Constructional Details

An electric motor is a device which converts an electrical energy into a mechanical energy. The motors operating on a.c. supply are called a.c. motor. As a.c. supply is commonly available, the a.c. motors are very popularly used in practice. The a.c. motors are classified as three phase induction motors, single phase induction motor, universal motors, synchronous motors etc. The three phase induction motors are widely used for various industrial application. The important features of three phase induction motors are self starting, higher power factor, good speed regulation and robust construction. This chapter explains the construction, working principle and characteristics of three phase induction motors as well as universal motors. The working of three phase induction motors is based on the principle of rotating magnetic field. Let us discuss, the production of rotating magnetic field.

Rotating Magnetic field (R.M.F)

The rotating magnetic field can be defined as the field or flux having constant amplitude but whose axis is continuously rotating in a plane with a certain speed. So if the arrangement is made to rotate a permanent magnet, then the resulting field is a rotating magnetic field. But ion this method, it is necessary to rotate a magnet physically to produce rotating magnetic field.

But in three phase induction motors such a rotating magnetic field is produced by supplying currents to a set of stationary windings, with the help of three phase a.c. supply. The current carrying windings produce the magnetic field or flux. And due to interaction of three phase fluxes produced due to three phase supply, resultant flux has a constant magnitude and its axis rotating in space, without physically rotating the windings. This type of field is nothing but rotating magnetic field. Let us study how it happens.

Production of R.M.F

A three phase induction motor consists of three phase winding as its stationary part called stator. The three phase stator winding is connected in star or delta. The three phase windings are displaced from each other by 120^{o}. The windings are supplied by a balanced three phase a.c. supply. This is shown in the Fig. The three phase windings are denoted as R-R' , Y-Y' and B-B'.

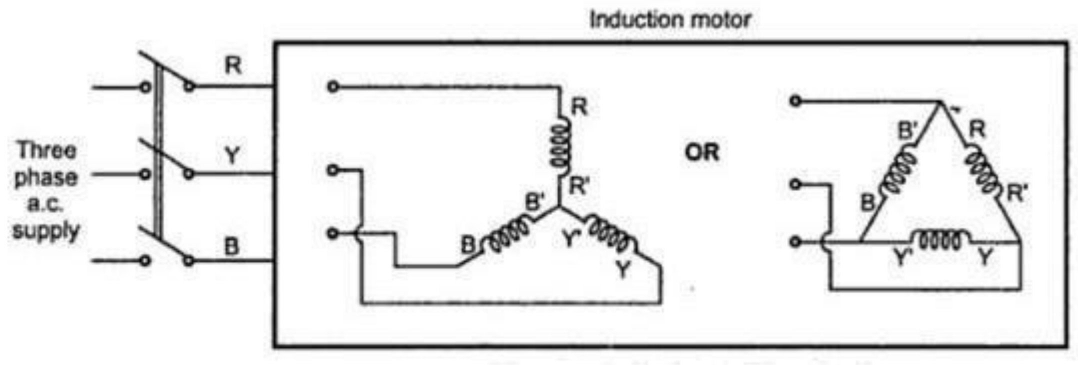


Fig 3.1. Star or delta connected 3phase winding

The three phase currents flow simultaneously through the windings and are displaced from each other by 120^o electrical. Each alternating phase current produces its own flux which is sinusoidal. So all three fluxes are sinusoidal and are separated from each other by 120^o. If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes Φ_R , $\Phi_Y$and Φ_B can be written as,

$$\Phi_R = \Phi_m \sin(\omega t) = \Phi_m \sin\theta \text{ ....(1)}$$

$$\Phi_Y = \sin(\omega t - 120^o) = \Phi_m \sin(\theta - 120^o) \text{ .... (2)}$$

$$\Phi_B = \Phi_m \sin(\omega t - 240^o) = \Phi_m \sin(\theta - 240^o) \text{...................................(3)}$$

