3- Phase Induction Motors

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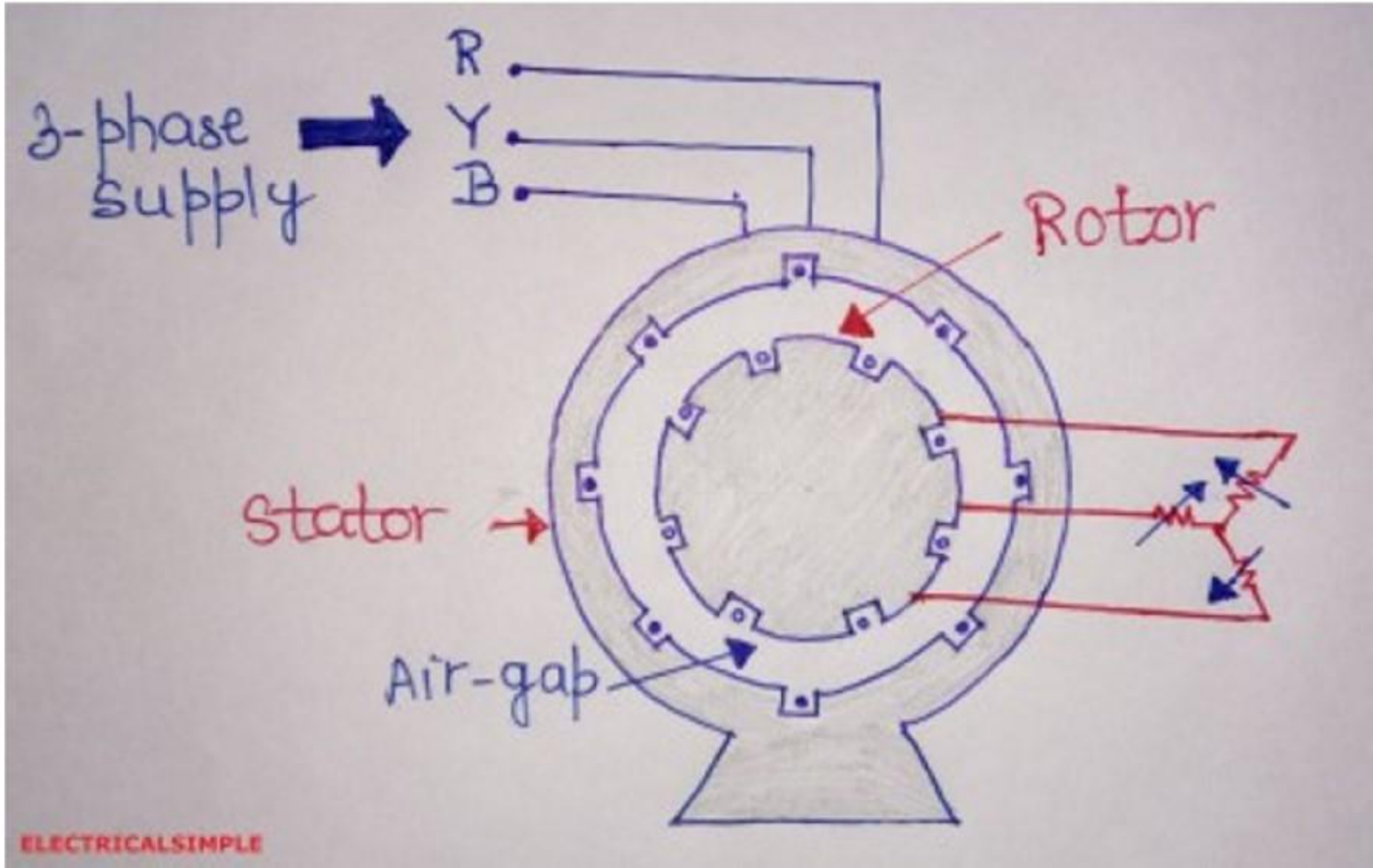
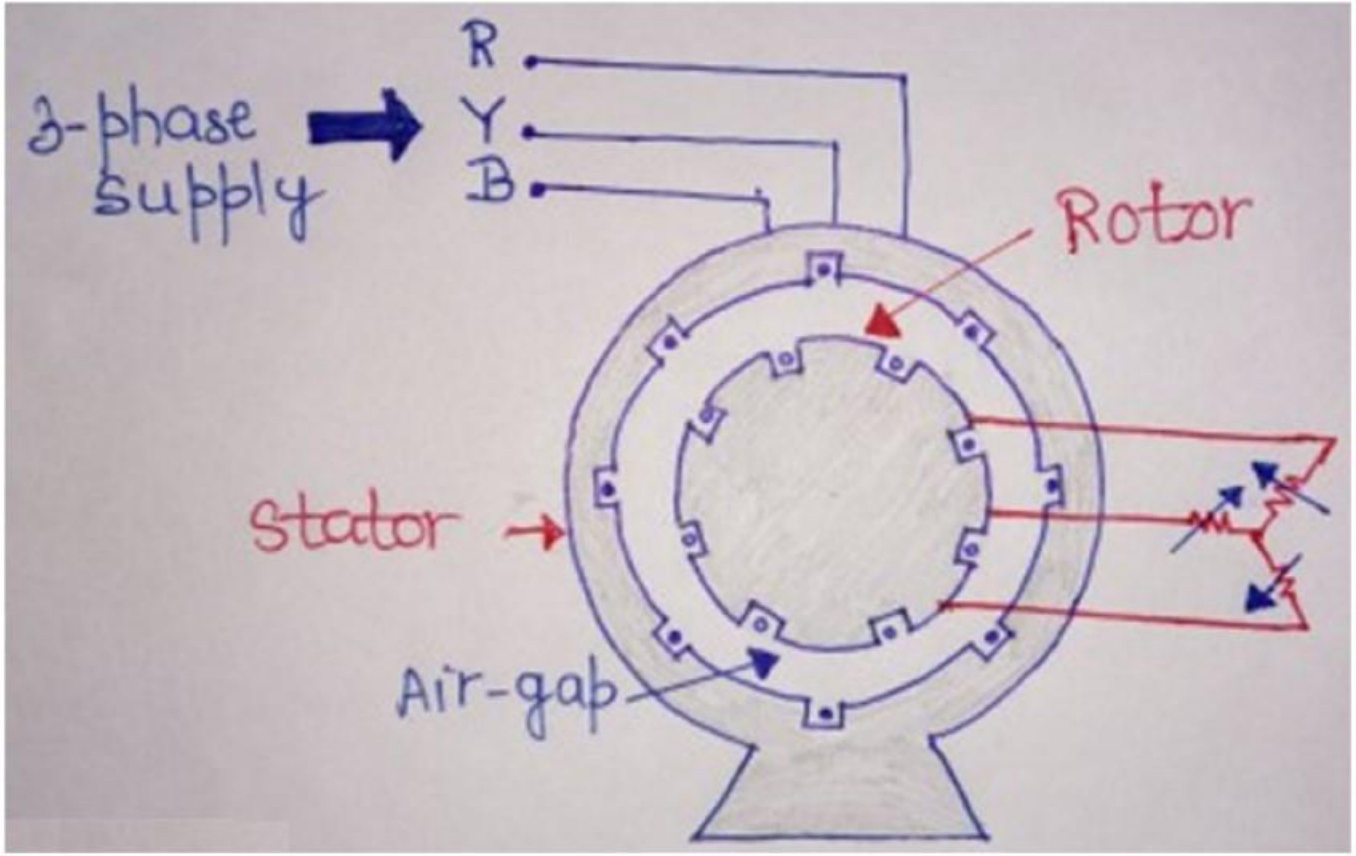
STATOR :

