- Three Phase Induction Motor
  - Constructional Details and Types
  - Operating Principle
  - Rotating Magnetic Field
  - Synchronous Speed
  - Slip
  - Induced EMF
  - Rotor Current and its Frequency
  - Torque Equation
- Three Phase Induction Generator
  - Working Principle
  - Voltage Build-up in an Induction Generator
  - Power Stages

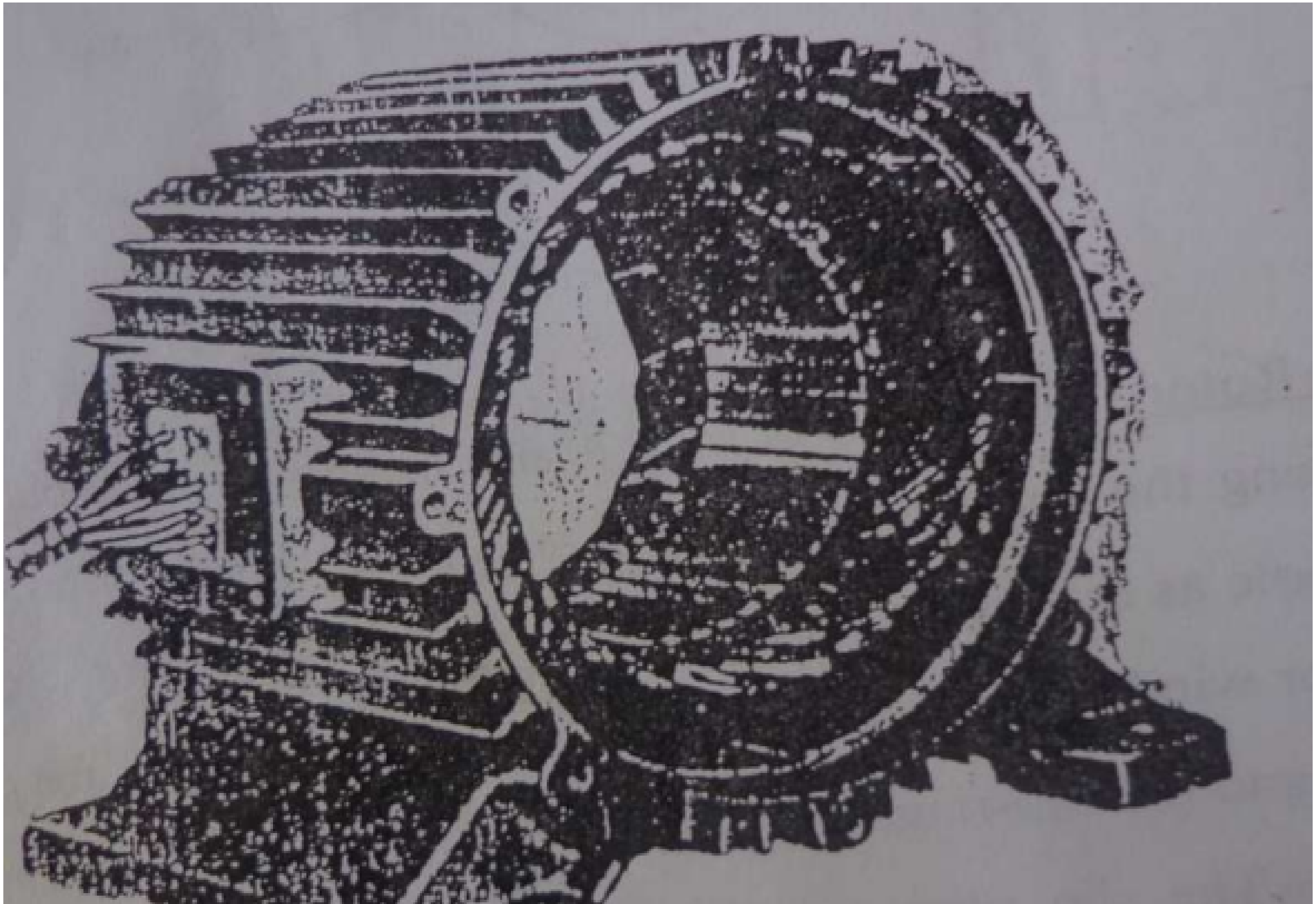
- The three-phase induction motors are the most widely used electric motors in industry.
- They run at essentially constant speed from no-load to full-load. However, the speed is frequency dependent and consequently these motors are not easily adapted to speed control.
- We usually prefer d.c. motors 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.

- 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.

- 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.



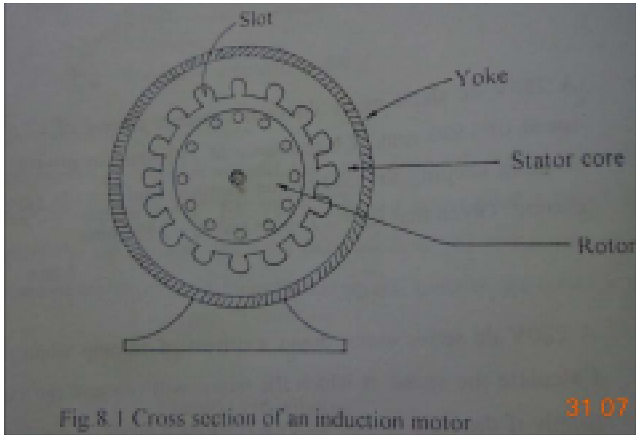


Figure 1: Cross-section of an Induction Motor

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 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.

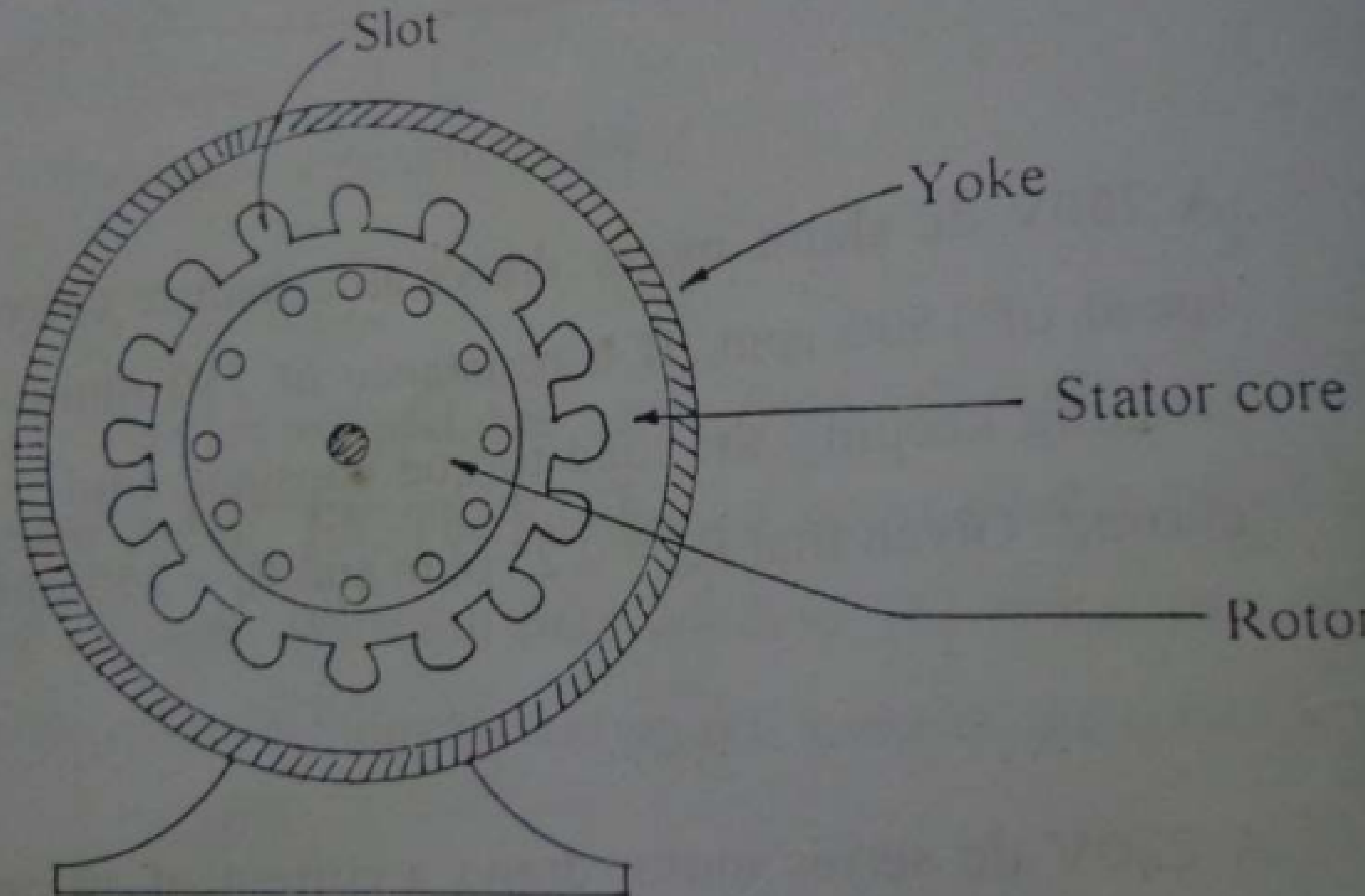
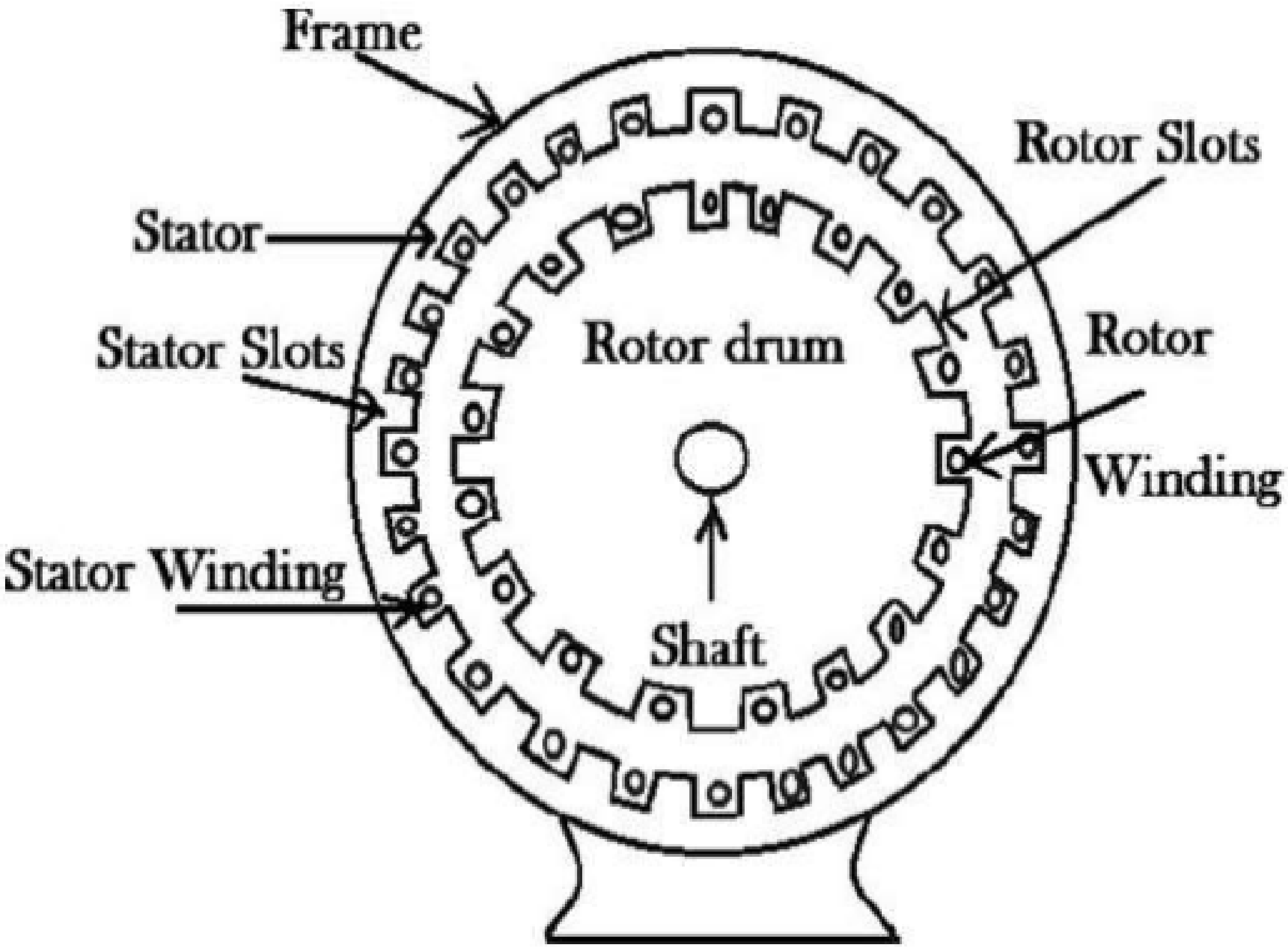