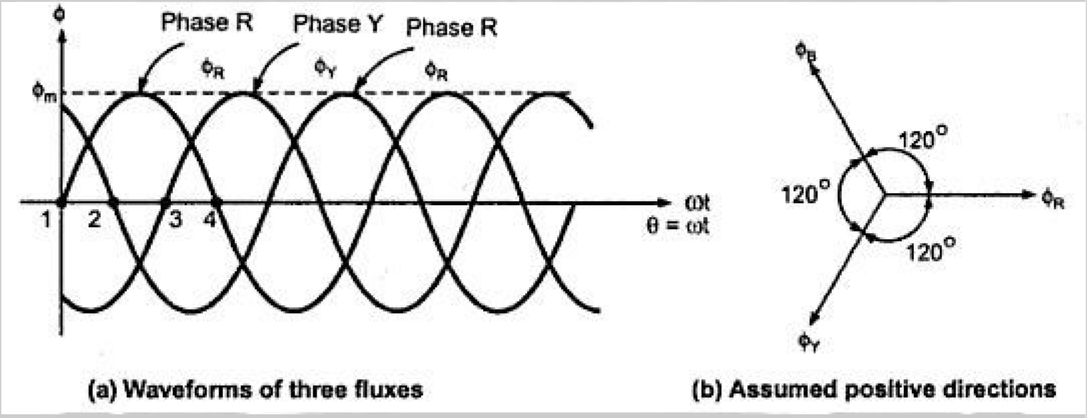
As winding are identical and supply is balanced, the magnitude of each flux is Φ_m. Due to phase sequence R-Y-B, flux lags behind Φ_R by 120^o and Φ_B lags Φ_Y by 120^o. So Φ_B ultimately lags Φ_R by 240^o. The flux Φ_R is taken as reference while writing the equations.

The Fig. 2(a) shows the waveforms of three fluxes in space. The Fig.2(b) shows the phasor diagram which clearly shows the assumed positive directions of each flux. Assumed positive direction means whenever the flux is positive it must be represented along the direction shown and whenever the flux is negative it must be represented along the opposite direction to the assumed positive direction.

Let Φ_R, Φ_Y and Φ_B be the instantaneous values of the three fluxes. The resultant flux Φ_T is the phasor addition of Φ_R, Φ_Y and Φ_B.

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

Let us find Φ_T at the instants 1, 2, 3 and 4 as shown in the Fig. 2(a) which represents the values of θ as 0^o, 60^o, 120^o and 180^o respectively. The phasor addition can be performed by obtaining the values of Φ_R, Φ_Y and Φ_B by substituting values of θ in the equation (1), (2) and (3).



(a) Waveforms of three fluxes (b) Assumed positive directions

fig 3.2 Phasor Diagram

Case 1 : $\theta = 0^o$

Substituting in the equations (1), (2) and (3) we get,

$\Phi_R = \Phi_m \sin 0^o = 0$

$\Phi_Y = \Phi_m \sin(-120^o) = -0.866\ \Phi_m$ $\Phi_B =$

$\Phi_m \sin(-240^o) = +\ 0.866\ \Phi_m$

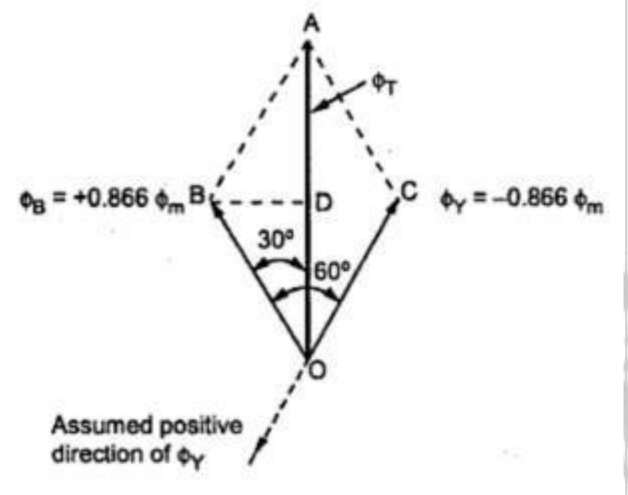


Fig. 3.3 Vector diagram of $\theta = 0^o$

The pahsor addition is shown in the Fig. 3.3. The positive values are are shown in assumed positive directions while negative values are shown in opposite direction to the assumed positive directions of the respective fluxes. Refer to assumed positive directions shown in the Fig 3.4.

