Three phase Induction machines

Introduction

- The three-phase induction motors are the most widely used electric motors in industry because of simple construction and better operating characteristics.
- These are also called as Asynchronous Motors, because an induction motor always runs at a speed lower than synchronous speed.
- 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.
- Operates on principle of electromagnetic induction.

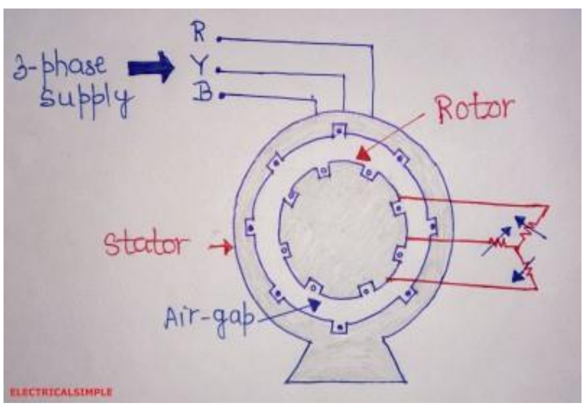
Construction

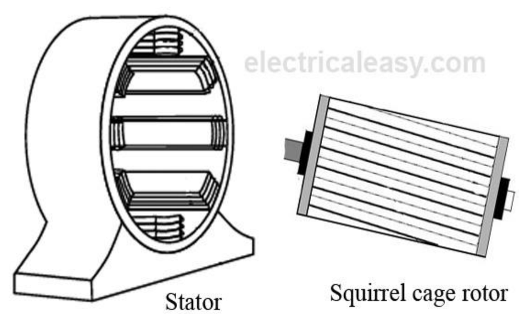
A 3-phase induction motor has two main parts

(i) Stator and

(ii) Rotor.

The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor.





i) **Stator:**

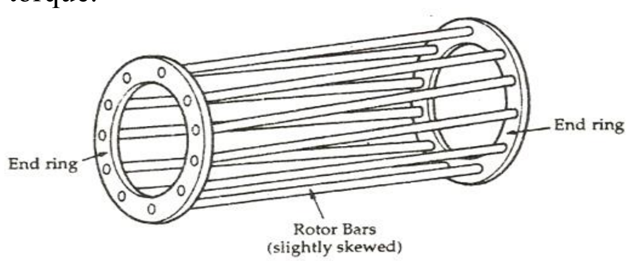
- Stationary part of motor
- stator construction of a three-phase induction machine is similar to that of a three-phase synchronous machine.
- It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses.
- A three-phase winding is placed in a number of slots in order to produce a rotating sinusoidal mmf wave.
- The stator of an induction motor consists of poles carrying supply current to induce a magnetic field that penetrates the rotor.
- The 3-phase stator winding is wound for a definite number of poles as per requirement of speed. Greater the number of poles, lesser is the speed of the motor and vice-versa.
- When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

ii) Rotor

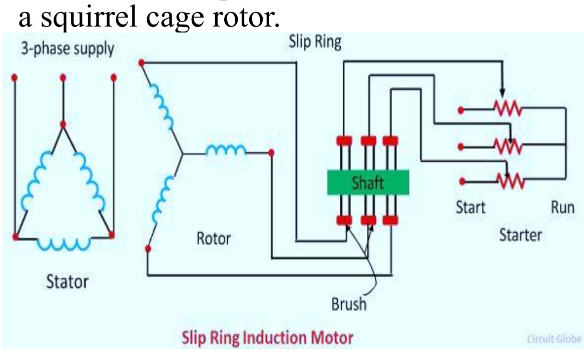
- Central rotating parts of the motors.
- Made of laminated silicon steel sheet.

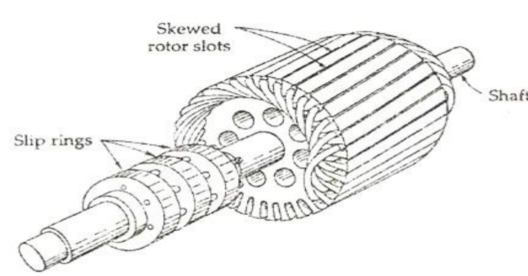
- It composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding.
- Cylindrical in shape with central shaft. The shaft is supported by bearing at both ends so that rotor rotates freely keeping an airgap of 1 to 4 mm between rotor and stator.
- Different from other types of machine that we have considered so far: there is no requirement for a power source on the rotor
- The winding placed in these slots (called rotor winding) may be one of the following two
    1. Squirrel cage Rotor
    2. Phase wound/slip ring Rotor

1. **<u>Squirrel cage rotor</u>:** It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminum bar is placed in each slot. All these bars are joined at each end by metal rings called end rings. This forms a permanently short-circuited winding which is indestructible. The entire construction (bars and end rings) resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator.
   Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction, maximum running torque. enabling it to operate in the most adverse circumstances. However, it suffers from the disadvantage of a low starting torque, High starting currents, Poor power factor. It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque.



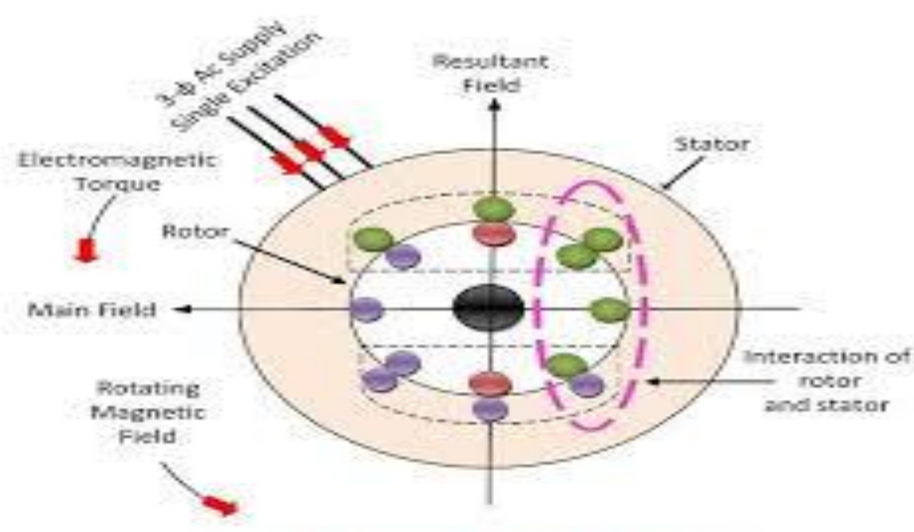
2. **<u>Wound Type Rotor or Slip Ring Type Rotor</u>** : It consists of a laminated cylindrical core and carries a 3- phase winding, similar to the one on the stator. The rotor winding is uniformly distributed in the slots and is usually star-connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a 3-phase star-connected rheostat. At starting, the external resistances are included in the rotor circuit to give a large starting torque. External resistance can be added in the rotor circuit through slip ring for reducing the starting current and simultaneously the starting torque. These resistances are gradually reduced to zero as the motor runs up to speed. When the motor attains normal speed, the three brushes are short-circuited so that the wound rotor runs like a squirrel cage rotor.





Principle of Operation of an Induction Motor

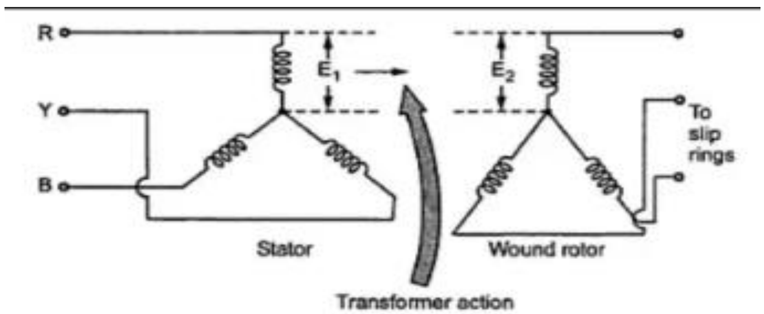
- **Production of Rotating Magnetic Field**
- When the three phase stator windings are fed by a three phase supply then, a magnetic flux of constant magnitude, but rotating at synchronous speed, is set up which rotates round the stator at synchronous speed Ns (= 120 f/P)..
- The flux passes through the air gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary. Due to the relative speed between the rotating flux and stationary conductors, an emf is induced in the rotor conductors, according to Faraday's laws of electro-magnetic induction. The frequency of the induced emf is same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors and its direction is given by Fleming's Right-hand rule. The induced voltage is: E= B.l.v
- Since the rotor bars or conductors form a closed circuit, currents start flowing in the rotor conductors, rotor current is produced.
- The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, mechanical force acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the same direction as the rotating field.
- The fact that rotor is urged to follow the stator field (i.e., rotor moves in the direction of stator field) can be explained by Lenz's law. Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.
- In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence, to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux.
- Thus, from the working principle of three phase induction motor, it may be observed that the rotor speed should not reach the synchronous speed produced by the stator. If the speeds become equal, there would be no such relative speed, so no emf induced in the rotor, and no current would be flowing, and therefore no torque would be generated.



