Poly phase Induction Motors

Advantages of 3-Ph Induction Motor:

The Induction motor is an A.C machine which converts A.C electrical energy into mechanical energy. The 3-Ph induction motor is commonly used ac motor for industrial/commercial applications because of the following advantages:

i. It is cheaper in cost
ii. Its construction is simple and robust i.e. mechanically strong.
iii. It has more Effiency and more reliable.
iv. It requires less maintenance and has more overload capacity.
v. Its starting (T_{st}) torque is more.

Construction of 3-Ph Induction Motor:

The 3-Ph induction motor mainly consists of two parts: (i) Stator (ii) Rotor

Stator

Stator is a stationary part. It is made-up of high grade steel laminations to reduce eddy current losses. The laminations are insulated from each other and slots are provided as shown in fig (i) to place the 3-ph stator winding in the stator slots. The stator winding is made of copper material and the stator winding may be star or delta connection. Here the stator poles are created by providing stator slots. When the 3-ph ac supply is given to the stator, a 3-ph alternating flux will setup in stator core and this stator flux is running with synchronous speed ($N_s = \frac{120\,f}{P}$) along with stator core.

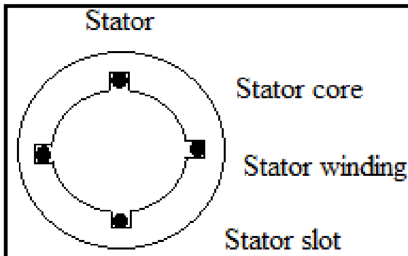


Figure1

Rotor

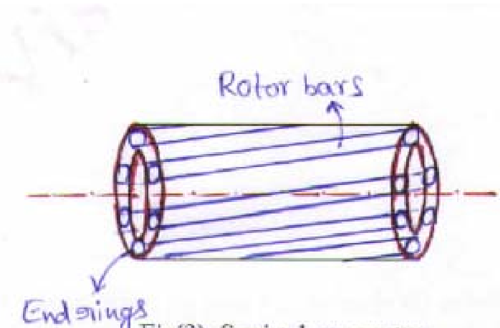
Rotor is rotating part. The rotor is in cylindrical shape and is laminated to reduce the eddy current losses. The rotor has rotor slots to house the rotor winding. Construction ally, the rotors are classified as two types. Those are

(i) Squirrel cage rotor **(ii) Phase wound or Slip ring rotor.**

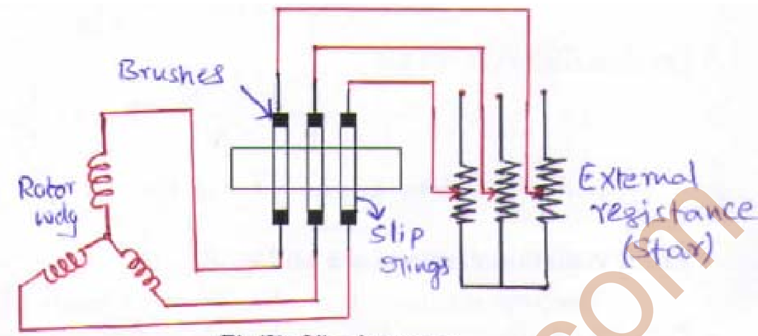
Squirrel cage rotor:

The squirrel cage rotor consists of cylindrical laminated core with slots nearly parallel to shaft as shown in fig fig (2) called skewed. At each end of the rotor, the rotor bar conductors are short circuited with end rings. The conductors and end rings combinely forms a cage as shown in fig (2). The skewing of rotor bars offers the following advantages:

(i) The locking tendency of the rotor is reduced.
(ii) More torque produced i.e. noise is reduced during the operation.



Fig(2): Squirrel cage rotor



Fig(3): Slip ring rotor

Phase wound or Slip ring rotor

This type of rotor consists of three slip-rings, which are mounted on the shaft with brushes resting on them as shown in Fig (3). The brushes are connected to star connected variable resistor. The main use of brushes and slip-rings are to connect the external resistance to rotor. The use of connecting external resistance to rotor circuit is

(i) It increases the starting torque and decreases the starting current.
(ii) It controls the speed of the motor.

