Module 5

Three Phase Induction Motors 8

Syllabus :

Construction, Working principle, Squirrel cage rotor and Phase wound rotor, Production of rotating magnetic field and Slip.

8.1 Introduction :

- The **induction motors** are basically **ac motors** i.e. they need an alternating voltage for their operation.
- **They can operate on either single phase or three phase ac supply**, however the single phase induction motors find very limited area of applications.
- In almost 85% applications the three phase induction motors are preferred.
- Depending on the type of rotor, the induction motor are classified into two types. Slip ring induction motors and squirrel cage induction motors.
- In this chapter, the principle of operation, electrical characteristics and torque-speed characteristics of three phase induction motor are discussed.

8.2 Induction Motor Windings :

- The three phase induction motor has **two windings** :
  1. Stator winding.
  2. Rotor winding.
- The stator winding is a 3 phase delta or star connected winding which is connected to the three phase ac supply.
- Rotor winding is a rotating winding which is mounted on the shaft of the induction motor.

8.3 Construction of Induction Motor :

- Basically induction motor consists of two main parts (i) the stationary frame called **stator** and (ii) the rotating armature called **rotor**
- Fig. 8.3.1(a) shows the stator and rotor.
- Similar to stator, the rotor drum is provided with slots.

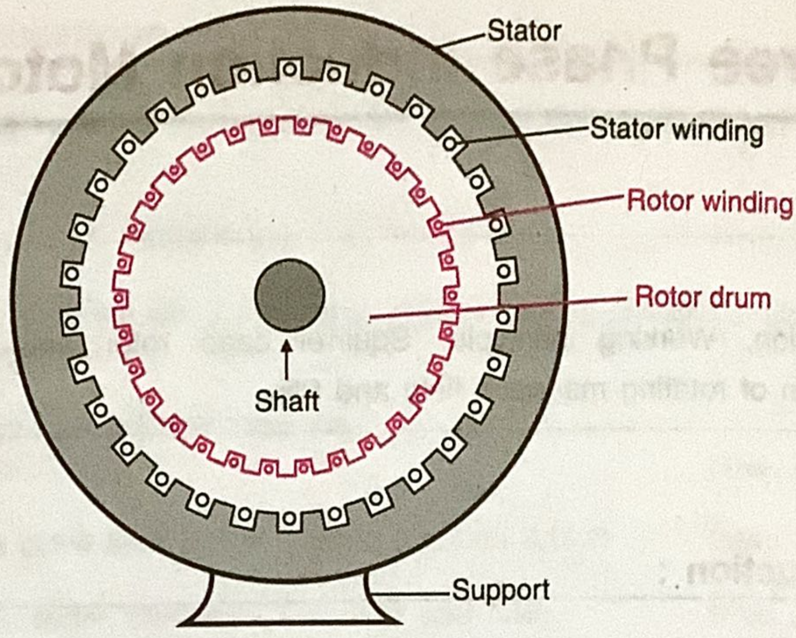


Fig. 8.3.1(a)

- The stator is a stationary winding which can be a star connected or delta connected and connected to the 3-phase ac supply through a switch as shown in Fig. 8.3.1(b).
- The function of stator winding is to produce a rotating magnetic field in the air gap between the stator and rotor.
- Rotor is the rotating winding.
- The rotor is not connected to any external supply. The current flows through the rotor due to the principle of induction. Hence the name induction motor.
- Rotors can be of two types namely squirrel cage rotors and wound rotors.

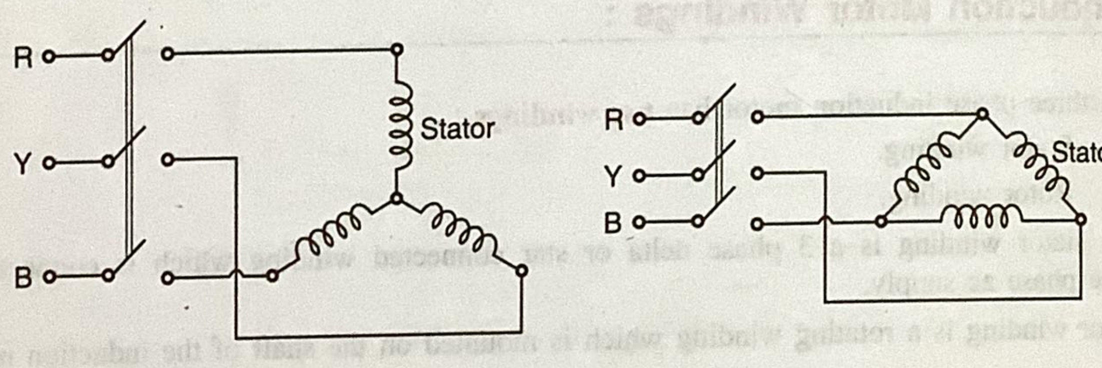
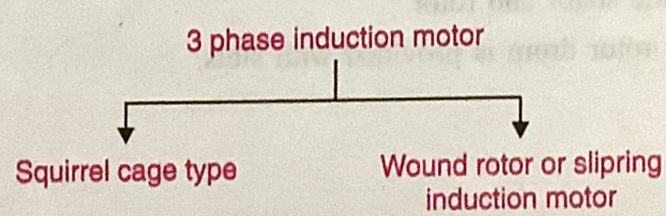


Fig. 8.3.1(b) : Stator winding connections

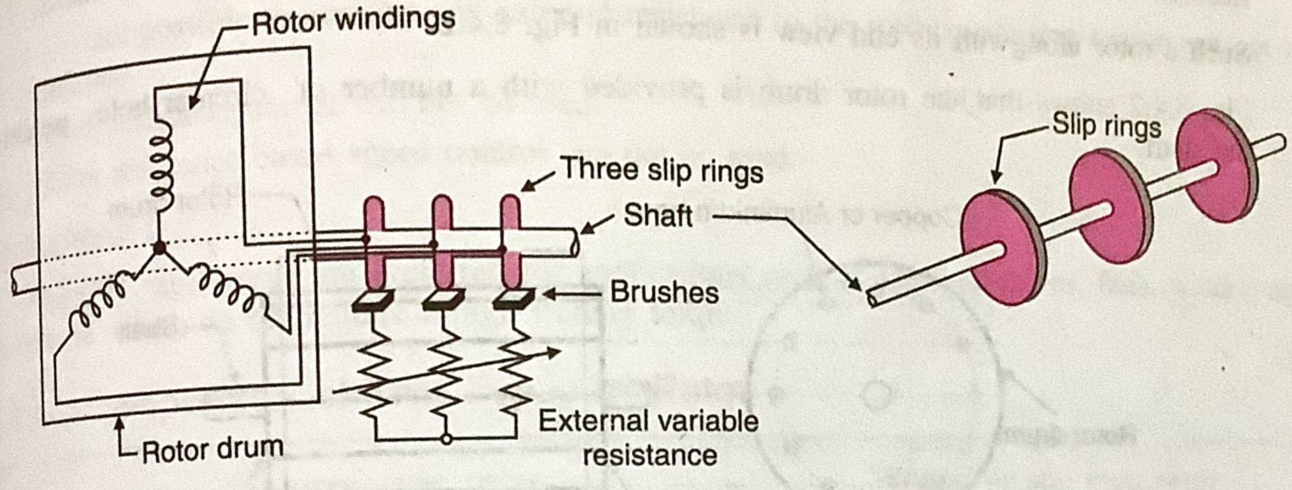
8.4 Types of Induction Motor :

Depending on the type of rotor used, the induction motors are classified into two categories.