Three Phase Induction Motor

Induction motor is called as rotating transformer

- Both transformer and induction motor works on the principle of electromagnetic induction.
- In induction motor, the Stator, when connected to three phase supply, works like primary of a transformer. It draws magnetizing current and sets up a magnetic field (though rotating) which links both primary (stator winding) and secondary (rotor winding).
- Due to rotating magnetic field, an open circuit voltage, depending upon the turn's ratio (stator number of turns per phase / rotor number of turns per phase) is induced across the slip rings (analogous to transformer secondary terminals).
- When the slip rings are short circuited, the motor behaves like a transformer with secondary short circuited. A heavy current flow in the rotor (secondary). Like in a transformer, ampere turn balance is maintained between stator(primary) and rotor (secondary), and therefore, rotor current is reflected into stator (primary).
- So, the power is transferred from stator (primary) to rotor (secondary) through magnetic field.



- In general induction motor is treated as transformer as,
  E_1 = Stator EMF per phase
  E_2 =Rotor induced emf per phase
  The transformation ratio E_2/E_1 = K constant = Turn's ratio = N_2/N_1
- So, if the stator supply voltage is known and ratio of stator turns per phase From that we obtain rotor induced emf per phase
- That's why we called induction motor as a rotating transformer
- In fact, that is how the equivalent circuit of an induction motor is developed.

Some terminology in induction machine

1) Slip

- In practice, the motor never succeeds in catching up with the stator field. If it really did so, then there would be no relative speed between the two, hence no rotor emf, no rotor current and so there will be no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference in speed depends upon the load on the motor.

- The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.,

  slip = $\frac{Ns - N}{Ns}$ where, Ns= synchronous speed

  N = rotor speed

The quantity Ns − N is sometimes called slip speed.

When the rotor is stationary or at starting (i.e., N = 0), slip s,

slip = $\frac{Ns - N}{Ns}$ = 1 or 100 %.

And, maximum emf is induced.

In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 5% so that it is essentially a constant-speed motor.

The rotor speed is N = Ns(1-S)

2) <u>Frequency of Rotor Current and voltage</u>

- When the rotor is stationary, the frequency of rotor current is same as the supply frequency. i.e. $f = \frac{P\,Ns}{120}$
- But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip speed. Let at any slip-speed, the frequency of the rotor current be f ’. Then,

  $$f_r = \frac{P\,(Ns - N)}{120}$$

- So, $\frac{f_r}{f} = \frac{Ns-N}{N} = S$

  $f_r = S\,f$
- Hence, rotor frequency = slip * supply frequency
- At standstill condition, N=0, so, $f_r = f$

3) <u>Effect of slip on rotor induced e.m.f.</u>

- The magnitude of the induced e.m.f. in the rotor also reduces by slip times the magnitude of induced e.m.f. at standstill condition.

  $$E_2r = sE_2$$

4) <u>Rotor current</u>

a) **<u>Rotor current at standstill condition</u>**

Let,

E_2 = emf induced in standstill condition

R_2 = resistance per phase of rotor

X_2 = reactance per phase of rotor = $2\pi f L_2$

$Z_2 = R_2 + jX_2$

So, rotor current per phase at standstill condition is given by

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{R_2 + jX_2}$$

And, power factor is given by, $\cos\phi_2 = \frac{R_2}{Z_2}$

b) <u>Rotor current at running condition</u>

Let,

Emf induced in rotor at slip, $E = s\,E_2$

R_2 = resistance per phase of rotor

X_2 = reactance per phase of rotor = $2\pi(sf)L_2$

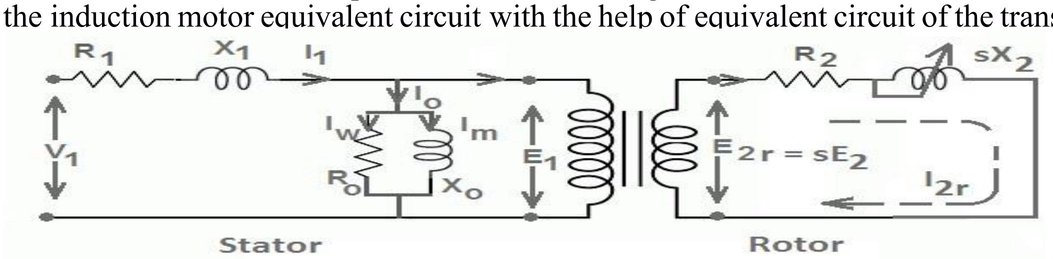
$Z_2 = R_2 + jsX_2$

So, rotor current per phase at slip condition is given by

$$I_2 = \frac{s\,E_2}{Z_2} = \frac{s\,E_2}{R_2 + j\,sX_2} = \frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}} = \frac{E_2}{\sqrt{(R_2/s)^2 + X_2^2}}$$

<u>Equivalent circuit of induction motor</u>

- The induction motor is equivalent to a rotating transformer. Hence, we can draw the induction motor equivalent circuit with the help of equivalent circuit of the transformer.



Basic Equivalent Circuit of I.M.

- V_1 is the per phase stator supply voltage. E_1 is the per phase stator induced voltage

  $E_{2r} = sE_2$ is the per phase rotor induced EMF (in running condition)

So, rotor current per phase at slip condition is given by

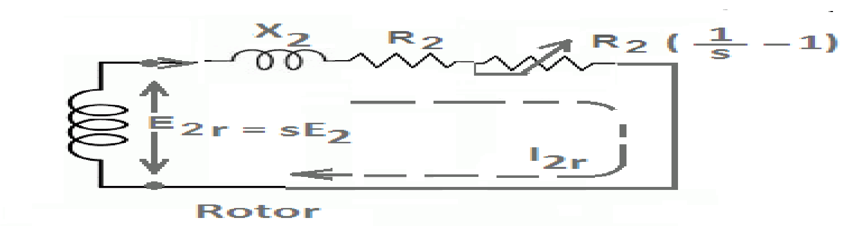
$$I_2 = \frac{sE_2}{Z_2} = \frac{sE_2}{R_2 + j\,sX_2} = \frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}} = \frac{E_2}{\sqrt{(R_2/s)^2 + X_2^2}}$$

- From the above expression, it is clear that the rotor circuit actually consists of a fixed resistance R_2 and a variable reactance sX_2, connected across $E_{2r} = sE_2$ is equivalent to a rotor circuit having a fixed reactance X_2 connected in series with a variable resistance R_2/s and supplied with constant voltage E_2.
- We can express resistance R_2/s in two parts as follows:
  $R_2/s = R_2 + R_2(1/s - 1)$

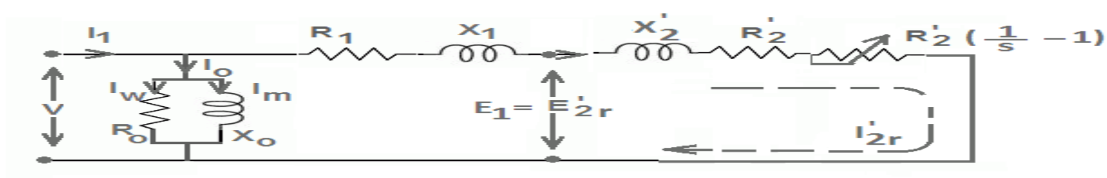
The first part R_2 is the rotor resistance and represents the rotor copper losses.