Comparison between Squirrel cage & Slip ring rotor

Squirrel cage rotor	Slip ring rotor
1. Simple and robust construction	1. Difficult in construction
2. It requires less maintenance because of absent of brushes.	2. It requires more maintenance.
3. No possibility of connecting external resistance to rotor circuit because the rotor bars are short circuited.	3. Additional resistance can be connected to rotor circuit to increase the starting torque and to reduce the starting current.
4. Higher Effiency and higher power factor	4. Effiency decreases due to power losses in additional resistance in rotor.
5. Its cost is low due to absent of brushes, slip-rings etc.	5. Its cost is more.

Slip

The Slip of the 3-Ph Induction Motor can be defined as, 'the difference between the synchronous speed (N_s) and rotor speed (N_r) and expressed in terms of synchronous speed (N_s) i.e.

$$\text{Slip (s)} = \frac{\text{Synchronous speed - Rotor speed}}{\text{Synchronous speed}} = \frac{N_s - N_r}{N_s} \quad \text{or}$$

Rotor speed (N_r) = N_s(1-s) rpm and Synchronous Speed (N_s) = $\frac{120\,f}{P}$ rpm

Practically, the value of slip(s) is very small i.e. at for small machines the slip may be 4% to 6% and for large machines the slip may be 1% to 2%.

Rotor Frequency (f_r)

At stand still or when the rotor is stationary, the frequency of the rotor current is the same as the supply frequency (f). But when the rotor is rotating the frequency depends on the slip speed i.e. if Synchronous Speed (N_s) = $\frac{120\,f}{P}$ and

frequency (f) = $\frac{N_s\,P}{120}$ ------------------- (1) also

Rotor frequency (f_r) = $\frac{(N_s - N_r)\,P}{120}$ ------------------ (2)

Dividing (2) by (1), we get

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s} \rightarrow s = \frac{f_r}{f}$$

Rotor frequency f_r = sf Hz

Rotor resistance, reactance and emf

The rotor resistance $R_2 = \rho l/a$, where l = length of rotor conductor, a = area of rotor conductor. Here the rotor resistance does not depends on frequency, so the rotor resistance under running and stand still (stationary) is same i.e. $R_2 = R_r$.

Let X_2 = Rotor reactance under standstill (stationary) = $2\pi\, f\, L_2$

Xr = Rotor reactance under running = $2\pi\, f_r\, L_2$

$= 2\pi\,(s\,f)\,L_2$

$= s\,(2\pi\, f\, L_2)$

$= s\,X_2$

Similarly the rotor emf under running is $E_r = s\,E_2$

Rotor Current and Rotor Power factor

Let R_2 = Rotor resistance/ph at stationary,

X_2 =Rotor reactance/ph at stationary = $2\pi f L_2$

f = supply frequency E_2 = Rotor emf/ph at stationary,

I_2 = Rotor current/ph at stationary

$R_r = R_2$ = Rotor resistance/ph, X_r =Rotor reactance/ph at running

E_r = Rotor emf/ph at running = s E_2, I_r = Rotor current/ph at running

Rotor reactance/ph under running is $X_r = 2\pi$ (sf) $L_2 = sX_2$, where f = supply frequency

Rotor Impedance under running is $Z_r = \sqrt{R_2^2 + X_r^2} = \sqrt{R_2^2 + (sX_2)^2}$

Rotor current/ph under running is $I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Rotor power factor under running is $\cos\phi_r = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Similarly at stand still i.e. slip (s)) = 1

Rotor reactance/ph at standstill is $X_2 = 2\pi f L_2$ where f = supply frequency

Rotor Impedance at standstill is $Z_2 = \sqrt{R_2^2 + X_2^2}$

Rotor current/ph at standstill is $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$

Rotor power factor at standstill is $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$

Torque Equation

Let Φ = Stator flux in wbs and running with speed of $N_s = \frac{120\,f}{P}$

$\cos\phi_r$ = Rotor power factor under running = $\frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$ and

I_r = Rotor current/ph under running = $\frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

The torque of the 3-ph induction is proportional to net flux (Φ) due to interaction of the stator and rotor fluxes, rotor current (I_r) and rotor power factor ($\cos\phi_r$) i.e. Torque (T) $=\Phi\, I_r \cos\phi_r$

Torque (under running) $T = \Phi\, I_r \cos\phi_r$ where $K = \frac{1}{2\Pi Ns}$

$$= \frac{1}{2\Pi Ns}\,\Phi \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$= \frac{1}{2\Pi Ns}\, E_2 \frac{sE_2\, R_2}{R_2^2 + (sX_2)^2} \qquad [\because E_2 = \Phi]$$