Fig.8.1 Cross section of an induction motor



- 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.

- Let total number of slots = 12
- Number of magnetic poles = 2

- Coil span = No. of slots/ No. of pole = 12/ 2 = 6
- Number of slots per phase = No. of slots/ No. of phase = 12/3 = 4
- Coil span is the number of teeths between two sides of a coil.
- The winding diagram is shown in figure 2 .
- The first coil of R-phase is started from the slot no-1 & brought back through the slot no- 7 so that coil span is 6. A line of the coil represents many number of turns. Since the no. of slots per phase is 4, two sets of coils shall be there in a phase group. Therefore, the second coil of R phase is started from the slot no- 2 & brought back through the slot no 8. So that the coil span is again 6. Hence, R & R’ are the starting and finishing end of R-phase winding. The starting of the Y- phase winding shall be 120°electrically apart.

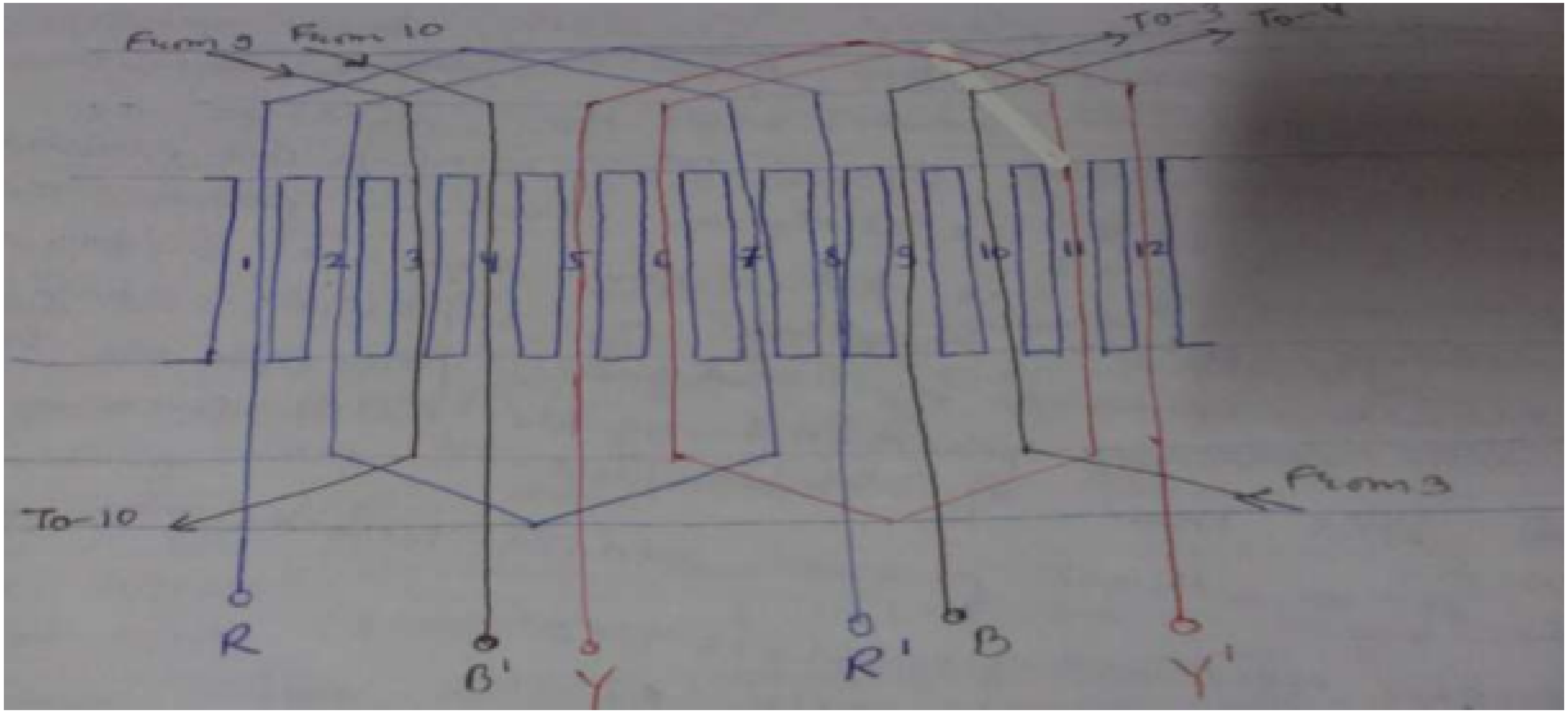


Figure 2: Three phase stator winding diagram for 12 slots, 2 pole

Here, 360^0 electrical (2 pole = 360°) = 12 slots

Therefore, 120^0 electrical = 12/360 *120 = 4 slots or teeths

Here, the starting of the Y- phase winding shall be from slot no. 5 so that there will be 4 no. of teeths between R &Y.

Similarly, the B-phase winding shall be started from slot no 9.

These three phase winding can be connected in star or delta as required.

- 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).