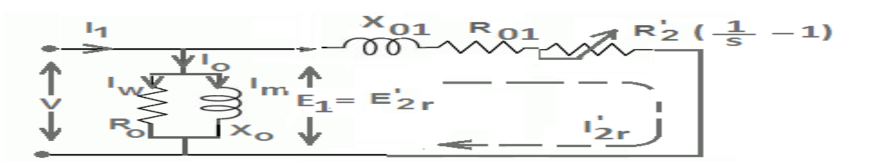
The second part $R_2(1/s - 1)$ is the load resistance R_L. It is the electrical equivalent of the mechanical load on the motor. It is the electrical power that is converted into the mechanical power by the motor.

- Hence equivalent rotor circuit of the induction motor can be drawn as under.



- **<u>Equivalent Circuit of Induction Motor Referred to Stator</u>**





Approximate Equivalent Circuit of I.M.

- Here, $R_{o1} = R_1 + R'_1$
  And $Xo_1 = X_1 + X'_1$ is equivalent resistance and reactance of induction motor referred to the stator.
- All the rotor parameters are transferred to the stator side as follows:
  $E_{2r}' = E_{2r}/k$
  $I'_2r = kI_{2r}$
  $X'_2 = X_2/k^2$ and $R'_2 = R_2/k^2$

- And K = turn ratio= $N_2/N_1 = E_2/E_1$

Induction Motor Phasor Diagram

- The stator winding corresponds to transformer primary and the rotor finding corresponds to transformer secondary. In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer.
- An induction motor at standstill condition is similar to a transformer at no load condition. Therefore, the method of drawing the induction motor phasor diagram is also same as that of a transformer phasor diagram. In this post we will discuss the phasor diagram of induction motor at standstill condition and at full load slip.

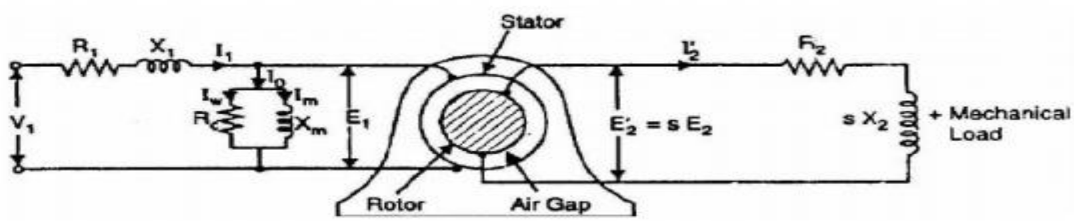


Fig: 3.8

- Let,

V1 = applied voltage per phase to the stator

R1 and X1 = Stator resistance and leakage reactance per phase respectively.

E1 = self-induced e.m.f.   is induced in the stator winding

E'2 (= s E_2 = s K E2 where K is transformation ratio) = mutually induced e.m.f.

induced in the rotor winding.

The flow of stator current I_1 causes voltage drops in R_1 and X_1.

$V_1 = - E_1 + I_1(R_1+jX_1)$

When the motor is at no-load, the stator winding draws a current I0. It has two components viz.,

(i) which supplies the no-load motor losses and

(ii) magnetizing component Im which sets up magnetic flux in the core and the air gap.

The parallel combination of Rc and Xm, therefore, represents the no-load motor losses and the production of magnetic flux respectively.

$I_0 = I_w + I_m$

Similarly,

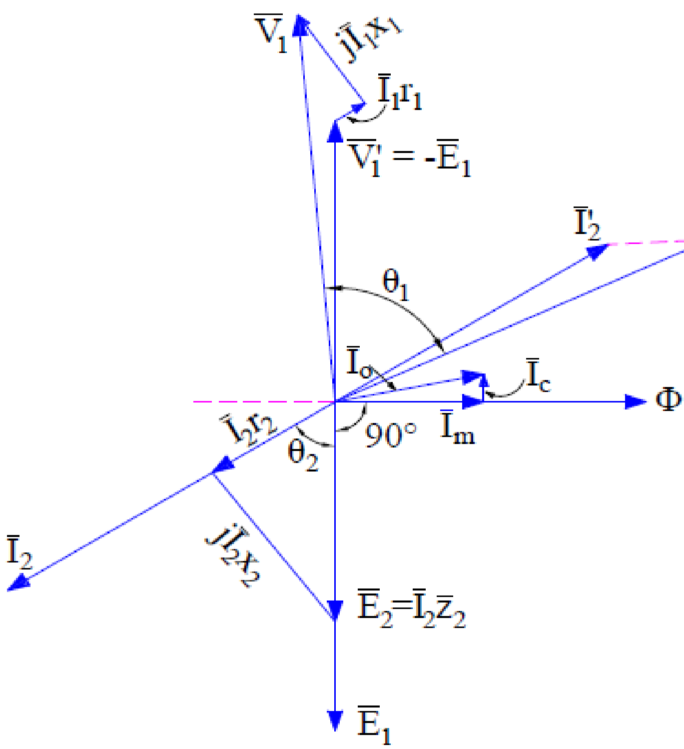
R2 and X2 = rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be sX_2 .

E'_2 = s E2 = s K **E**1 = induced voltage/phase in the rotor. Since the rotor winding is short-circuited, the whole of e.m.f. E'_2 is used up in circulating the rotor current I'_2.

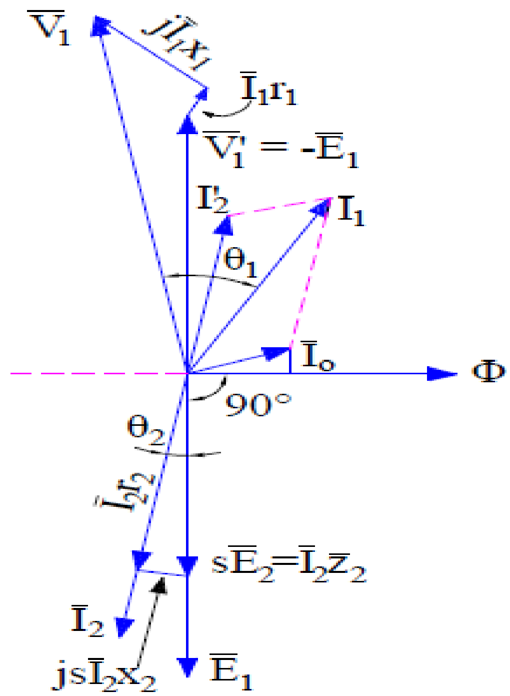
$E'_2 = I'_2 (R_2 + jsX_2)$

- The rotor currents I'2 is reflected as I''_2 (= K I'_2) in the stator.
- The phasor sum of I''_2 and I_0 gives the stator current I_1.
- Ø = resultant air gap flux per pole
- Now we are at a stage to draw the induction motor phasor diagram. Let us take the resultant air gap flux Ø as the reference. The induced emf always lags behind the resultant flux Ø by 90°.
- Also, the induced emf E_1 and E_2 in stator and rotor winding will lag behind the Ø by 90°. This is shown in the below phasor diagram of induction motor.

i) **Induction Motor Phasor Diagram at Standstill Condition:**



ii) **Induction Motor Phasor Diagram at Full Load Slip:**



TORQUE EQUATION IN INDUCTION MOTOR

- Torque of a three-phase induction motor is proportional to flux per stator pole, rotor current and the power factor of the rotor. $T \propto \phi\, I_2 \cos\phi_2$

$$T = \mathbf{k}\, \phi\, I_2 \cos\phi_2$$

where, ϕ = flux per stator pole,

I_2 = rotor current at standstill,

ϕ_2 = angle between rotor emf and rotor current,

K = Constant of proportionality = $3*60 / 2\pi N_s$

Now,

Let, E_2 = rotor emf at running condition

we know, rotor emf is directly proportional to flux per stator pole, i.e., $E_2 \propto \phi$.

Therefore, $T \propto E_2\, I_2 \cos\phi_2$

$$T = k\, E_2\, I_2 \cos\phi_2$$

And, rotor current per phase at running condition is given by

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

power factor is given by, $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$

Hence, torque developed by rotor $T = \mathbf{k}\, E_2 * \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} * \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$

$$= k*s\,E_2^2 * \frac{R_2}{R_2^2 + (sX_2)^2}$$

where k = Constant of proportionality = 3/ (2 Π n_s) where n_s = speed in rps

- The above equation is the torque equation for an induction motor under running condition. So, torque developed at any load condition can be obtained, by knowing the slip of the induction motor at that load condition. As per this Torque equation, the developing torque in Induction Motor is directly proportional to the square of the applied voltage.