BD is drawn perpendicular from B on Φ_T. It bisects Φ_T.

$\therefore$ OD = DA = $\Phi_T/2$

In triangle ∟OBD = 30^o

$\therefore$ $\cos 30^o = OD/OB = (\Phi_T/2)/(0.866\ \Phi_m)$

$\therefore$ $\Phi_T = 2 \times 0.866\ \Phi_m \times \cos 30^o$

$= 1.5\ \Phi_m$

So magnitude of Φ_T is 1.5 Φ_m and its position is vertically upwards at $\theta = 0^o$.

Case 2 $\theta = 60^o$

Equation (1),(2) and (3) give us,

$\Phi_R = \Phi_m \sin 60^o = +0.866\ \Phi_m$

$\Phi_Y = \Phi_m \sin(-60^o) = -0866\ \Phi_m$ $\Phi_B =$

$\Phi_m \sin(-180^o) = 0$

So Φ_R is positive and Φ_Y is negative and hence drawing in appropriate directions we get phasor diagram as shown in the Fig. 3(b).

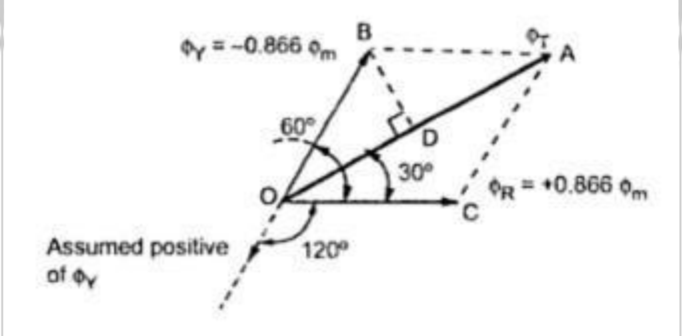


Fig 3.4 Vector diagram of $\theta = 60^o$

Doing the same construction, drawing perpendicular from B on at D we get the same result as,

$$\Phi_T = 1.5\ \Phi_m$$

But it can be seen that though its magnitude is 1.5 Φm it has rotated through 60^oin space, in clockwise direction, from its previous position.

Case 3 : $\theta = 120^o$

Equations (1),(2) and (3) give us,

$$\Phi_R = \Phi m \sin 120^o = +0.866\ \Phi m$$

$$\Phi_Y = \Phi m \sin 0^o = 0$$

$$\Phi_B = \Phi m \sin (-120^o) = -0.866\ \Phi m$$

So Φ_R is positive and Φ_B is negative. showing Φ_R and Φ_B in the appropriate directions, we get the phasor diagram as shown in the Fig . 3.5.

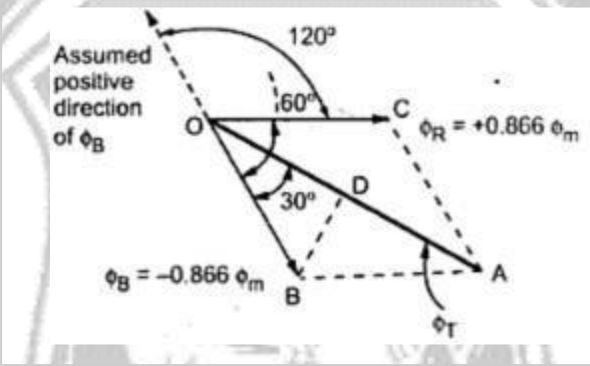


Fig. 3.5 Vector diagram of θ = 120 ^{o}

After doing the construction same as before i.e. drawing perpendicular from B on Φ_T, it can be provided again that,

$$\Phi_T = 1.5\ \Phi m$$

But the position of Φ_T is such that it has rotated further through 60^o from its previous position, in clockwise direction. And from its position at $\theta = 0^o$, it has rotated through 120^o in space, in clockwise direction.