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

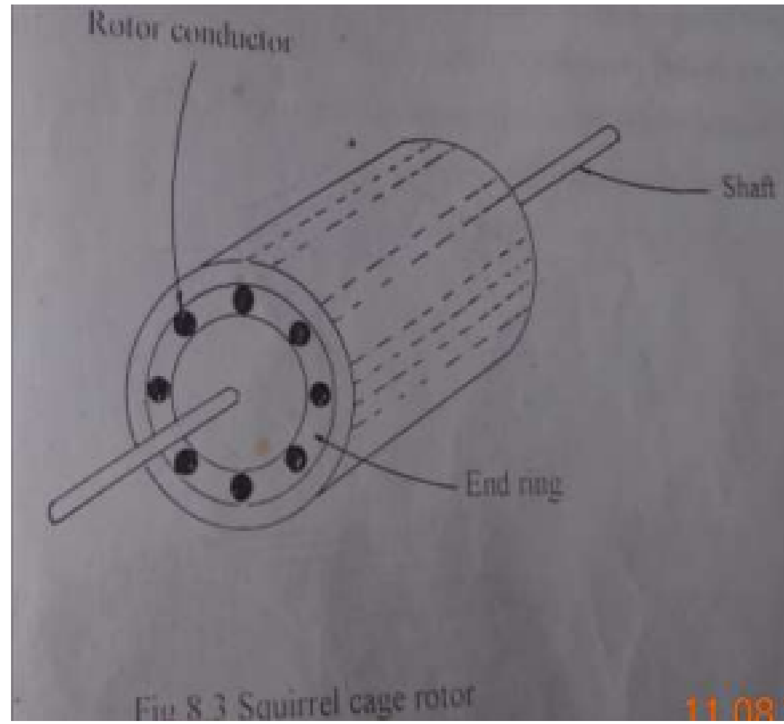


Figure 3: Squirrel Cage Rotor

Figure 3: Squirrel Cage 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.

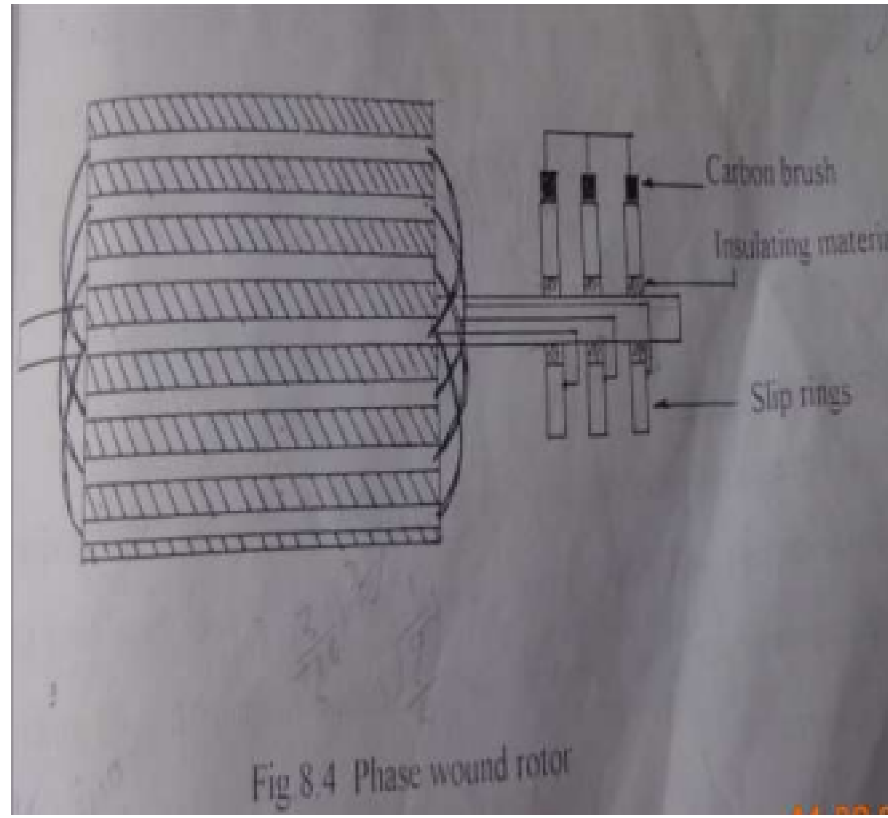
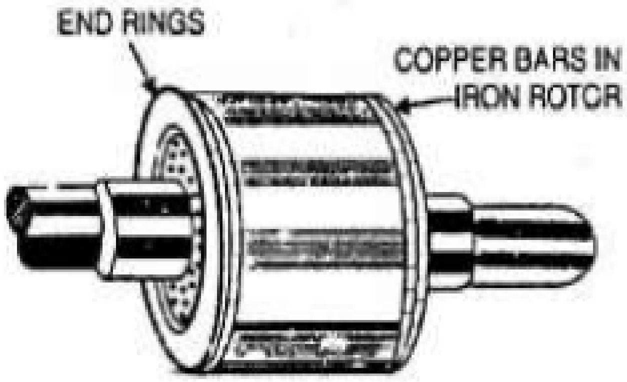


Figure 4: Phase Wound Rotor



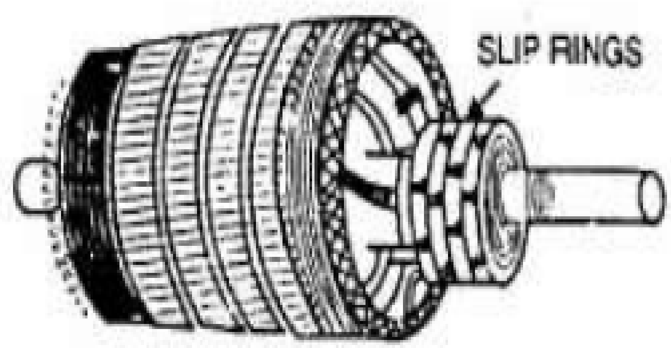


Figure 5: Squirrel Cage Rotor Figure 6: Phase Wound Rotor

- 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 – ø 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.

