Three Phase Induction Motors

Outline

- Three Phase Induction Motor
  - Constructional Details and Types
  - Operating Principle
  - Rotating Magnetic Field
  - Synchronous Speed
  - Slip
  - Induced EMF
  - Torque Equation

Introduction

- The three-phase induction motors are the most widely used electric motors in industry.
- They run at essentially constant speed from no-load to full-load.
- However, the speed is frequency dependent and consequently these motors are not easily adapted to speed control.
- We usually prefer d.c. motors when large speed variations are required.
- Nevertheless, the 3-phase induction motors are simple, rugged, low-priced, easy to maintain and can be manufactured with characteristics to suit most industrial requirements
- Like other electrical machines, the asynchronous machine is reversible i.e., it can operate as both a motor & a generator. The mode of operation of the machine is determined by the speed of the rotating field in relation to the motor.
- An asynchronous machine may be considered to be a transformer in the sense that the power is transferred from the stator (primary) to the rotor (secondary) winding only by mutual induction. For this reason, such a machine is often called the induction machine.

Introduction

- Like any electric motor, a 3-phase induction motor has a stator and a rotor.

- The stator carries a 3-phase winding (called stator winding) while the rotor carries a short-circuited winding (called rotor winding). Only the stator winding is fed from 3-phase supply.

- The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction and hence the name.

- The induction motor may be considered to be a transformer with a rotating secondary and it can, therefore, be described as a "transformertype"a.c. machine in which electrical energy is converted into mechanical energy.

Construction
Frame:

- It is the outer body of the motor.
- Its functions are to support the stator core and winding to protect the inner parts of the machine and serve as a ventilating housing or means of guiding the coolant into effective channels.
- The frame may be die- cast or fabricated.
- Machines up to about 50 kw rating may have frame die-cast in a strong silicon- aluminum alloy, sometimes with the stator core cast in. the frames for medium & large machines are almost exclusively fabricated.
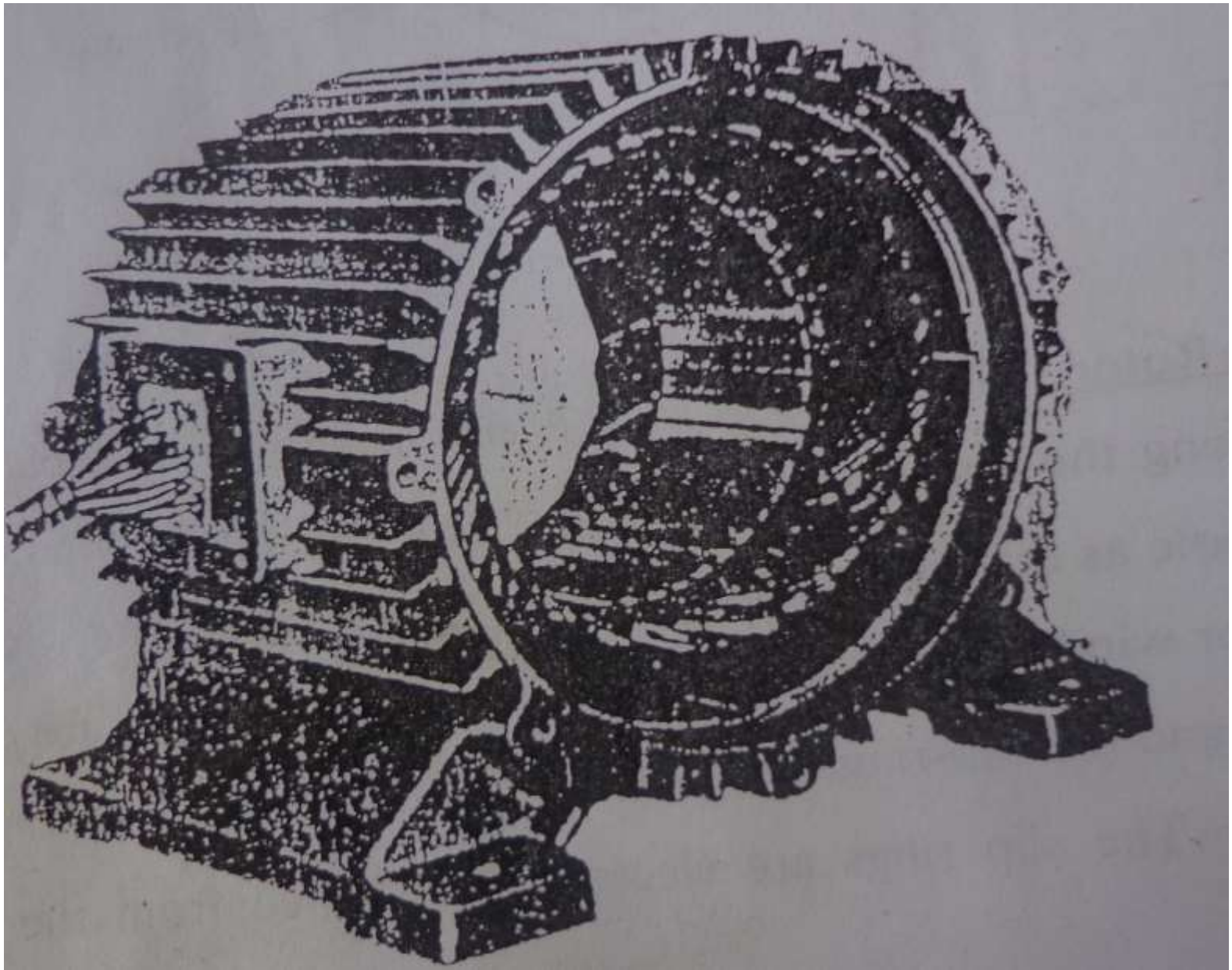
Construction
Stator or primary or field winding

- Stator is the stationary part of the motor.

- It is made up of number of circular stampings as shown in the figure 1.

- The stator core is to carry the alternating flux which produces hysteresis & eddy current losses. In order to reduce eddy currents and hysteresis loss in the stator core it is assembled of high grade, low electrical loss, and silicon steel punching.
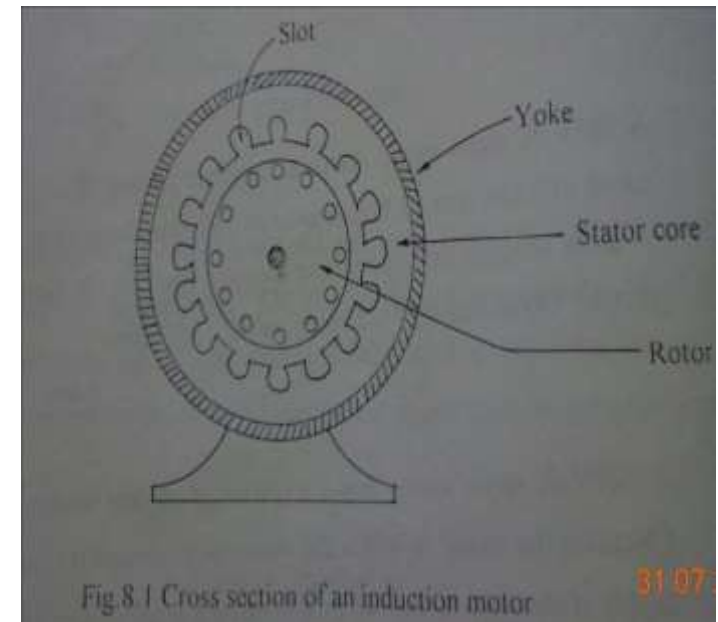

Fig.8 | Cross section of an induction motor

Figure 1: Cross-section of an Induction Motor

The air gaps between the stator and rotor is made as small as practicable (0.3 to 0.35 mm in small machines and 1 to 1.5 mm in high power machines) so as to make air- gap reluctance minimum.