The stator hosts a three phase winding distributed symmetrically on its inner periphery.
This stator winding is energized from a three phase supply.



ROTOR:

The rotor also hosts a 3 phase winding on its periphery. But, the rotor winding is not energized from any source and is short- circuited on itself with or without external resistance.



Three phase Induction motor working principle(1/3)

(1)When the 3 phase stator winding is energized from a 3 phase supply, a **rotating magnetic field** is produced which rotates around the stator at synchronous speed.

(2) The rotating magnetic field cuts the rotor conductors, which as yet, are stationary. Due to this flux cutting, emfs are induced in the rotor conductors. As rotor circuit is short circuited, therefore, currents start flowing in it.

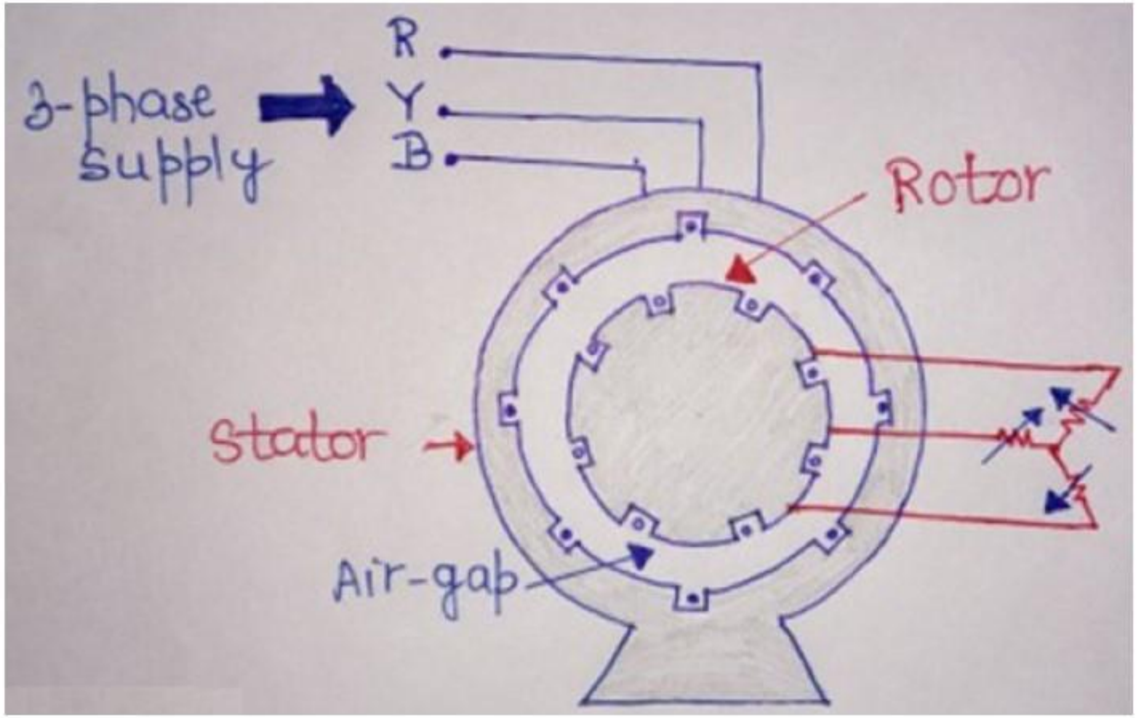
(3) Now, as per Lenz's law , "the direction of induced current will be such that it opposes the very cause that produced it " .