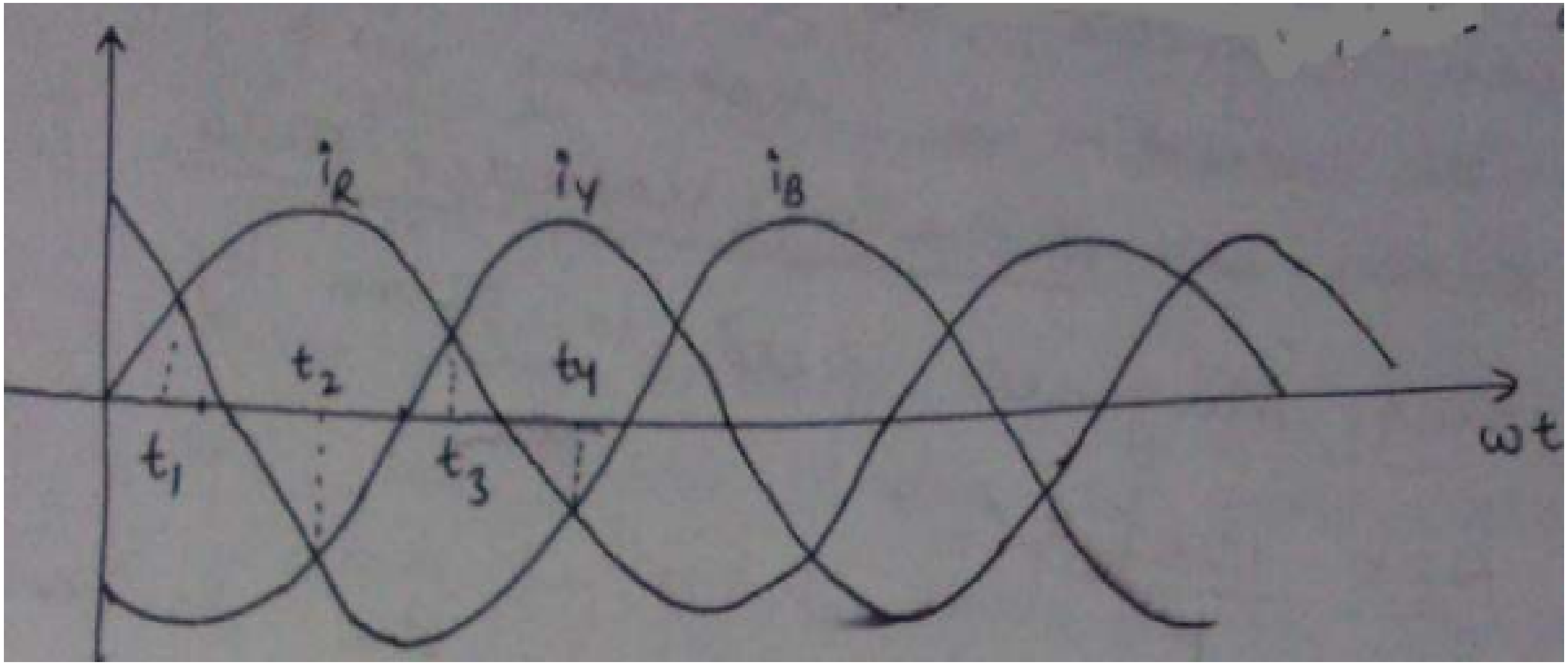


Figure 7: Waveforms of Three Phase Stator Currents

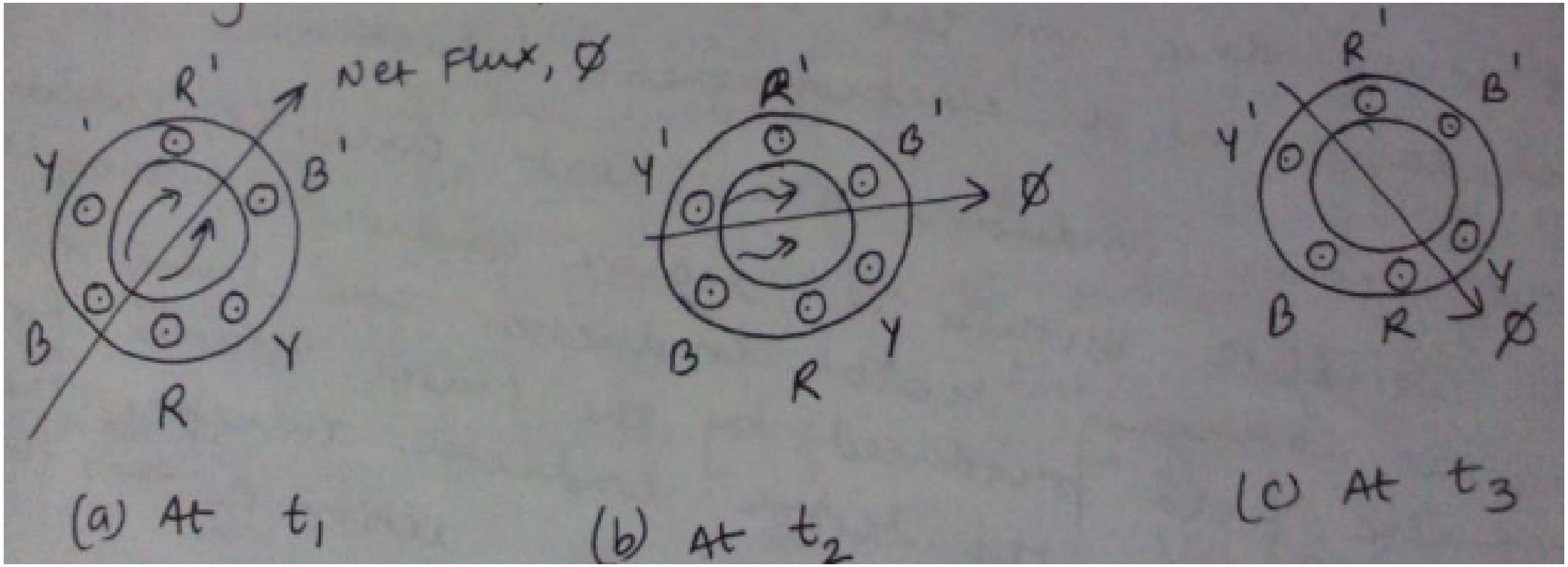


Figure 8: Direction of Stator Currents and Magnetic Flux Distribution at Various Instant

The three phase current developed will magnetize the stator core. At instant of t_l, 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.

- When the three phase stator windings are supplied by three phase laminated balanced voltage source, three phase current will flow through stator windings. These three phase current will magnetize the stator core.

- Let us consider a two pole machine and suppose that the three phase winding is concentrated with one slot per phase per pole as shown in the earlier slide. The end connection of the coils are not shown.

- R and R' represents the starting end and finishing end of the R-phase windings.

- The' ' indicates the direction of current flowing inward and the mark ' ' indicates the direction of current flowing outward.

- Let us assume that the current is position when the current is flowing inward through R,Y and B.

- When three phase current flows through the stator windings, each phase winding will produce their own magnetic flux whose nature will be as same as waveforms of three phase current and are shown in the next slide.

- The three flux ϕ_R, ϕ_Y, & ϕ_B are alternating in nature & they are 120^0 out of phase with each other. Their mathematical equations are as follows:

- Figure below shows the phasor diagram of these magnetic fluxes showing their positive direction.
- The net magnetic flux at any time at the central space of the machine will be equal to the vector sum of these fluxes.

- At wt= 0^o

- Therefore at this instant, the current through the coil R-R’ is zero, the current through the coil

Y-Y’ is and the direction is negative and the current through the coil B-B’ is & the direction is positive.

The direction of the net magnetic flux is also shown in the figure as determined by the right hand screw rule.

The magnitude of the net magnetic flux can be

calculated as follows:

When, $\omega t = 60^{\circ}$

- At this instant, the current through the coil R-R’ is and the direction is positive.
- The current through the coil Y-Y’ is and the

direction is negative. The current through the coil B-B’ is zero.

- The direction of the net magnetic flux has been changed through 60^o in the clockwise direction.
- The magnitude of the net magnetic flux can be

calculated as follows.

- Note that the magnitude of net magnetic flux is again $1.5\Phi_m$. Similarly, when wt = 120^o, the net magnetic flux is again $1.5\Phi_m$.

Therefore, from the above analysis it is clear that the stator winding produces a uniformly rotating magnetic field of constant value. The speed of the rotating magnetic field is given by

Where,

f = frequency of the voltage applied across the stator windings. P= No. of magnetic poles for which the stator winding is wound. This speed is also known as“**synchronous speed**”.

- 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.

- 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.

- Let N = Speed of the rotor in RPM
- Then, $(N_S – N)/ N_S$ 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,

$$S= (N_S – N)/ N_S$$

- 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 = 1470 RPM

Then, $S = (N_S - N)/ N_S = (1500 - 1470)/ 1500 = 0.02$

🗣 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.

- 🗣 The speed of a polyphase induction motor must always be less than the synchronous speed & that, as the load is increased, the speed of the motor will decrease.
- 🗣 The difference between the speed of the stator field, known as synchronous speed (N_S), & the actual speed of the rotor (N) is known as the slip & is denoted by S.

🗣 Though the speed can be expressed in RPM or in radians per second, but usually it is expressed as a fraction or percentage of synchronous speed. 🗣 Fraction slip, S = (Synchronous speed –

Rotor speed)/ Synchronous speed $= (N_S - N) / N_S$

- And, percentage slip,

$$= (N_S - N) / N_S * 100$$

- At normal load, the slip of an induction motor is usually between 2 & 5 percent.At no-load, the slip is as small as 0.5 percent.

- At the starting, rotor speed 'N' is zero, therefore, the relative speed $(N_S - N)$ 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

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

And, $N_S - N = SN_S = S^* (120f)/P$

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

Substituting $N_S - N = S * (120f)/ P$ 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.
- 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.

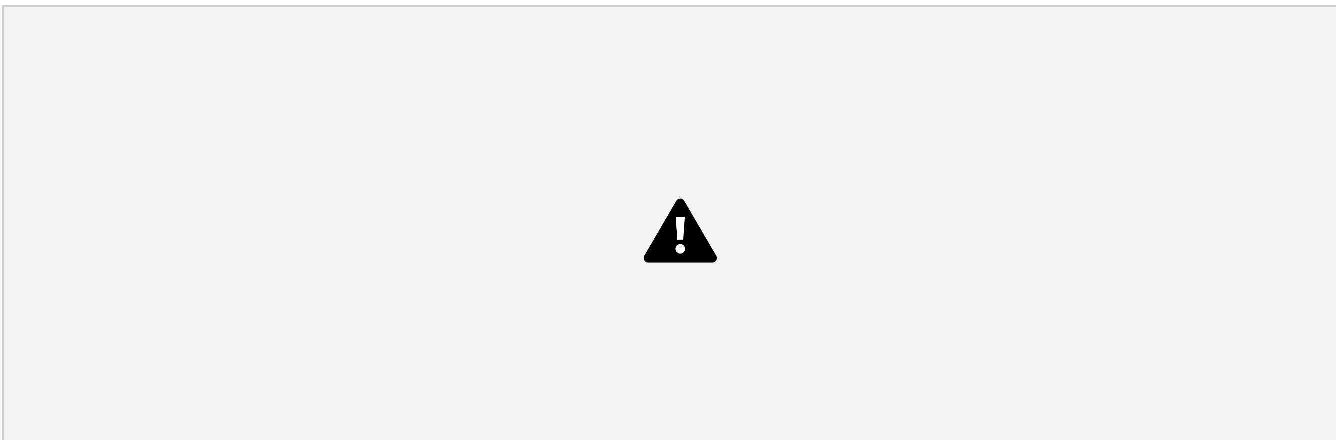


Fig. Equivalent Circuit of induction motor at standstill condition

Fig. Equivalent Circuit of induction motor at running condition

Here,

- V_I = supply voltage to stator winding per phase
- I_I = Stator current per phase
- I_0 = No- load stator current per phase (the total magnetizing current)
- E_I = 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_l= Stator winding resistance per phase
- X_l= 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 isY or Δ connected

- 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, $\text{Cos } \theta_r = R_2 / \sqrt{[R_2^2 + (SX_2)^2]}$

- And the active power of rotor circuit,

$= E_r I_r \cos\theta_r$ per phase

- We can write,

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

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

- At the starting $N = 0$, 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 $ø_2$,

] = R/Z

- $\cos ø_2 = R_2 / \sqrt{[R_2^2 + X_2 2}$
- The torque developed by the rotor is proportional to the active component of the rotor current & stator flux.
- But, rotating flux,

or,

- But, $E_r = SE_2$,
- Thus,

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

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

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

- At starting, $N = 0$, $S = 1$
- Therefore, starting torque is given by

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

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

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

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

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

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

Or, $\{R_2^2/S^2\} = X_{22}$

Or, $S^2 = R_2^2/X_{22}$

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 $S = R_2/X_2$.

- 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:

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

- When, $N = N_S$, $S = \{N_S - N\}/N_S = 0$ 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 $\{SE_2{}^2R_2\}/ R_2{}^2$
- Or $T_r[S/R_2]$
- Or T_r 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.