Stator or primary or field winding

- The inner circumference of the stator core has alternate number of slots and teeths on which stator windings are placed.

- Generally, three phase windings are provided on these slots which are uniformly distributed and each phase windings are spaced $120°$ electrically apart.

- The winding are insulated from the slots with the help of an insulating paper.

- These three phase windings are fed from 3 phase supply.

- These windings, when supplied by 3 phase voltage, creates definite number of magnetic poles on the stator core.

- Stator core is protected by the outer covering called as yoke made of cast iron.

Rotor or secondary winding :

- The rotor comprises of a cylindrical laminated iron core, much the same as that of a DC machine with slots around the core, carrying the rotor conductors.

- It is the central rotating part of the motor.

- It is cylindrical in shape with a central shaft. The shaft is supported by bearings at both ends so that the rotor rotates freely keeping an air gap between the rotor &stator (air gap of about 1 to 4 mm).

Types of Rotor

There are two types of rotors:
1. Squirrel cage rotor
2. Phase wound rotor

Squirrel Cage Rotor:

- Almost 90% of induction motors are provided with squirrel cage rotor because of its very simple, robust & almost instructible construction.

- In cage construction, copper, brass or aluminium balls are placed, as the rotor conductors, parallel or approximately parallel to the shaft (one bar in each slot) & close to the rotor surface the conductors are not insulated from the core. Since, the rotor currents naturally follow the path of least resistance i.e., the rotor conductors.

- At both ends of the rotor, the rotor conductors are all short- circuited by the continuous end rings of similar material to that of the rotor conductors.
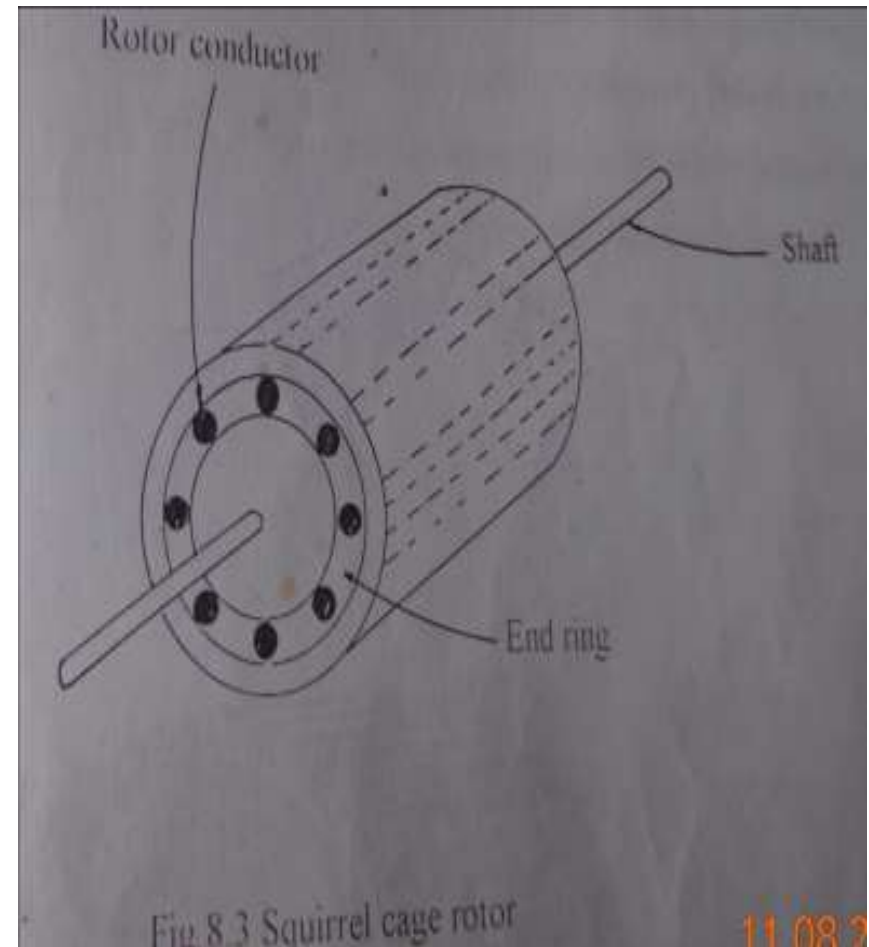

Fig 8.3 Squirrel cage rotor

Figure 3: Squirrel Cage Rotor

Phase wound rotor (Slip ring rotor)

- Phase wound rotor is wound with an insulated winding similar to that of the stator except that the number of slots is smaller & fewer turns per phase of a heavier conductor are used.

- This type of rotor are also made up of cylindrical laminated core, but has open slots along the outer circumference, on which 3- phase winding are provided.

- The three ends of the rotor winding are connected to the three separate slip- rings & the slip- rings are short circuited by the carbon brushes with or without external resistance.
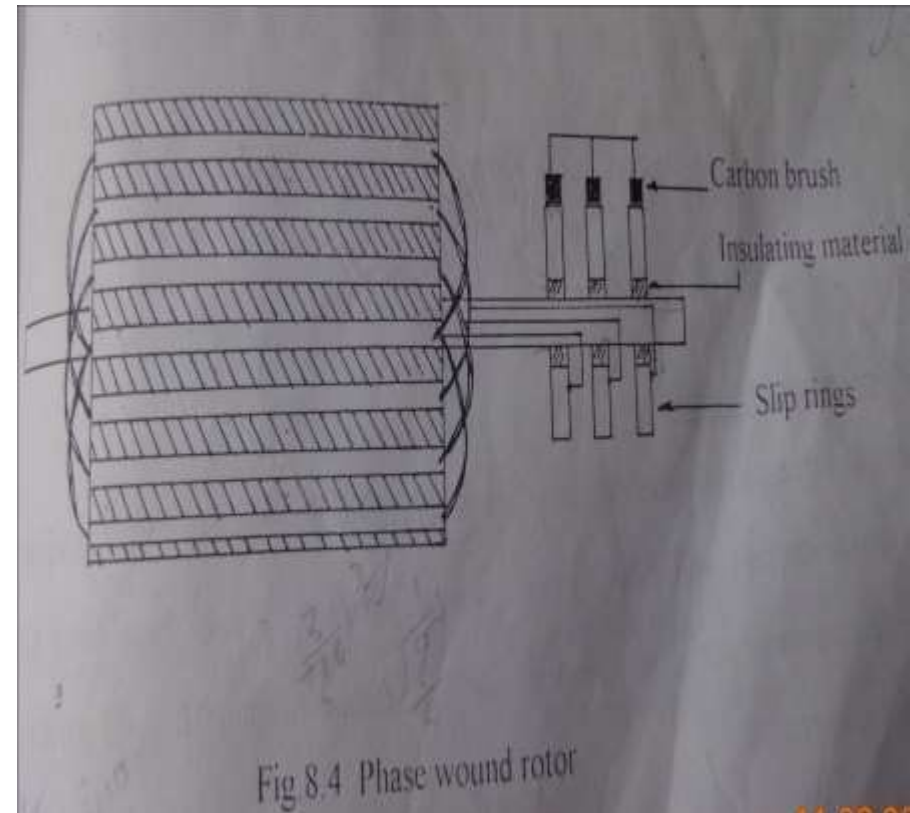