8.4.1 Wound Rotor or Slip Ring Type Rotor :

- Fig. 8.4.1(a) shows the construction of wound rotor or slip-ring induction rotor.



(a) **Construction of slipring rotor or a wound rotor** (b) **Sliprings**

Fig. 8.4.1

- The rotor winding is connected in the star connection like a normal three phase star connected transformer.
- Fig. 8.4.1(a) shows that alongwith the rotor drum, the motor shaft also carries three sliprings which are circular in shape and rotate at the same speed as that of the rotor.
- The rotor winding terminals are permanently connected to these sliprings.
- The sliprings are continuously in contact with three brushes which pressed against the sliprings.
- Many a times an external resistance is necessary to be connected in the rotor resistance. So a variable resistance is connected in the rotor winding.
- Such an external resistance is essential to develop a high starting torque.
- Thus external resistance can be added through the combination of sliprings and brushes.
- In other words the rotor is accessible to the user due to the use of sliprings and brushes.

Disadvantages of slip ring rotor :

1. More wear and tear so frequent maintenance.
2. Increased loss in rotor so reduced efficiency.
3. Poor p.f. at full load.
4. Needs a rotor resistance starter.
5. Low pull out torque.

Advantages of slip ring rotor :

1. External resistance can be connected to rotor. So it is possible to adjust the starting torque.
2. High starting torque can be obtained.
3. Speed control using rotor resistance control is possible to achieve.

Applications :

Slip ring rotors are preferred for applications such as cranes, elevators, lifts, compressors etc. which need high starting torque.

8.4.2 Squirrel Cage Rotor :

- When higher starting torque is not the requirement, the rotor is constructed in a very simple manner.
- Such a rotor alongwith its end view is shown in Fig. 8.4.2.
- Fig. 8.4.2 shows that the rotor drum is provided with a number of circular holes, parallel to the shaft.

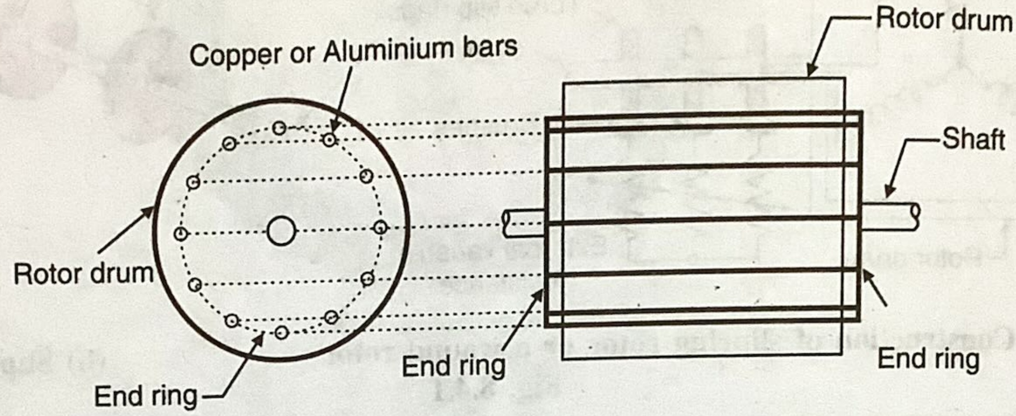


Fig. 8.4.2

- Solid copper or aluminium bars are placed in these holes and all these bars are welded to two end rings to establish electrical contact between them.
- For clarity end ring is shown by a dotted line in the elevation.
- The bars and the end rings together look like a cage and hence such a rotor is called a **cage rotor or a squirrel cage rotor.**
- Note that due to short circuiting of rotor bars, the rotor assembly is not accessible to the user.
- No external connections can be made to the cage type rotor, therefore it is not possible to conneet any external resistance to the rotor.

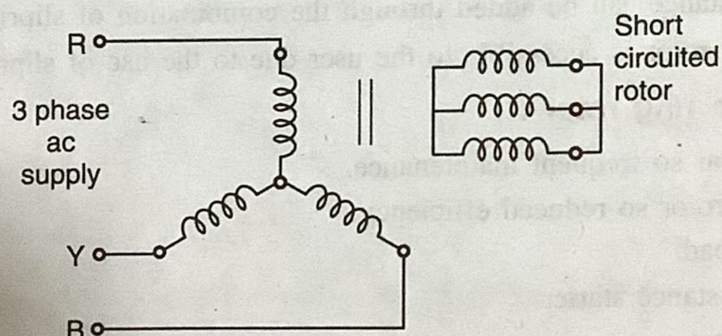


Fig. 8.4.3 : Schematic diagram of squirrel cage I. M.

Advantages of squirrel cage rotor :

1. Simple construction.
2. Frequent maintenance is not required since sliprings and brushes are absent.
3. Less rotor copper loss so high efficiency.

Disadvantages :

1. Small starting torque.
2. It is not possible to connect any external resistance to the rotor so starting torque can not be adjusted.
3. Rotor resistance starter can not be used.
4. Rotor resistance based speed control can not be used.

Applications :

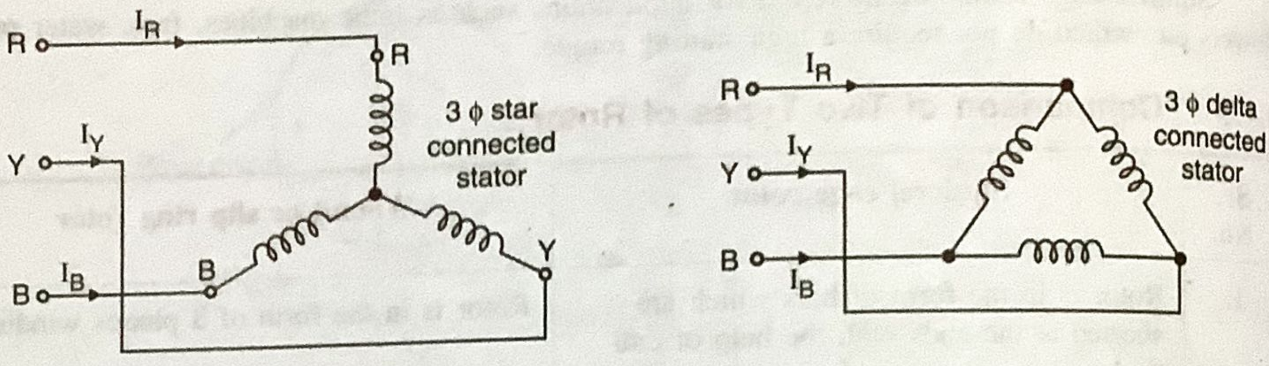
Squirrel cage rotors are preferred for applications such as lathe machines, fans, water pumps, blowers etc. which do not require a high starting torque.