Case 4 : $\theta = 180^o$

From equations (1),(2) and (3),

$$\Phi_R = \Phi m \sin (180^o) = 0$$

$$\Phi_Y = \Phi m \sin (60^o) = +0.866\ \Phi m$$

$$\Phi_B = \Phi m \sin (-60^o)$$

$$= -0.866\ \Phi m$$

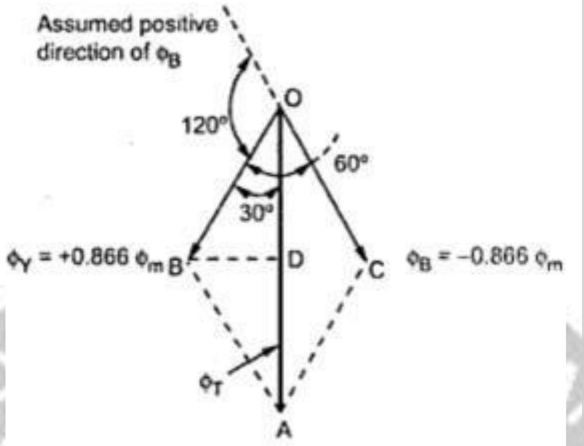


Fig. 3.6 Vector diagram of θ = 180°

So $\Phi_R = 0$, Φ_Y is positive and Φ_B is negative. Drawing Φ_Y and Φ_B in the appropriate directions, we get the phasor diagram as shown in the Fig. 3.6.

From phasor diagram, it can be easily proved that, $\Phi_T = 1.5\ \Phi m$

Thus the magnitude of Φ_T once again remains same. But it can be seen that it has further rotated through 60° from its previous position in clockwise direction.

So for an electrical half cycle of 180°, the resultant Φ_T has also rotated through . This is applicable for the windings from the above discussion we have following conclusions :

a) The resultant of the three alternating fluxes, separated from each other by , has a constant amplitude of 1.5 Φm where Φm is maximum amplitude of an individual flux due to any phase.

b) The resultant always keeps on rotating with a certain speed in space.

Key point : This shows that when a three phase stationary windings are excited by balanced three phase a.c. supply then the resulting field produced is rotating magnetic field. Though nothing is physically rotating, the field produced is rotating in space having constant amplitude.

Speed of R.M.F.

There exists a fixed relation between frequency f of a.c. supply to the windings, the number of poles P for which winding is wound and speed N r.p.m. of rotating magnetic field. For a standard frequency whatever speed of R.M.F. results is called synchronous speed, in case of induction motors. It is denoted as .

$$N_s = \frac{120\,f}{P} = \text{Speed of R.M.F.}$$

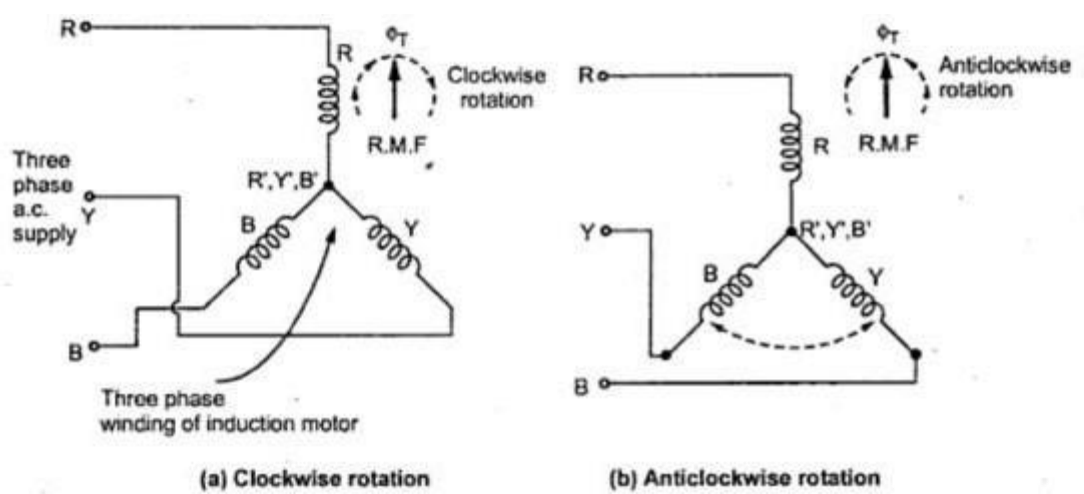
= (120 f)/P = speed of R.M.F.