Fig 8.4 Phase wound rotor

Figure 4: Phase Wound Rotor
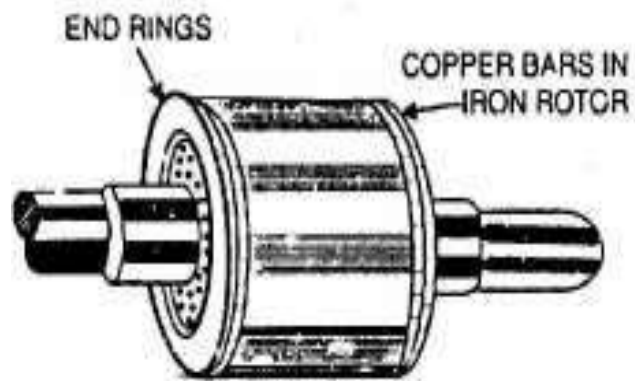
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Types of Rotor

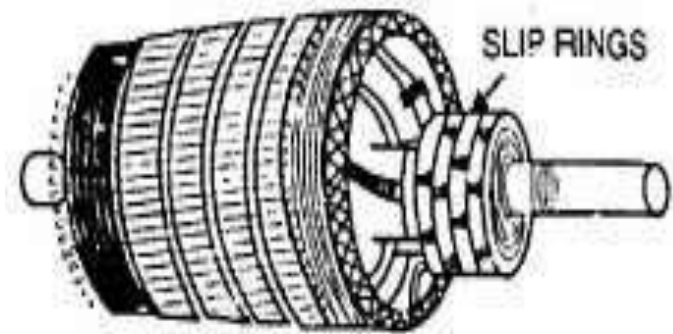
Figure 5: Squirrel Cage Rotor

Figure 6: Phase Wound Rotor

Operating Principle

- When the stator or primary winding of a 3 phase induction motor is connected to a 3 phase AC supply, a rotating magnetic field is established which rotates at synchronous speed. Hence, three phases current will flow though stator windings. These three phase current will magnetize the stator core.

- The direction of revolution of the magnetic field will depend upon the phase sequence of the primary currents and, therefore, will depend upon the order of connection of the primary terminals to the supply.

- The direction of rotation of the field can be reversed by interchanging the connection to the supply of any two leads of a $3 - \emptyset$ induction motor.

- The number of magnetic poles of the revolving field will be the same as the number of poles for which each phase of the primary or stator winding is wound.

