Unit - 3(b)

Three - Phase Induction Motors

Introduction

* With the almost universal adoption of a.c system of distribution of electrical energy, the field of application of a.c. motors have widened considerably.

* A motor is an electromechanical energy conversion device. It converts the input electrical energy to mechanical energy (rotation).

* An electric motor which runs on a.c. supply is called an a.c motor.

* AC motors are classified based on the principle of operation as follows:

A.C. Motors

- Synchronous Motors
  - Plain Synchronous Motors
  - Super-Synchronous Motors
- Asynchronous Motors
  - Induction Motors
    - Squirrel cage
      - Single cage
      - Double cage
    - Slip ring
  - Commutator Motors
    1. Series
       a. single-phase
       b. universal
    2. Compensated
       a. conductively
       b. inductively
    3. Shunt
       a. compensated
       b. simple
    4. Repulsion

* Out of all these motors, three - phase induction motors are widely used for industrial applications.

* Induction motors have the following advantages :-
  i) Its construction is rugged, simple and almost unbreakable.
  ii) Its cost is low & is highly reliable
  iii) Its efficiency is high
  iv) It works with reasonably good power factor at rated load
  v) Its maintenance requirements are less.
  vi) Induction motors are self - starting. Hence, motors of smaller ratings do not require a starter. The starting arrangements for larger motors are fairly simple.

* However, they have the following disadvantages :-
  (i) It is essentially a constant speed motor & the speed cannot be varied easily.
  (ii) Its speed reduces to some extent with increase in load.
  (iii) It has somewhat lesser starting torque.

Construction

* A three - phase induction motor essentially consists of two parts :-
  a) Stator
  b) Rotor

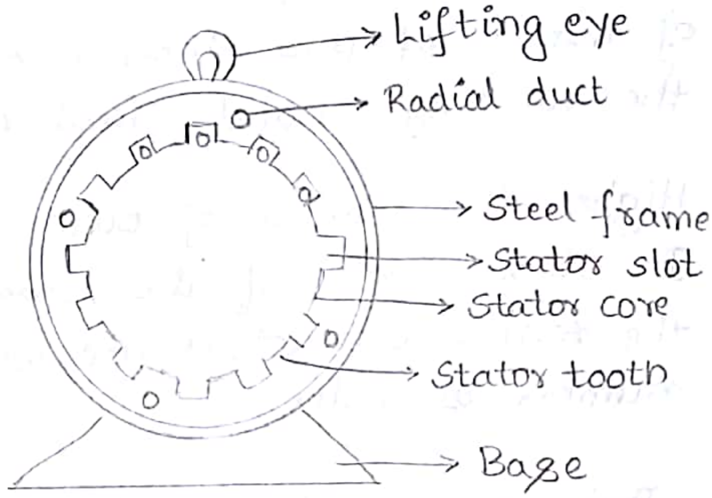
* The stator is the stationary part while the rotor is the rotating part of the induction motor.

* Stator

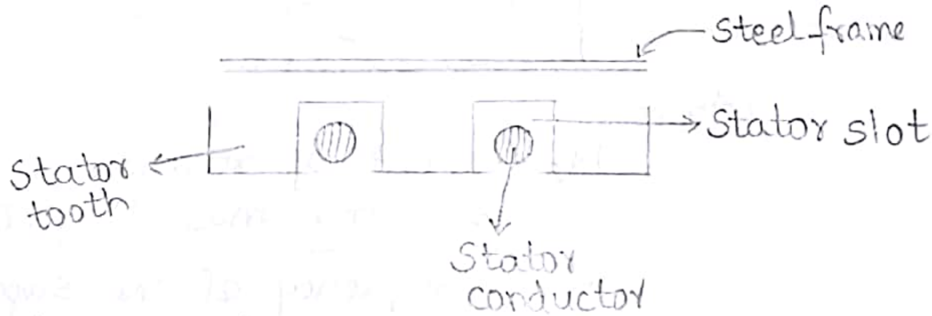
→ The stator core is a hollow cylindrical structure.

→ It is made up of high-grade, low electrical loss, thin silicon steel laminations, each about 0.4 mm thick.

→ These laminations are slotted on the inner periphery.



[Cross-sectional view of stator]



[Enlarged view of a part of stator]

→ Large number of uniform slots are cut on the inner periphery. The stator conductors are placed inside these slots.

→ The stator slot might house one or more conductors. The stator conductors are always insulated from one another & also from the slots.

→ The conductors are connected as a balanced star or delta winding. These are called the stator conductors.

→ When three-phase supply is given to the stator conductors, a magnetic field of constant magnitude, and rotating in space is produced.

→ The conductors are wound to obtain a definite number of poles (an electromagnet). The choice of number of poles depends on the speed of the rotating magnetic field required.

→ Higher the number of poles, lesser is the speed. In other words, if the speed required is lower, the stator conductors are wound to get higher number of poles.

→ This is according to the relation,

$$\boxed{N_s = \frac{120f}{p}}$$

where

N_s = speed of rotation of the rotating magnetic field in rpm

f = frequency of the supply

p = number of poles.