(4) Here, the cause of emf induction is the relative motion between the rotating field and the stationary rotor conductors. Hence, to reduce this relative motion, the rotor starts rotating in the same direction as that of the stator field and tries to catch it but, can never catch it due to friction and windage and therefore emf induction continues and motor keeps rotating.

Thus, ***principle of 3 phase induction motor*** explains why rotor rotates in same direction as the rotating field and why *induction motor is self starting*.

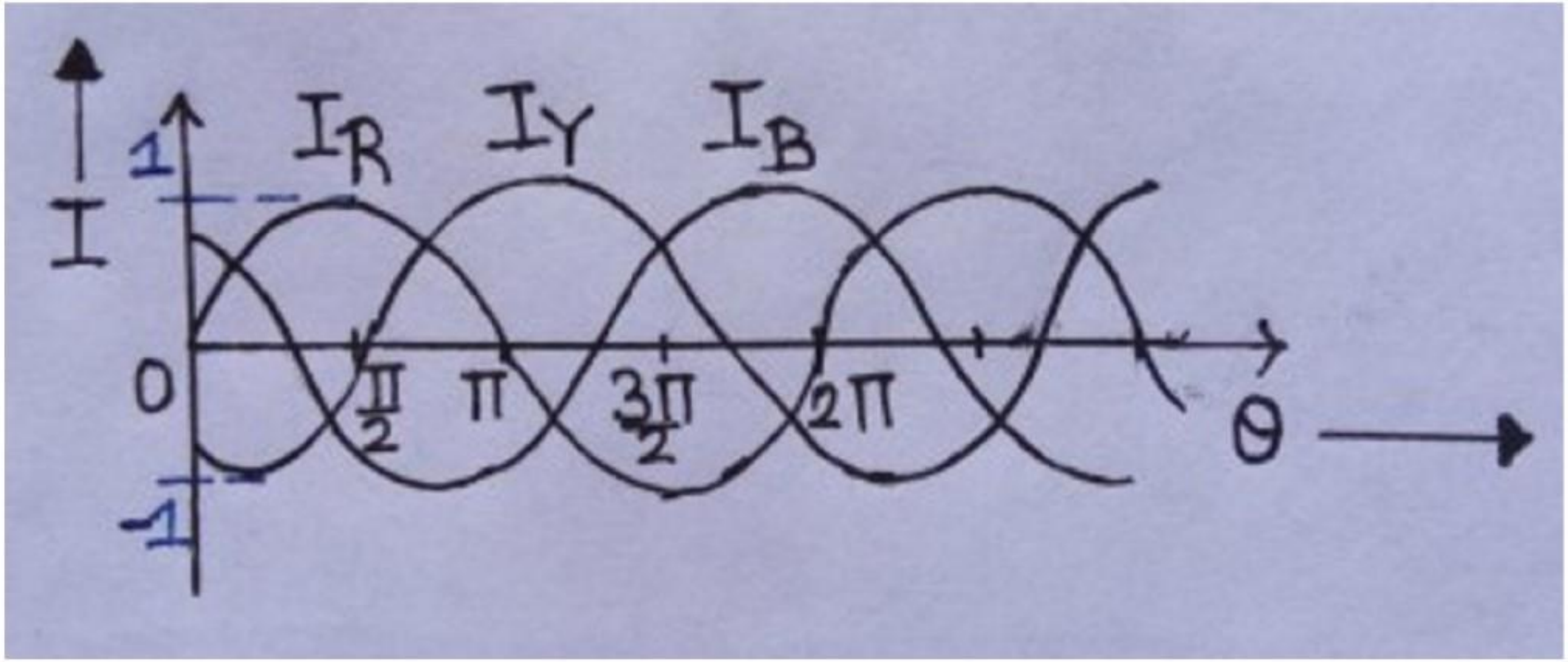
Three phase Induction motor-classification

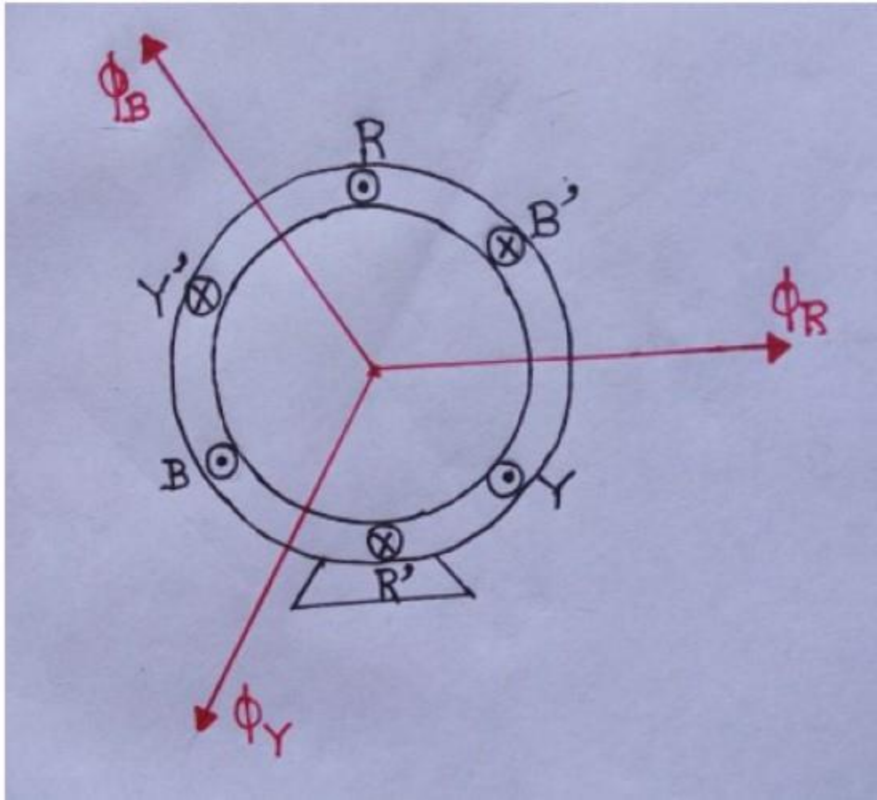
- When rotor winding is short-circuited with no external resistance in series, it is called a ***squirrel cage induction motor***.
- when rotor winding is shorted through a external resistance in series, it is called ***slip ring induction motor***.