- The speed at which the field produced by the primary currents will revolve is called the synchronous speed of the motor & is given by expression, $N_s = (120\ f)/\ p$, where f is the supply frequency &p is the number of poles on stator.
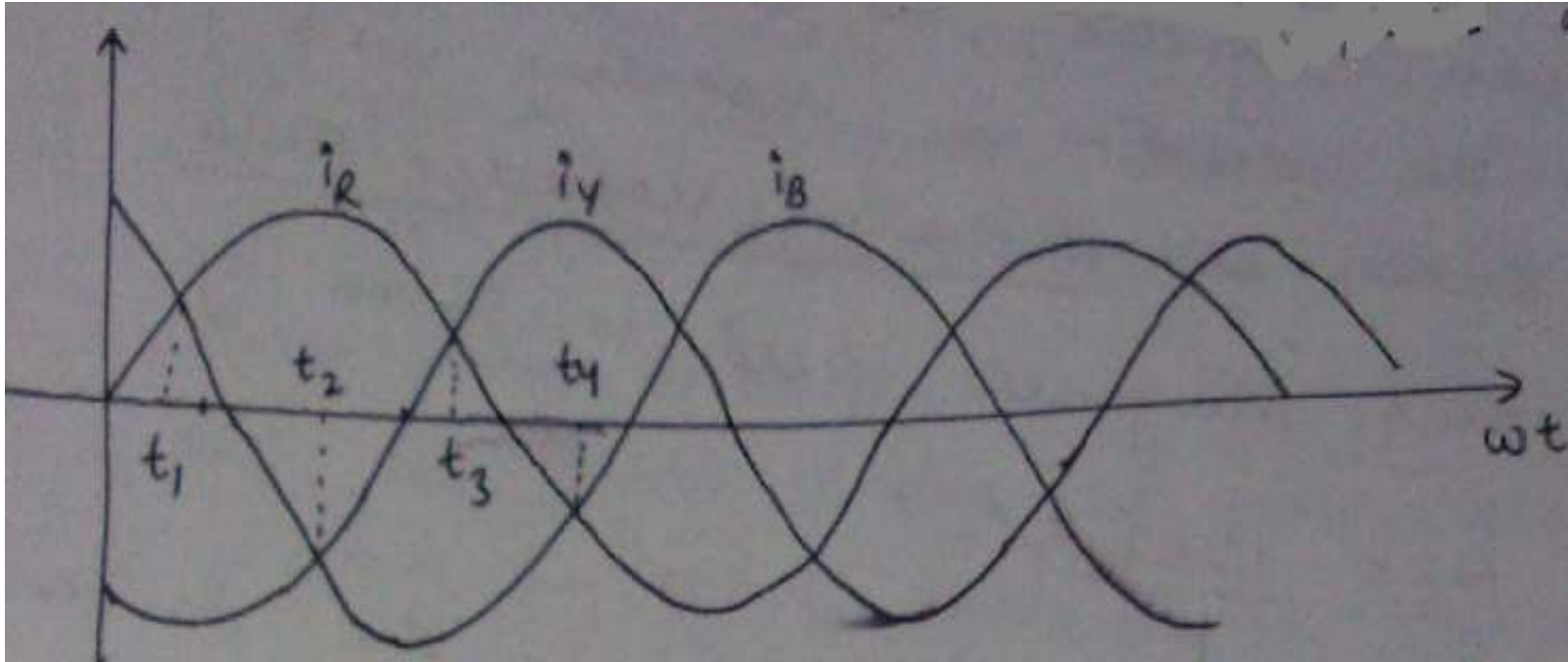
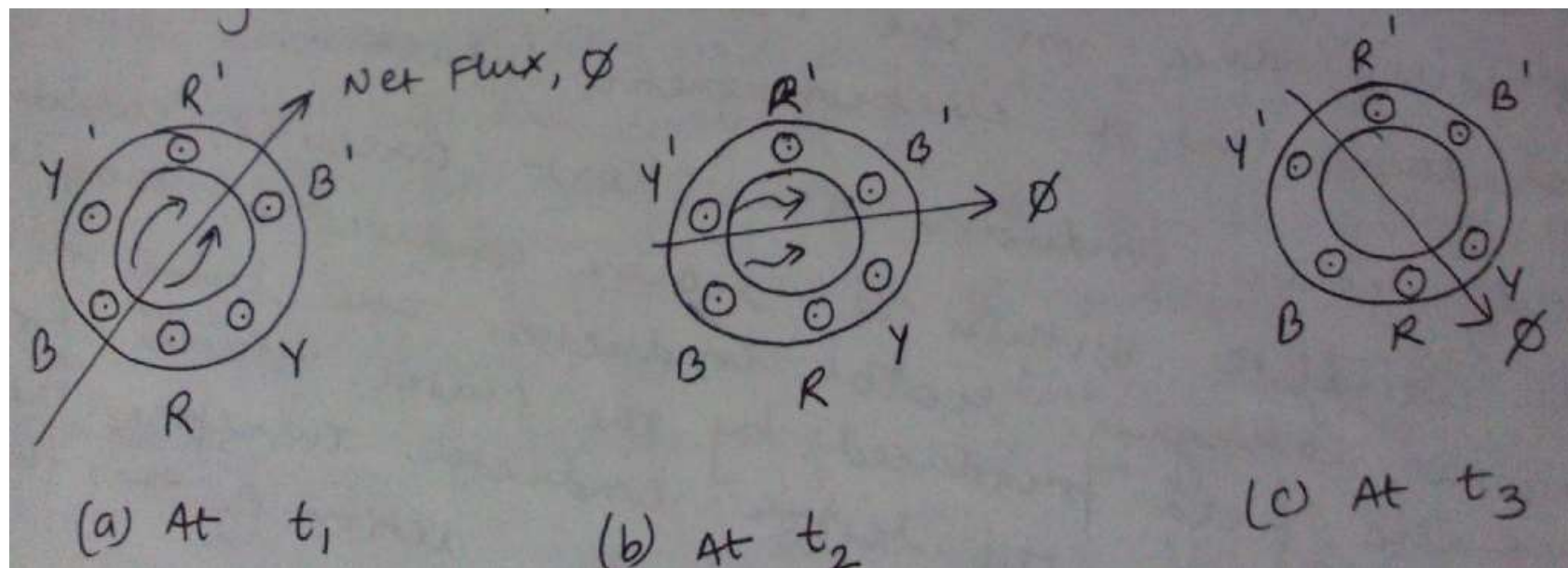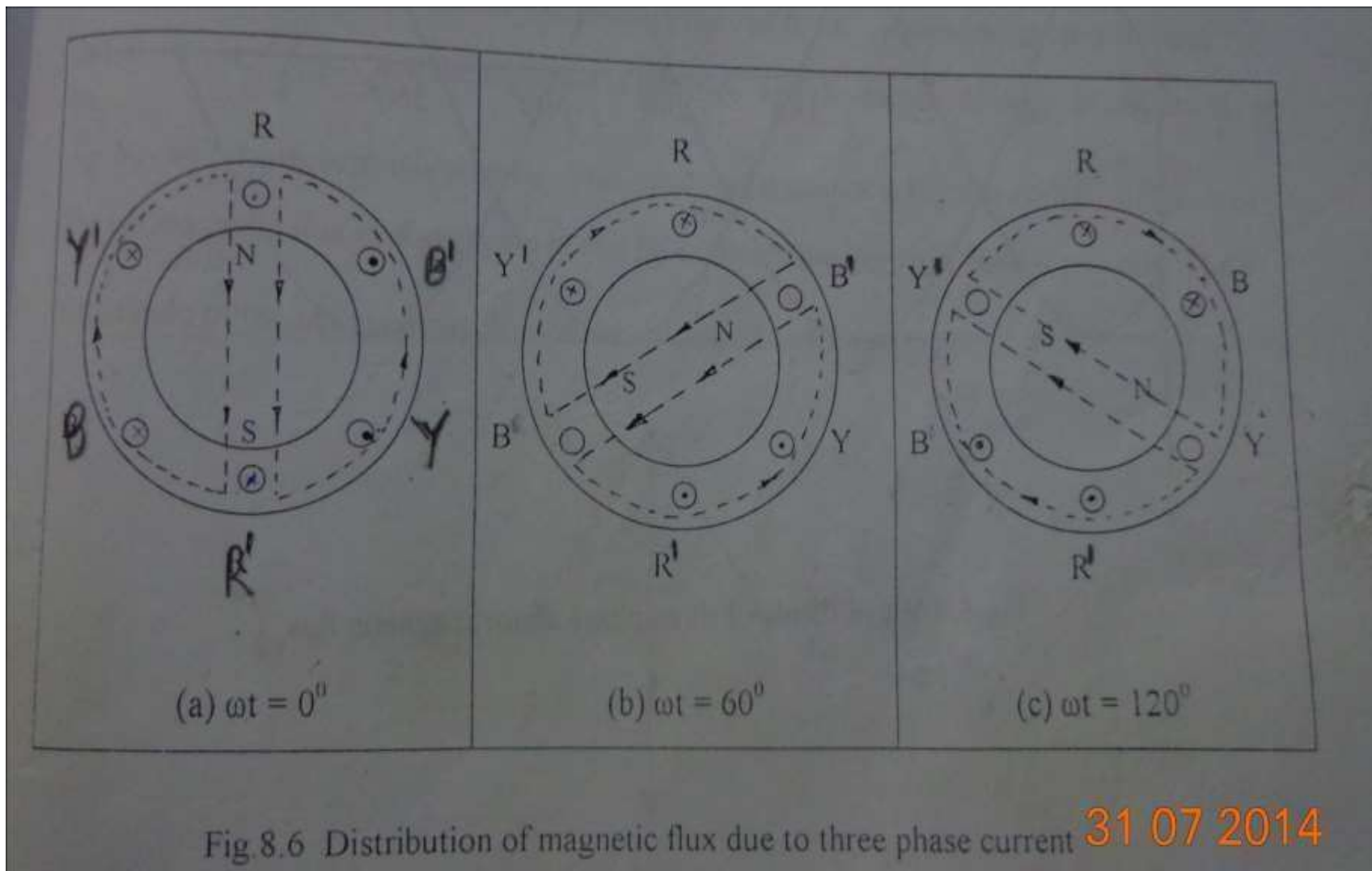**Figure 7: Waveforms of Three Phase Stator Currents**

Figure 8: Direction of Stator Currents and Magnetic Flux Distribution at Various Instant

The three phase current developed will magnetize the stator core. At instant of t_1, the current through R phase and B phase are positive and the current through Y-phase is negative.

Therefore, the direction of the net magnetic flux will be as shown in the figure 8 (a). Similarly, fig. 8 (b), fig. 8 (c) shows the direction of net flux at the instant of t_2 and t_3 respectively.

- Here, we can see that the direction of net magnetic flux 'ø' is changing with respect to time in clockwise direction. The magnitude of the net magnetic flux will be constant. Such magnetic field, whose magnitude is constant and the direction is rotating in a particular direction, is known as Rotating Magnetic Field. And, the speed of rotating magnetic field is given by: $N_S = 120f/ p$.

- This rotating magnetic field cuts the rotor conductor (which are at rest at starting), hence, emf will induce on the rotor conductor according to Faraday's law of electromagnetic induction.

- As the rotor conductors are short circuited, current will circulate within the rotor conductors. Now, these current carrying rotor conductors are lying in the magnetic field produced by the stator. Hence, force will develop on the rotor conductor. Therefore, the rotor starts rotating under the action of this force.

- The direction of rotation can be determined by Lenz's law.

- The direction of force will be in such a way that it oppose the cause by which the emf was induced in the rotor conductor. This main cause of rotor emf is the relative speed between the rotating magnetic field and the rotor. Therefore, in order to reduce this relative speed, the rotors will rotate in the same direction of rotating magnetic field. The rotor will try to catch up the speed of rotating magnetic field (N_S), but it never succeeds to do so &always runs at a speed less than the synchronous speed.

Fig. 8.6 Distribution of magnetic flux due to three phase current

(a) $\omega t = 0^0$ (b) $\omega t = 60^0$ (c) $\omega t = 120^0$

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How torque is produced in induction motor

- The rotating magnetic field produced by the stator cuts the rotor conductor (which are at rest at starting), hence emf will induce on the rotor conductor according to Law of Electromagnetic Induction.

- As the rotor conductors are short circuited, current will circulate within the rotor conductors.

- Now these current carrying rotor conductors are lying in the magnetic field produced by the stator.