The speed of rotation of the rotating magnetic field is also called as <u>synchronous speed</u> (N_s)

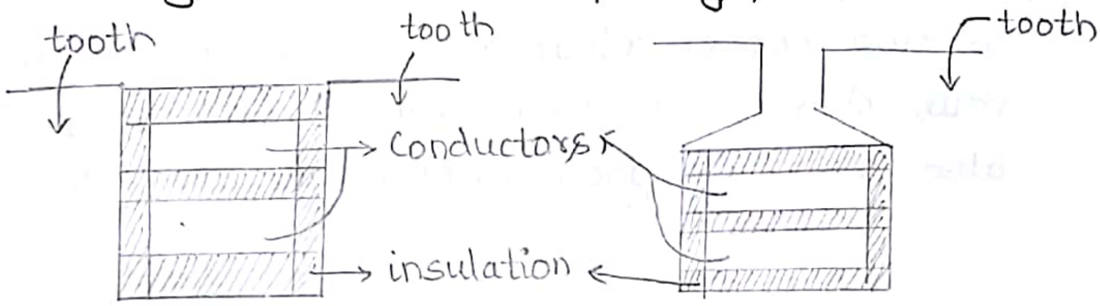
→ Radial ducts are provided for cooling purposes.

<u>Note</u>:- The number of poles 'p', produced in the rotating field is $p = 2n$, where 'n' is the number of slots per pole per phase.

→ In large motors (where more number of conductors need to be placed in each slot), the slots are of open type to facilitate insertion of coils, which are well insulated before being placed in the slots.

→ In small size motors, the slots are semi-closed type.

→ The coils may be externally wound & inserted through the narrow openings, one wire at a time.



(open slot) (Semi-closed slots)

* <u>Rotor</u>

→ The rotor is the rotating part of the induction motor. It is mounted on a shaft to which any mechanical load can be connected.

→ The rotor is placed inside the stator. The core is also laminated in construction and uses cast iron or silicon steel.

→ It is cylindrical, with slots on its periphery.

→ The rotor conductors are placed in rotor slots.

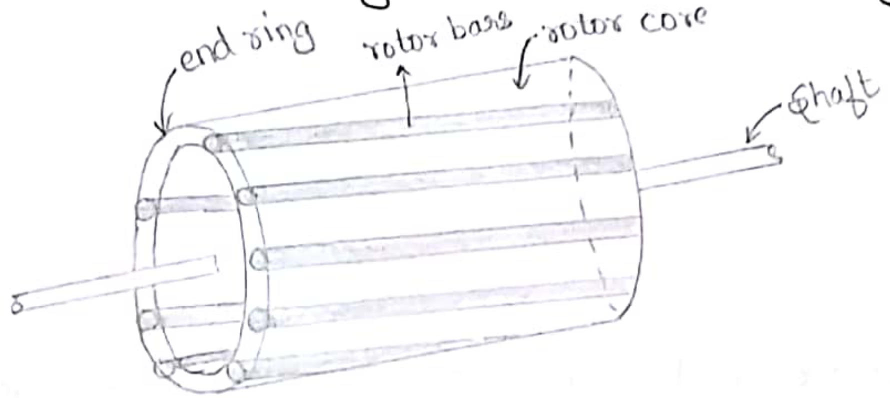
→ There are 2 types of rotors

a) squirrel-cage rotor

b) slip-ring (wound rotor) rotor

→ Squirrel Cage rotor

- Nearly 90% of the induction motors in various applications have squirrel-cage rotor.
- The rotor core is cylindrical and is built up of thin laminations.
- The rotor contains parallel slots in which uninsulated heavy bars of copper or aluminium are placed. They are called as rotor conductors. One bar is placed in one slot.
- All bars are brazed or welded at both ends to two copper rings called the end rings, thus short circuiting them at both ends. This also provides good mechanical strength.



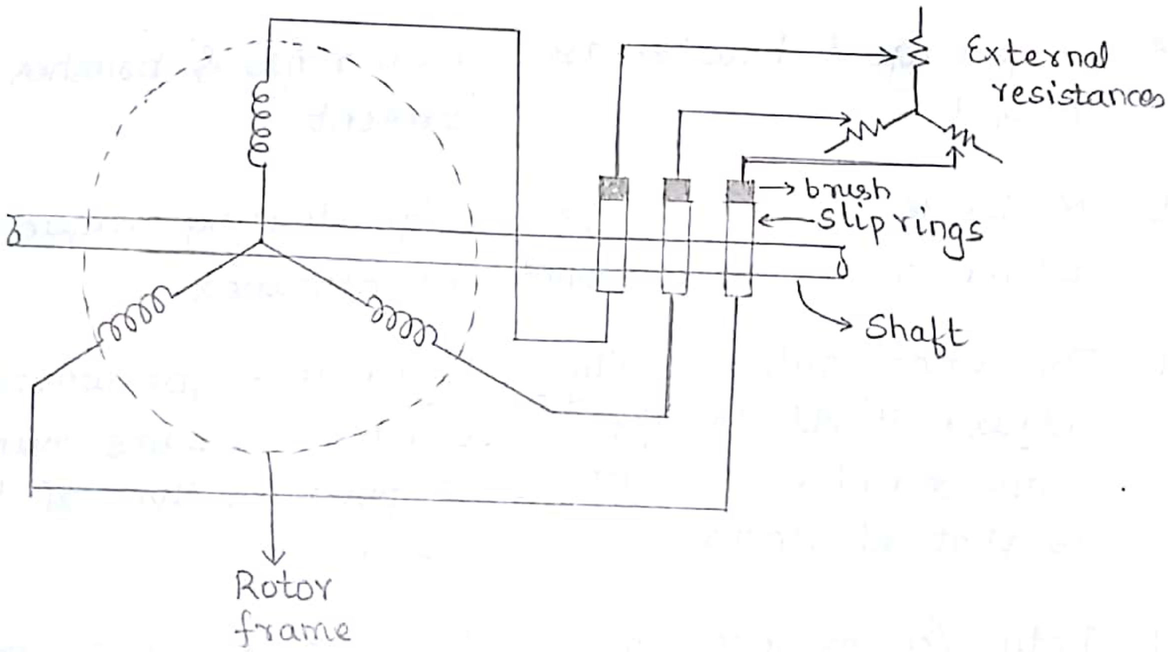
- As the bars are permanently shorted to each other through end rings, the entire rotor resistance is very small. Therefore, no external resistance can be added. Therefore, during starting the torque cannot be changed.
- In this type of rotor, the slots are not parallel to the shaft, but are skewed slightly. This offers the following advantages:
  - i) reduces the noise due to magnetic hum and makes the motor operation quieter
  - ii) it reduces the magnetic locking tendency between the stator teeth & rotor teeth