How rotating magnetic field is produced in Induction Motor ?

Consider 3-phase currents, displaced in time by 120^0 as shown. When 3-phase windings displaced in space by 120^0 are fed by these 3-phase currents, individual phases produce magnetic fluxes and the assumed positive directions of these fluxes are shown below.





Lets analyze each of these fluxes and their resultant Φ, at every instant of time 60^0 apart.

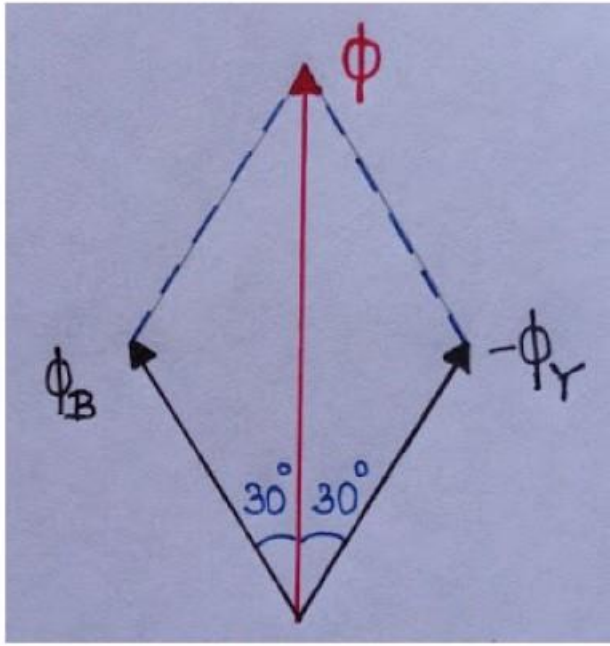
(1) when $\Theta=0^0$ $\quad I_R = 0$, $I_Y = \frac{-\sqrt{3}}{2}$ and $I_B = \frac{\sqrt{3}}{2}$

As fluxes will be proportional to these currents, Let their values be

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

Where, Φ_m = maximum value of magnetic flux due to any phase.

Vectorically the fluxes are shown along with their resultant flux (in red) Φ. The negative sign have been taken into account in vector diagram.



The resultant flux Φ is given by

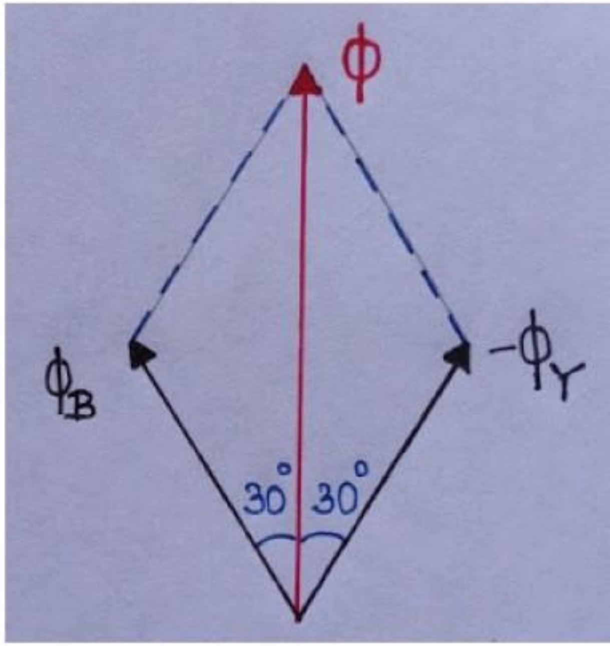
$$\Phi = \Phi_B \cos 30^0 + \Phi_Y \cos 30^0$$

$$= \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right) + \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right)$$

$$= 2\left(\frac{\sqrt{3}}{2} \times \Phi_m \times \frac{\sqrt{3}}{2}\right)$$

$$= 1.5\ \Phi_m$$

So, resultant flux has magnitude equal to $1.5\ \Phi_m$ and is vertically directed.