- Hence force will develop on the rotor conductor. Therefore, the rotor starts rotating under the action of this force.

- The direction of rotation can be determined by Lenz's law.

- The direction of force will be in such a way that it oppose the cause by which the emf was induced in the rotor conductor.

- The main cause of rotor emf is the relative speed between the rotating magnetic field & the rotor.

Torque Production

- Therefore, in order to reduce in this relative speed, the rotor will rotate in the same direction of the rotating magnetic field.

- The rotor will try to catch up the speed of the rotating magnetic field (N_S), but it never succeeds to do so and always runs at a speed less than the synchronous speed.

- If the rotor catches speed of N_S, the relative speed between the rotating field & the rotor will be zero. Hence, no current will induce in the rotor conductors & no force will develop on the rotor. Then, the speed of rotor will slow down. Hence, in continuous state the rotor rotates with a speed which is always less than the synchronous speed. Therefore, an induction motor is also called as an asynchronous motor.

Fig 8.9 Torque production
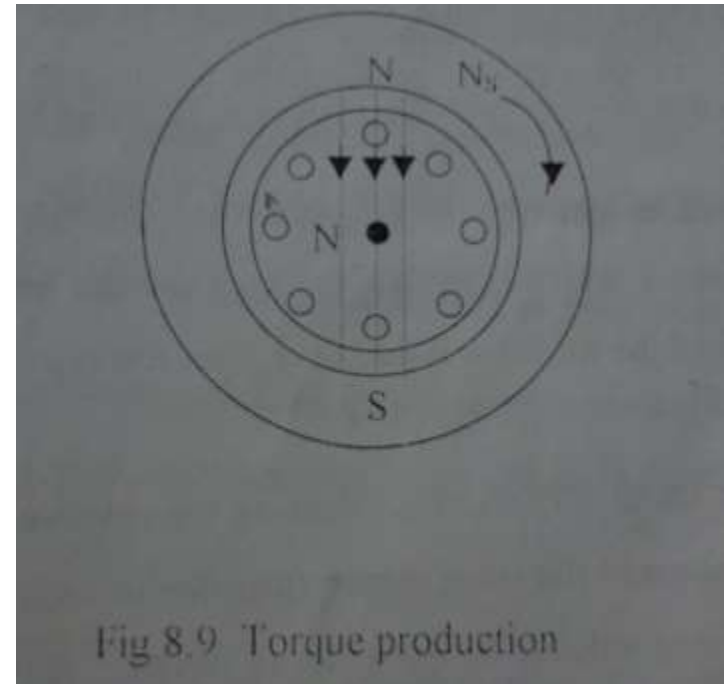
- Let N_r = Speed of the rotor in RPM

- Then, $(N_S - Nr)/ N_S$ is a factor indicating the fraction by which the speed of the rotor is less than the synchronous speed(N_S). this factor is known as slip & given by,

$$S = (N_S - N_r)/ N_S$$

- For example: If the number of pole 'P' = 4 and f = 50 Hz

Then, N_S = 120f/P

   $= (120 * 50)/ 4 = 1500$ RPM

- If the speed of the rotor, N_r = 1470 RPM

Then, $S = (N_S - N_{r)}/ N_S = (1500 - 1470)/ 1500 = 0.02$

- That means the speed of the rotor is 2% less than the synchronous speed.

- The slip of an induction motor changes with respect to the load on the motor. If the load on the motor increases, the speed of the rotor decreases, then the slip of the rotor increases.

Slip

- At the starting, rotor speed 'N' is zero, therefore, the relative speed $(N_S - Nr)$ is maximum & maximum emf will induce in the rotor circuit (just like in secondary winding of a transformer) & the frequency of emf enduced in rotor circuit is same as that of supply voltage frequency 'f'.

- When the rotor rotates, the frequency of rotor emf is given by $S.f$ and the magnitude of rotor emf is given by $E_r = S. E_2$

    Where, E_r = emf induced in the rotor circuit at running condition

    $\quad\quad E_2$ = emf induced at stand still condition

- The frequency of rotor current (or emf) induced by the relative motion between rotor conductors & the stator revolving magnetic field is given by the equation,

Rotor emf frequency $(f') = $ (relative speed in RPM) / (120/ P) ……… (1)

$$= (N_S - Nr)/ (120/P)$$

And, $N_S - Nr = SN_S = S*$ (120f/ P

Since, slip, $S = (N_S - Nr)/ N_S$

Substituting $N_S - Nr = S*(120f)/ P$ in eqn (1), we get,

- Rotor emf frequency, $f' = S*[(120f)/ P]*[P/120] = S. f$

- Thus, the frequency of rotor current (or emf) in an induction motor is given by the product of slip S & the supply frequency, f. That is why, it is also called the slip frequency.

Equivalent circuit of an induction motor

- The equivalent circuit of an induction motor is very much similar to that of a transformer.

- The stator winding corresponds to the primary winding

- The only difference is that, in the case of transformer, the secondary winding is stationary, whereas, in the case of induction motor, the rotor is not stationary.

- Hence, by comparing with the equivalent circuit of a transformer, the equivalent circuit of an induction motor can be drawn as shown in figure.
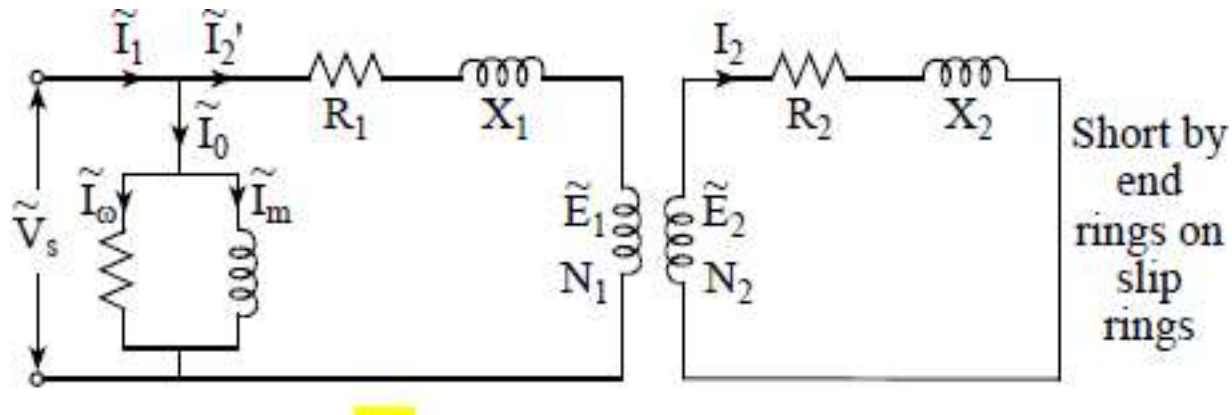
Fig. Equivalent Circuit of induction motor at standstill condition
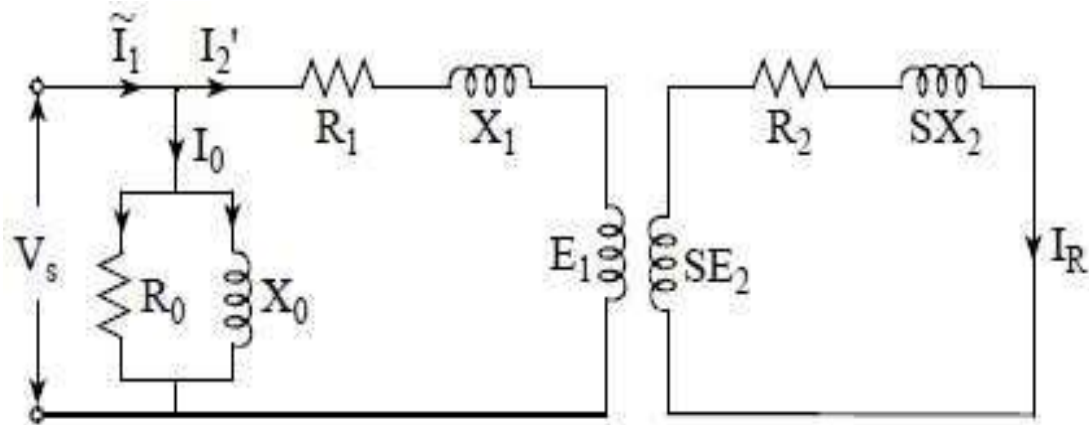