→ Phase-wound (slip-ring) rotor

⁜ In this type of construction, the rotor is laminated, cylindrical core having uniform slots in its outer periphery.

⁜ The rotor slots house the rotor winding (3-phase winding) connected in star or delta

⁜ The open ends of the winding are brought out and connected to three slip rings, mounted on the rotor shaft, with carbon brushes resting on them.

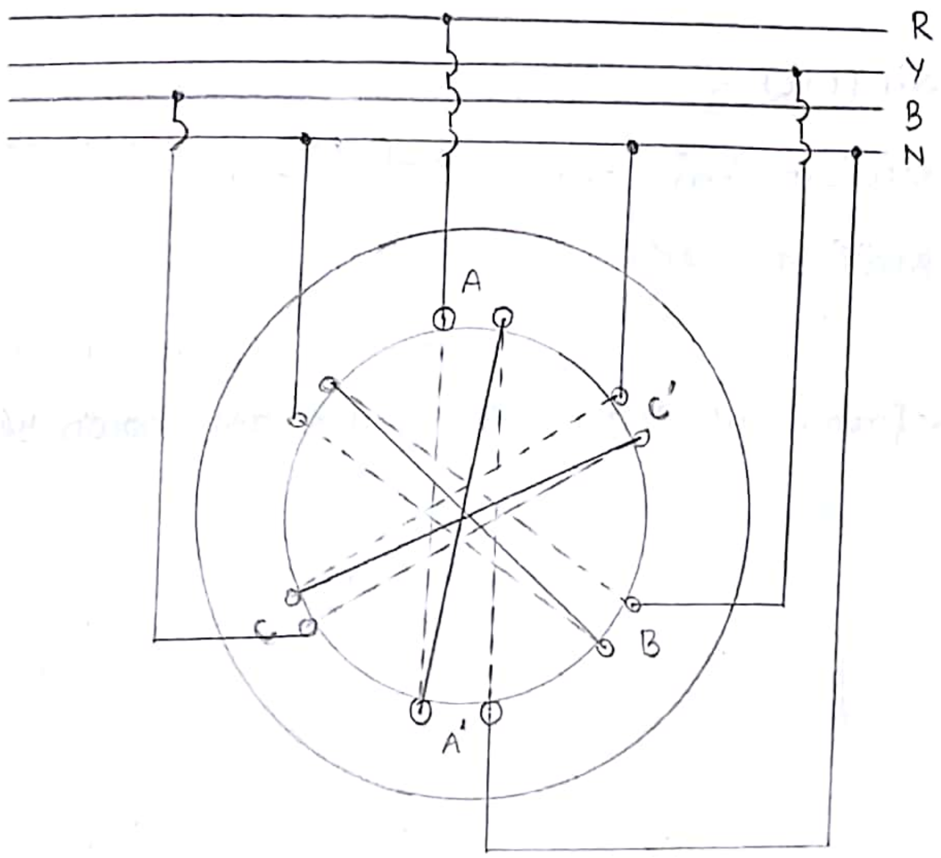


⁜ Using the slip-ring & brush assembly, it is possible to connect external resistances which are used as starters for effective starting of the motor.

⁜ In the running condition, the slip rings are shorted. This is possible by connecting a metallic collar which gets pushed and connects all slip rings together, shorting them. At the same time brushes are also lifted from the slip rings. This reduces frictional loss, wear & tear.

	Squirrel-cage rotor	Slip-ring rotor.
1.	Rotor consists of solid copper bars which are shorted with the help of end rings	Rotor consists of conductors connected in star or delta connection.
2.	Construction is simple	construction is complicated
3.	External resistances cannot be added	Slip rings & brushes can be used to add external resistances
4.	Slip rings & brushes are absent	Slip rings & brushes are present.
5.	Moderate starting torque which cannot be controlled	High starting torque can be obtained.
6.	The rotor automatically adjusts itself for the same number of poles as that of stator	Rotor must be wound for exactly the same number of poles as that of the stator.
7.	Rotor copper losses are low & hence the efficiency is high	Rotor copper losses are relatively higher & hence the efficiency is relatively lower.
8.	Construction is simple, robust & maintenance-free	Rotor is delicate & frequent maintenance is necessary & hence is costly.
9.	Speed control by rotor resistance is not possible	Rotor resistance starter can be used.