Where f = Supply frequency in Hz

p = Number of poles for which winding is wound

This is the speed which R.M.F rotates in space. Let us see how to change direction of rotation of R.M.F.

Direction of R.M.F



(a) Clockwise rotation (b) Anticlockwise rotation

Fig. 3.7 Direction of RMF

The direction of the R.M.F. is always from the axis of the leading phase of the three phase winding towards the lagging phase of the winding. In a phase sequence of R-Y-B, phase R leads Y by 120^o and Y leads B by120^o. So R.M.F. rotates from axis of R to axis of Y and then to axis of B and so on. So its direction is clockwise as shown in the Fig. 3.7. This direction can be reversed by interchanging any two terminals of the three phase windings while connecting to the three phase supply. The terminals Y and B are shown interchanged in the Fig. 3.8. In such case the direction of R.M.F. will be anticlockwise.

As Y and B of windings are connected to B and Y from winding point of view the phase sequence becomes R-Y-B. Thus R.M.F. axis follows the direction from R to B to Y which is anticlockwise.

Key point : Thus by interchanging any two terminals of three phase winding while connecting it to three phase a.c. supply, direction of rotation of R.M.F. gets reversed.

Construction of Three Phase Induction motor

Basically the induction motor consists of two main parts, namely

1. The part i.e. three phase windings,which is stationary called stator.
2. The part which rotates and is connected to the mechanical load throughshaft called rotor.

The conversion of electrical power to mechanical power takes place in a rotor. Hence rotor develops a driving torque and rotates.

Stator

The stator has a laminated type of construction made up of stampings which are 0.4 to 0.5 mm thick. The stampings are slotted in its periphery to carry the stator winding. The stampings are insulated from each other. Such a construction essentially keeps the iron losses to a minimum value. The number of stampings are stamped together to build the stator core. The built up core is then fitted in a casted or fabricated steel frame. The choice of material for the stampings is generally silicon steel, which minimises the hysteresis loss. The slots in the periphery of the stator core carries a three phase winding, connected either in star or delta. This three phase winding is called stator winding. It is wound for definite number of poles.

This winding when excited by a three phase supply produces a magnetic rotating field as discussed earlier. The choice of number of poles depends on the speed of the rotating magnetic field required. The radial ducts are provided for the cooling purpose. In some cases, all the six terminals of three phase stator winding are brought out which gives flexibility to the user to connect them either in star or delta. The Fig. 1 shows a stator lamination.

