = 180°$, the values of the three fluxes are;

$\phi_A = 0$




Tl their resultant are as shown in Fig.11.10. It is observed that the resul

From the above discussion, we can conclude that as $\theta = \omega t$ varies from $\theta = 0$ to $\theta = 2\pi$, the resultant flux also rotates with the same angular velocity $\omega$ and having a constant magnitude of 1.5 $\phi_m$ . Therefore, when a three phase supply is given to the stator winding, a rotating magnetic field of constant magnitude 1.5 $\phi_m$ and rotating with synchronous speed $N_S = 120\ f / P$ is produced.

## 11.4 Working Principle:

When a three phase supply is given to the three phase stator winding, a magnetic field of constant magnitude 1.5 $\phi_m$ and rotating with the synchronous speed $N_S$ is produced. This rotating magnetic field sweeps across the rotor conductors and hence, an e.m.f. is induced in the rotor conductors. The direction of the induced e.m.f. is such as to oppose the very cause of it i.e. the relative speed between the rotating magnetic field and the static rotor. As the rotor conductors are short circuited on themselves, the induced e.m.f. sets up a current in the rotor conductors in such a direction as to produce a torque, which rotates the rotor in the same direction as the magnetic field, as shown in Fig. 11.11, so that the relative speed decreases. The speed of the rotor gradually increases and tries to catch up with the speed of the rotating magnetic field. But, it fails to reach the synchronous speed, because, if it catches up with the speed of the magnetic field, the relative speed becomes zero and hence, no e.m.f. will be induced in the rotor conductors, the torque becomes zero. Hence, the rotor will not be able to catch up with the speed of the magnetic field, but rotates at a speed slightly less than the synchronous speed.

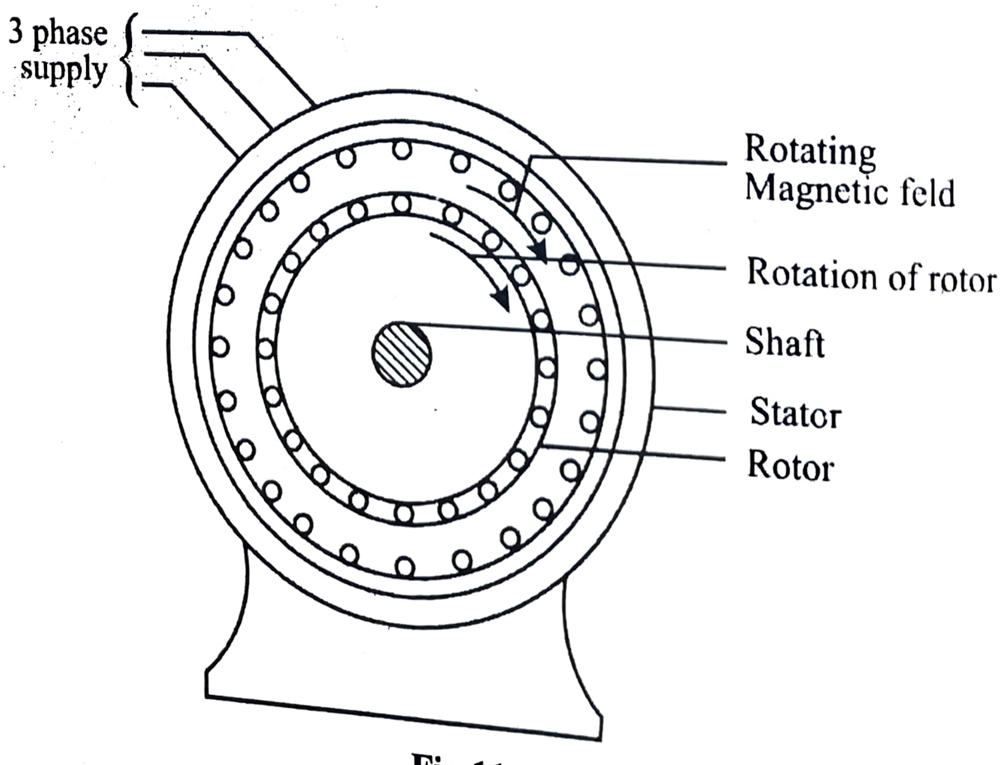



**Fig.11.11**

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

$$\therefore \text{ Slip speed} = N_S - N \quad (11.2)$$

The *slip* of an induction motor is defined as the ratio of the slip speed to the synchronous speed

$$S = \frac{N_S - N}{N_S} \qquad (11.3)$$

The slip of an induction motor is usually expressed as a percentage and the percentage slip is given by,