Production of Rotating Magnetic Field (RMF)



* It will now be shown that when three-phase windings displaced in space (i.e., physically displaced) by 120°, are supplied by three-phase currents, displaced in time by 120°, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

* The three-phase windings of the stator (connected in star or delta) are supplied by a balanced 3ϕ AC supply. The three phase currents, displaced from each other by 120°, flow through the conductors.

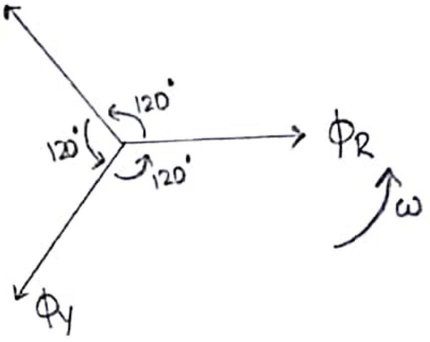
* Each alternating phase current produces its own flux which is sinusoidal. If the phase sequence

of the supply is RYB, then the equations for the three fluxes & their phasor are given below.

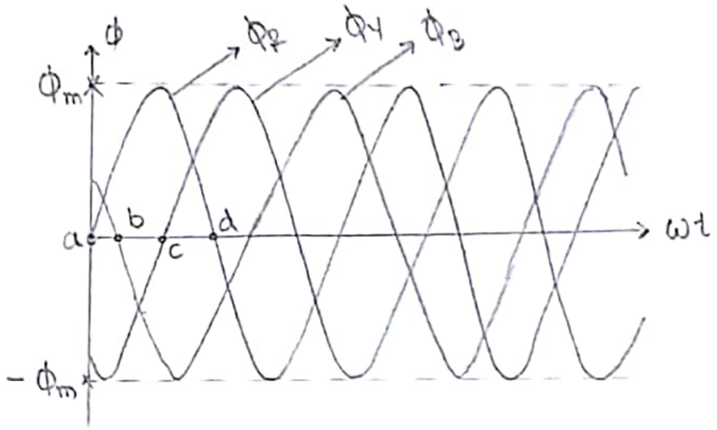
$\phi_R = \phi_m \sin(\omega t)$

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

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



* The waveforms of these fluxes are as shown below.



a → $\omega t = 0°$
b → $\omega t = 60°$
c → $\omega t = 120°$
d → $\omega t = 180°$

* The resultant flux at any instant (ωt) is given by the phasor sum of the three individual fluxes ϕ_R, ϕ_Y and ϕ_B at that instant.

* Note that the flux ϕ_R is taken as reference.

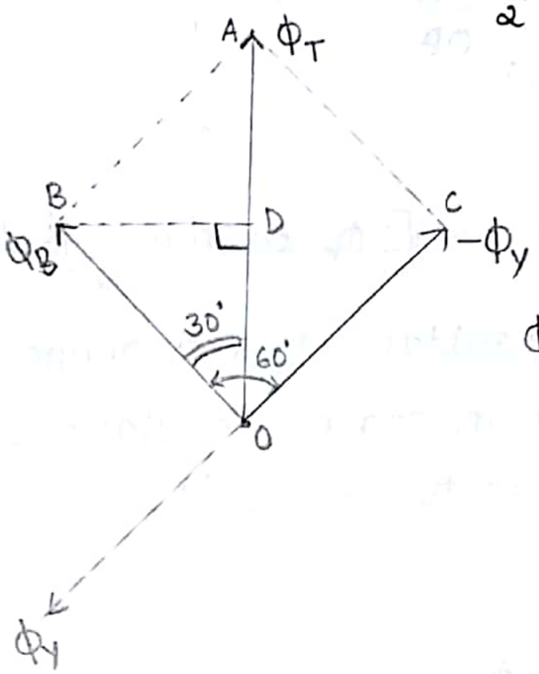
* Since the windings are balanced (i.e., each phase has the same impedance) & the supply is also balanced, the magnitude (amplitude) of each flux is ϕ_m.

* At $\omega t = 0^\circ$,

$$\phi_R = \phi_m \sin(0) = 0$$

$$\phi_y = \phi_m \sin(0 - 120^\circ) = \phi_m \sin(-120^\circ) = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(0 - 240^\circ) = \phi_m \sin(-240^\circ) = \frac{\sqrt{3}}{2}\phi_m$$



$\phi_T \rightarrow$ Resultant flux.

BD is drawn perpendicular to OA. This perpendicular bisects OA. Thus, $OD = DA = \frac{\phi_T}{2}$.

In Δ^{le} OBD, $\angle BOD = 30^\circ \Rightarrow \cos 30^\circ = \frac{OD}{OB} = \frac{\phi_T/2}{\phi_B}$

$$\Rightarrow \phi_T = 2\phi_B \cos 30^\circ$$

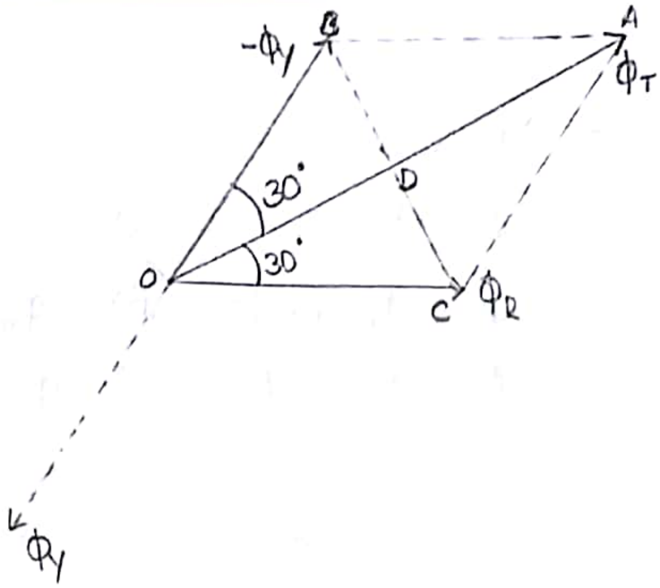
$$= 2\left(\frac{3}{2}\phi_m\right)\cos 30^\circ$$