8.4.3 Comparison of Two Types of Rotor :

Sr. No.	Squirrel cage rotor	Wound or slip ring rotor
1.	Rotor is in the form of bars which are shorted at the ends with the help of end rings.	Rotor is in the form of 3 phases winding.
2.	No slip rings or brushes.	Slip rings and brushes are used.
3.	Simple construction.	Construction is complicated.
4.	External resistances can not be connected.	It is possible to connect the external resistance to the rotor.
5.	Small or moderate starting torque.	High starting torque can be obtained.
6.	Starting torque can not be adjusted.	Starting torque can be adjusted by adjusting the external resistance.
7.	Frequent maintenance is not required due to absence of sliprings and brushes.	Frequent maintenance is necessary due to the use of sliprings and brushes.
8.	Rotor resistance starter can not be used.	Rotor resistance starter can be used.
9.	Speed control using rotor resistance control can not be used.	Speed control using rotor resistance control is possible to achieve.
10.	Less rotor copper loss.	High rotor copper loss.
11.	Higher efficiency.	Low efficiency.
12.	Applications include lathes, fans, water pumps, blowers etc.	Applications include cranes, elevators, compressors, lifts etc.

8.5 Rotating Magnetic Field (RMF) :

- The induction motor operates on the principle of **rotating magnetic field (RMF)** which is produced by the stator winding of the induction motor in the air gap between the stator and the rotor.
- The stator is a three phase stationary winding which can be either star connected or delta connected, as shown in Fig. 8.5.1.



(a) Star connected stator **(b) Delta connected stator**

Fig. 8.5.1 : Stator windings

- Whenever the ac supply is connected to the stator windings, line currents I_R, I_Y and I_B start flowing. Note that these line currents are phase shifted by 120° with respect to each other.
- Due to each line current a sinusoidal flux is produced in the air gap. These fluxes have the same frequency as that of the line currents i.e. 50 Hz and they also are 120° phase shifted with respect to each other.
- Let the flux produced by the line current I_R be ϕ_R, that produced by I_Y be ϕ_Y and that produced by I_B be ϕ_B.
- Mathematically they are represented as follows :

$$\phi_R = \phi_m \sin \omega t = \phi_m \sin \theta \quad \text{...(8.5.1)}$$

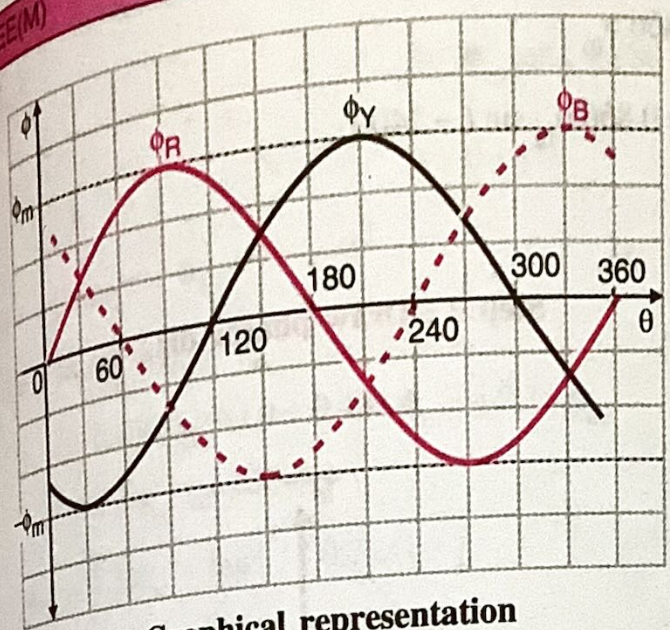
$$\phi_Y = \phi_m \sin(\omega t - 120^\circ)$$

$$= \phi_m \sin(\theta - 120^\circ) \quad \text{...(8.5.2)}$$

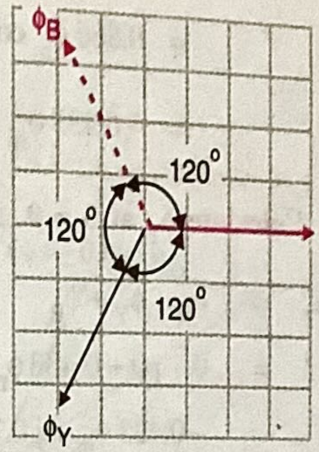
and $$\phi_B = \phi_m \sin(\omega t - 240^\circ)$$

$$= \phi_m \sin(\theta - 240^\circ) \quad \text{...(8.5.3)}$$

- These fluxes are represented graphically in Fig. 8.5.2(a) and using the phasors in Fig. 8.5.2(b).



(a) Graphical representation



(b) Phasor diagram

Fig. 8.5.2 : Representation of fluxes produced by the line currents I_R, I_Y and I_B

8.5.1 Production of RMF :

- The effective or total flux (ϕ_T) in the air gap between the stator and rotor is equal to the phasor sum of the three component fluxes ϕ_R, ϕ_Y and ϕ_B.

$$\therefore \ \bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B \qquad ...(8.5.4)$$

- In order to prove that a RMF is set up in the air gap, we will follow the steps given below :

Steps to be followed :

Step 1 :	At different values of θ such as 0, 60, 120, 180, ... 360° obtain the value of total flux ϕ_T.
Step 2 :	For every value of θ in step 1, draw the phasor diagrams to prove that ϕ_T is a rotating quantity.

- Let us use the phasor ϕ_R as the reference phasor i.e. all the angle are expressed and drawn with respect to this phasor.

ϕ_T at $\theta = 0^\circ$

- At $\theta = 0^\circ$ in Fig. 8.5.3(a), the component fluxes are represented as follows :

$$\phi_R = \phi_m \sin 0 = 0 = 0 + j\,0$$

$$\phi_Y = \phi_m \sin(0 - 120)$$

$$= -0.866\,\phi_m \angle -120^\circ$$

$$= -0.866\,\phi_m \cos(-120) - j\,0.866\,\phi_m \sin(-120)$$

$$= 0.433\,\phi_m + j\,0.75\,\phi_m$$

$$\text{and} \quad \phi_B = \phi_m \sin(0-240) = 0.866\,\phi_m$$

$$= 0.866\,\phi_m \cos(-240) + j\,0.866\,\phi_m \sin(-240)$$

$$= -0.433\,\phi_m + j\,0.75\,\phi_m$$

Step 1 : Calculate ϕ_T at $\theta = 0^\circ$:

$$\bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B$$

$$= 0 + j\,0 + 0.433\,\phi_m + j\,0.75\,\phi_m$$

$$-0.433\,\phi_m + j\,0.75\,\phi_m$$

$$\therefore \phi_T = 0 + j\,1.5\,\phi_m$$

$$= \sqrt{0^2 + (1.5\,\phi_m)^2} \angle \tan^{-1}\left(\frac{1.5}{0}\right)$$

$$\therefore \phi_T = \underbrace{1.5\phi_m}_{\text{Magnitude of } \phi_T = 1.5\phi_m} \angle \underbrace{\pm 90^\circ}_{\phi_T \text{ leads reference by } \pm 90^\circ}$$

The phasor diagram is shown in Fig. 8.5.3(a).

It shows that at $\theta = 0^\circ$, ϕ_T leads ϕ_R by 90°.