- 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 $\{SE_2{}^2R_2\}/ S^2X_2{}^2$

Or, $T_r 1/S$

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

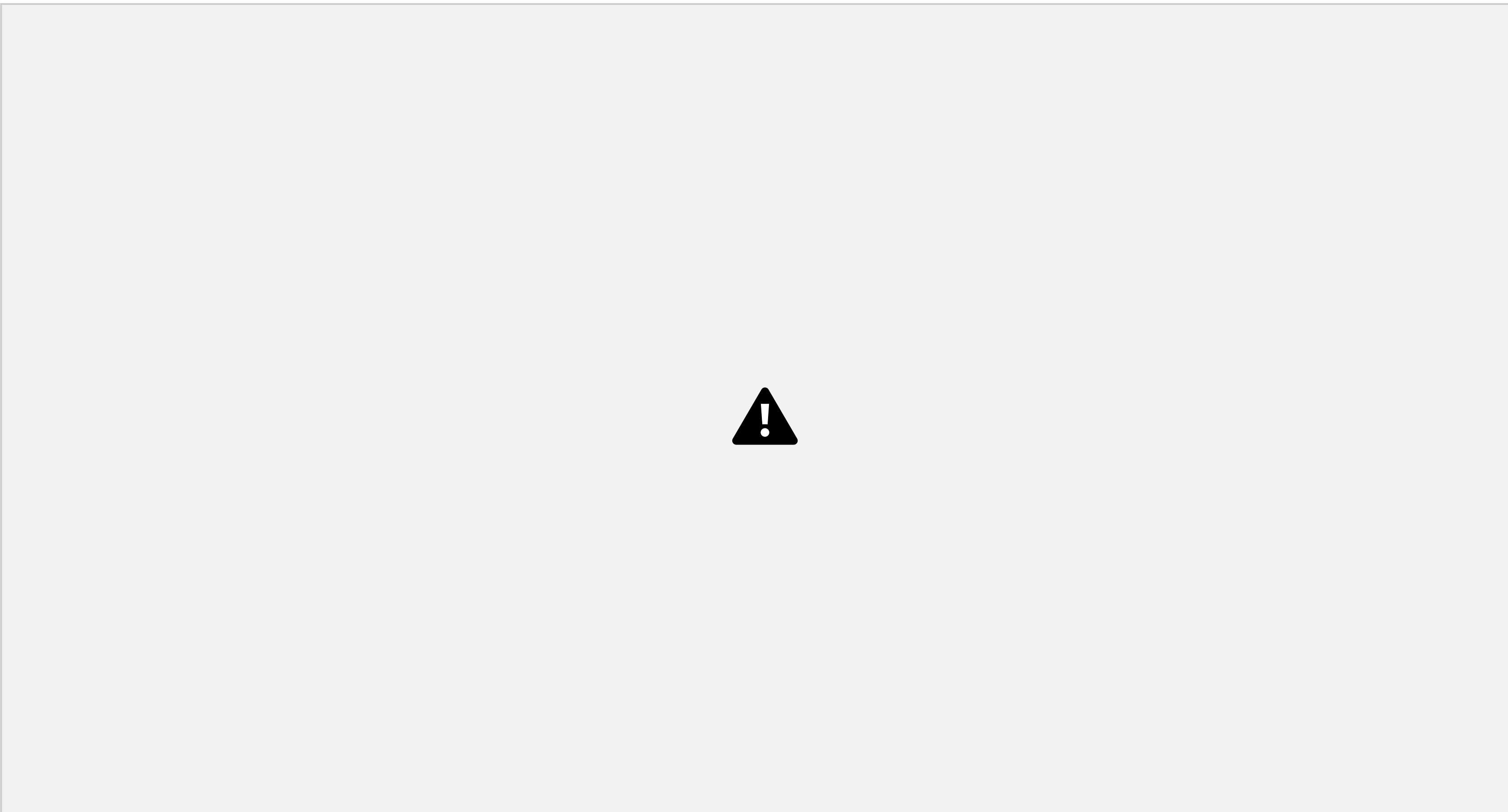


Figure 9: Torque-Slip Characteristics of 3-Phase Induction Motor

- 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.

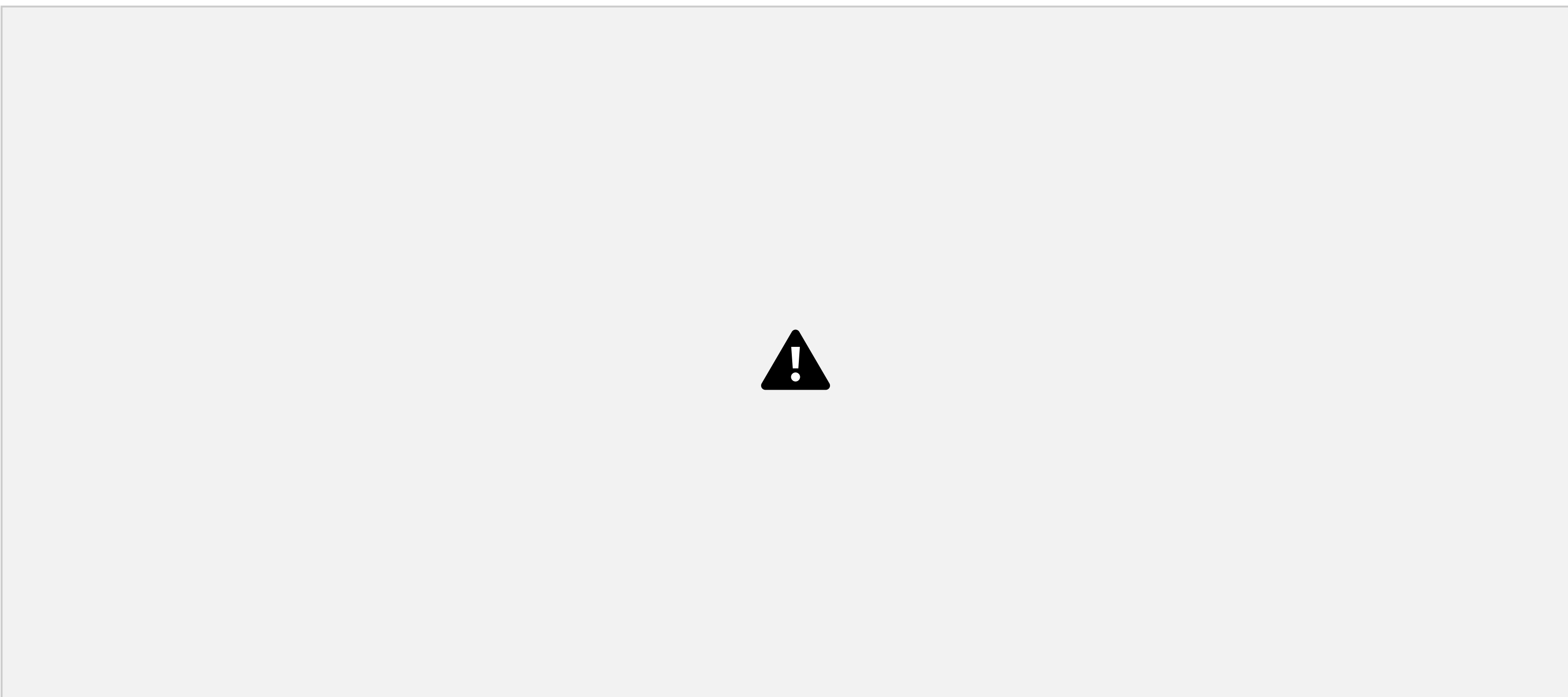


Figure 10: Torque-Slip Curves

- Hence, maximum torque will develop at a speed corresponding to slip(S) = R_2/X_2.If the motor is overloaded so that speed goes below this value, the motor will not be able to develop more torque to overcome the increased load.
- From figure 10, it is seen that variation of rotor resistance does not change the magnitude of maximum torque, T_{max} merely changes the value of slip at which it occurs.
- Larger the rotor resistance, the greater is the slip at which the maximum torque occurs.
- For a given value of torque(T), slip 'S' is proportional to rotor resistance R_2, so addition of external resistance in the rotor circuit does not lower the torque curve but merely stretches it so that the same torque values occur at lower speeds (or higher slips) (see figures 10 & 11).