(2) when $\Theta=60^0$

The individual fluxes will be $\Phi_R = \frac{\sqrt{3}}{2}\Phi_m$, $\Phi_Y = \frac{-\sqrt{3}}{2}\Phi_m$ and $\Phi_B = 0$

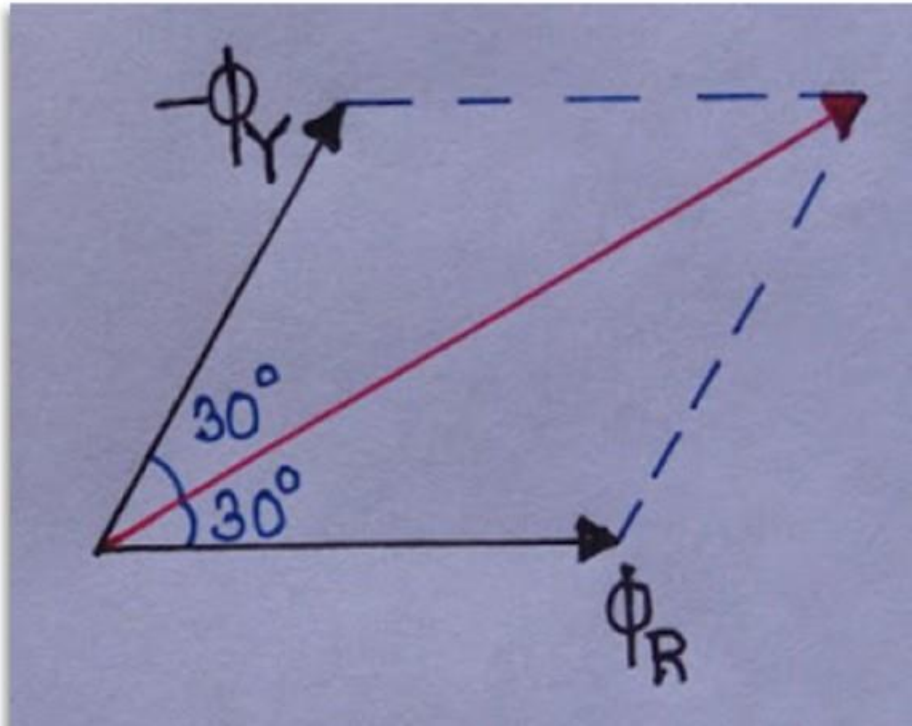
Represented in phasors as shown.

The resultant flux is given by $\Phi = \Phi_R \cos 30^0 + \Phi_Y \cos 30^0$

$$= \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right) + \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right)$$

$$= 1.5\,\Phi_m$$

So, resultant flux has magnitude 1.5 times maximum flux due to any phase and has rotated 60^0 clockwise.



(3) when $\Theta = 120^0$

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

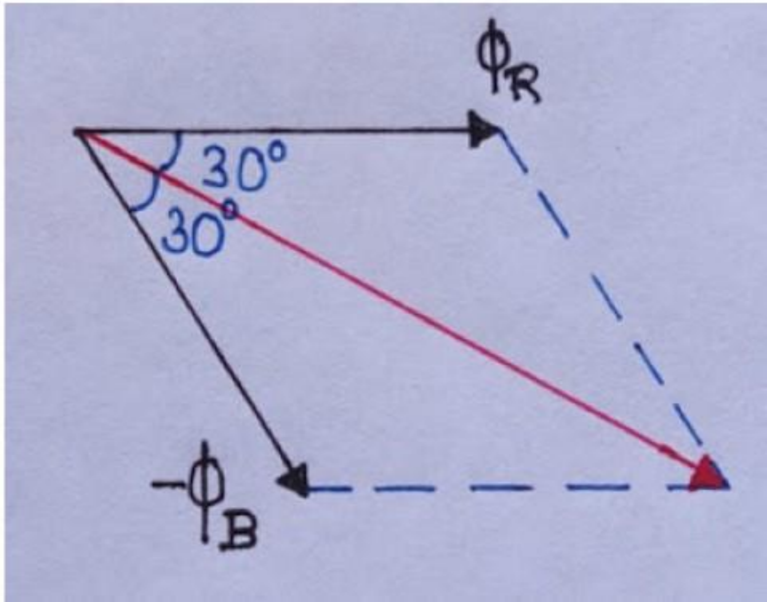
The individual fluxes along with the resultant are represented in phasors as shown.

The resultant flux is given by $\Phi = \Phi_R \cos 30^0 + \Phi_B \cos 30^0$

$$= \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right) + \left(\frac{\sqrt{3}}{2}\Phi_m \cos 30^0\right)$$

$$= 1.5\,\Phi_m$$

So, resultant flux has magnitude $1.5\Phi_m$ and has rotated 60^0 clockwise from last position.



(4) when $\Theta = 180^0$

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

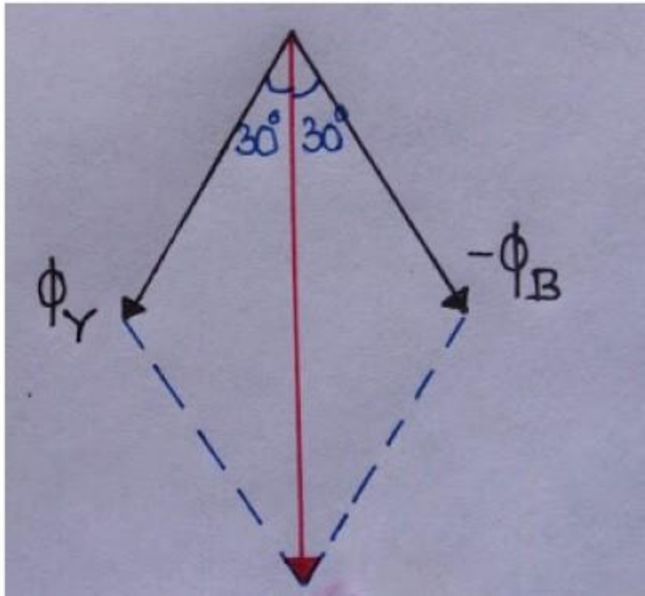
The individual fluxes along with the resultant are represented in phasors as shown.