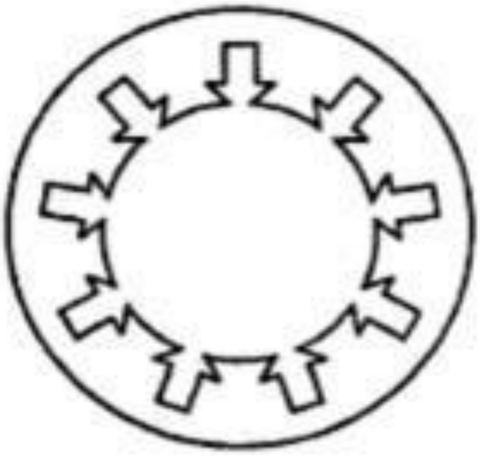


Fig.3.8 Stator lamination

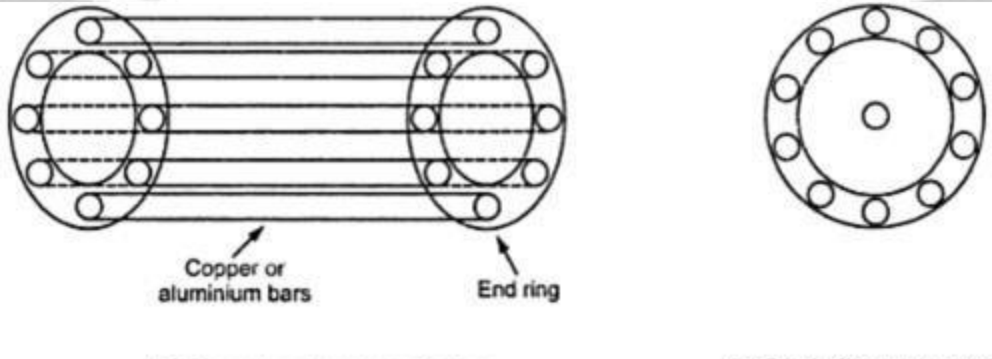
Rotor

The rotor is placed inside the stator. The rotor core is also laminated in construction and uses cast iron. It is cylindrical, with slots on its periphery. The rotor conductors or winding is placed in the rotor slots. The two typed of rotor constructions which are used for induction motors are,

1. Squirrel cage rotor and
2. Slip ring wound rotor

Squirrel CageRotor

The rotor core is cylindrical and slotted on its periphery. The rotor consists of uninsulated copper or aluminium bars called rotor conductors. The bars are placed in the slots. These bars are permanently shorted at each end with the help of conducting copper ring called end ring. The bars are usually brazed to the end rings to provide good mechanical strength. The entire structure looks like a cage, forming a closed electrical circuit. So the rotor is called squirrel cage rotor. The construction is shown in the Fig. 3.9.



(a) Cage type structure of rotor

(b) Symbolic representation

Fig. 3.9 Squirrel cage rotor

As the bars are permanently shorted to each other through end ring, the entire rotor resistance is very very small. Hence this rotor is also called short circuited rotor. As rotor itself is short circuited, no external resistance can have any effect on the rotor resistance. Hence no external resistance can be introduced in the rotor circuit. So slip ring and brush assembly is not required for this rotor. Hence the construction of this rotor is very simple.

Fan blades are generally provided at the ends of the rotor core. This circulates the air through the machine while operation, providing the necessary cooling. The air gap between stator and rotor is kept uniform and as small as possible.

In this type of rotor, the slots are not arranged parallel to the shaft axis but are skewed as shown in the Fig. 3.10.

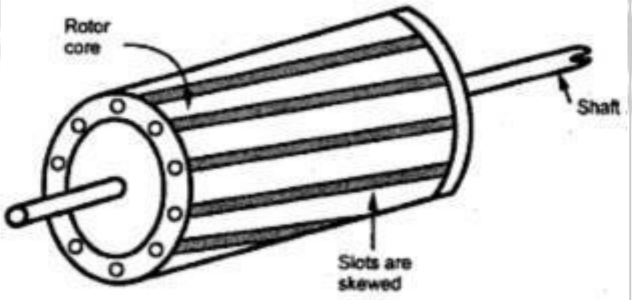


Fig. 3.10 Skewing in rotor construction

The advantages of skewing are,

1. A magnetic hum i.e. noise gets reduced due to skewing hence skewing makes the motor operation quiter.
2. It makes the rotor operation smooth.
3. The stator and rotor teeth may get magnetically locked. Such a tendency of magnetic locking gets reduced due to skewing.
4. It increases the effective transformation ratio between stator and rotor.

Slip Ring Rotor or Wound Rotor

In this type of construction, rotor winding is exactly similar to the stator. The rotor carries a three phase star or delta connected, distributed winding, wound for same number of poles as that of stator. The rotor construction is laminated and slotted. The slots contain the rotor winding. The three ends of three phase winding, available after connecting the winding in star or delta, are permanently connected to the slip rings. The slip rings are mounted on the same shaft. We have seen that slip slip rings are used to connect external stationary circuit to the internal rotating circuit. So in this type of rotor, the external resistances can be added with the help of brushes and slip ring arrangement, in series with each phase of the rotor winding. This arrangement is shown in the Fig. 3.9.