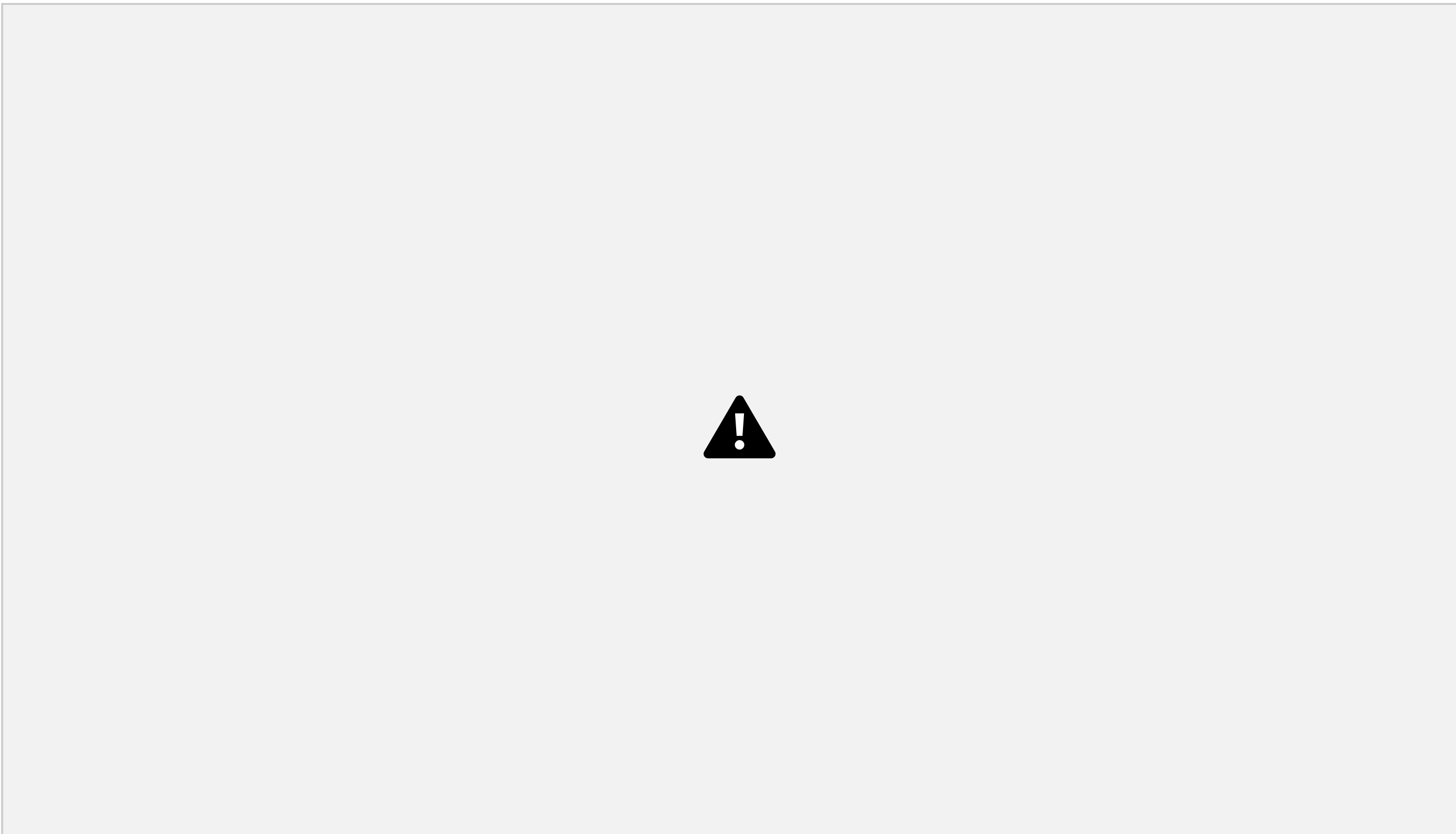


Figure 11: Torque-Speed Curves

- We know, at normal running condition,

$$T_r \propto S/R_2$$

- And at starting, $T_S \propto R_2/S$
- Therefore, if we add some resistance in series with the rotor winding, the starting torque will increase, but running torque will decrease.
- Hence, external rotor resistance are used where high starting torque is required once the motor has picked up to its normal operating speed (N), the external rotor resistance is removed to improve the running torque.

- 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_2low 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.

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.

- 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.

- 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 (ø) 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.

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, N = 1152 RPM
- Synchronous speed, $N_S = 120f/p$

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

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

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, $S = \{N_S – N\}/ N_S$

Or, $4/100 = \{1200 – N\}/ 1200$

Or, $4/100 * 1200 = 1200 – N$

Or, $48 = 1200 – N$

Or, $N = 1200 – 48$

Or, $N = 1152$ 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,

$$I_r = E_r/\sqrt{\{R_2{}^2 + X_2{}^2\}} = \{80/\sqrt{3}\} / \sqrt{\{(0.1)^2 + (4)^2} = 46.18/4 = 11.54 \text{ A}$$

- 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, $S = \{N_S – N\} / N_S = \{1500 – 1400\} / 1500 = 100/1500 = 1/15 = 6.69\%$

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

$= 3.08/ 0.2849 = 10.81$ A

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

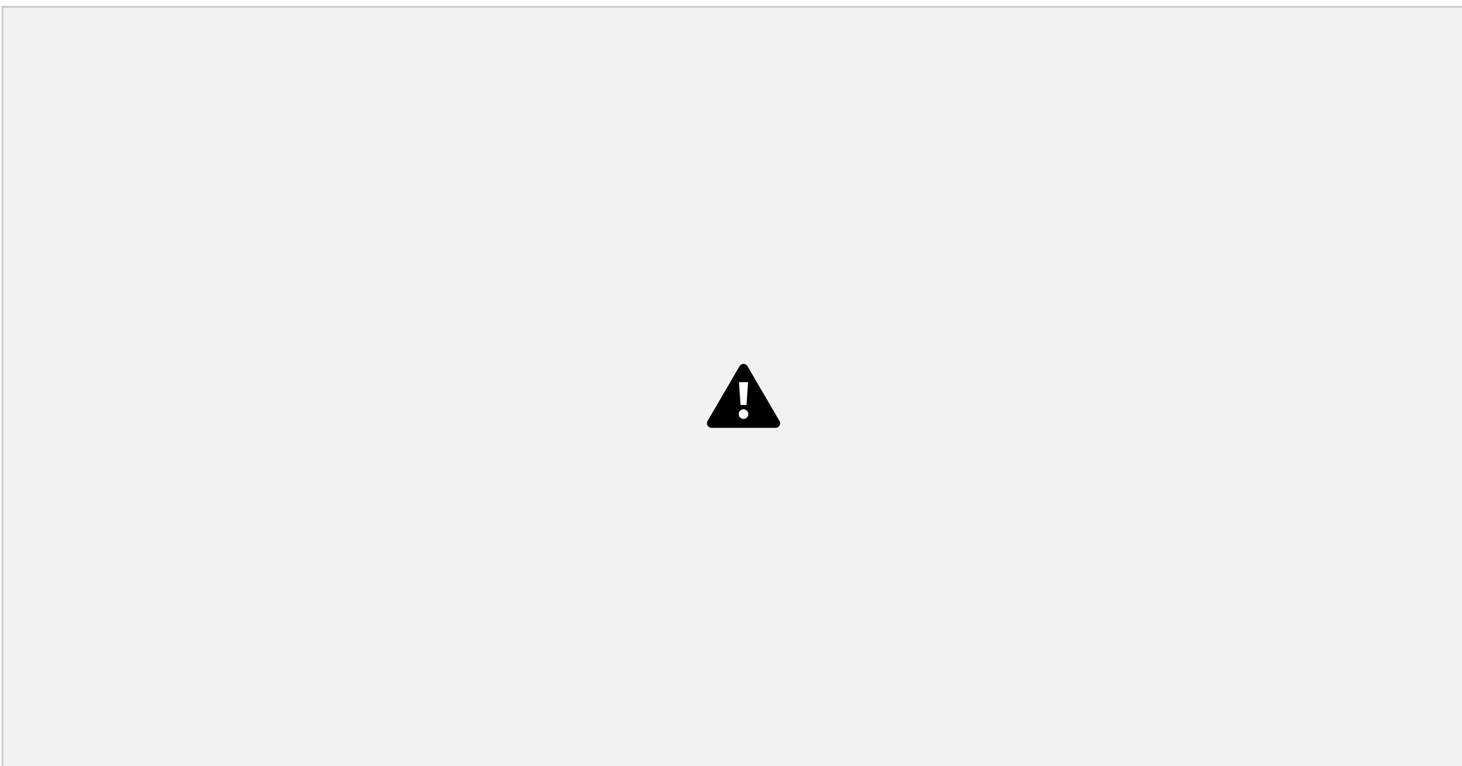
4) A three phase delta connected 440volts,50Hz,4 pole induction motor has a rotor.Standstill emf per phase of 130volts.If the motor is running at 1440 rpm.Calculate for this speed.

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



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

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

- An induction motor can also be used as a generator driving it by some prime mover above the synchronous speed.
- An induction generator is a type of an electrical generator that is mechanically & electrically similar to a polyphase induction motor. Induction generators produce electrical power when their shaft is rotated faster than the synchronous frequency of the equivalent induction motor. Induction generators are often used in wind turbines & some micro hydro installations due to their ability to produce useful power at varying rotor speeds.
- Induction generators are mechanically and electrically similar than other generator types. They are also more rugged, requiring no brushes or commutators.

- Induction generators are not self-exciting, meaning they require an external supply to produce a rotating magnetic flux.
- The external supply can be supplied from the electrical grid or from the generator itself, once it starts producing power the rotating magnetic flux from the stator induces currents in the rotor, which also produces a magnetic field.
- If the rotor turns slower than the rate of the rotating flux, the machine acts like an induction motor. If the rotor is turned faster it acts like a generator producing power.
- If the rotor of the induction machine is driven by a speed above the synchronous speed, the stator winding will generate three phase emf provided air gap-flux is maintained by supplying reactive power from external source.