Starting Torque/ Standstill Torque Of Induction Motor

- At the start condition the value of s = 1. Therefore, the starting torque is obtained by putting the value of s = 1, we get $\quad Tst = k* E_2^2 * \frac{R_2}{R_2^2 + X_2^2}$

Condition for maximum starting torque

If supply voltage V is constant, then the flux and hence, E_2 both are constant. So,

$$T = k* \frac{E_2^2 R_2}{R_2^2 + X_2^2} = k* \frac{R_2}{R_2^2 + X_2^2}$$

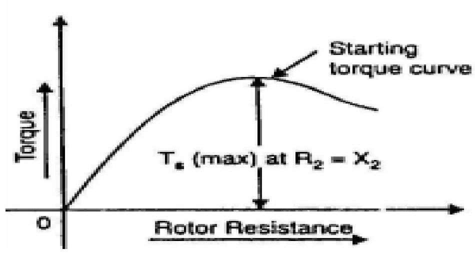
Torque will be maximum if $\frac{dT}{dR_2}=0$,

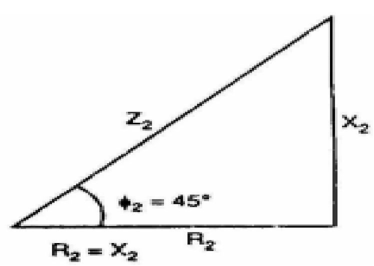
$$\text{so, } \frac{dT}{dR_2} = \frac{d}{dR_2}\left(k* \frac{R_2}{R_2^2 + X_2^2}\right)$$

$$0 = K\left(\frac{1}{R_2^2 + X_2^2} - \frac{R_2 * 2R_2}{(R_2^2 + X_2^2)^2}\right)$$

$$R_2^2 + X_2^2 = 2R_2^2$$

$$R_2 = X_2$$





Hence starting torque will be maximum when: Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, φ_2 = 45° and rotor power factor is 0.707 lagging which is obtained from impedance diagram.

Condition for maximum running torque

If supply voltage V is constant, then the flux and hence, E_2 both are constant. So,

$$T = k* \frac{s\,E_2^2 R_2}{R_2^2 + (sX_2)^2} = k* \frac{s\,R_2}{R_2^2 + (sX_2)^2}$$

Torque will be maximum if $\frac{dT}{dS}$=0,

so, $\frac{dT}{dS} = \frac{d}{dR_2}\left(k^* \frac{s R_2}{R_2^2 + (sX_2)^2}\right)$=0

Or, $\frac{K\,[R_2 \{R_2^2 + (sX_2)^2\} - 2\,s\,X_2^2\,(sR_2)]}{(R_2^2 + (sX_2)^2)} = 0$

$R_2^2 + (sX_2)^2 - 2s\,X_2^2 = 0$

Solving we get, R_2= sX_2

Hence, torque under running condition is maximum when at that the slip which makes rotor reactance per phase equal to rotor resistance per phase.

And, maximum torque $T_{max} = k^* \frac{s E_2^2}{2R_2} = k^* \frac{s E_2^2}{2sX_2} = k^* \frac{E_2^2}{2X_2}$

- The above equation shows that the maximum torque is independent of the rotor resistance.
- If s_{Max} is the value of slip corresponding to the torque which is maximum then from the equation. i.e., $S_{max} = R_2/X_2$
- Therefore, the speed of the rotor at maximum torque is given by the equation shown below. i.e., $N_{max} = N_s(1-S_{max})$

Torque-speed/slip characteristic

- The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.
- The range of slip is between zero to one and the range of rotor speed is between zero (standstill) and Ns (synchronous speed).
- If a curve is drawn between the torque and slip for a particular value of rotor resistance R2, the graph thus obtained is called torque-slip characteristic. Torque slip and Torque speed curve obtain from the torque equation.
- Torque slip and Torque speed curve obtain from the torque equation.

  $T = k^* \frac{s E_2^2 R_2}{R_2^2 + s^2 X_2^2}$

- If R_2 and X_2 are kept constant, then the torque τ will depend upon the slip s. The torque-slip characteristic curve is divided into three regions:

  i) Low-slip region

  ii) Medium-slip region

  iii) High-slip region

i) **Low-slip region / normal operating range**

- During normal operating range: Speed = 0.8Ns to Ns or slip= 0.2 from 0
- The value of slip is very low. Therefore, the terms s X_2 is significantly small compared to R_2.
- Hence, the torque equation is given by

$$T = k^* \frac{sE_2^2 R_2}{R_2^2} \quad \text{Neglecting } s^2 X_2^2$$

or, $T = k^* \frac{sE_2^2}{R_2}$

or, $T \,\alpha\, \frac{s}{R_2}$

or, $T \,\alpha\, s$ if R_2 is kept constant.

From the above relation, we can see that the torque is proportional to the slip. Hence, when the slip is small, the torque-slip curve is a straight line.

ii) **Medium-slip region**

- As slip increases, the term $(sX_2)^2$ becomes large, so that R_2^2 may be neglected in comparison with $(sX_2)^2$.
- Hence, the torque equation is given by

$$T = k^* \frac{sE_2^2 R_2}{s^2 X_2^2} \quad \text{Neglecting } R_2^2$$

or, $T = k^* \frac{R_2 E_2^2}{s X_2^2}$

or, $T \,\alpha\, \frac{1}{s}$ for constant E_2 and R_2

Thus, the torque is inversely proportional to slip towards standstill conditions. We can represent the torque-slip characteristic by a rectangular hyperbola.

- For intermediate values of the slip, the graph changes from one form to another. In doing so, it passes through the point of maximum torque when $R_2 = sX_2$.
- The maximum torque developed in an induction motor is called the **pull-out torque** or breakdown torque. This developed torque is a measure of the short-time overloading capability of the motor.

iii) **High-slip region**

- Beyond the maximum torque point, the value of torque starts decreasing. As a result, the motor slows down and stops. At this stage, the overload protection must immediately disconnect the motor from the supply to prevent damage due to overheating of the motor.
- The motor operates for the values of the slip between s = 0 and $s = s_M$. Where, s_M is the value of the slip corresponding to the maximum torque. For a typical induction motor, the pull-out torque is 2 to 3 times the rated full load torque. The starting torque is about 1.5 times the rated full load torque.

- The starting torque is given by $T_{st} = k^* E_2^2 * \frac{R_2}{R_2^2 + X_2^2}$

Thus, induction motor has some torque at slip = 1 which is called starting torque.

The complete curve is shown in figure below.

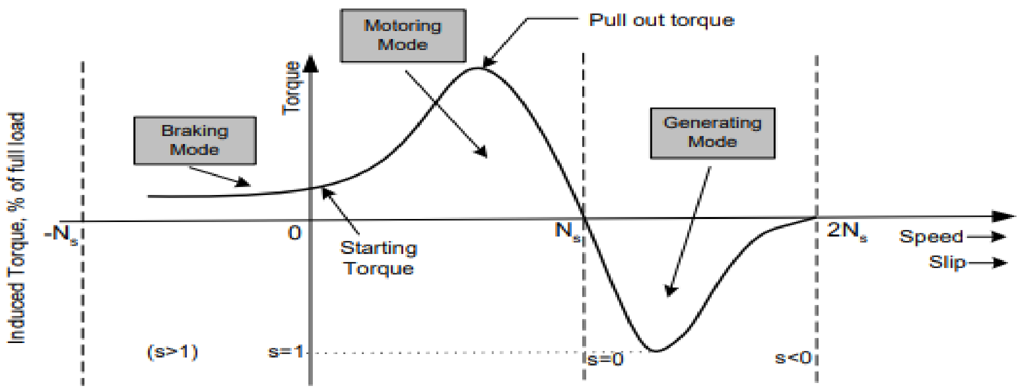
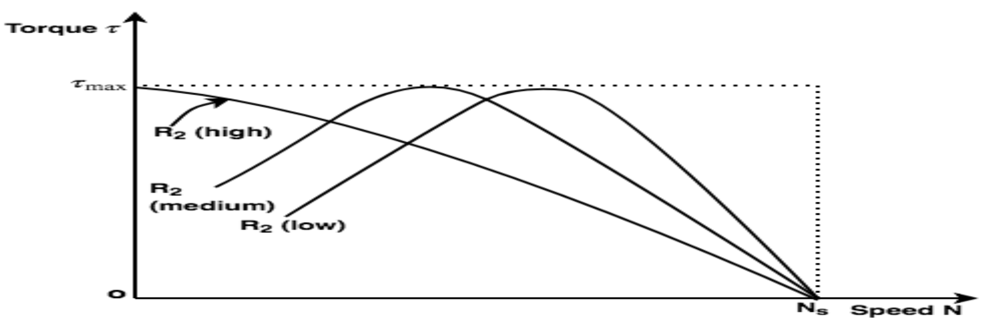