Torque at running $= \frac{1}{2\Pi Ns} \frac{sE_2^2\, R_2}{R_2^2 + (sX_2)^2}$ N-m

Similarly

Torque (Stand still or starting) $T_{st} = \frac{1}{2\Pi Ns} \frac{E_2^2\, R_2}{R_2^2 + X_2^2}$ N-m $\quad [\because E_2 \,\square\, \Phi]$

Torque – Slip Curves/Characteristics

The expression for torque developed by the 3-Ph induction motor is

$$\text{Torque} = K \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \text{ N-m ------- (1)}$$

The torque – slip characteristics of a 3-ph induction motor can explain as follows:

(i) When the rotor speed is equal to synchronous speed i.e. $N_r = N_s$, Slip (s) = 0 and from equation (1) the torque is zero.

(ii) When the load on the motor is increases, the speeds decreases and slip increases. The value of sX_2 is very small compared to R_2 and is neglected for constant rotor emf E_2.

From equation (1) Torque = $K \frac{s R_2}{R_2^2}$

Hence, for low value of slip, the torque – slip curve is represented as a straight line as shown in Fig(5).

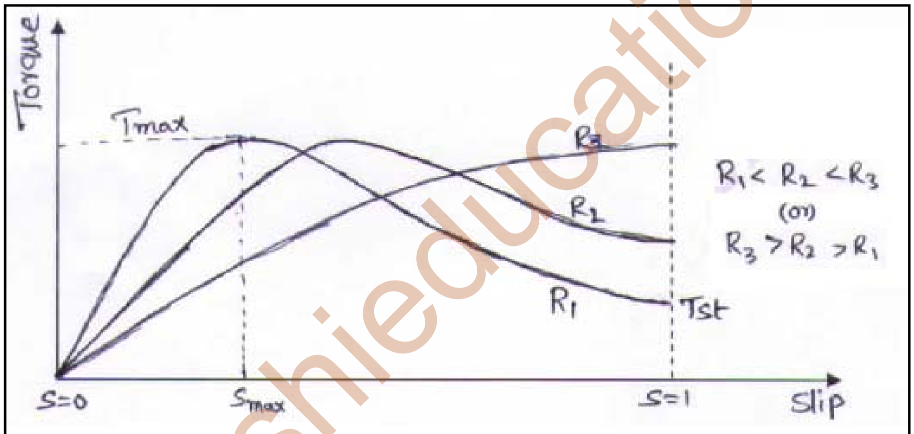


Fig. (5): Torque - slip curves

As the load increases further, the speed decreases when slip increases. This result in increase in torque and reaches to maximum when slip = R_2 / X_2.

(iii) With the increase load beyond maximum torque (T_{max}), the slip increases further. Now the value of sX_2 is more compared to R_2 and R_2 is neglected, so

From equation (1) Torque = $K \frac{s}{s^2 X_2^2}$ or Torque = $\frac{1}{\text{slip(s)}}$

Hence for high value of slip, the torque-slip curve is falling from maximum value as shown in fig (5).

The figure (5) shows the torque-slip curve of 3-ph induction motor and this curve represents rectangular hyperbola. The magnitude of the torque at $N_r = 0$ or slip =1 i.e. at stand still, is called starting torque (T_{st}). The magnitude of the starting torque and maximum torque depends on rotor resistance (R_2).

Production of Rotating Magnetic Field:

When the 3-ph AC supply is given to stator, a rotating magnetic flux is developed and is rotating with a speed of synchronous speed N_s.

Let Φ_m = Maximum flux

Φ_R, Φ_Y and Φ_B are fluxes due to R, Y and B phases and are given by

$\Phi_R = \Phi_m \sin wt$, $\Phi_Y = \Phi_m \sin(wt - 120)$ and $\Phi_B = \Phi_m \sin(wt - 240)$

(i) When wt = 0^o i.e

$$\Phi_R = 0, \quad \Phi_Y = -\frac{\sqrt{3}}{2}\Phi_m \quad \text{and} \quad \Phi_B = \frac{\sqrt{3}}{2}\Phi_m$$

From the vector diagram (Fig.a)