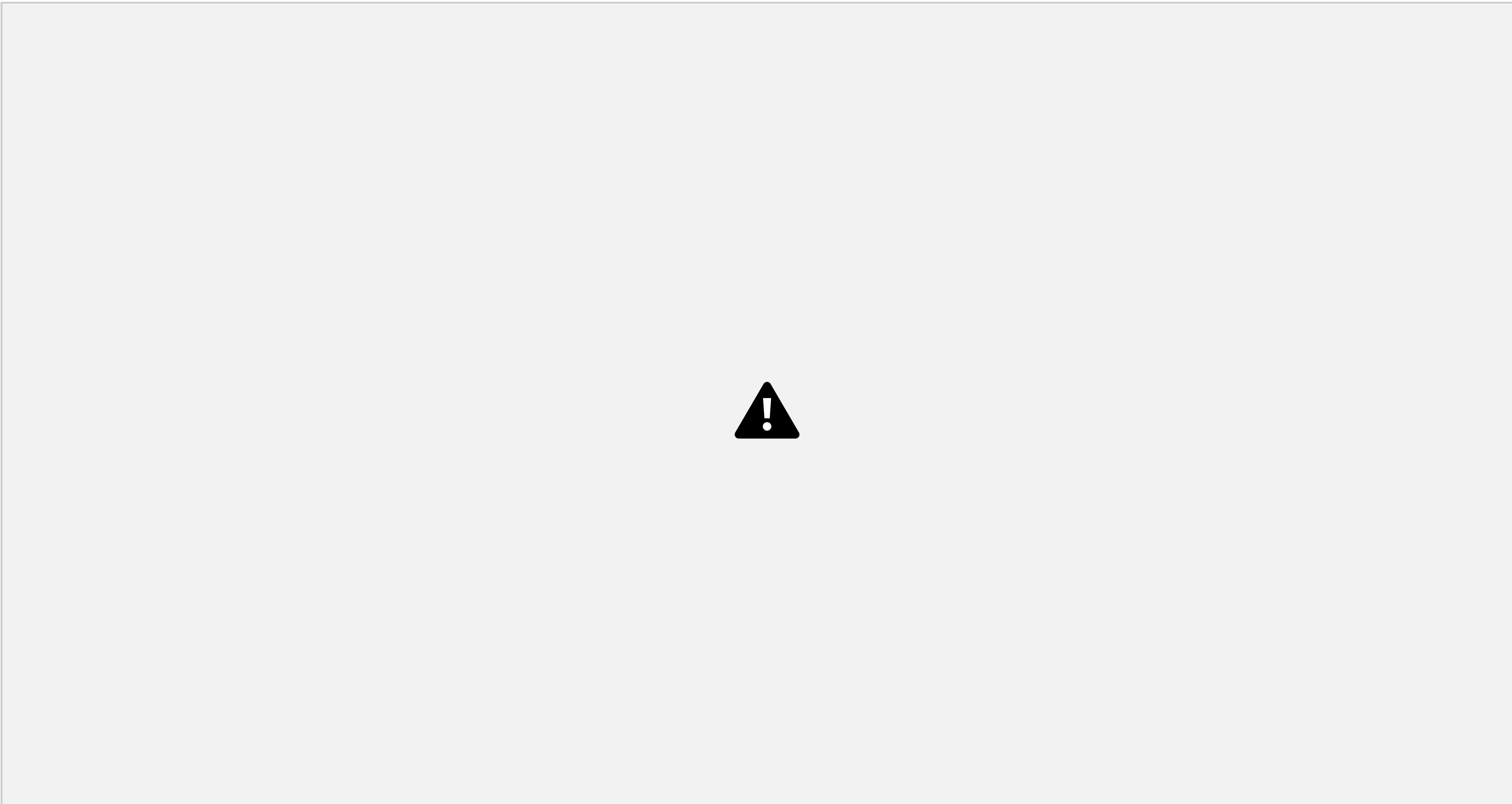


Figure 12: Power Stages

1) Consider, an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the

stator pulls the rotor to run behind it (the machine is acting as a motor).

2) Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.
3) If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field.
4) This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).

Induction generator is not a self-excited machine. Therefore, when running as a generator, the machine takes reactive power from the AC power line and supplies active power back into the line. Reactive power is needed for producing rotating magnetic field. The active power supplied back in the line is proportional to slip above the synchronous speed.

It is clear that, an induction machine needs reactive power for excitation, regardless whether it is operating as a generator or a motor. When an induction generator is connected to a grid, it takes reactive power from the grid. But what if we want to use an induction generator to supply a load without using an external source (e.g. grid)?

A capacitor bank can be connected across the stator terminals to supply reactive power to the machine as well as to the load. When the rotor is rotated at an enough speed, a small voltage is generated across the stator terminals due to residual magnetism. Due to this small generated voltage,capacitor current is produced which provides further reactive power for magnetization.

- The reactive power required for the machine cannot be obtained from the mechanical power input therefore, capacitor has to be used to obtain reactive power requirement to establish air gap magnetic flux. The capacitors are used as shown in figure 13.

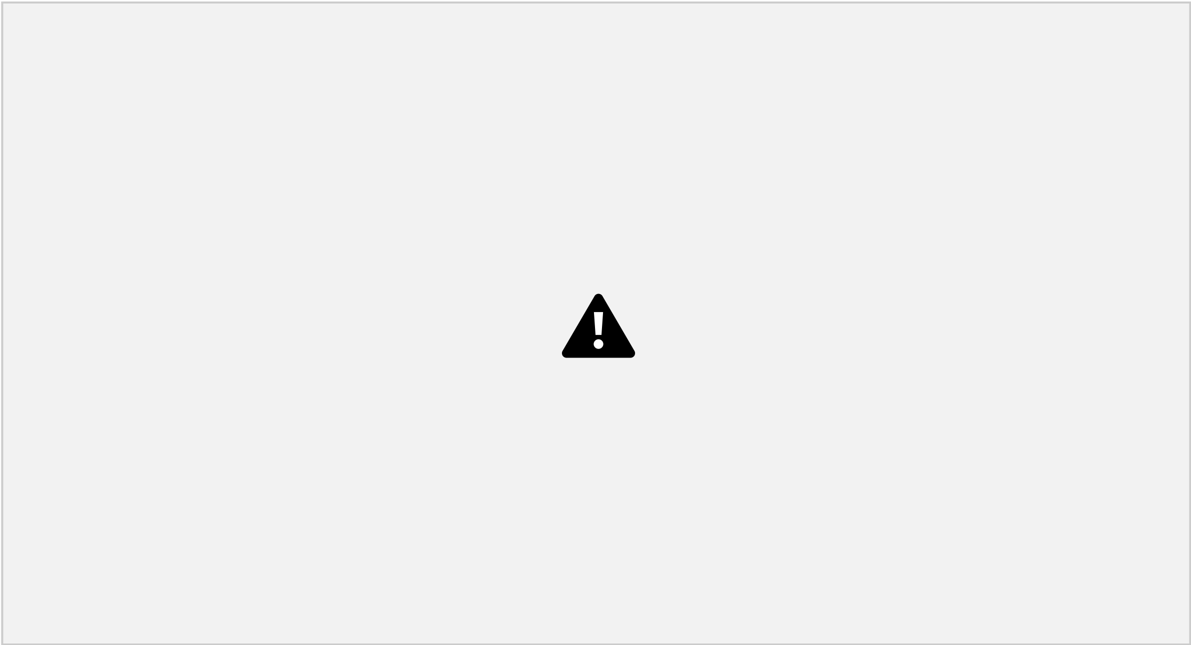


Figure:13 Induction Generator with Excitation Capacitor

🗣 These capacitor acts as excitation for the machine.

🗣 As the machine is driven above the synchronous speed the slip becomes negative as shown in the torque slip characteristics (see figure 14). 🗣 The torque is also negative which signify that the torque is not developed by the machine but torque is given to the machine by the prime mover.