Step 2 : Draw phasor diagram at $\theta = 0^\circ$:

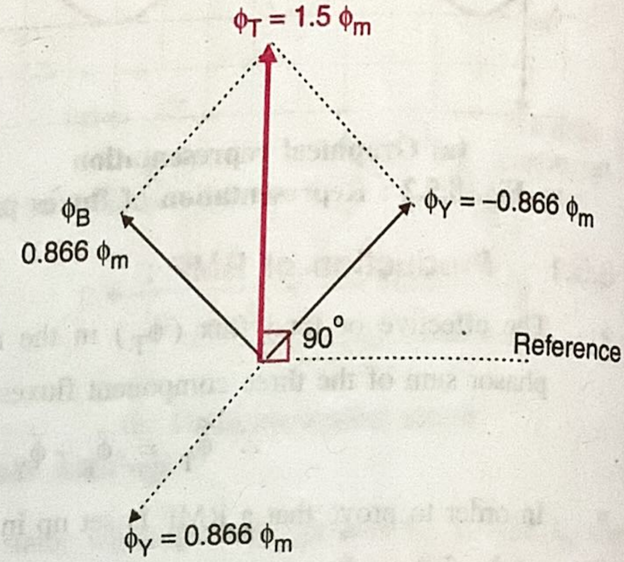


Fig. 8.5.3(a) : ϕ_T at $\theta = 0^\circ$

$\boxed{\phi_T \text{ at } \theta = 60^\circ}$

- At $\theta = 60^\circ$ the component fluxes are given by,

$$\phi_R = \phi_m \sin(60^\circ) = 0.866\,\phi_m \angle 0^\circ$$

$$= 0.866\,\phi_m \cos 0 + j\,0.866\,\phi_m \sin 0$$

$$= 0.866\,\phi_m + j\,0$$

$$\phi_Y = \phi_m \sin(60-120)$$

$$= \phi_m \sin(-60)$$

$$= -0.866\,\phi_m \angle -120^\circ$$

$$= -0.866\,\phi_m \cos(-120) - j\,0.866\,\phi_m \sin(-120)$$

$$= 0.433\,\phi_m + j\,0.75\,\phi_m$$

$$\phi_B = \phi_m \sin(60-240)$$

$$= \phi_m \sin(-180^\circ) = 0\angle -240^\circ$$

$$= 0 + j\,0$$

Step 1 : Calculate ϕ_T at $\theta = 60^\circ$:

$$\bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B$$

$$= 0.866\,\phi_m + j\,0 + 0.433\,\phi_m + j\,0.75\,\phi_m$$

$$= 1.3\,\phi_m + j\,0.75\,\phi_m$$

$$\therefore \quad \phi_T = 1.5\,\phi_m \angle \tan^{-1}[0.75/1.3]$$

$$\therefore \phi_T = \underbrace{1.5\phi_m}_{\text{Magnitude of } \phi_T = 1.5\phi_m} \angle \underbrace{+30^\circ}_{\phi_T \text{ leads reference by } 30^\circ}$$

Step 2 : Phasor diagram at $\theta = 60^\circ$:

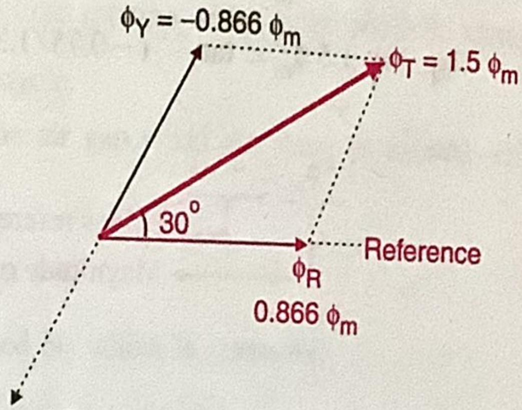


Fig. 8.5.3(b) : ϕ_T at $\theta = 60^\circ$

It shows that at $\theta = 0^\circ$, ϕ_T leads by 30°. The phasor diagram is shown in Fig. 8.5.3(b).

$\boxed{\phi_T \text{ at } \theta = 120^\circ}$

- At $\theta = 120^\circ$ the component fluxes are given by,

$$\phi_R = \phi_m \sin(120^\circ)$$

$$= 0.866\,\phi_m \angle 0^\circ = 0.866\,\phi_m + j\,0$$

$$\phi_Y = \phi_m \sin(120 - 120) = 0$$

$$= 0 + j\,0$$

$$\phi_B = \phi_m \sin(120 - 240)$$

$$= \phi_m \sin(-120)$$

$$= -0.866\,\phi_m \angle -240^\circ$$

$$= -0.866\,\phi_m \cos(-240) - j\,0.866\,\phi_m \sin(-240)$$

$$= 0.433\,\phi_m - j\,0.75\,\phi_m$$

Step 1 : Calculate ϕ_T at $\theta = 120^\circ$:

$$\bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B$$
$$= 0.866\,\phi_m + j\,0 + 0.433\,\phi_m - j\,0.75\,\phi_m$$
$$= 1.3\,\phi_m - j\,0.75\,\phi_m$$
$$\therefore \quad \phi_T = 1.5\,\phi_m \angle \tan^{-1}(-0.75/1.3)$$

$$= \underbrace{1.5\phi_m}_{\text{Magnitude of } \phi_T \text{ is } 1.5\phi_m} \underbrace{\angle -30^\circ}_{\phi_T \text{ lags reference by } 30^\circ}$$

Step 2 : Phasor diagram at $\theta = 120^\circ$:

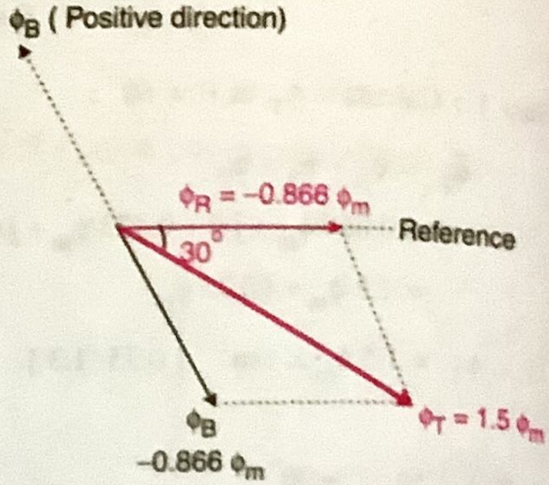


Fig. 8.5.3(c) : ϕ_T at $\theta = 120^\circ$

- It shows that at $\theta = 120^\circ$, ϕ_T lags by 30°. The phasor diagram for $\theta = 120^\circ$ is shown in Fig. 8.5.3(c).

$\boxed{\phi_T \text{ at } \theta = 180^\circ}$

- Similarly we can prove that ϕ_T at $\theta = 180^\circ$ is given by,

$$\phi_T = 1.5\,\phi_m \angle -90^\circ$$

- The phasor diagram for $\theta = 180^\circ$ is shown in Fig. 8.5.3(d).