Fig. Equivalent Circuit of induction motor at running condition

Here,

- V_1 = supply voltage to stator winding per phase
- I_1 = Stator current perphase

- I_0 = No- load stator current per phase (the total magnetizing current)
- E_1 = Stator emf per phase
- E_2 = Rotor emf per phase (Standstill condition emf)
- E_r = Rotor emf per phase at running condition
- S = Slip of the induction motor
- R_1 = Stator winding resistance per phase
- X_1 = Stator winding leakage reactance per phase
- R_2 = Rotor resistance per phase
- X_2 = Rotor leakage reactance per phase at standstill
- I_2 = Rotor circuit current per phase at standstill condition
- I_r = Rotor circuit current per phase (is a slip frequency current)
- This applies whether the stator winding is Y or Δ connected

Power in the rotor of the induction motor

- The rotor current I_r lags E_r by an angle θ_r,

$$\theta_r = \tan^{-1}[SX_2/R_2]$$

- The power factor of the rotor circuit is given by,

$$\cos\theta_r = R_2 / \sqrt{[R_2^2 + (SX_2)^2]}$$
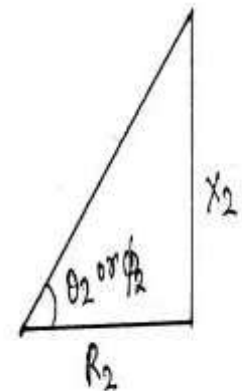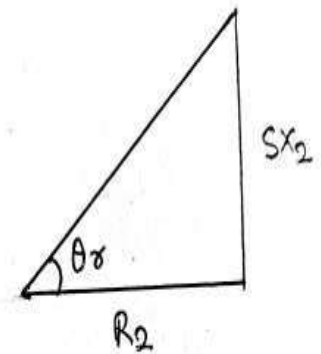
- And the active power of rotor circuit,

$$= E_r I_r \cos\theta_r \text{ per phase}$$

- We can write,

$$I_r = SE_2 / \sqrt{[R_2^2 + (SX_2)^2]} \quad \text{since } E_r = SE_2$$

Where, E_2 & X_2 are the standstill (or line frequency) values

- At the starting $Nr = 0$, and $S = (N_S - N) / Ns = 1$

- Therefore, percent slip $= 100$

- Hence, the rotor current is given by, $I_2 = E_2 / \sqrt{[R_2^2 + X_2^2]}$

- I_2 lags with E_2 by ϕ_2,

- $\cos\phi_2 = R_2 / \sqrt{[R_2^2 + X_2^2]} = R/Z$

Torque developed by the Rotor

- The torque developed by the rotor is proportional to the active component of the rotor current & stator flux.

$$T_r \propto \emptyset I_r Cos\theta_r$$

- But, rotating flux, $\emptyset \propto E_1 \propto E_2$

  or, $$T_r \propto E_2 \times \frac{E_r}{\sqrt{R_2^2 + (SX_2^2)}} \times \frac{R_2}{\sqrt{R_2^2 + (SX_2^2)}}$$

- But, $E_r = SE_2$,

- Thus,

$T_r \propto E_2 * SE_2 / [\sqrt{R_2^2 + (SX_2)^2}] * R_2 / [\sqrt{R_2^2 + (SX_2)^2}]$

$\propto [SE_2^2 * R_2] / [R_2^2 + \{SX_2\}^2]$

Or, $T_r = K. [SE_2^2 R_2] / [R_2^2 + \{SX_2\}^2]$ ……..Running condition

- At starting, $Nr = 0$, $S = 1$

- Therefore, starting torque is given by

$$T_S = K. [E_2^2 R_2] / [R_2^2 + X_2^2]$$

Condition For Maximum Torque

- Let, $Y = 1/T_r$; $T_r = \{KSE_2^2 R_2\} / \{R_2^2 + S^2X_2^2\}$
- Then, $Y = \{R_2^2\}/\{KSE_2^2R_2\} + \{S^2X_2^2\}/\{KSE_2^2R_2\}$

Or, $Y = R_2/\{KSE_2^2\} + \{SX_2^2\}/\{KE_2^2R_2\}$

- Y will be minimum when, $dY/dS = 0$

i.e., $\{-R_2\}/\{KS^2E_2^2\} + \{X_2^2\}/\{KE_2^2R_2\} = 0$

Or, $\{R_2\}/\{KS^2E_2^2\} = \{X_2^2\}/\{KE_2^2R_2\}$

Or, $\{R_2^2/S^2\} = X_2^2$

Or, $S^2 = R_2^2/X_2^2$

Or, $S = R_2/X_2$ condition for Y minimum or T_r maximum

- Hence, maximum torque will develop at a speed corresponding to slip $S = R_2/X_2$.

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Torque-slip or Torque-speed Characteristic of an Induction Motor

- The torque-slip characteristic of an induction motor is a curve showing the torque developed by the rotor at various values of slip or speed.

- The general equation of torque is:

$$T_r = K \cdot \{SE_2^2 R_2\} / \{R_2^2 + S^2 X_2^2\}$$

- When, $Nr = N_S$, $S = \{N_S - Nr\}/N_S = 0$ then, $T_r = 0$

- This corresponds to the point F of the curve shown in fig 9.

- At normal speed close to the synchronous speed N_S, the value of the slip 'S' is very small. Hence, the value of SX_2 is very small with compared to R_2 i.e., SX_2 is negligible w. r. to R_2,

- Therefore, $T_r \propto \{SE_2^2 R_2\} / R_2^2$

- Or $T_r \propto [S/R_2]$

- Or $T_r \propto S$

- Thus, R_2 is constant.

- Hence, the torque T_r increases proportionately as 'S' increases or the torque T_r increases as the speed decreases.

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Torque-slip or Torque-speed Characteristic of an Induction Motor

- Maximum torque will develop at a slip $S= R_2/X_2$ which is indicated as C in figure.

- If the slip is further increased (or speed is decreased) beyond this value, the value of SX_2 will be very high w.r.t. R_2. Then, R_2 becomes negligible w.r.to SX_2.