$$\Rightarrow \phi_T = \frac{3}{2}\phi_m$$

$$\Rightarrow \phi_T = 1.5\,\phi_m$$

So magnitude of ϕ_T is $1.5\phi_m$ and its direction is vertically upwards.

* At $\omega t = 60°$.



$\phi_R = \phi_m \sin(60°) = \frac{\sqrt{3}}{2}\phi_m$.

$\phi_Y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = \phi_m \sin(-180°) = 0$

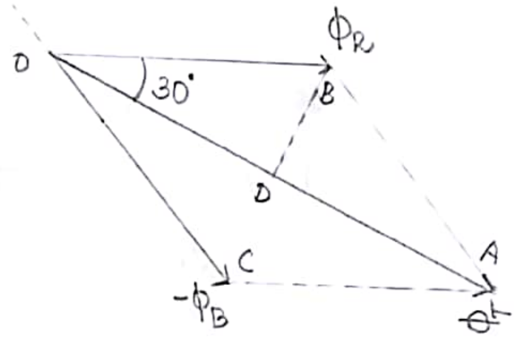
In Δ^{le} DOC, $\cos 30° = \frac{OD}{OC}$

$\therefore \cos 30° = \frac{\phi_T/2}{\phi_R}$

$\Rightarrow \phi_T = 2\cos 30°\, \phi_R = 2\frac{\sqrt{3}}{2}\phi_m \cos 30° = \frac{3}{2}\phi_m = 1.5\phi_m$

Therefore, the resultant has a magnitude of $1.5\phi_m$ and has rotated in space, in clockwise direction, through 60° ($\omega t = 0$ to $\omega t = 60°$).

* At $\omega t = 120°$



$\phi_R = \phi_m \sin(120) = \frac{\sqrt{3}}{2}\phi_m$

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

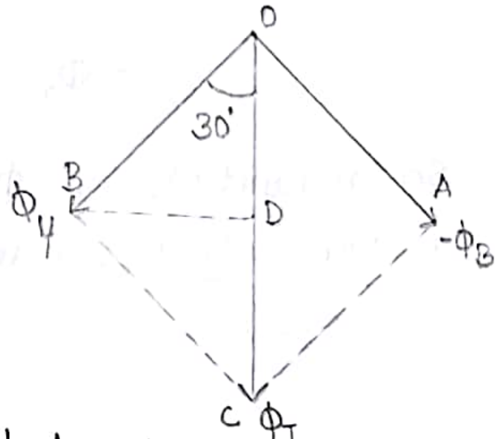
$\phi_B = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m$

In Δ^{le} BOD, $\cos 30° = \frac{\phi_T/2}{\phi_R} = \frac{\phi_T/2}{\sqrt{3}/2\,\phi_m}$

$\therefore \phi_T = 2 * \frac{\sqrt{3}}{2}\phi_m \cos 30° = \frac{3}{2}\phi_m = 1.5\phi_m$.

The resultant flux has a magnitude of $1.5\phi_m$ & has rotated through 60° from the previous position.

* At $\omega t = 180°$,



$\phi_R = \phi_m \sin(180) = 0$

$\phi_Y = \phi_m \sin(+60°) = +\frac{\sqrt{3}}{2}\phi_m$

$\phi_B = \phi_m \sin(+120) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_T = 2 * \frac{\sqrt{3}}{2}\phi_m \cos 30° = 1.5\phi_m$.

The resultant flux has a magnitude of $1.5\phi_m$ & has rotated in space through 60° from the previous position

* So, for an electrical half cycle of 180°, even the resultant flux ϕ_T has rotated through 180° in space.

* Conclusions

1. The resultant of the three alternating fluxes, separated from each other by 120°, has a constant amplitude of $1.5\,\phi_m$ where ϕ_m is the maximum amplitude of an individual flux due to any phase.

2. The resultant always rotates with a certain speed in space.

* This shows that when a three-phase windings in the stator of the induction motor is supplied from a balanced 3ϕ alternating source, a magnetic field of a constant magnitude ($1.5\phi_m$), rotating in space is produced.

* Though nothing in the stator is physically rotating, the field produced by the stator conductors is rotating in space, having a constant magnitude.