The resultant flux is given by $\Phi = \Phi_Y \cos 30^0 + \Phi_B \cos 30^0$

$$= \left(\frac{\sqrt{3}}{2}\,\Phi_m \cos 30^0\right) + \left(\frac{\sqrt{3}}{2}\,\Phi_m \cos 30^0\right)$$

$$= 1.5\,\Phi$$

Again, resultant flux has magnitude $1.5\Phi_m$ and has rotated 60^0 clockwise from last position. Similar analysis can be continued for next Θs upto full cycle i.e $\Theta = 360^0$.



i.e 1.5 times the maximum value of flux due to any phase.

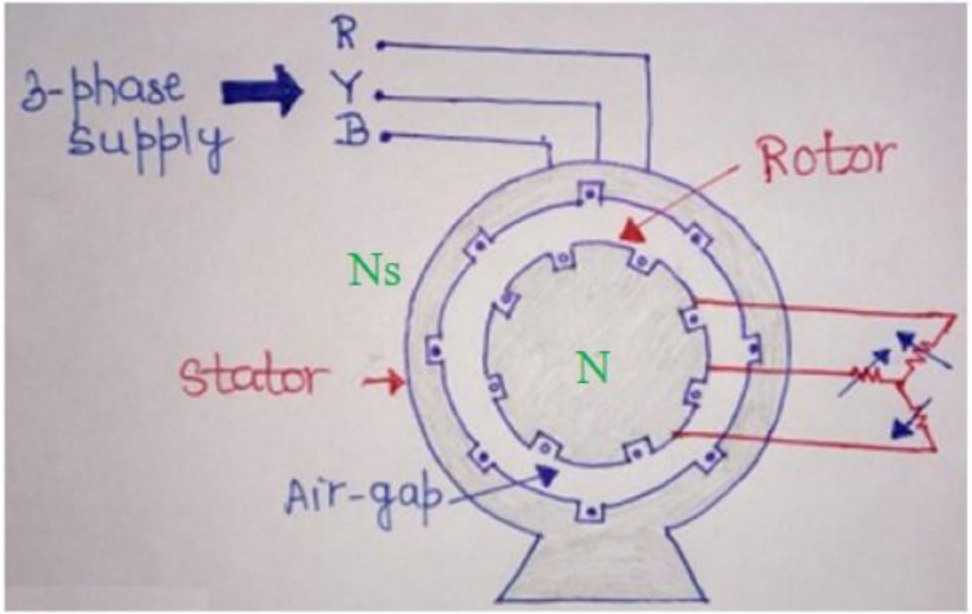
(2) The resultant flux rotates around the stator at a speed called synchronous speed.

Thus, it is true to assume that a **rotating magnetic field** is produced in space as if actual magnetic poles of permanent magnet were being rotated mechanically.

Induction Motors Slip

The difference between the synchronous speed and rotor speed can be expressed as a percentage of synchronous speed, known as the slip:

$$s = \frac{Ns - N}{Ns} \text{ X } 100\ \%$$



Where s = slip,

Ns = synchronous speed (rpm),

N = rotor speed (rpm)

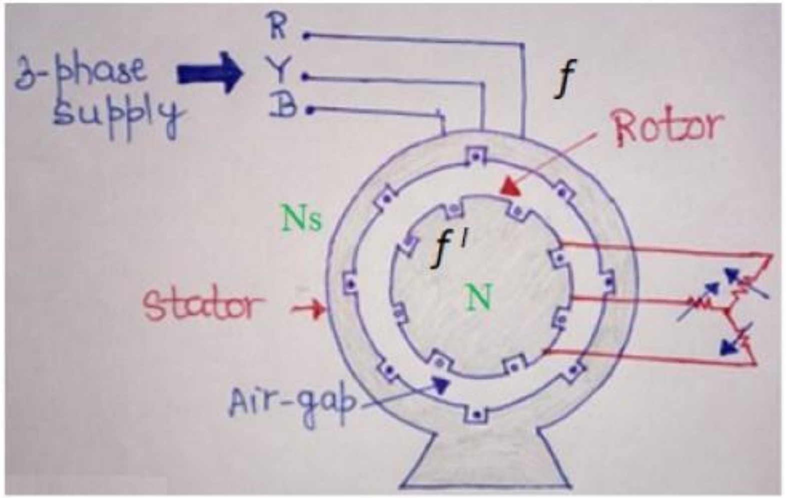
- Slip speed = Ns – N
- Rotor speed N= Ns (1-S)
- when the rotor is stationary, Rotor speed N=0,hence slip =1 or 100%
- If the rotor runs at synchronous speed, i.e. $N=N_S$, then slip =0

Rotor current Frequency (1/2)

- we know that the frequency of supply frequency = f
- Also we know that the speed of rotating magnetic field $=N_S=120\ f/P$
- When the rotor is stationary, the frequency of rotor current is same as the supply frequency.
- But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip speed.
- Let at any slip-speed, the frequency of the rotor current be f'

$$N_s - N = \frac{120 f'}{P} \quad \text{......(1)}$$

$$N_s = \frac{120 f}{P} \quad \text{......(2)}$$



Rotor current Frequency (2/2)

$$(1)/(2) = \frac{N_s - N}{N_s} = \frac{\dfrac{120 f'}{P}}{\dfrac{120 f}{P}} = \frac{f'}{f}$$

$$s = \frac{f'}{f}$$

$$f' = sf$$

- When the rotor is stand still ,slip =1,then rotor frequency =f

i.e. supply frequency

Effect of slip on rotor circuit

- Let, E_2= rotor emf per phase at standstill

  R_2= rotor resistance per phase

  X_2=rotor reactance per phase at standstill

  Z_2 =rotor impedance per phase at standstill

  f_2=frequency of rotor current at standstill
- When rotor is stationary, S=1, under these conditions the per phase rotor emf E_2 has a frequency equal to that of supply frequency 'f'.
- When rotor starts rotating, relative speed between stator and rotor is decreased. Hence the rotor induced emf which is proportional to relative speed and is also decreased. Hence for slip 'S', rotor emf will be slip times the induced emf at stand still.
- Under running condition, $E_r = sE_2$ $\quad f_r=sf_2$ $\quad X_r=sX_2$