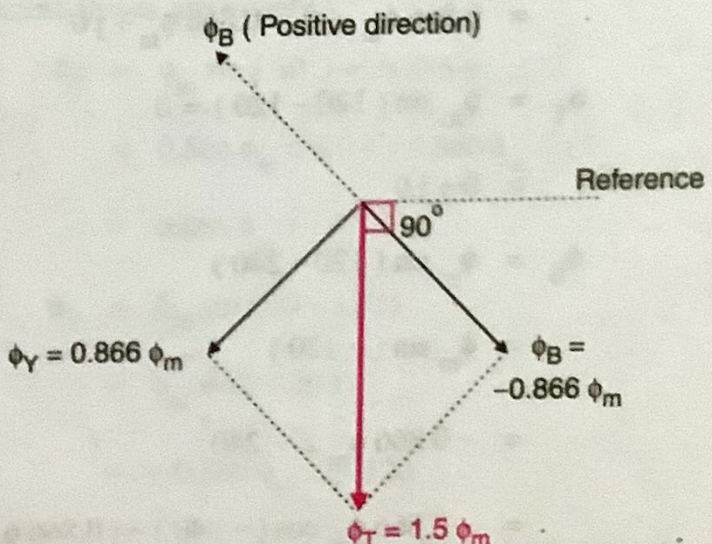


Fig. 8.5.3(d) : ϕ_T at $\theta = 180^\circ$

- Thus ϕ_T keeps shifting its position from 90° to 30° to -30° to -90° and so on. In other words ϕ_T rotates in the clockwise direction in space.

Conclusions

- From the discussion held till now and by referring to the phasor diagrams of Fig. 8.5.3(a) through Fig. 8.5.3(d) we can draw the following conclusions.

1. The magnitude of ϕ_T at any value of θ from 0° to 360°.
2. ϕ_T rotates in the clockwise direction in space. One rotation of ϕ_T corresponds to change in θ from 0 to 360° i.e. corresponding to one cycle.

- In this way we get the rotating magnetic field in the air gap when the stator is excited with a $3\,\phi$ supply. The amplitude of RMF is constant.

8.5.2 Speed of RMF (Synchronous Speed) :

The RMF rotates at a speed called synchronous speed N_s which is given by,

$$N_s = \frac{120\, f_1}{P} \text{ RPM} \qquad ...(8.5.5)$$

where f_1 = Frequency of the stator supply

P = Number of poles of the motor.

8.5.3 Direction of RMF :

- The direction of RMF depends on the phase sequence of the ac supply being connected to the stator winding.
- As we have proved, the RMF rotates in the clockwise direction if the phase sequence is R,Y, B i.e. the normal sequence as shown in Fig. 8.5.4(a).

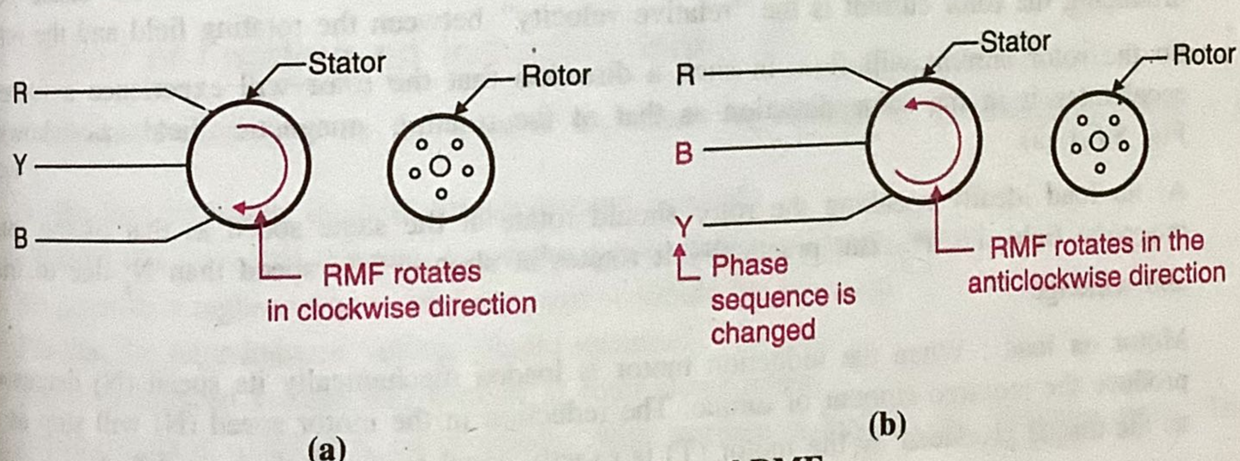


Fig. 8.5.4 : Direction of RMF

- But if we interchange any two phases of the ac supply to get a new phase sequence say R, B, Y then the direction of RMF will reverse. It will start rotating in the anticlockwise direction as shown in Fig. 8.5.4(b).
- The direction of motor can be reversed by reversing the direction of RMF.

8.6 Principle of Operation :

- The three phase stator winding of induction motor is connected to the three phase ac supply as shown in Fig. 8.6.1(a).

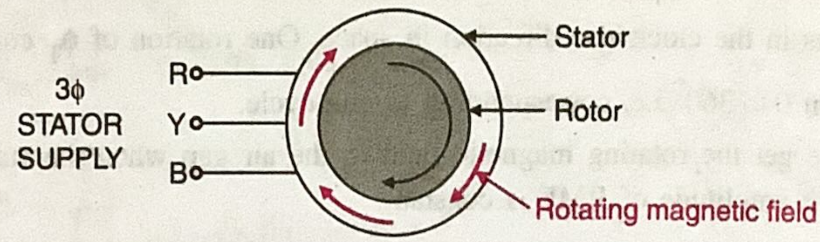


Fig. 8.6.1(a) : Principle of operation of induction motor

- Due to ac voltage applied, current starts flowing in the stator conductors.
- Due to the three phase stator current a rotating magnetic field of constant amplitude and rotating at a constant speed is set up in the air gap between stator and rotor. (see Fig. 8.6.1(a)).
- The rotating magnetic field rotates at a speed called as Synchronous Speed (N_s). The synchronous speed $N_s = \frac{120 f_1}{P}$ where f_1 = stator supply frequency and P = Number of poles of the motor.
- The rotor winding is still stationary. So the rotating magnetic field cuts the stationary rotor conductors and induces an emf in the rotor winding.
- The rotor induced voltage gives rise to rotor currents. The direction of the rotor current is such that it will oppose the very cause that produces the current. And the cause behind producing the rotor current is the "relative velocity" between the rotating field and the rotor.
- So the rotor current will flow in such a direction that the rotor will experience a force that accelerates it in the same direction as that of the rotating magnetic field as shown in Fig. 8.6.1 (a).
- At no load ideally speaking the rotor should rotate at the same speed as that of the rotating magnetic field. i.e. N_s. But practically it rotates at slightly less speed than N_s due to friction and windage.
- Motor on load : When the induction motor is loaded mechanically its speed (N) decreases to produce the required amount of torque. The reduction in the motor speed (N) will stop as soon as the torque produced by the motor (T) is exactly equal to the load torque (T_L).
- The percentage difference between the synchronous speed (N_s) and the actual speed (N) is known as slip (s).

$$s = \frac{N_s - N}{N} \quad ...(8.6.1)$$

- The stator winding of the induction motors can be either star connected or delta connected.