- Therefore, $$T_r \propto \{SE_2{}^2R_2\} / S^2X_2{}^2$$

Or, $$T_r \propto 1/S$$

- Hence, the torque decreases with the increase in slip & finally the torque becomes $T_S = OA$ at $S=1$ i.e., $Nr= 0$

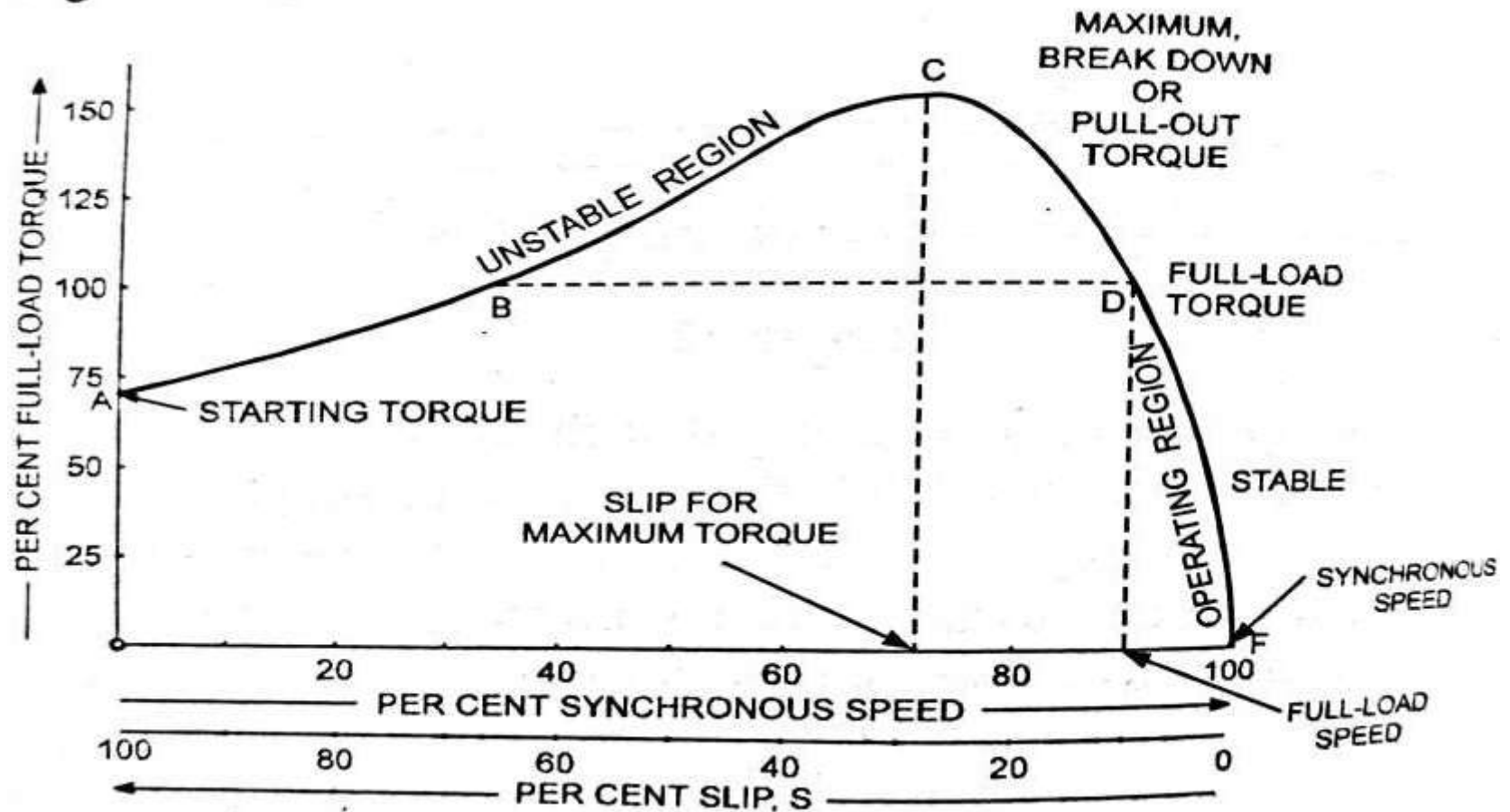# Torque-slip or Torque-speed Characteristic of an Induction Motor

Figure 9:Torque-Slip Characteristics of 3-Phase Induction Motor

Effect of Rotor Resistance on T–S Characteristics

- From the torque equation it is obvious that, for a constant supply voltage, when rotor resistance R_2 is very small compared with SX_2, the torque for a given slip is directly proportional to R_2, but when rotor resistance R_2 is large compared with SX_2, the torque for a given slip is inversely proportional to R_2.
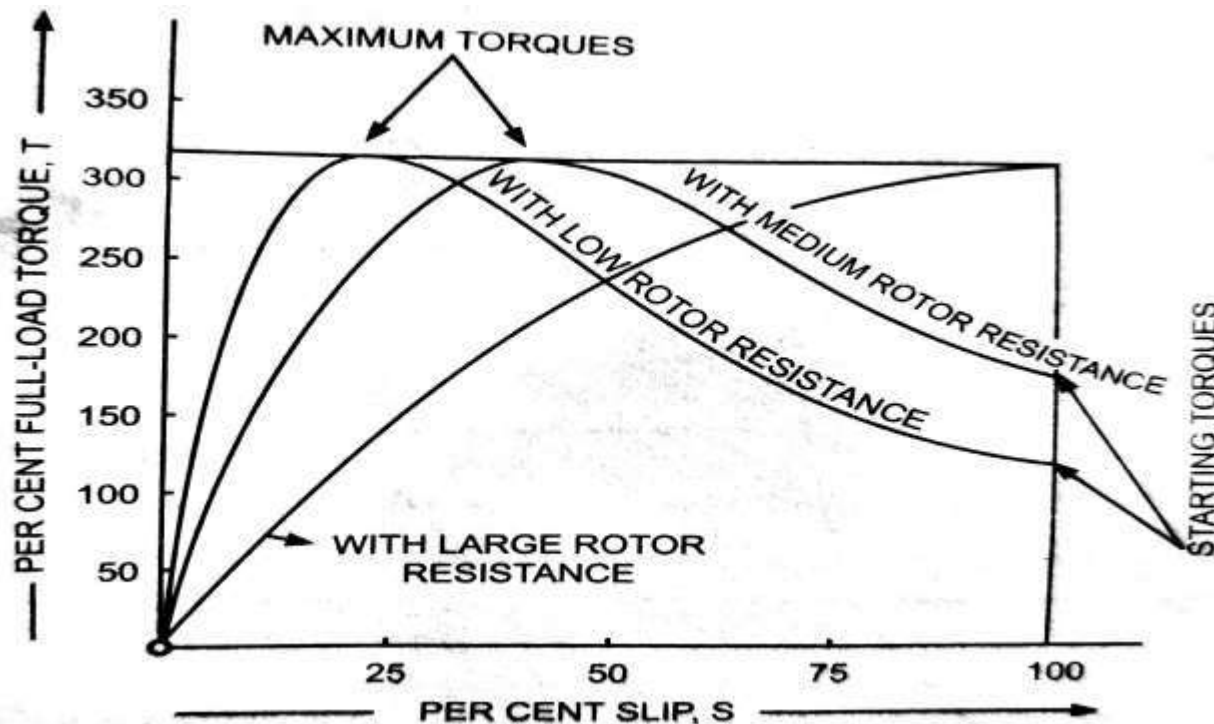

Figure 10: Torque-Slip Curves

Advantages and disadvantages of squirrel cage over phase wound 3 phase induction motors

Advantages:

● Squirrel cage induction motor are comparatively cheaper than wound rotor induction motors &are simple &rugged in construction.

● A cage rotor needs considerably less conductor material than a wound rotor, so copper loss in cage rotor is low & efficiency of a cage motor is a little more than that of a wound rotor motor.

● Cage motor is more rugged in construction and needs no slip- rings, brushes, etc., therefore, its maintenance cost is low.

● Cage motor is explosion proof, because the absence of slip- rings and brushes eliminates risk of sparking.

● Cage motor can be cooled better because of the bare end rings. Also, there is more space for rotor fans.