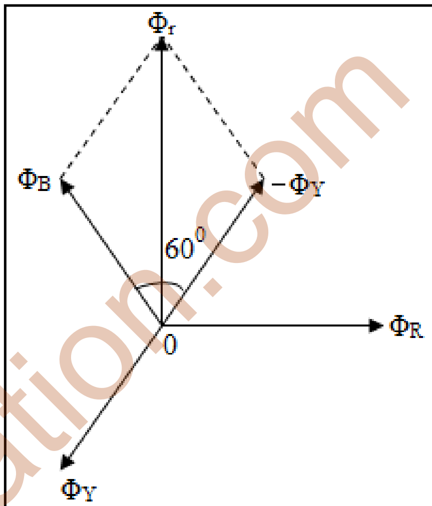


Fig. (a)

Resultant flux $\Phi_r = \sqrt{\Phi_B^2 + (-\Phi_Y)^2 - 2\Phi_B(-\Phi_Y)\cos(60)}$

$$= \sqrt{\Phi_B^2 + \Phi_Y^2 + 2\Phi_B\Phi_Y\cos(60)}$$

$$= \sqrt{(\frac{\sqrt{3}}{2}\Phi_m)^2 + (\frac{\sqrt{3}}{2}\Phi_m)^2 + 2(\frac{\sqrt{3}}{2}\Phi_m)(\frac{\sqrt{3}}{2}\Phi_m)\frac{1}{2}}$$

$$= \sqrt{\frac{9}{4}\Phi_m}$$

$$= \frac{3}{2}\Phi_m$$

Resultant flux $\Phi_r = 1.5\Phi_m$

(ii) When wt = 60^o i.e.

$$\Phi_R = \frac{\sqrt{3}}{2}\Phi_m, \quad \Phi_Y = -\frac{\sqrt{3}}{2}\Phi_m \quad \text{and} \quad \Phi_B = 0$$

From the vector diagram (Fig.b)

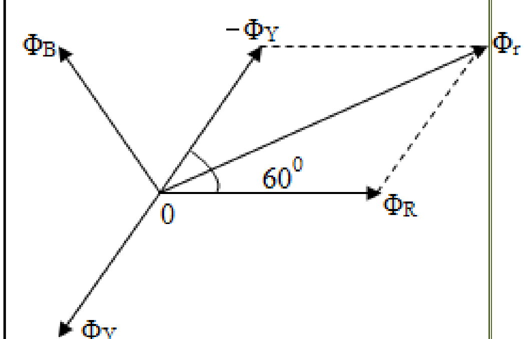


Fig. (b)

Resultant flux $\Phi_r = \sqrt{\Phi_R^2 + (-\Phi_Y)^2 - 2\Phi_R(-\Phi_Y)\cos(60)}$

$$= \sqrt{\Phi_R^2 + \Phi_Y^2 + 2\Phi_R\Phi_Y\cos(60)}$$

$$= \sqrt{(\frac{\sqrt{3}}{2}\Phi_m)^2 + (\frac{\sqrt{3}}{2}\Phi_m)^2 + 2(\frac{\sqrt{3}}{2}\Phi_m)(\frac{\sqrt{3}}{2}\Phi_m)\frac{1}{2}}$$

$$= \sqrt{\frac{9}{4}\Phi_m}$$

$$= \frac{3}{2}\Phi_m$$

Resultant flux $\Phi_r = 1.5\Phi_m$

(ii) When wt = 120^o i.e.

$$\Phi_R = \frac{\sqrt{3}}{2}\Phi_m, \quad \Phi_Y = 0 \quad \text{and} \quad \Phi_B = -\frac{\sqrt{3}}{2}\Phi_m$$

From the vector diagram (Fig.c)

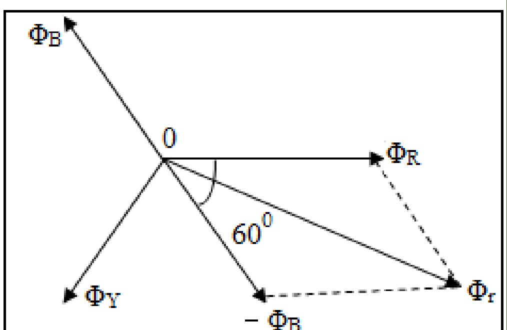


Fig. (c)

$$\text{Resultant flux } \Phi_r = \sqrt{\Phi_R^2 + (-\Phi_B)^2 - 2\Phi_R(-\Phi_B)\cos(60)}$$