* The speed of the rotating magnetic field for a standard frequency is called synchronous speed (N_s) given by

$$\boxed{N_s = \frac{120f}{p}}$$

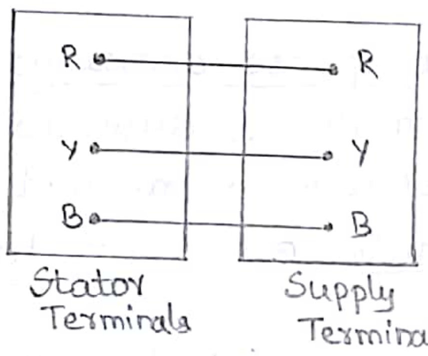
where $f \rightarrow$ supply frequency

$p \rightarrow$ number of poles of stator winding

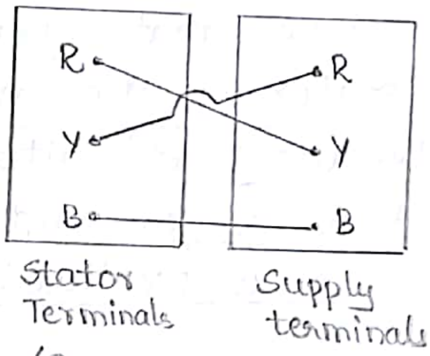
An important note

* The direction of the RMF depends on the supply phase sequence. The phase sequence of the supply can be reversed by interchanging any two terminals of the 3ϕ winding while connecting it to the 3ϕ supply.

* Thus, by interchanging any two terminals of the 3ϕ winding while connecting it to a 3ϕ supply, the direction of RMF gets reversed. Hence, the direction of rotation of induction motor also gets reversed.



(Positive Rotation)



(Reversed Rotation)

Working Principle (How does an induction motor rotate?)

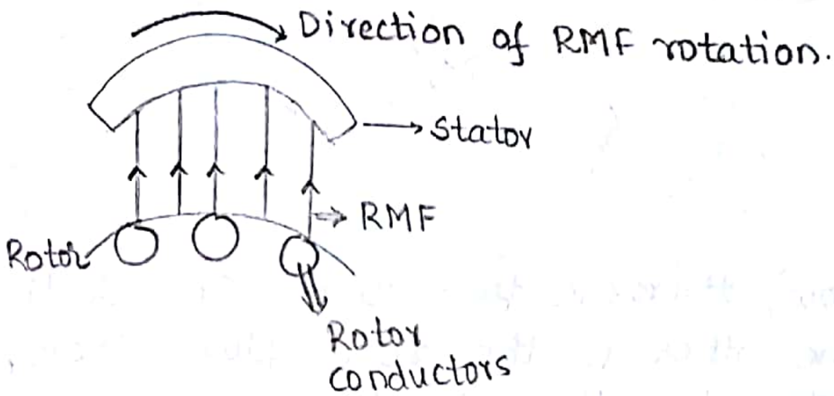
* Induction motors work on the principle of electro-magnetic induction.

* When a 3ϕ supply is given to the 3ϕ stator winding, a rotating magnetic field of constant magnitude is produced. The speed of the RMF is given by

$$N_s = \frac{120f}{p}$$

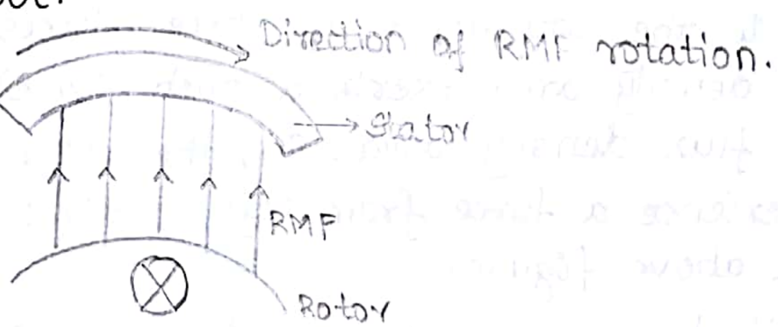
f = supply frequency
p = number of poles

* This rotating field produces the effect of rotating magnetic poles. Let the direction of rotation of the RMF be clockwise, as shown below.



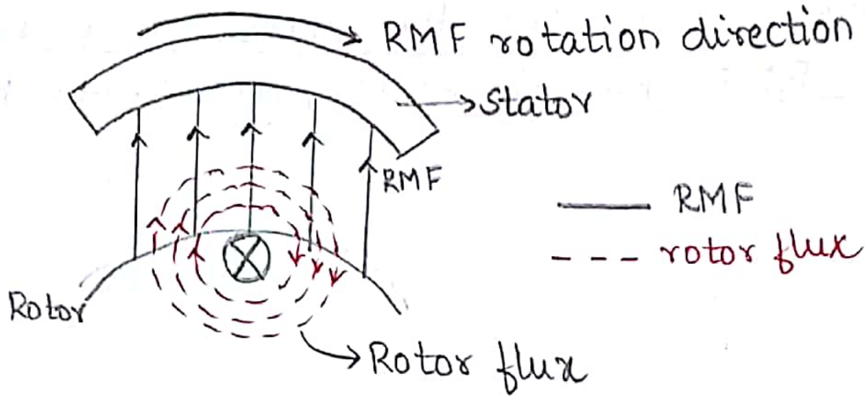
* Now at this instant, the rotor is stationary (standstill) and the stator RMF is rotating. Therefore, there is a relative motion between RMF & rotor conductors. Now this gives a rate of change of flux linkages (conductor stationary, field linking changing). Since the flux linkage changes, an EMF is induced in the rotor conductors. This is called rotor induced EMF.

* As the rotor forms a closed circuit, ac currents flows in the rotor conductors. Let the direction of the current be going into the paper, denoted by ⊗ symbol.