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

## 11.5 Frequency of Rotor Current:

When the rotor is stationary, the frequency of the rotor current is the same as the supply frequency. When the induction motor is rotating, the frequency of the current induced in the rotor conductors is proportional to the relative speed or slip speed. If $f^1$ is the frequency of the induced current in the rotor, then

$$N_S - N = \frac{120 f^1}{P} \qquad (11.4)$$

But $$N_S = \frac{120 f}{P} \qquad (11.5)$$

Where, $f$ = frequency of the supply

From equation (11.4) and (11.5), we get,

$$\frac{N_S - N}{N_S} = \frac{f^1}{f} = S$$

$$\therefore \; f^1 = S f \qquad (11.6)$$

The frequency of the rotor current is slip times the frequency of the supply.

$f \rightarrow$ frequency of supply

$f' \rightarrow$ frequency of the rotor current

## 11.6 Starters for 3 Phase Induction Motors:

Need for Starters.

Three phase induction motors are self starting. But induction motors, at the time of starting, draw about 5 to 7 times the full load current and produce only 1.5 to 2.5 times the full load torque, when they are directly connected to the supply. This large initial inrush of current is due to the absence of back e.m.f. during starting. This large starting current is objectionable, as it causes large line drop and affects the operation of other connected apparatus to the line. Hence, starters are invariably used for three phase induction motors. In the case of slip-ring induction motors, resistance can be included in the rotor circuit during starting and can be removed, when the motor picks up speed. This method can't be used to start squirrel cage induction motors, as the rotors of these motors are permanently short circuited. In the case of squirrel cage induction motors, the starting current is limited by applying a reduced voltage during starting and full voltage is applied, when the motor has picked up its speed.

## 11.7 Methods of Starting Squirrel Cage Induction Motors:

Following are the three methods of starting squirrel cage induction motors:

i) using primary resistors

ii) using auto-transformers and

iii) using star-delta starter

As the most frequently used starter for a three phase induction motor is star-delta starter, only this starter is discussed.