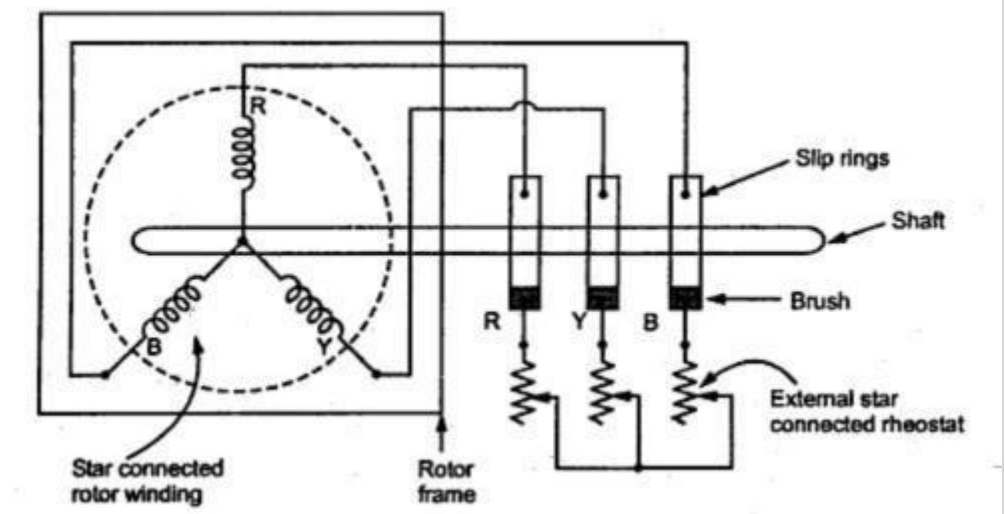


Fig. 3.11 Slip rings or wound rotor

Key point : This way the value of rotor resistance per phase ca be controlled. This helps us to control some of the important characteristics of the motor like starting torque, speed etc.

In the running condition, the slip rings are shorted. This is possible by connecting a metal collar which gets pushed and connects all the slip rings together, shorting them. At the same time brushes are also lifted from the slip rings. This avoids wear and tear of the brushes due to friction. The possibility of addition of an external resistance in series with the rotor, with the help of slip sings is the main feature of this type of rotor.

Working Principle of 3-Phase Induction Motor

Induction motor works on the principle of electromagnetic induction.

When a three phase supply is given to the three phase stator winding, a rotating magnetic field of constant magnitude is produced as discussed earlier. The speed of this rotation magnetic field is synchronous speed N_s r.p.m.

$$N_s = \frac{120\,f}{P} = \text{speed of rotating magnetic field}$$

Where f = supply frequency.

p = Number of poles for which stator winding is wound.

This rotating field produces an effect of rotating poles around a rotor. Let direction of rotation of this rotating magnetic field is clockwise as shown in the Fig. 3.11.

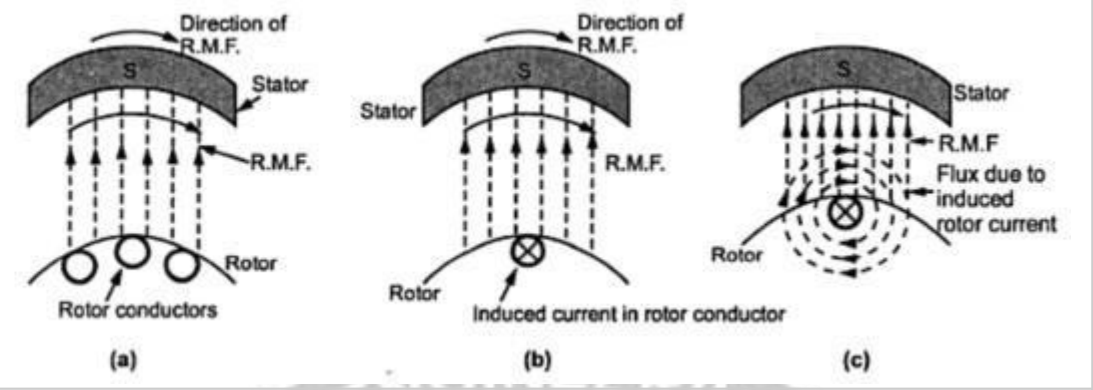


Fig. 3.12 stator flux acting on rotor flux

Now at this instant rotor is stationary and stator flux R.M.F. is rotating. So its obvious that there exists a relative motion between the R.M.F. and rotor conductors. Now the R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever conductors cuts the flux, e.m.f. gets induced in it. So e.m.f. gets induced in the rotor conductors called rotor induced e.m.f. This is electro-magnetic induction. As rotor forms closed circuit, induced e.m.f. circulates current through rotor called rotor current as shown in the Fig.3.12. Let direction of this current is going into the paper denoted by a cross as shown in the Fig. 3.12.