8.6.1 Direction of Rotation :

- As the rotor always rotates in the same direction as that of the rotating magnetic field, the only way to reverse the direction of rotation of motor is to reverse the direction of rotating field.
- To do so the phase sequence has to be changed by interchanging any two phases as shown in Fig. 8.6.1 (b).

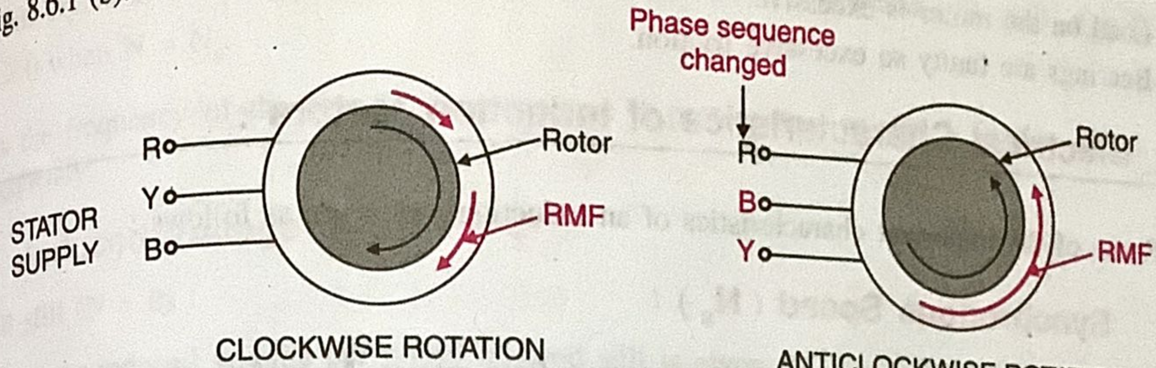


Fig. 8.6.1(b) : Direction reversal of induction motor

8.6.2 Can the Actual Speed or Slip Speed N be Equal to N_s ?

- Ideally the rotor speed should be equal to the synchronous speed if the mechanical load is zero.
- But practically N is never equal to N_s. In fact N is always less than N_s.
- The reason for this is that as soon as $N = N_s$, the relative velocity between the RMF and rotor becomes zero. Hence the induced current in the rotor becomes zero. So the torque produced by the motor will be zero, and the motor slows down.
- This happens everytime when N tends to become equal to N_s. Therefore the rotor can not rotate at synchronous speed.

8.7 Effect of Loading on Induction Motor :

As the mechanical load on the rotor is increased, the reaction of the induction motor is as follows :

1. As the load increases, the load torque demand increases.
2. To meet this increased demand, the motor has to produce a larger torque.
3. To generate a higher torque, the rotor current should be increased.
4. For that the rotor induced voltage should increase.
5. The rotor induced voltage will increase if rotor slows down.
6. Hence the rotor speed goes on decreasing with increase in load on the induction motor. This is the effect of loading on an induction motor.

How long does the motor speed decrease ?

- The motor speed decreases as long as the motor torque is less than the load torque.
- As soon the motor torque is equal to the load torque, an equilibrium is reached and the speed stops decreasing.
- The motor speed will stabilize to a new lower speed.

8.7.1 Possible Reasons for Motor Fail to Start :

Various possible reasons for motor failing to start are as follows :

1. The supply voltage may be too low.
2. Only two phases are on.
3. One or more input fuses may be open (blown).
4. Load on the motor is excessive.
5. Bearings are faulty so excessive friction.

8.8 Electrical Characteristics of Induction Motors :

Some of the important characteristics of an induction motor are as follows :

8.8.1 Synchronous Speed (N_s) :

- It is the speed at which the rotating magnetic field rotates. N_s is dependent only on the stator frequency f_1 and number of poles P.
- If the number of poles P is constant then the only way to change the synchronous speed is to change the stator frequency f_1.

$$N_s = \frac{120\, f_1}{P} \quad ...(8.8.1)$$

- Equation (8.8.1) shows that the speed of induction motor can be varied by varying the stator frequency.

8.8.2 Slip s :

- On loading, the induction motor slows down to produce required torque.
- The difference between the synchronous speed (N_s) and the actual motor speed (N) is indicated by the slip "s".
- The percent slip is defined as,

$$\% s = \frac{N_s - N}{N_s} \times 100 \% \quad ...(8.8.2)$$

or

$$s = \frac{\omega_s - \omega}{\omega_s} \times 100 \% \quad ...(8.8.3)$$

- The actual speed N can be expressed in terms of s as,

$$N = N_s (1 - s) \quad ...(8.8.4)$$

- The value of slip will vary between 0 and 1 for the motoring operation. At stand still $N = 0$ hence $s = 1$ whereas at $N = N_s$, $s = 0$.
- The slip will be greater than 1 for plugging and the slip will be negative for the induction motor to operate as a generator.

8.8.3 Frequency of Rotor Induced emf (f_r) : (Slip Frequency)

- A three phase voltage is induced in the rotor winding, due to the relative velocity between rotor and RMF (rotating magnetic field). The frequency of this voltage is dependent on slip s.

$$f_r = s f_1 \qquad ...(8.8.5)$$

- From Equation (8.8.5), $f_r = f_1$ when $s = 1$ i.e. when $N = 0$, at stand still and $f_r = 0$ when $s = 0$ when $N = N_s$.
- As the frequency of the rotor induced voltage is proportional to slip, it is also called as slip frequency.

8.8.4 Induced Voltage in the Rotor :

At stand still (N = 0) :

- The rotor induced voltage per phase at stand still is given by,

$$E_2 = \frac{N_2}{N_1} E_1 \qquad ...(8.8.6)$$

where N_2 = Number of rotor turns per phase

N_1 = Number of stator turns per phase

E_1 = stator voltage per phase.

- Equation (8.8.6) is very similar to that of a transformer where the secondary voltage is proportional to the turns ratio of the windings.

8.9 Torque-Slip Characteristics of Induction Motor :

The torque-slip or torque-speed characteristics of an induction motor is as shown in Fig. 8.9.1. The characteristic can be divided into three sections :

(i) Forward motoring.

(ii) Plugging and

(iii) Regeneration.

Forward motoring :

- The forward motoring region corresponds to the values of slip between 0 and 1.
- In the forward motoring region of the characteristics shown in Fig. 8.9.1, the motor rotates in the same direction as that of rotating magnetic field.
- The torque produced by the motor is zero at synchronous speed or for s = 0. This is because the induced voltage in rotor is zero when $N = N_s$.
- The torque increases as the slip increases while the air gap flux remains constant.
- Once the torque reaches its maximum value T_{max}, at the critical slip $s = s_m$, the torque decreases, with increase in slip due to reduction in air gap flux.

Stable region of operation :

- In the forward motoring region ($0 \le s \le 1$) of the torque-speed characteristic of Fig. 8.9.1, the region of ($0 \le s \le s_m$) is said to be a stable region of operation and the operating point of the motor should be in this region of the characteristic.
- This is stable region because in this region with increase in the torque demand, the motor speed decreases.
- The region of ($s_m \le s \le 1$) is unstable region as in this region with increase in torque the speed of the motor increases.