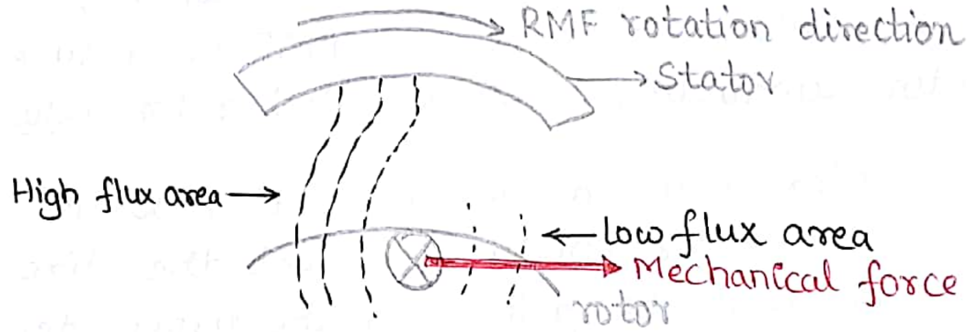


* Any current carrying conductor produces its own flux. So the rotor conductors carrying current produce a flux called rotor flux. Its magnitude depends on the rotor current, while the direction can be found using right hand thumb rule. For the assumed

direction of current, the direction of rotor flux is clockwise as shown below.



* Now, there are two fluxes. One is the RMF, & the other is the rotor flux. These two fluxes interact with each other as shown below. On the left of the rotor conductors, two fluxes are in the same direction and hence add up. This gives high flux area. On the right side, two fluxes are in opposite direction & they cancel each other to give low flux area.



* Due to the interaction of these fluxes, the high flux density area exerts a push (force) on the low flux density area. So, the rotor conductors experience a force from left to right in this case. (see above figure).
* Similarly, every rotor conductor experiences force which is exerted on the rotor. Observe that the direction of the force experienced is same as the direction of RMF. Hence, <u>rotor starts rotating in the same direction as that of the RMF.</u>

* Explanation in terms of Lenz's law.

→ According to Lenz's law, the direction of induced current in the rotor is so as to oppose the cause producing it.

→ The cause for rotor current is the rotor induced EMF which is induced because of the relative motion between the RMF & the rotor conductors.

→ Hence to oppose this relative motion i.e., to reduce the relative speed, the rotor experiences a turning force (i.e., torque) in the same direction as that of the RMF and tries to catch up the speed of the RMF.

→ Thus, the motor always rotates in the same direction as that of RMF.

* Let

N_s = Speed of RMF (in rpm) or synchronous speed.

N = Speed of rotor rotation (in rpm)

$N_s - N$ = Relative speed between RMF & rotor (in rpm).

* Can $N = N_s$?

→ When the rotor starts rotating, it tries to catch the speed of RMF.

→ If it did succeed in catching up to RMF speed, then the relative motion between RMF & rotor would be zero ($N_s - N = 0$). This implies there would be no induced EMF, and no rotor current. Hence, there would be no rotor flux, no interaction of flux & hence no torque. Eventually, the motor would stop. But immediately there would exist a relative speed (or relative motion) between the rotor & RMF, and the motor would start.

→ But due to inertia of rotor, the rotor is never able to catch up to the RMF speed, in steady state.

→ Hence, the rotor of the induction motor never rotates at synchronous speed. Thus,

$$\boxed{N \neq N_s}$$

→ In addition, since the rotor is unable to catch up to the RMF speed, we can write

$$\boxed{N < N_s}$$

→ Since it does not run at synchronous speed, induction motors are classified under asynchronous motors.

Slip & Its Significance

* When the rotor of the induction motor rotates, (in the same direction as that of RMF), it runs at a speed (N) less than the speed of the RMF i.e., the synchronous speed (N_s).

* The difference between the synchronous speed and the rotor speed is called the slip speed.

$$\therefore \boxed{\text{Slip speed} = (N_s - N)}$$

* This speed decides the magnitude of the induced EMF & rotor current, which in turn decide the torque produced.

* Generally, the slip speed is expressed as a fraction of the synchronous speed.

* The slip of an induction motor is defined as the difference between the synchronous speed (N_s) and the speed of rotor rotation (N), expressed as a fraction of synchronous speed. It is represented by 's'.

$$\therefore \boxed{s = \frac{(N_s - N)}{N_s}}$$

Since it is a ratio of speeds, slip has no unit.

* In percentage, slip is expressed as,

$$\boxed{\% s = \left(\frac{N_s - N}{N_s}\right) * 100}$$

* In terms of slip, the rotor speed i.e., the speed of the induction motor (N) can be expressed as,

$$\boxed{N = N_s(1-s)}$$ in rpm, if N_s is in rpm.

* Slip at standstill (at rest)

→ When the motor is at standstill i.e., when it is at rest, the speed is zero. Thus at standstill, $N = 0$.

$$\therefore S_{standstill} = \frac{N_s - 0}{N_s} = \frac{N_s}{N_s}.$$

$$\therefore \boxed{S_{standstill} = 1}$$

→ Thus, the maximum value of slip for an induction motor is 1.

* Can $S = 0$?

→ If slip is zero,

$$S = 0 = \frac{N_S - N}{N_S}$$

$$\Rightarrow N_S - N = 0$$

$$\text{or } N_S = N \text{ .... IMPOSSIBLE.}$$

→ Since $N_S = N$ is not possible for an induction motor, we conclude that slip of an induction motor can NEVER be zero.

* Practically, motor slip lies between 1% and 5% i.e., 0.01 to 0.05.

* The slip of the motor when it rotates when full mechanical load (rated load) is connected to its shaft is called the full-load slip.