Any current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. For assumed direction of rotor current, the direction of rotor flux is clockwise as shown in the Fig. 3.12. This direction can be easily determined using right hand thumb rule. Now there are two fluxes, one R.M.F. and other rotor flux. Both the fluxes interact with each as shown in the Fig. 3.12. On left of rotor conductor, two fluxes cancel each other to produce low flux area. As flux lines act as stretched rubber band, high flux density area exerts a push on rotor conductor towards low flux density area. So rotor conductor experience a force from left to right in this case, as shown in the Fig. 1(d), due to interaction of the two fluxes.

As all the rotor conductors experience a force, the overall rotor experiences a torque and starts rotating. So interaction of the two fluxes is very essential for a motoring action. As seen from the Fig. 3.13, the direction of force experienced is same as that of rotating magnetic field. Hence rotor starts rotating in the same direction as that of rotating magnetic field.

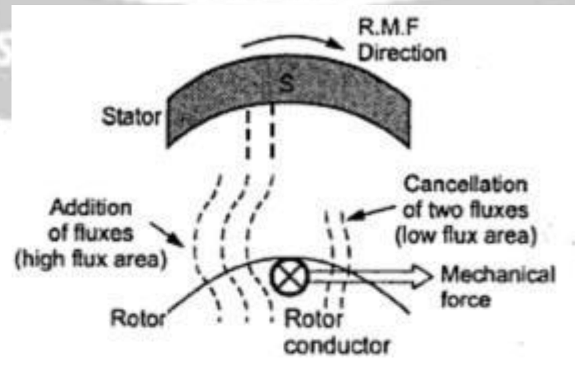


Fig 3.13 armature reaction

Alternatively this can be explained as : according to Lenz's law the direction of induced current in the rotor is so as to oppose the cause producing it. The cause of rotor current is the induced e.m.f. which is induced because of relative motion present between the rotating magnetic field and the rotor conductors. Hence to oppose the relative motion i.e. to reduce the relative speed, the rotor experiences a torque in the same direction as that of R.M.F. and tries to catch up the speed of the rotating magnetic field.

So, Ns = Speed of rotating magnetic field in r.p.m.
N = Speed of rotor i.e. motor in r.p.m.
Ns - N = Relative speed between the two, rotating magnetic field and the rotor conductors.

Thus rotor always rotates in same direction as that of R.M.F.

Can N = Ns ?

When rotor starts rotating, it tries to catch the speed of rotating magnetic field.

If it catches the speed of the rotating magnetic field, the relative motion between rotor and the rotating magnetic field will vanish (Ns - N = 0). In fact the relative motion is the main cause for the induced e.m.f. in the rotor. So induced e.m.f. will vanish and hence there can not be rotor current and the rotor flux which is essential to produce the torque on the rotor. Eventually motor will stop. But immediately there will exist a relative motion between rotor and rotating magnetic field and it will start. But due to inertia of rotor, this does not happen in practice and motor continues to rotate with a speed slightly less than the synchronous speed of the rotating magnetic field in the steady state. The induction motor never rotates at synchronous speed. The speed at which it rotates is hence called subsynchronous speed and motor sometimes called synchronous motor.

$$\therefore \quad N < Ns$$

So it can be said that rotor slips behind the rotating magnetic field produced by stator. The difference between the two is called slip speed of the motor.

Ns - N = Slip speed of the motor in r.p.m.

This speed decides the magnitude of the induction e.m.f. and the rotor current, which in turn decides the torque produced. The torque produced is as per the requirements of overcoming the friction and iron losses of the motor along with the torque demanded by the load on the rotor.