  Where, E_r = Rotor emf under running conditions

  X_r = Rotor reactance under running conditions

Torque of an Induction motor

- As we know, the torque T_a is proportional to the product of armature current and flux per pole.

$$T_a \ \alpha \ \varphi \ I_a$$

- In induction motor, $T_a \ \alpha \ \varphi \ I_2 \cos\phi_2$

Where, I_2 = rotor current at standstill

ϕ_2 = angle between rotor emf and rotor current

K= constant

- Denoting rotor emf at standstill by E_2 , then we have $E_2 \ \alpha \ \varphi$

Hence, $T_{st} \ \alpha \ E_2 I_2 \cos\phi_2 = K_1 E_2 I_2 \cos\phi_2$

Where, K_1 = constant.

Starting Torque of induction motor

- The torque developed by the motor at the instant of starting is called starting torque.
- Let, E_2= rotor emf per phase at standstill

  R_2= rotor resistance per phase

  X_2=rotor reactance per phase at standstill

  Z_2 =rotor impedance per phase at standstill $= \sqrt{(R_2^2 + X_2^2)}$

Then, $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}}$ $\qquad \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$

Starting torque, $T_{st} = K_1 E_2 I_2 \cos\phi_2 = K_1 E_2 \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}} \quad = K_1 \frac{E_2^2 R_2}{(R_2^2 + X_2^2)}$

Torque under running condition

- Let, E_2= rotor emf per phase at standstill
  R_2= rotor resistance per phase
  X_2=rotor reactance per phase at standstill
  Z_2 =rotor impedance per phase at standstill
  f_2=frequency of rotor current at standstill

Under running condition,

$$E_r = sE_2$$
$$f_r=sf_2$$
$$X_r=sX_2$$

Where, E_r = rotor emf under running conditions
X_r = rotor reactance under running conditions

Torque under running condition

- $T_r \; \alpha \; T_r \; \alpha \; E_r I_r \cos\phi_r = K_1 E_r I_r \cos\phi_r$

$$E_r = sE_2 \qquad I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \qquad \cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

- $T_r = K_1 \; S \; E_2 \dfrac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \dfrac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Since, $T_{st} = K_1 E_2 I_2 \cos\phi_2$

$$= K \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

Torque-slip characteristics(1/3)

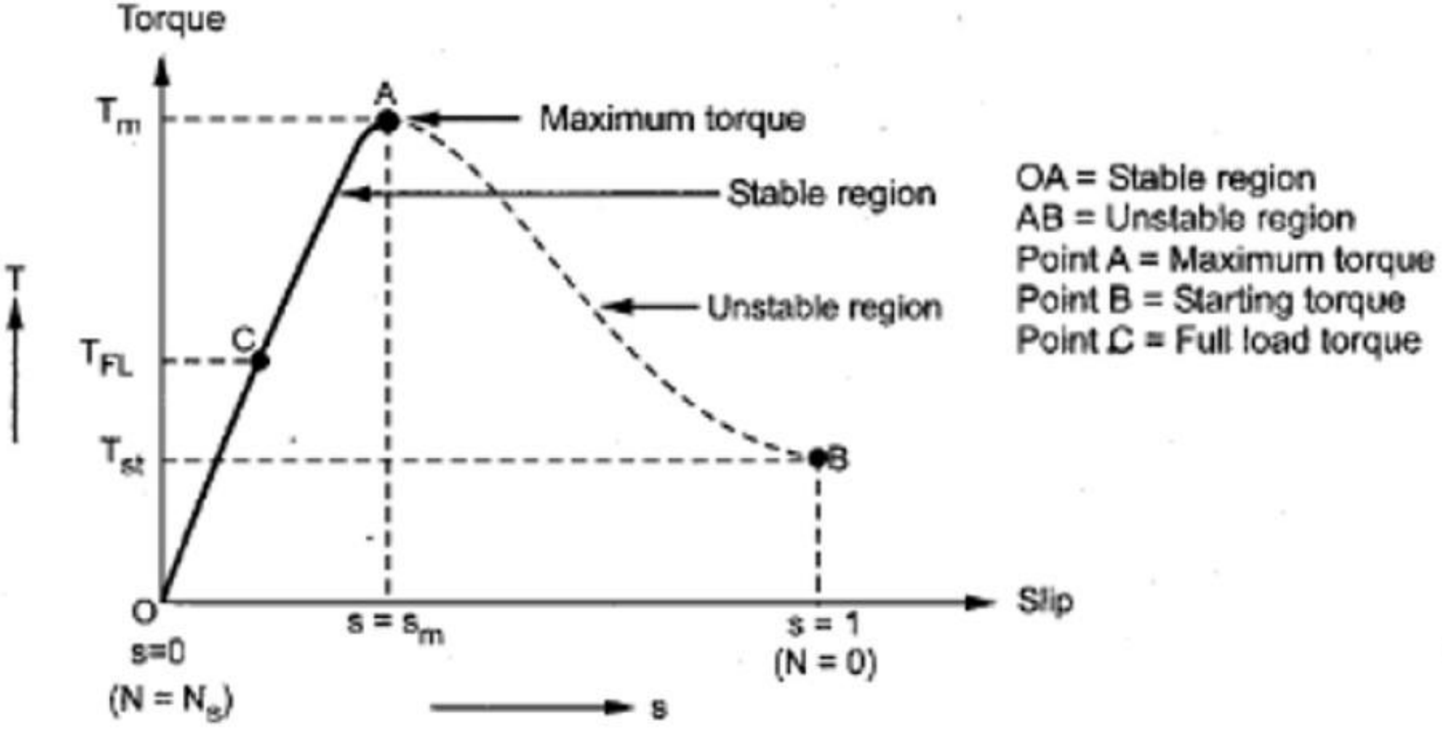
- The curve obtained by plotting torque against slip from s = 1 (at start) to s =0 (at synchronous speed) is called torque-slip characteristics of the induction motor.