## 11.8 Star-Delta Starter:

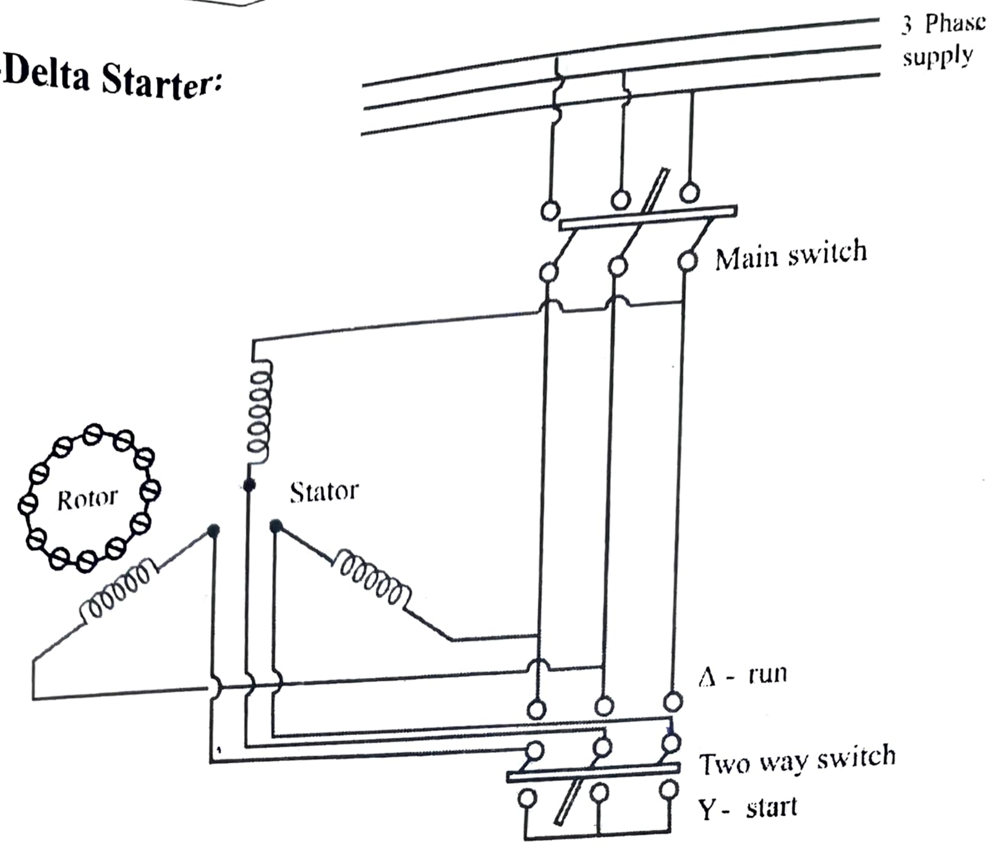



**Fig. 11.12**

This method of starting is used for induction motors, which are built to run with a delta connected stator winding. It consists of a two-way switch, which connects the stator winding in star during starting and then in delta for normal running. The connections are as shown in the Fig.11.12. When the stator winding is star connected during starting, the applied voltage across each phase of the stator phase is $V/\sqrt{3}$, where V is the applied line voltage and hence, the starting current is given by,

$$I_{st} = \frac{I_{sc}}{\sqrt{3}}$$

Where, $I_{st}$ = Starting current

$I_{sc}$ = Starting current that would have flown in the stator winding, when the motor is directly switched.

Thus the starting current is reduced to $\frac{1}{\sqrt{3}}$ times the current that would have flown through the stator winding, if direct supply was given.

When the two way switch is closed on to Y side, the motor starts rotating and now the switch is closed on to the Δ side. The motor picks up speed as full voltage is now applied and the motor reaches its rated speed.

The relation between the starting torque and the full load torque developed in the induction motor is given by,

$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 S_f = \left(\frac{I_{sc}}{\sqrt{3}\, I_f}\right) S_f$$

$$= \frac{1}{3}\left(\frac{I_{sc}}{I_f}\right)^2 S_f = \frac{1}{3} a^2 S_f \qquad (11.7)$$

Where, $a = \dfrac{I_{sc}}{I_f}$

This method of starting is cheap. Hence, it is used for motors used in machine tools, pumps etc.,

## NUMERICAL PROBLEMS

**11.1** A 4 pole, 3 phase, 50 Hz induction motor is running on no load with a slip of 3%. Calculate the speed of the induction motor. **(1,455 r.p.m.)**

**11.2** The rotor current of three phase, 4 pole, 50 Hz induction motor has a frequency of 2 Hz at full load. Calculate the slip and speed at full load. **(0.04, 1,440 r.p.m.)**

**11.3** A 3 phase, 8 pole, 60 Hz induction motor has a rotor e.m.f. of 10 V induced in the rotor winding, at standstill. Calculate the voltage and frequency induced in the rotor winding when it rotates at 864 r.p.m. **(0.4 V, 2.4 Hz)**

**11.4** An 8 pole induction motor is supplied by a 10 pole alternator running at 1,500 r.p.m. If the motor runs with a slip of 4%, what is its speed? **(1,440 r.p.m.)**

**11.5** An 8 pole, 50 Hz induction motor has a slip of 2% on no load. On full load, the slip is 5%. Find the change in speed from no load to full load. **(22.5 r.p.m.)**

**11.6** An 8 pole, three phase alternator is coupled to an engine running at 750 r.p.m. and supplies a three phase induction motor having a full load speed of 1,440 r.p.m. The frequency of the rotor current is 2 Hz. Find the percentage slip and the number of poles of the motor. **(4%, 4)**

**11.7** A 4 pole, three phase induction motor runs at 1,470 r.p.m., when connected to a 50 Hz supply. Find the percentage slip and the frequency of the rotor currents. **(2%, 1 Hz)**

**11.8** An 8 pole, three phase induction motor is supplied at 50 Hz and the frequency of the e.m.f. induced in the rotor is 2 Hz. Find the slip and speed of the motor. **(0.04, 720 r.p.m.)**

## QUESTION BANK

1. Mention the advantages and disadvantages of a three phase induction motor.
2. With neat figures, give the constructional details of a three phase induction motor.
3. How are three phase induction motors classified? Give the constructional details of their rotors.
4. Show that a rotating magnetic field is produced, when a three phase balanced supply is given to the stator winding of a three phase induction motor.
5. Explain clearly the working principle of a three phase induction motor.
6. Define slip of an Induction motor and derive the relation between the supply frequency and rotor current frequency.
7. Mention the advantages and disadvantages of squirrel cage and slip ring induction motors.
8. Explain why a starter is required for a three phase induction motor. With a circuit diagram, explain the working of a star - delta starter for a three phase induction motor.