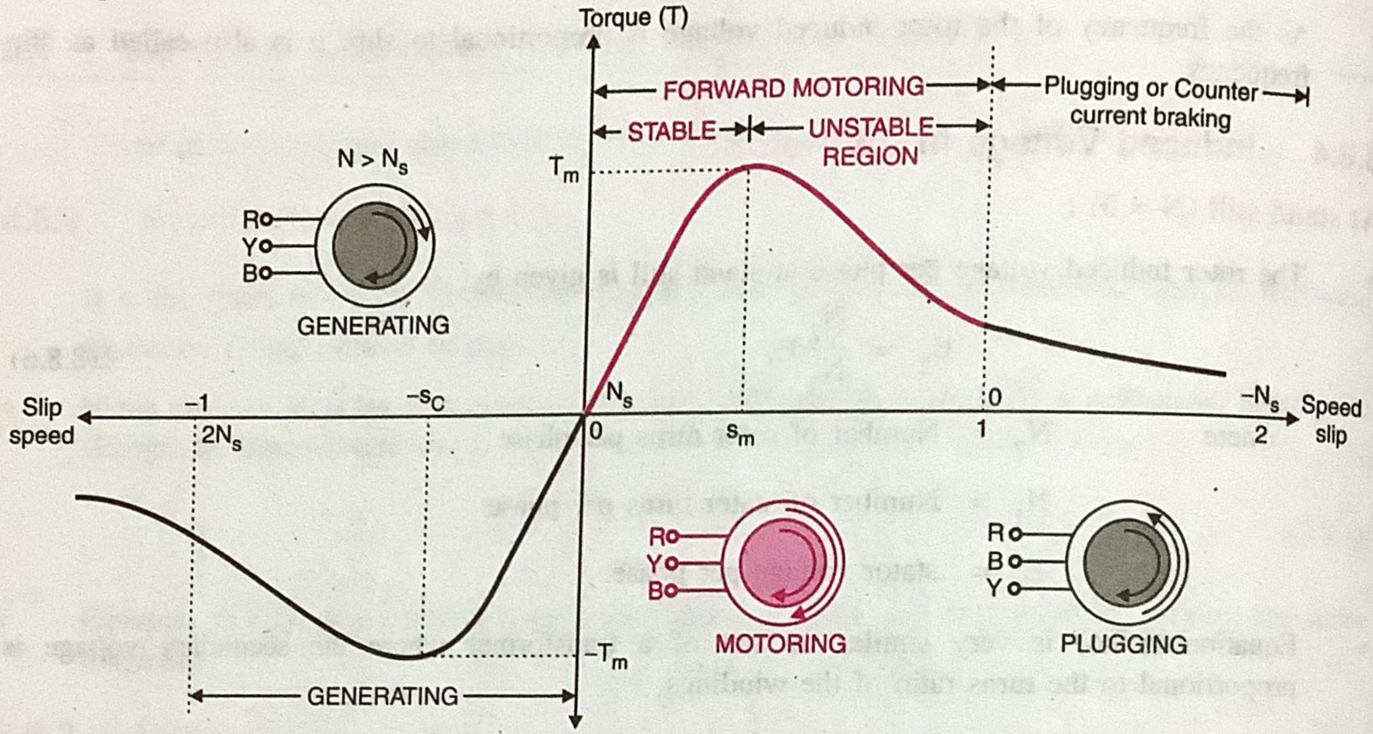


Fig. 8.9.1 : Torque-speed characteristics of induction motor

Generating region :

- For the generating region, the slip needs to be negative and between 0 and -1 as shown in Fig. 8.9.1.
- The slip will be negative if and only if the rotor speed N is higher than the synchronous speed Ns. However rotor and rotating magnetic field both rotate in the same direction.

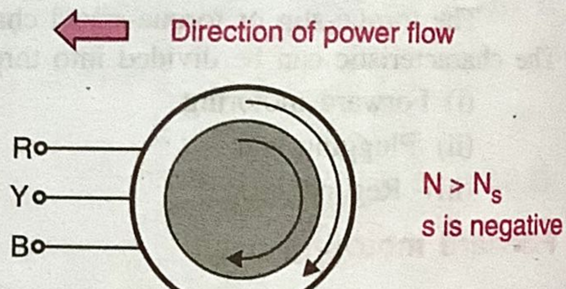


Fig. 8.9.2 : Generating mode

- To torque produced is in the opposite direction to that of the motoring mode so it is shown to be negative.
- On this region, the motor acts as a generator, and returns the power back to the ac source as shown in Fig. 8.9.2. Maximum torque in the generating mode is obtained at a slip $s = -s_m$.

Plugging or counter current braking :

- As shown in Fig. 8.9.1, the motor operates in the plugging or counter current braking mode for values of $s > 1$.

But $s = \frac{N_s - N}{N_s}$ therefore to get values of $s > 1$, N must be negative i.e. N_S and N must have opposite directions i.e. the RMF (rotating magnetic field) and rotor should rotate in opposite directions.

- This is achieved by interchanging any two phases of the stator supply as shown in Fig. 8.9.3.
- The motor is already rotating therefore due to inertia it continues to rotate in the same direction.

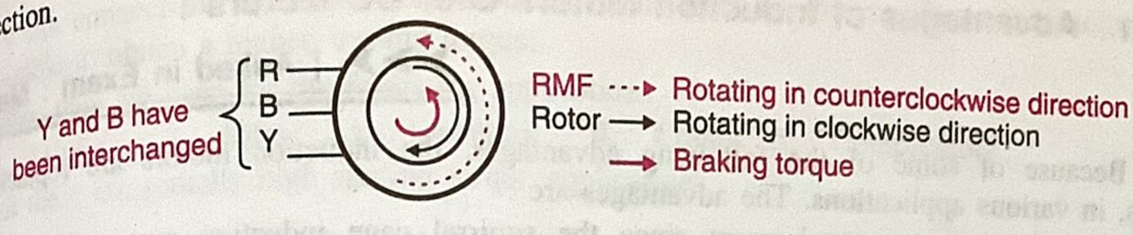


Fig. 8.9.3 : Plugging or counter current braking

- The motor current is high and motor heating takes place in this mode of operation. This is a major disadvantage of plugging.
- The advantage of plugging is the high braking torque produced by the rotor current.

Why the name counter current braking ?

The name of this type of braking is counter current braking because the braking takes place due to a torque which is produced by a current which flows in the opposite direction to that in the normal motoring operation.

8.9.1 Pull Out Torque or Breakdown Torque :

- The maximum torque T_m obtained at $s = s_m$ is also called as the pull out torque or breakdown torque.
- If the load torque increases beyond the pull out torque then the induction motor will be pushed into the unstable region and will finally come to a stand still.

8.10 Reversal of Direction of Rotation :

- We have already mentioned that, the direction of rotation of a rotor is same as that of the direction of rotating magnetic field.
- Hence if the rotating magnetic field is reversed. Then the direction of motor can be reversed.
- Two of the three phases should be interchanged to reverse the direction of rotation.
- Fig. 8.10.1 shows the arrangement for reversing the direction of the induction motor.