$$T \;\alpha\; \frac{sE2^2R2}{R2^2 + (sX2)^2}\ \text{N-m}$$

$$T \;\alpha\; \frac{sR2}{R2^2 + (sX2)^2}\ \text{N-m}$$

Since E2 is also constant

i) When slip is zero torque is also zero, hence curve will start from origin



Torque-slip characteristics(2/3)

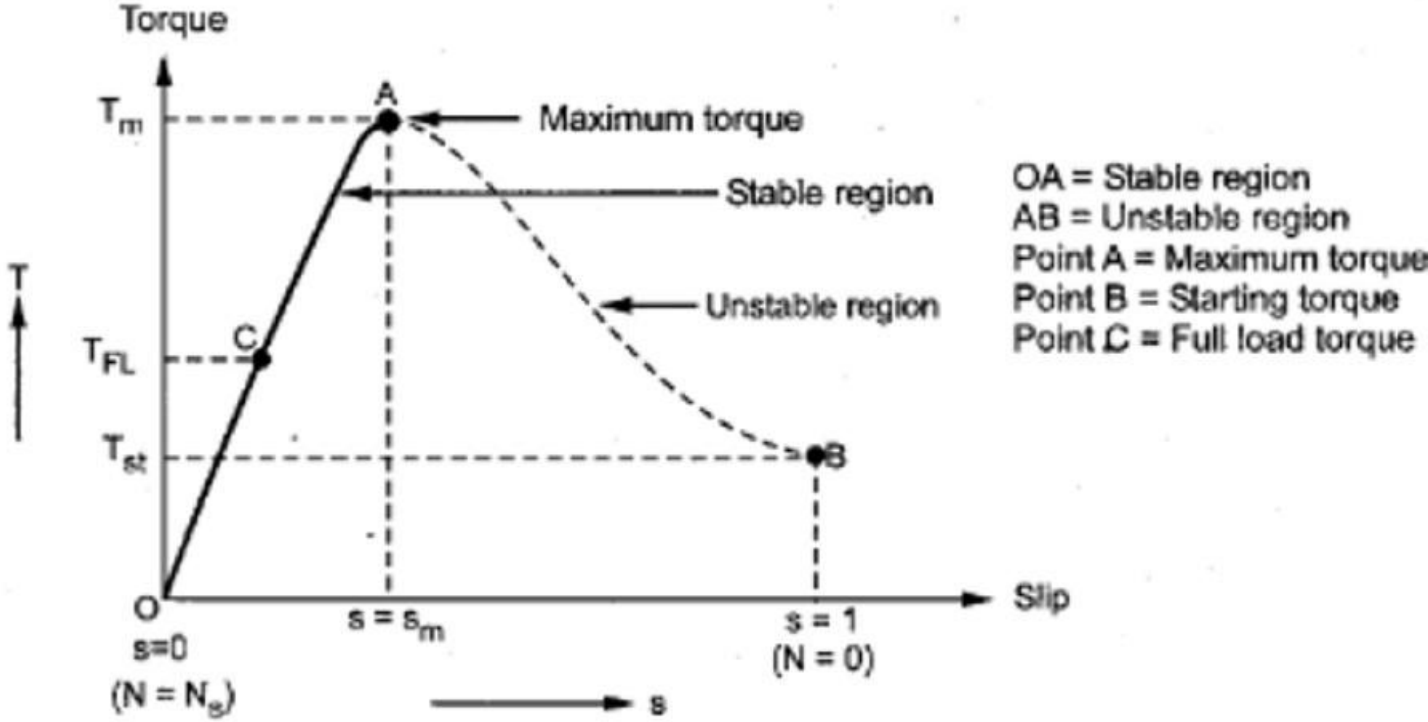
ii) Low slip region:

In low slip region, 's' is very very small. Due to this, the term$(SX_2)^2$ is so small as compared to R2 2 that it can be neglected.

$$\text{Therefore } T = \frac{sR_2^{\,2}}{R_2^{\,2}} \;\alpha\; s$$; as R2 is constant

Hence in low slip region torque is directly proportional to slip. Hence the graph is straight line in nature.

At N = Ns, s = 0 hence T = 0.



Torque-slip characteristics(3/3)

iii) At $s=R_2/X_2$, we get maximum torque

iv) High slip region

- In this region, slip is high i.e. slip value is approaching to 1. Here it can be assumed that the term R_2^2 is very very small as compared to $(s\,X_2)^2$.
- Hence neglecting R_2^2 from the denominator, we get

$$T \,\alpha\, \frac{sR2}{(sX2)^2} \,\alpha\, \frac{1}{s}$$

- So in high slip region, torque is inversel proportional to the slip.
- Hence its nature is like rectangular hyperbola.