Figure 1.17 Torque-slip and Torque-speed characteristics of induction motor

Effect of Rotor Resistance on T-S curve

- At normal running condition, $T \propto \frac{S}{R_2}$
- At starting, $T_s \propto \frac{R_2}{s}$
- Therefore, if we add some resistance in series with rotor winding, the starting torque will be increases but running torque will decreases.
- The effect of rotor resistance on T-S curve is shown in figure,



- Hence, external rotor resistance is used where high starting torque is required. Once motor picked up to its normal operating speed, the external rotor resistance is removed to improve running toque.
- Rotor resistance can be increased up to that when Starting torque becomes equal to Maximum value of torque, because after that Starting torque gets reduced. This value of resistance is called Critical Resistance.
- When slip at starting becomes equal to slip corresponding to maximum torque.
- Value of Critical Resistance (x) = $X'_2 - R'_2$
- Thus by adding external resistance to rotor till it becomes equal to, the maximum torque can be achieved at start.

- If such a high resistance is kept permanently in the circuit, there will be large copper losses ($I^2 R$) and hence efficiency of the motor will be very poor. Hence such added resistance is cut-off gradually and finally removed from the rotor circuit, in the normal running condition of the motor. So, this method is used in practice to achieve higher starting torque hence resistance in rotor is added only at start.

__Methods of Starting 3-Phase Induction Motors__

- An induction motor is similar to a transformer whose secondary is short circuited. Thus, at normal supply voltage, like in transformers, the initial current taken by the primary is very large for a short while.
- If an induction motor is directly switched on from the supply, it takes 5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line. Hence, it is not advisable to start induction motors of higher ratings (generally above 25kW) directly from the mains supply.
- Therefore, it is desirable and necessary to reduce the magnitude of stator current at starting and several methods are available for this purpose.

  i) Direct-on-line starting

  (ii) Stator resistance starting

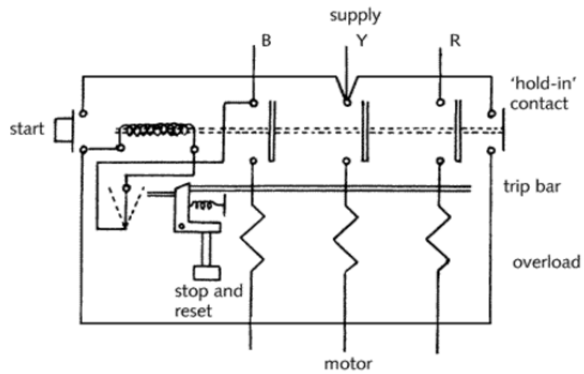
  (iii) Autotransformer starting

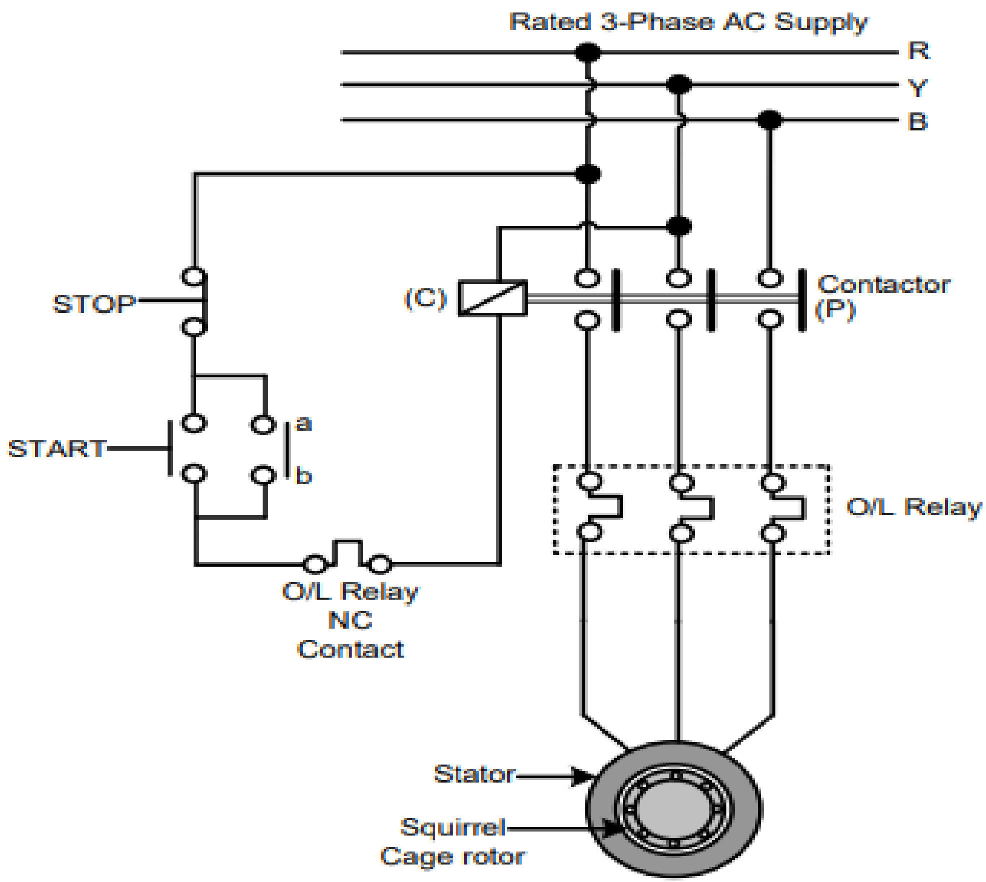
  (iv) Star-delta starting

  (v) Rotor resistance starting

i) **__Direct-On-Line (DOL) Starters__**

- The direct on-line starter method, of an induction motor is simple and economical. In this method, the starter is connected directly to supply voltage. By this method small motors up to 5 kW rating is started to avoid the supply voltage fluctuation.
- Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor. In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used





(ii) **Stator resistance starting \ Using Primary Resistors**

- In this method, external resistances are connected in series with each phase of stator winding during starting. This causes voltage drop across the resistances so that voltage available across motor terminals is reduced and hence the starting current. The starting resistances are gradually cut out in steps (two or more steps) from the stator circuit as the motor picks up speed. When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the rotor.
- This method suffers from two drawbacks. First, the reduced voltage applied to the motor during the starting period lowers the starting torque and hence increases the accelerating time. Secondly, a lot of power is wasted in the starting resistances.

- This method is not applicable to motor requiring high starting torque.