- A squirrel cage induction motor has very small length of overhang, so it has low rotor overhang leakage flux. This causes standstill reactance X_2 low for a cage rotor than wound rotor. So a cage motor has more pull out torque, greater maximum power output & better operating power factor as compared to a wound rotor motor.

- Other advantages of squirrel cage motors are nearly constant speed, high overload capacity and simple starting arrangement which may be made automatic.

Disadvantages:

The disadvantages of squirrel cage induction motors are:

- Since in cage rotors, rotor bars are permanently short- circuited, it is not possible to insert any external resistance in the rotor circuit for the purpose of increasing starting torque consequently its starting torque is low with large starting current.

- <u>Note</u>: Starting torque vary between 1.5 & 2 times the full- load torque with starting current 5 to 9 times the full- load current power factor is also low at start in case of cage motors.

- speed control mechanism is almost not available.

- Squirrel cage induction motors are very sensitive to fluctuations in supply voltage.

- The total energy loss during starting of cage motor is much more than with the slip ring induction motor & this fact is very important where frequent starting is required.

Application of 3-phase induction motor:

- Squirrel cage induction motor is suitable for constant speed industrial drives of small power where speed control is not required & where starting torque requirements are of medium or low value such as for printing machinery, flour mills, and other shaft drives of small power.

- Phase wound or slip ring induction motor are used in application where high starting torque is required such as cranes,hoists,conveyors e.t.c.

What are the main differences between transformer and induction machine?

- Induction machine is moving equipment &a transformer is stationary.

- In a transformer, primary & secondary frequencies are same but in induction machine they are different.

- The transformer does not have any air gap between primary & secondary but in induction machine there is an air gap between stator and rotor.

- In induction machine rotating magnetic flux (ϕ) is produced, but in transformer it is not rotating. The reason is that in induction machine, the conductors are space- displaced phase winding carrying appropriate time displaced current, but it is not in the transformer.

- In a transformer, the energy received in the secondary is electrical energy but is induction motor, it is mechanical energy.

Numericals

1) A six pole 60 Hz induction motor runs at 1152 rpm. Determine the synchronous speed and slip.

- Solution:
- Here,
- $P = 6$
- $f = 60$ Hz, $Nr = 1152$ RPM
- Synchronous speed, $N_S = 120f/p$

  $= (120*60)/6 = 1200$ RPM

- Slip, $S = (N_S - Nr)/ N_S = (1200 - 1152)/ 1200 = 4\%$

2) A six pole three phase 60 Hz induction motor runs at 4% slip at a certain load. Determine: Synchronous speed, Rotor speed, Frequency of rotor current

Solution:

- Here, P= 6, f = 60 Hz, Slip = 4%
- Synchronous speed, N_S = 120f/ P = (120*60)/6 = 1200 RPM
- Rotor Speed,

Slip, S = $\{N_S - Nr\}$ / N_S

Or, 4/100 = $\{1200 - Nr\}$/ 1200

Or, 4/100 * 1200 = 1200 – Nr

Or, 48 = 1200 – Nr

Or, Nr = 1200 – 48

Or, Nr = 1152 RPM

Frequency of the rotor current, f_r = S.f

= 4/100 * 60 = 2.4 Hz

3) A 4 pole, 50 Hz, three phase slip ring induction motor has star connected stator & rotor winding the emf induced in the rotor is 80 volts between slip rings at standstill on open circuit. Calculate rotor current and stator current at standstill condition and when running at 1400 RPM. Given that rotor winding has a resistance of 0.1 Ω per phase & reactance of 4Ω per phase. The stator to rotor turn ratio is 2:1.

Solution:

Here, transformation ratio is defined as,

Stator turn per phase/ Rotor turn per phase $= 2/1$

Let I_S & I_r be the stator & rotor current per phase respectively. At starting,

$I_r = E_r/\sqrt{\{R_2^2 + X_2^2\}} = \{80/\sqrt{3}\} \quad \sqrt{\{(0.1)^2 + (4)^2\}}$

$= 46.18/4 = 11.54 A$

● Therefore, $I_S = 2 I_r = 2 * 11.54 = 23.08 A$

- And now, when the motor is running,

N_S = 120f/P = {120 * 50}/ 4 = 1500 RPM

And, N_r = 1400 RPM (given value)

Therefore, Slip, S = {$N_S - Nr$} / N_S = {1500 – 1400} / 1500

$= 100/1500 = 1/15 = 6.69\%$

- $I_r = SE_2/ \sqrt{ R_2^2 + (SX_2)^2}$
- $= \{0.0667 * 80/\sqrt{3}\}/ \sqrt{(0.1)^2 + (0.0667 * 4)^2}$

$= 3.08/ 0.2849 = 10.81 A$

- Therefore, $I_S = 2 I_r = 2 * 10.81 = 21.62 A$

4) A three phase delta connected 440volts,50Hz,4 pole induction motor has a rotor.Standstill emf per phase of 130volts.If the motor is running at 1440 rpm.Calculate for this speed.

a) The slip
b) The frequency of the rotor induced emf
c) The value of the induced emf per phase and
d) Stator to rotor turn ratio

Solution:

Stator voltage per phase $(E_1) = 440$ V

Stand still rotor voltage per phase $(E_2) = 130$ V

Speed of the induction motor $(N) = 1440$ rpm

Frequency $(f) = 50$ Hz.

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

i. Slip (s) $= \dfrac{N_s - N}{N_s}$

$$= \frac{1500 - 1440}{1500}$$

$$= 0.04$$

$$= 4\%$$

ii. Frequency of the rotor induced emf,

$f_r = S \times f = 0.04 \times 50 = 2$ Hz

iii. The value of the rotor induced emf at this speed,

$E_r = SE_2 = 0.04 \times 130 = 5.2$ V

iv. Stator to rotor turn ratio $= \dfrac{E_1}{E_2} = \dfrac{440}{130} = 3.38$

5) A 8-polve, 50 Hz, 3–f induction motor develops a starting torque of 50 N-m. The rotor winding has and impedance of (0.8 + i4) W per phase. At what speed motor will develop maximum torque and calculate the magnitude of maximum torque.   [IOE-2070,2072 and 2075]

Solution:

Number of pole of induction machine (P) = 8

Frequency (f) = 50 Hz

Rotor resistance per phase (R_2) = 0.8 ohm

Rotor leakage reactance per phase(X_2)=4 ohm

Starting torque (T_S)=50N-m

N_S=120f/p =120*50/8 =750 rpm

The slip at which maximum torque occurs

S =R_2/X_2=0.8/ 4=0.2

The speed of rotor at which maximum torque occurs is

Nr=(1-S)N_S=(1-0.2)*750 = 600 rpm

Now,

$$T_r = \frac{KSE_2{}^2 R_2}{R_2{}^2 + (S \times 2)^2}$$

At starting, $S = 1$,

$$T_s = \frac{KE_2{}^2 R_2}{R_2{}^2 + X_2{}^2} \quad \text{............ (i)}$$

At maximum torque, $S = \dfrac{R_2}{X_2}$

$$T_{max} = \frac{KE_2{}^2}{2X_2} \quad \text{............(ii)}$$

Dividing equation (ii) by equation (i), we get,

$$\frac{T_{max}}{T_s} = \frac{R_2{}^2 + X_2{}^2}{2\,R_2 X_2}$$

or, $T_{max} = \dfrac{(0.8)^2 + 4^2}{2 \times 0.8 \times 4} \times 50$

$T_{max} = 130\ \text{N–m}$