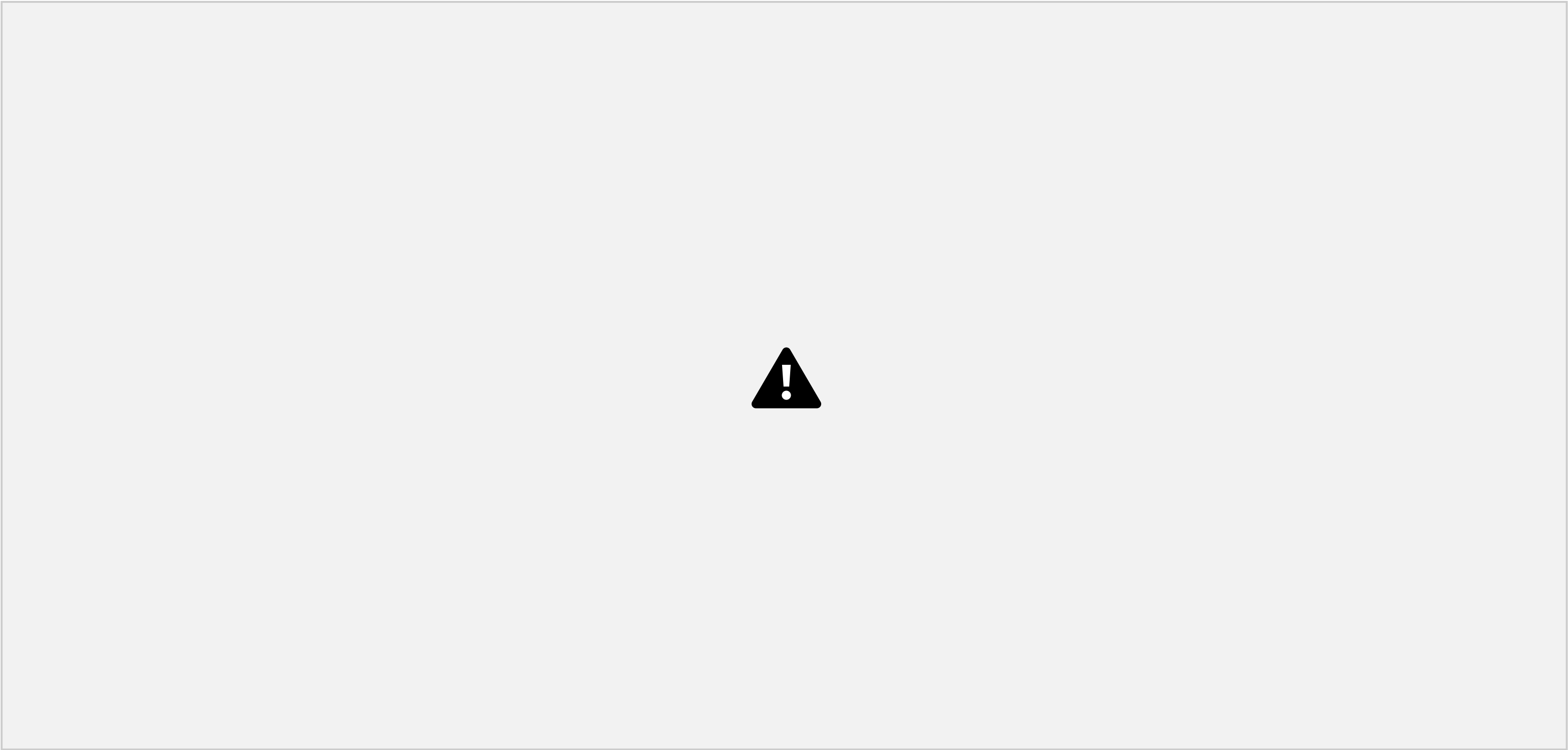


Figure 14: T – S Characteristics of Induction Machine

- If a proper value of capacitor is selected, the magnetizing current can be sufficient to increase the existing air gap flux.
- With an increased air gap flux, induced voltage increases resulting in more magnetizing current flow.
- This process of voltage build-up continues until induced voltage

reaches a limit constrained by the saturation curve of the machine and the reactance of the capacitor.

- The equivalent circuit of an induction machine in such a condition can be represented by figure 15.

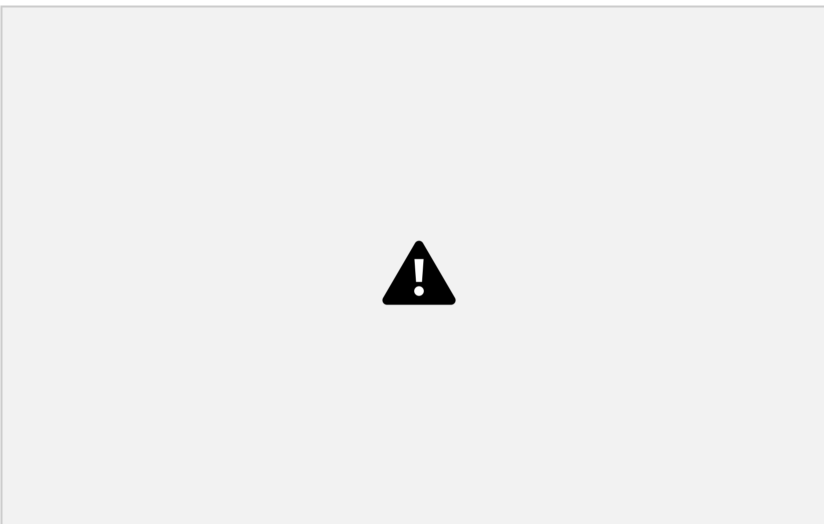


Figure 15: Equivalent Circuit for no load Excitation Condition

- X = Total leakage reactance
- i_{μ} = magnetizing current
- X_m = Magnetizing reactance
- e = induced emf in stator
- X_c = capacitive reactance
- Self excitation occurs when

X_c < or = $(X_m + X)$

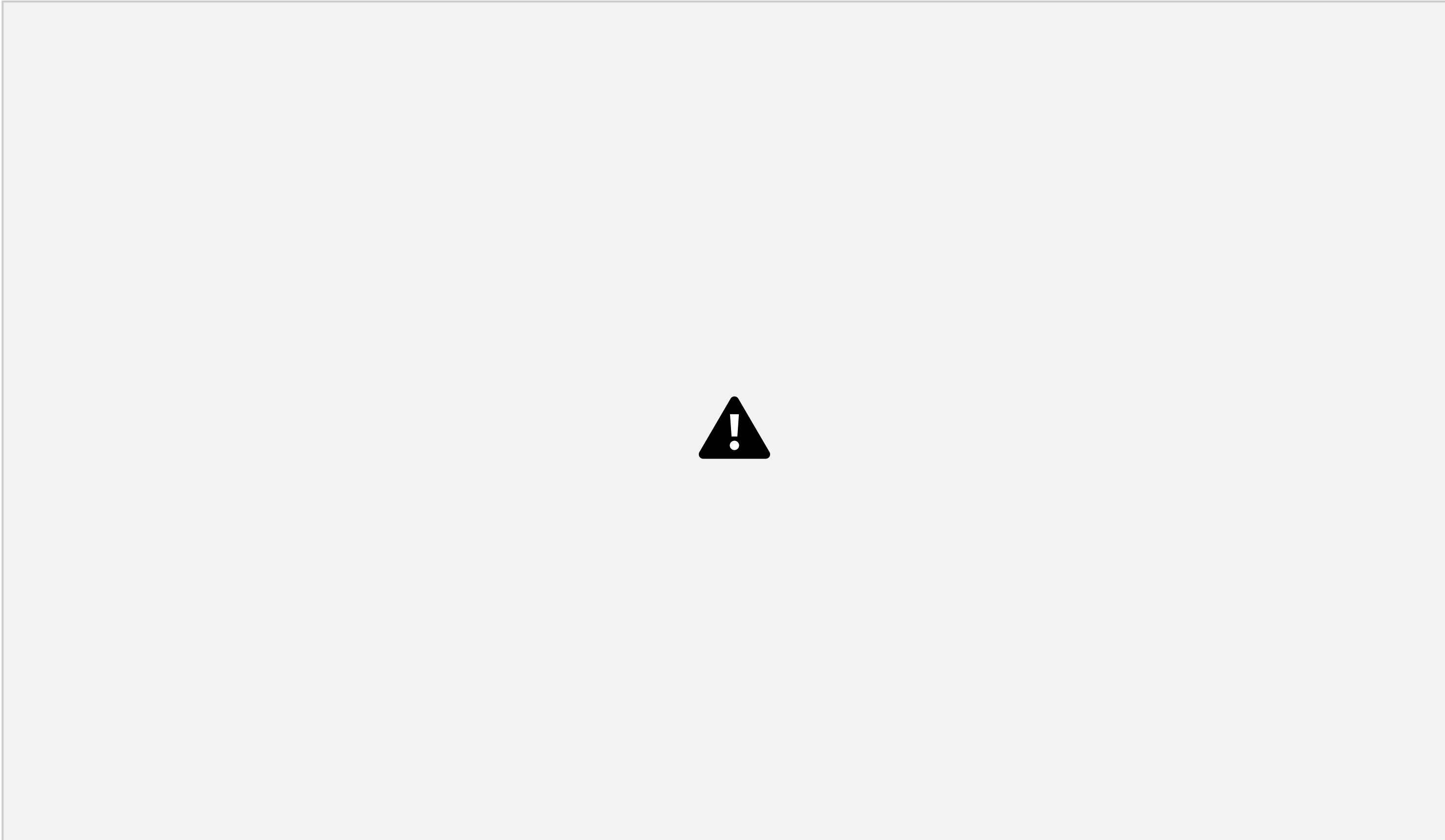


Figure 16: No-Load Saturation Curve and Final Build-up Voltage

- In Figure 16, curve ‘E’ shows machine excitation characteristics and C_1, C_2, C_3, C_4represent the volt-amp characteristics of the capacitors of different rating used for excitation.

- For any point on the excitation curve,

$$e/i_m = (X_m + X) = X_c \text{ ....Eq. 1}$$

- For practical purpose equation 1 is true when the leading VA rating of the capacitor is equal to the lagging or magnetizing VA of the machine for reactiveVA balance in the system.
- Thus, the slope of the curves of C_1, C_2, C_3, C_4gives the reactance of the capacitor required to produce the voltage corresponding to points of intersection with curve 'E'.
- As the value of the capacitor decreases, its reactance increases, i.e. the slope increases with resulting decrease in terminal voltage until characteristics 'C' coincides with the curve 'E'.
- The curve 'C_3' gives infinite number of possible solutions.

- Below this capacitance, the machine will not excite and hence will be inoperative.

- The capacitance corresponding to C_3represents critical value of capacitance below which the machine cannot build-up the voltage.
- With excitation capacitance C_1, the final build-up voltage in the stator is E_1 and at this instant, the magnetizing current requirement is i_{m1}.
- If the capacitance is decreased to C_2, then the final build-up voltage in the stator is only $E_2$and at this instant, the magnetizing current requirement is i_{m2}.

- The induction generator has become very popular as small scale hydro power generators in remote rural area because of the following reasons: - Commercially available ordinary induction motor can be used as a generator.
- Much cheaper than synchronous generator.

- Easy operation & less maintenance problem.

Induction or asynchronous generators are more rugged and require no commutator and brush arrangement (as it is needed in case of synchronous generators).

One of the major disadvantage of induction generators is that they take quite large amount of reactive power.