* Thus, we can write the range of slip as,

$$\boxed{0 < S \leq 1}$$

Indicates that slip is never zero

Indicates that Slip can be unity

Note:-

→ As the motor gets loaded, the speed reduces. i.e., the motor retards. Since 'N' reduces, $(N_S - N)$ increases. Hence we say that as the motor is loaded, the motor tends to retard and its slip increases.

Effects of slip

* In case of an induction motor, $N = 0$ at start & $s = 1$. Under this condition as long as $s = 1$, the frequency of the induced emf in the rotor is same as the supply frequency.

* As the motor starts rotating & it gathers speed, the frequency of induced EMF is affected by the slip. Due to this, several other parameters are affected.

* Effect on rotor frequency

→ The speed of rotation of RMF is given by,

$$N_s = \frac{120f}{p}$$

where f = supply frequency.

→ At start when $N = 0$, $s = 1$ and stationary rotor has maximum relative motion w.r.t RMF & hence maximum EMF gets induced in the rotor conductors. The frequency of the induced EMF at start is same as that of the supply frequency.

→ As the motor rotates & reaches its speed $N (< N_s)$, the relative speed of rotor w.r.t RMF reduces and becomes equal to the slip speed $N_s - N$. The induced EMF depends on the rate of change of flux linkages i.e., on the relative motion. Hence in running condition, the magnitude of the induced EMF & its frequency both reduce.

→ Remember that the rotor is always wound for the same number of poles as that of stator i.e., p.

→ If f_r is the frequency of rotor induced EMF in running condition at slip speed $N_s - N$, then we can write

$$(N_s - N) = \frac{120 f_r}{p}.$$

$$\therefore \quad \frac{N_s - N}{N_s} = \frac{120 f_r / p}{120 f / p}$$

But $\dfrac{N_s - N}{N_s} = s$, the slip.

$$\therefore \quad s = \frac{f_r}{f}$$

$$\Rightarrow \boxed{f_r = sf}$$

Thus, frequency of rotor induced EMF is slip times the supply frequency.

* Effect on magnitude of rotor induced EMF.

→ When the rotor is at standstill $(N=0, s=1)$, maximum EMF is induced in the rotor.

Let,

E_2 = EMF induced in rotor at standstill. (per phase EMF)

→ As the rotor gains speed, 'N' increases & hence the relative speed between RMF and rotor i.e., $N_s - N$ decreases. Hence the rotor induced EMF also decreases. Let,

E_{2r} = Rotor induced EMF per phase in running condition.

→ Now,

$$E_2 \propto N_s \quad \text{and} \quad E_{2r} \propto (N_s - N).$$

$$\therefore \frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s}.$$

But $$\frac{N_s - N}{N_s} = s.$$

$$\therefore \frac{E_{2r}}{E_2} = s$$

$$\Rightarrow \boxed{E_{2r} = s E_2}$$

Thus, we say that the magnitude of induced EMF in the rotor is equal to slip times the magnitude of the rotor induced EMF at standstill.

* Effect on torque

→ The EMF induced in the rotor in running condition,

$$E_{2r} \propto (N_s - N)$$

→ The rotor current during running condition is directly proportional to this induced EMF

$$I_{2r} \propto E_{2r}.$$

→ The torque produced is directly proportional to the rotor current.

$$T \propto I_{2r}$$

$$\Rightarrow T \propto (N_s - N)$$

$$T = k(N_s - N) \qquad k = \text{constant}$$

$$T = k N_s \frac{(N_s - N)}{N_s}$$

Let $k N_s = k_1$, another constant.

$$\therefore T = k_1 s \Rightarrow \boxed{T \propto s}$$

→ This shows that as slip increases, the torque on the rotor correspondingly increases.

Applications of Induction Motors.

1. Squirrel-cage type motors have moderate starting torque & constant speed characteristics. Hence they are preferred for driving fans, blowers, water pumps, grinders, lathe machines, drilling machines, printing machines, etc.

2. Slip-ring induction motors can have high starting torque, as high as maximum torque. Hence they are preferred for lifts, hoists, elevators, cranes, compressors.

Necessity of a starter

* 3ϕ Induction motors are self-starting due to the rotating magnetic field. However, certain device called the Starter is invariably used, especially with large motors.

* In 3ϕ induction motor, the magnitude of the rotor induced EMF depends on slip. This induced EMF effectively decides the magnitude of the rotor current.

* But at start, the speed of motor is zero & the slip is unity. So the magnitude of rotor induced EMF is very large at start. As rotor conductors are short circuited, the large induced EMF circulates a very high current in the rotor bars at start.

* To supply this current i.e., to induce a very large current in rotor bars, the stator has to draw a very large current from the supply.

* This current can be of the order of 5 to 8 times the full load current & it is drawn at start.

* Drawing such heavy currents, known as inrush current, has two effects :-

  i) there is a possibility of damage of the motor winding

  ii) it causes a very large line voltage drop, and the other appliances connected to the same lines may be subjected to abnormal voltage spikes, which may affect their working.

* To avoid such effects, it is necessary to limit the current drawn by the motor at start.

* The starter is a device which is used to limit high starting current drawn by the motor by reducing the supply voltage to the motor at the time of starting. Once the rotor gets accelerated, full rated voltage is applied.

* The starter not only limits the starting current but also provide protection to the induction motor against overloading & low voltage situations. It also provides protection against single- phasing (i.e., the phenomenon where one phase of the motor gets disconnected due to some faults or blown fuses).