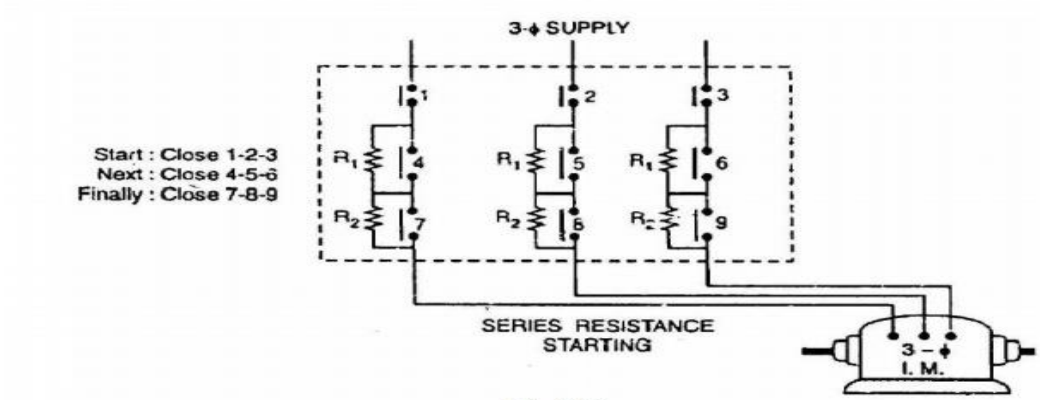
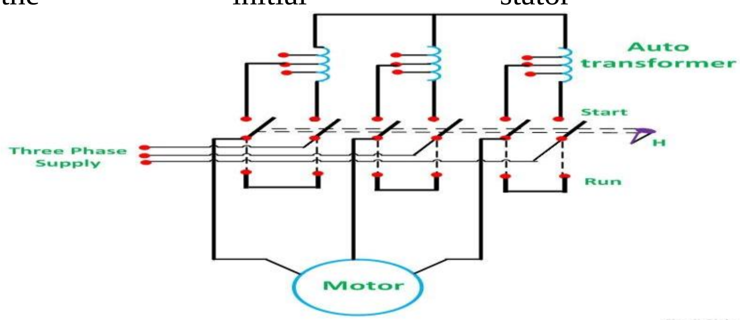


Fig: 3.23

(iii) **Autotransformer starting**

- An Auto transformer Starter is suitable for both star and delta connected motors. In this method, the starting current is limited by using a three-phase auto transformer to reduce the initial stator applied voltage.



- It is provided with a number of tapping's. The starter is connected to one particular tapping to obtain the most suitable starting voltage. A double throw switch S is used to connect the auto transformer in the circuit for starting. When the handle H of the switch S in the START position. The primary of the auto transformer is connected to the supply line, and the motor is connected to the secondary of the auto transformer.
- When the motor picks up the speed of about 80 percent of its rated value, the handle H is quickly moved to the RUN position. Thus, the auto transformer is disconnected from the circuit, and the motor is directly connected to the line and achieve its full rated voltage. The handle is held in the RUN position by the under-voltage relay.
- If the supply voltage fails or falls below a certain value, the handle is released and returns to the OFF position. Thermal overload relays provide the overload protection.

(iv) **Star-delta starting**

- The stator winding of the motor is designed for delta operation and is connected in star during the starting period. When the machine is up to speed, the connections are changed to delta. The circuit arrangement for star-delta starting is shown in Fig.

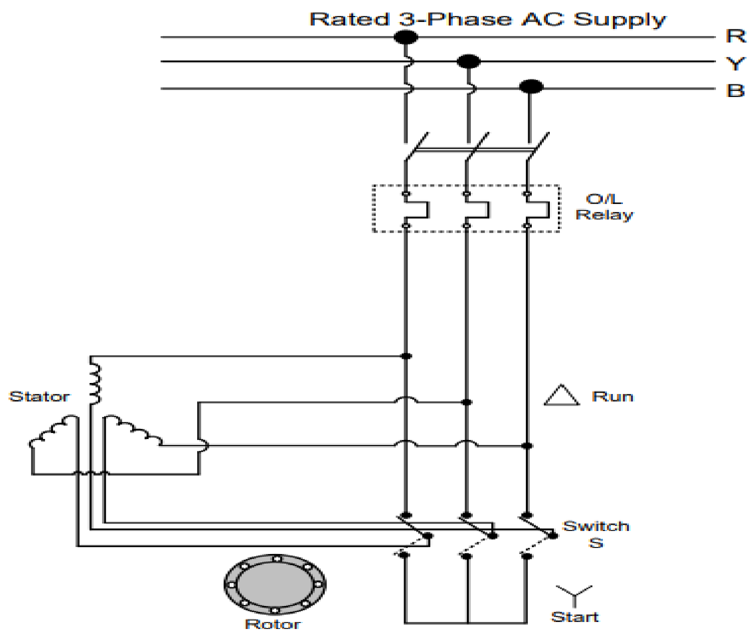


Figure 1.25Star-Delta starter

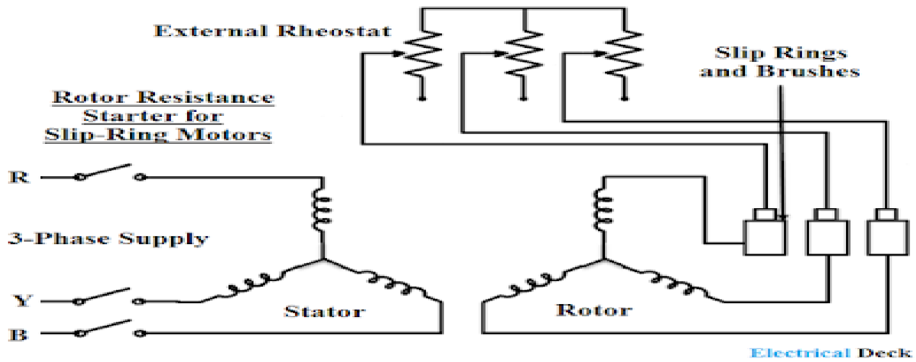
- The six leads of the stator windings are connected to the changeover switch as shown. At the instant of starting, the changeover switch is thrown to "Start" position which connects the stator windings in star. Therefore, each stator phase gets $V/\sqrt{3}$ volts where V is the line voltage. This reduces the starting current.
- When the motor picks up speed, the changeover switch is thrown to "Run" position which connects the stator windings in delta. Now each stator phase gets full line voltage V.
- The disadvantages of this method are:

(a) With star-connection during starting, stator phase voltage is $1/\sqrt{3}$ times the line voltage. Consequently, starting torque is $(1/\sqrt{3})^2$ or 1/3 times the value it would have with Δ-connection. This is rather a large reduction in starting torque. Hence a star-delta starter is equivalent to an auto-transformer of ratio 1/(sqrt. 3) or 58% reduced voltage.

(b) The reduction in voltage is fixed. This method of starting is used for medium-size machines (up to about 25 H.P.).

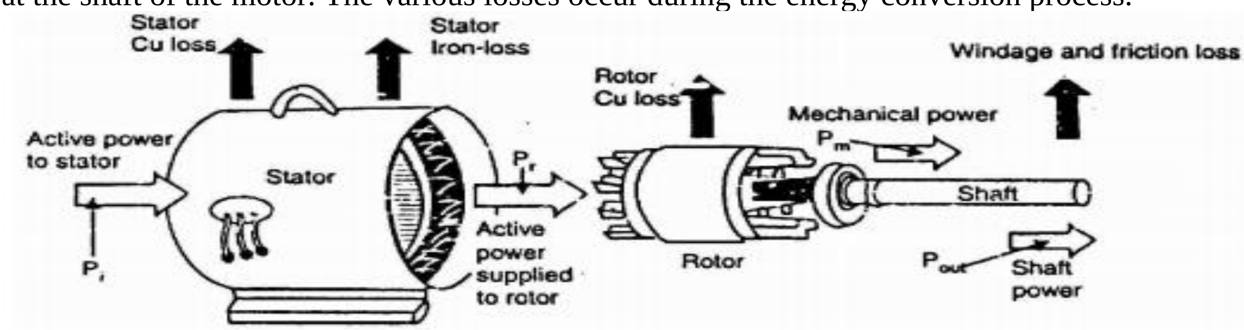
(v) <u>Rotor resistance starting</u> (for slip ring motor)

- In the rotor resistance stator, a variable resistance is connected with the rotor circuit to limit the rotor current. The arrangement is shown in the figure.
- The external resistance is inserted in each phase of the rotor circuit through slip rings and brush. At starting the resistance is kept to its maximum value. As the motor picks up speed, the resistance is gradually down to a low value and finally cut off.
- When the motor attains normal speed, the rotor windings are short-circuited through the slip rings and brushes as the external resistance been removed. This operation may be manual or automatic.
- This method not only limits the starting current but also increases the starting torque due to added rotor resistance. This starter is not suitable for squirrel cage induction motors because external resistance cannot be inserted in the squirrel-cage rotor.



Losses in induction motor

- The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses occur during the energy conversion process.