$$= \sqrt{\Phi_R^2 + \Phi_B^2 + 2\Phi_R\Phi_B\cos(60)}$$

$$= \sqrt{(\frac{\sqrt{3}}{2}\Phi_m)^2 + (\frac{\sqrt{3}}{2}\Phi_m)^2 + 2(\frac{\sqrt{3}}{2}\Phi_m)(\frac{\sqrt{3}}{2}\Phi_m)\frac{1}{2}}$$

$$= \sqrt{\frac{9}{4}}\Phi_m$$

$$= \frac{3}{2}\Phi_m$$

Resultant flux $\Phi_r = 1.5\Phi_m$

(iv) When wt = 180° i.e

$$\Phi_R = 0, \quad \Phi_Y = \frac{\sqrt{3}}{2}\Phi_m \quad \text{and} \quad \Phi_B = -\frac{\sqrt{3}}{2}\Phi_m$$

From the vector diagram (Fig.d)

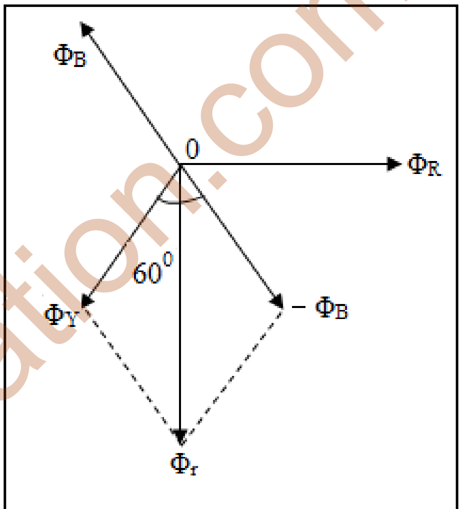


Fig. (d)

$$\text{Resultant flux } \Phi_r = \sqrt{\Phi_Y^2 + (-\Phi_B)^2 - 2\Phi_Y(-\Phi_B)\cos(60)}$$

$$= \sqrt{\Phi_Y^2 + \Phi_B^2 + 2\Phi_Y\Phi_B\cos(60)}$$

$$= \sqrt{(\frac{\sqrt{3}}{2}\Phi_m)^2 + (\frac{\sqrt{3}}{2}\Phi_m)^2 + 2(\frac{\sqrt{3}}{2}\Phi_m)(\frac{\sqrt{3}}{2}\Phi_m)\frac{1}{2}}$$

$$= \sqrt{\frac{9}{4}}\Phi_m$$

$$= \frac{3}{2}\Phi_m$$

Resultant flux $\Phi_r = 1.5\Phi_m$

From the above analysis, it is clear that at any instance of time the resultant flux is 1.5 times the maximum flux. The direction of the rotating magnetic field in the stator core is in clockwise direction and this magnetic field is rotating with a speed of Ns = 120f /P

Operating or Working principle or why the 3-ph induction motor is self starting machine

When the 3-ph AC supply is given to stator of Induction motor, a rotating magnetic field of constant magnitude and rotating with synchronous speed is produced. This rotating magnetic field cuts the stationary rotor conductor and an emf is induced across the rotor conductors. The magnitude of this emf depends on relative speed between the stator flux and rotor conductors. Since the rotor

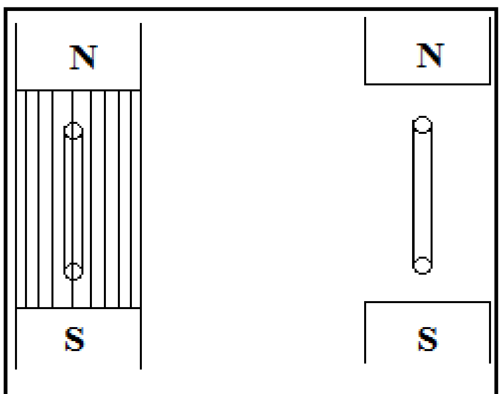


Fig. (a) Fig. (b)

conductors forms a closed circuit, current will passes through the rotor conductors called rotor current. Now around the current carrying rotor conductors a magnetic field will setup in the form of concentric circles as shown in Fig.(a). The direction of the magnetic field around the rotor conductors is determined by skew rule or right hand thumb rule.

Now, because of interaction of stator flux and flux around the current rotor conductors, the flux strengthens the right and weakens the left of the rotor conductors at top of the rotor conductors and weakens right and strengthens on left of the rotor conductors at bottom of the rotor conductors as shown in Fig.(b). this resulting movement in the rotor will be in anti clock wise direction.

"From the above discussion it is clear that an induction motor is a self starting motor."