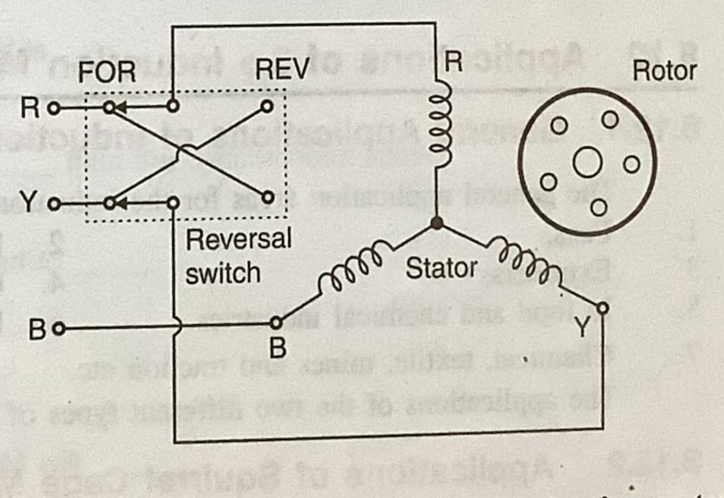


Fig. 8.10.1 : Direction reversal of an induction motor

- When the reversal switch is in the "FOR" i.e. forward direction, the phase sequence is normal i.e. R, Y, B.

- But when the switch is thrown in the "REV" i.e. reverse direction, the R and Y phases get interchanged, making the phase sequence Y, R, B.
- This will reverse the RMF (Rotating Magnetic Field) and hence will reverse the motor direction.

8.11 Advantages and Disadvantages :

8.11.1 Advantages of Induction Motors over DC Motors :

>>> [Asked in Exam : May 05 !!!]

Because of some of the following advantages, the induction motors are replacing the dc motors, in various applications. The advantages are :

1. Low maintenance requirement since the squirrel cage induction motor does not use the commutators and brushes.
2. Ruggedness, smaller size and weight.
3. Low cost.
4. They can operate in dusty and explosive environments, because the brushes are not being used. Therefore there is no possibility of sparking.
5. They can operate at higher speeds, of the order of 12,000 RPM. This is again possible as the brushes are absent so no friction.
6. Its torque-speed characteristics is similar to d.c. shunt motor characteristics. So it runs at almost constant speed at all loads with the speed decreasing slightly with increase in speed.
7. It can produce sufficient torque.
8. Speed control by using thyristors can give a wide range of speeds.

8.11.2 Disadvantages of Induction Motors :

1. As will be explained later on, the efficiency of induction motors varies with speed.
2. In induction motors the flux and armature (stator) current cannot be controlled separately, as there is only stator winding and rotor is not accessible for the user.
3. Low starting torque.
4. Lagging and low power factor.
5. Speed control by electrical methods is not easy.

8.12 Applications of 3 ϕ Induction Motor :

8.12.1 General Applications of Induction Motor :

The general application areas for the induction motors are as follows :

1. Fans,
2. Pumps,
3. Extruders,
4. Conveyors,
5. In food and chemical industries,
6. Paper and sugar industries etc.
7. Chemical, textile, mines and traction etc.

The applications of the two different types of induction motors have been listed below.

8.12.2 Applications of Squirrel Cage Motors :

- The squirrel cage motors have small or moderate starting torques and it is not possible to use external rotor resistances for increasing the starting torque.

- These are constant speed motor.
- So these motors are preferred for the following applications.
  1. Fans and blowers
  2. Grinders
  3. Drilling machines
  4. Blowers and water pumps
  5. Lathe machines
  6. Printing machines.

8.12.3 Applications of Slip Ring Induction Motors :

- We can connect the external rotor resistance to the rotor of slip ring induction motor. So it is possible to obtain a higher starting torque.
- Hence they are used for the following applications
  1. Hoist 2. Lifts 3. Elevators 4. Cranes 5. Compressors.

All these are actually high starting torque applications.

8.13 Comparison of AC and DC Motors :

Table 8.13.1

Sr. No.	Parameter	DC motors	AC motors
1.	Supply	DC	AC
2.	Maintenance	Frequent	Less frequent
3.	Speed	Low	High
4.	Size and weight	Large	Small
5.	Speed control	Rheostatic control, field control	Stator voltage control, stator frequency contorl.
6.	Applications	Lathe machine, drilling and milling machines, printing machinary, paper machinary, pumps, blowers and fans.	Fans, pumps, extruders, conveyors, in paper and sugar industries, traction, chemical and textile industry.

Review Questions

Short Answer Questions :

Q. 1 The speed of RMF is called as ______.

Ans. : synchronous speed.

Q. 2 The expression for synchronous speed is ______.

Ans. : $N_s = 120 f_1 / P$.

Q. 3 The actual speed of IM is always ______ than the synchronous speed.

Ans. : less.

Q. 4 The value of slip at synchronous speed is ______.

Ans. : 0.

Q. 5 The value of slip at starting is ______.

Ans. : 1.

Q. 6 On mechanical loading the speed of IM will ______.

Ans. : decrease.

Q. 7 For the generator operation, the slip should be ______.

Ans. : negative.

Q. 8 The value of slip should be _____ for plugging.

Ans. : between 1 and 2.

Q. 9 The __________ operates on the principle of rotating magnetic field (RMF).

Ans. : induction motor.

Q. 10 The direction of RMF depends on the __________ of the ac supply being connected to the stator winding.

Ans. : phase sequence.

Q. 11 The _____ is a stationary winding which can be a star connected or delta connected

Ans. : stator.

Q. 12 The parameters like supply frequency, supply voltage, number of poles or external stator resistance can be controlled on the _____ side for controlling the speed.

Ans. : stator.

Q. 13 _____ of the _____ phases should be interchanged to reverse the direction of rotation.

Ans. : Two, three.

Q. 14 The __________ motors have small or moderate starting torques and it is not possible to use external rotor resistances for increasing the starting torque.

Ans. : squirrel cage.

Long Answer Questions :

Q. 1 Sketch and explain torque-speed characteristics of 3-phase induction motor.

Q. 2 State any two applications of : 3-ph squirrel cage induction motor.

Q. 3 Compare A.C. and D.C. motor on the basis of :

(1) Supply (2) Speed control (3) Maintenance (4) Applications

Q. 4 Name 2 types of 3 phase induction motor and state one application of each.

Q. 5 State which is suitable for following application and why ?

(1) Flour mills (2) Cranes.

Q. 6 What is the principle behind the working of three phase I.M. ?

Q. 7 Draw neat constructional diagram of squirrel cage rotor and label the parts.

Q. 8 Compare squirrel cage and slip ring induction motor on the basis of

(A) Rotor construction. (B) Starting torque.

(C) Efficiency. (D) Application.

Q. 9 Define the slip of induction motor.

Q. 10 State the advantages of induction motor over dc motor.

Q. 11 State the disadvantages of induction motor.

Q. 12 State the applications of 3 ϕ induction motor.

Q. 13 Explain the production of RMF.

Q. 14 How the direction of IM be reversed ?

Q. 15 What is the effect of loading on induction motor ?

Q. 16 Define the following :

i) Synchronous speed N_s ii) Slip s iii) Frequency of rotor emf.

Q. 17 List various losses in induction motor.

□□□