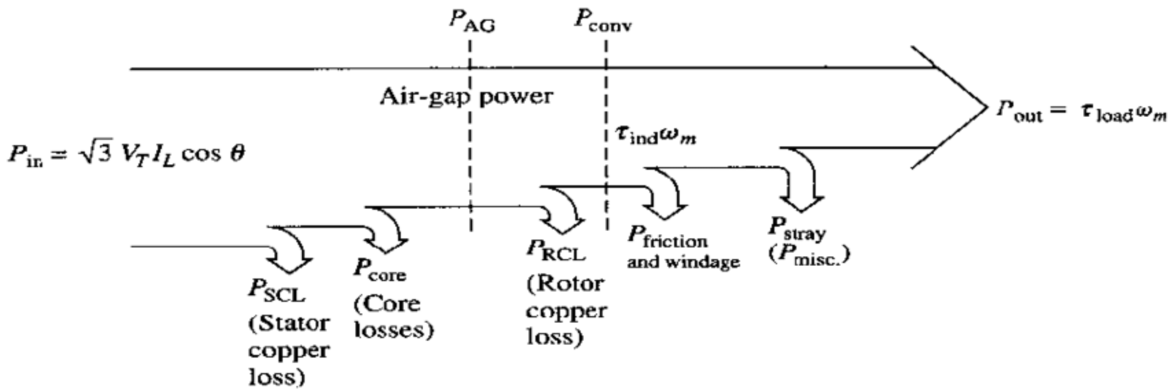


- There are two types of losses occur in three phase induction motor. These losses are,
  1. Fixed losses:
     (i) Stator iron loss
     (ii) Friction and windage loss
     iii) Mechanical loss
- The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small. The no-load test is performed on induction motor to determine the constant losses in the induction motor.
  2. Variable losses:
     (i) Stator copper loss
     (ii) Rotor copper loss
- These losses occur due to the resistance of rotor winding as well as the resistance of stator winding. These losses are also called copper losses.

  These are proportional to the square of stator and rotor currents respectively. As these currents depend on the load, copper losses vary with the change in load.
- The blocked rotor test is performed on induction motor to determine the variable losses.
- When electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power. The following points may be noted from the diagram:
- Stator input, Pi = Stator output + Stator losses = Stator output + Stator Iron loss + Stator Cu loss
- Rotor input, Pr = Stator output. It is because stator output is entirely transferred to the rotor through airgap by electromagnetic induction.
- Mechanical power available, Pm = Pr − Rotor Cu loss This mechanical power available is the gross rotor output and will produce a gross torque Tg.

- Mechanical power at shaft, Pout = Pm − Friction and windage loss Mechanical power available at the shaft produces a shaft torque Tsh.
- Clearly, Pm − Pout = Friction and windage loss

Power flow diagram in induction motor



The power flow is given by the equation shown below.

- Input power, $P_{in} = \sqrt{3}\, VL\, ILcos\phi_i$ where, $cos\phi_i$ is input power factor
- Stator copper losses $P_{SCL} = 3\, I_1^2 R_1$
- Stator core losses P_{core} = Hysteresis and Eddy current losses in the stator core = $3\, E_1^2/R_c$
- Output power of the stator is transferred to the rotor of the machine across the air gap between the stator and the rotor. It is called the air gap P_{AG} of the machine. $P_{AG} = 3I_2^2\, (R_2/s)$
- The Power output of the stator = air gap power = input power to the rotor
- Rotor copper losses $P_{RCL} = 3\, I_2^2 R_2$
- Rotor core losses = Hysteresis and eddy current losses in the rotor core.
- $P_{convectional} = P_{AG} - P_{RCL} = 3\, I_2^2\, [\, R_2\{(1/s) - 1\} = (1-s)P_{AG} = \tau_{ind}\omega_m$
- Friction and Windage losses P_{fw}
- Stray load losses $P_{misc.}$, consisting of all losses not covered above, such as losses due to harmonic fields.
- Developed Mechanical power = Rotor input – Rotor copper loss – rotor friction, windage and stray loss

Relation between P_2, P_c, and P_m

The rotor input P_2, rotor copper loss P_c and gross mechanical power developed P_m and torque T_g are related through the slip s

- $\boldsymbol{Rotor\ gross\ output, Pm = 2\pi N \times Tg}$
- $\boldsymbol{Rotor\ input, P2 = 2\pi Ns \times Tg}$
- $\boldsymbol{Rotor\ copper\ loss, Pc = P2 - Pm,}$

$\therefore \boldsymbol{Pc} = \boldsymbol{2\pi}(\boldsymbol{Ns} - \boldsymbol{N}) \times \boldsymbol{Tg}$

- $\boldsymbol{Rotor\ copper\ loss}/\boldsymbol{rotor\ input} = (\boldsymbol{Ns} - \boldsymbol{N})/\boldsymbol{Ns} = \boldsymbol{s}$

  $\therefore \boldsymbol{Rotor\ copper\ loss} = \boldsymbol{s} \times \boldsymbol{rotor\ input} = \boldsymbol{sP}2$

Also,

$\boldsymbol{Rotor\ input} = \boldsymbol{rotor\ copper\ loss}\ /\boldsymbol{s}$

Rotor gross output, Pm = input (P2) − rotor Cu loss

= P2 − s × rotor input

= (1 − s) *P2

$\therefore$ rotor gross output, Pm = (1 − s) *rotor input

- Similarly,
- $\boldsymbol{rotor\ gross\ output}, \boldsymbol{Pm}\ /\ \boldsymbol{rotor\ input}, \boldsymbol{P2} = (\boldsymbol{1} - \boldsymbol{s}) = \boldsymbol{N}/\boldsymbol{Ns}$

$$\boldsymbol{Pm}/\boldsymbol{P2} = \boldsymbol{N}/\boldsymbol{Ns}$$

$\therefore \boldsymbol{rotor\ efficiency} = \boldsymbol{N}/\boldsymbol{Ns}$

$\boldsymbol{rotor\ copper\ loss}/\boldsymbol{rotor\ gross\ output} = \boldsymbol{s}/(\boldsymbol{1} - \boldsymbol{s})$

Hence, $\therefore \boldsymbol{P2} : \boldsymbol{Pm} : \boldsymbol{Pc} :: \boldsymbol{1} : (\boldsymbol{1} - \boldsymbol{s}) : \boldsymbol{s}$

Efficiency of Three Phase Induction Motor:

Efficiency is defined as the ratio of the output to that of input,

$\boldsymbol{Efficiency} = \boldsymbol{output\ power}/\boldsymbol{input\ power}$

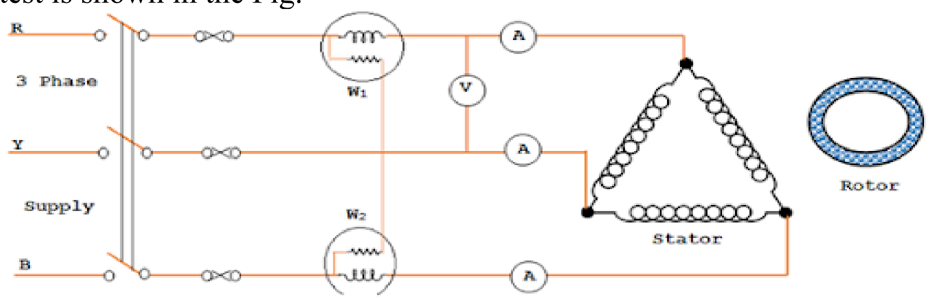
Test on Induction Motor:

1) **Stator-Resistance Test**
   This test is performed to determine the resistance of each phase winding of the stator.
   Let R be the dc value of the resistance between any two terminals of the motor; then the per-phase resistance is R, = 0.5 R for star Connection
   R, = 1.5 R for delta connection

The measured value of the resistance may be multiplied by a factor ranging from 1.05 to 1.25 in order to convert it from its dc value to its ac value. This is done to account for the skin effect. The multiplying factor may be debatable at power frequencies of 50 or 60 Hz, but it does become significant for a motor operating at a frequency of 400 Hz.

2) No Load Test:

- In this test, the motor is made to run without any load i.e., no load condition.
- The speed of the motor is very close to the synchronous speed but less than the synchronous speed.
- The rated voltage Vo is applied to the stator. The input line current Io and total input power Wo is measured.
- The two-wattmeter method is used to measure the total input power. The circuit diagram for the test is shown in the Fig.



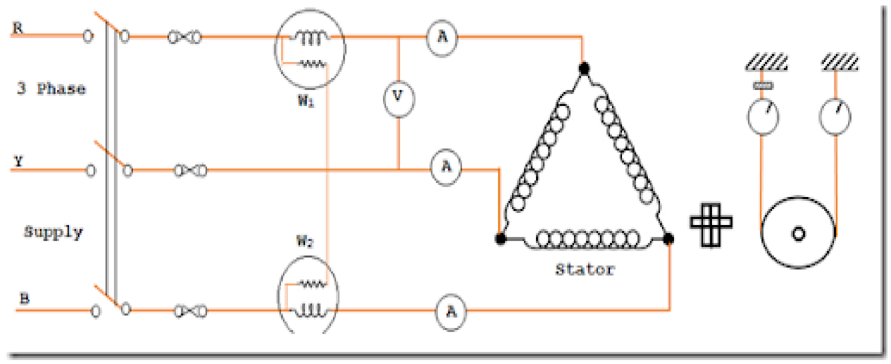
- The total power input W_o is the algebraic sum of the two wattmeter readings.
- The calculations are, $\boldsymbol{W_0} = \sqrt{3}\,\boldsymbol{V_0 I_0} \cos \emptyset_0$

$$\cos \emptyset_0 = W_0 / \sqrt{3}\, V_0 I_0$$

- Active component of no-load current, $\boldsymbol{Ic} = \boldsymbol{I_0} \cos \emptyset_0$
- Magnetizing component of no-load current, $\boldsymbol{Im} = \boldsymbol{I_0} \sin \emptyset_0$
- No-load branch Resistance, $\boldsymbol{R_0} = \boldsymbol{V_0}/\boldsymbol{I_c}$
- No-load branch Reactance, $\boldsymbol{X_0} = \boldsymbol{V_0}/\boldsymbol{I_0}$
- The rotor frequency is s times supply frequency and on no load, it is very small. Rotor iron losses are proportional to this frequency and hence are negligibly small.
- Thus, W_o consists of stator iron loss and friction and windage loss which are consists for all load conditions.

2) **Blocked Rotor Test:**

- In this test, the rotor is locked and it is not allowed to rotate.
- Thus, the slip s = 1 and $R_{L'} = R_{2'}$ (1-s)/s is zero. If the motor is slip ring induction motor, then the windings are short circuited at the slip rings.
- In short circuit test, the reduced voltage (about 10 to 15 % of rated voltage) just enough such that stator carries rated current is applied.
- Now the applied voltage V_{sc}, the input power W_{sc} and a short circuit current I_{sc} are measured.
- As $R_{L'} = 0$, the equivalent circuit is exactly similar to that of a transformer and hence the
- calculations are similar to that of short circuit test on a transformer



- Calculations

  $W_{sc} = \sqrt{3}\, V_{sc} I_{sc} \cos \phi_{sc}$

  $\cos \phi_{sc} = W_{sc} / \sqrt{3}\, V_{sc} I_{sc}$
- Equivalent circuit parameters: $W_{sc} = 3 I_{sc}^2 R_{1e}$
- Equivalent resistance referred to stator, $R_{1e} = W_{sc} / (3 I_{sc}^2)$
- Equivalent impedance referred to stator, $Z_{1e} = V_{sc} / I_{sc}$
- Equivalent reactance referred to stator, $\therefore X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}$
- During this test, the stator carries rated current hence the stator copper loss is also dominant. Similarly, the rotor also carries short circuit current to produce dominant rotor copper loss.
- As the voltage is reduced, the iron loss which is proportional to voltage is negligibly small. The motor is at standstill hence mechanical loss i.e., friction and windage loss is absent.

Numerical Exercise

Example

A three-phase, 460 V, 100 hp, 60 Hz four-pole induction machine delivers rated output power at a slip of 0.05 (this can be stated as a slip of 5%). Determine the

(a.) synchronous speed.
(b.) motor speed.
(c.) frequency of the rotor circuit.
(d.) slip speed.

(a.) $n_s = 120\,\dfrac{f}{P} = 120\,\dfrac{60}{4} = 1800\ \text{rpm}$

(b.) $n = n_s(1-s) = 1800(1-0.05) = 1710\ \text{rpm}$

(c.) $f\quad = sf = (0.05)(60) = 3\ \text{Hz}$

(d.) $n_{slip} = sn_s = (0.05)(1800) = 90\ \text{rpm}$

Example no. 2:

A 480 V, 50 hp, three phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW and the rotor copper losses are 700 W. The friction loss is 600 W and the core losses are 1800 W, find:

- The air gap power.
- The converted power.
- The output power.
- The efficiency of the motor.

Example no. 2 solution:

a) $P_{in} = \sqrt{3}V_T I_L \cos(\theta)$

$P_{in} = \sqrt{3}(480)(60)(0.85) = 42.4\text{ kW}$

$P_{AG} = P_{in} - P_{SCL} = 42.4 - 2 = 40.4\text{kW}$

b) $P_d = P_{AG} - P_{RCL} = 40.4 - 0.7 = 39.7\text{ kW}$

c) $P_{out} = P_d - P_{rot} = 39.7 - 2.4 = 37.3\text{ kW}$

d) $\eta = \dfrac{P_{out}}{P_{in}} = \dfrac{37.3}{42.4} = 88\%$

Example no. 3:

A 460 V, 25 hp, 60 Hz, four pole, Y-connected induction motor has the following impedances:

$R_1 = 0.641\ \Omega$ $R_2 = 0.332\ \Omega$

$X_1 = 1.106\ \Omega$ $X_2 = 0.464\ \Omega$ $X_m = 26.3\ \Omega$

Mechanical loss is 100 W and core loss is 1 kW for a slip = 2.2%, find:

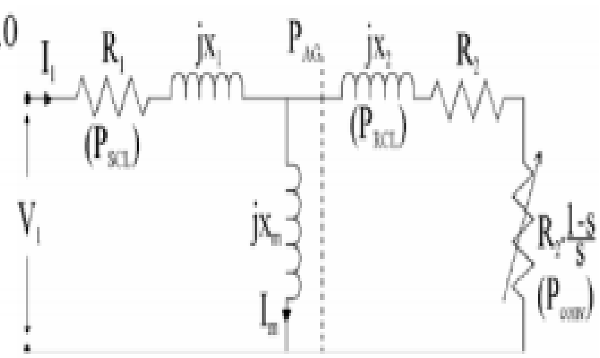
(a) The speed.
(b) The stator current.
(c) Power factor
(d) The developed and output power
(e) The developed and output torque
(f) Efficiency

Example no. 3 solution:

$$a)\ n_s = \frac{120f}{P} = \frac{(120)(60)}{4} = 1800\ \text{rpm}$$

$$n_m = (1-s)n_s = (1-.022)(1800) = 1760\ \text{rpm}$$

$$b)\ Z_{total} = \left\{\left(\frac{R_2}{s} + jx_2\right) \| (jx_m)\right\} + (R_1 + jx_1) = 14.0$$



$$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88\angle -33.6$$

$$c)\ p.f. = \cos(33.6) = 0.833\ lagging$$

$$d) P_{in} = \sqrt{3}(480)(18.88)(0.833) = 12.53\ \text{kW}$$

$$P_{SCL} = 3I_1^2 R_1 = 3(18.88)^2(0.641) = 685\ \text{W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12{,}530 - 685 = 11.845\text{kW}$$

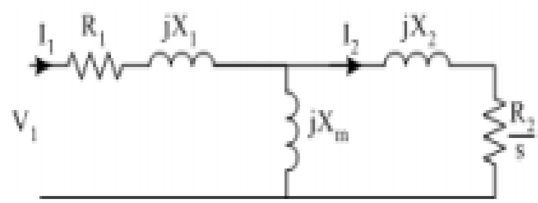
A 480V, 60 Hz, 6-pole, three-phase, delta-connected induction motor has the following parameters:

$$R_1=0.461\ \Omega,\ R_2=0.258\ \Omega,\ X_1=0.507\ \Omega,\ X_2=0.309\ \Omega,\ X_m=30.74\ \Omega$$

Rotational losses are 2450W. The motor drives a mechanical load at a speed of 1170 rpm. Calculate the following information:

i. Synchronous speed in rpm
ii. slip
iii. Line Current
iv. Input Power
v. Airgap Power
vi. Torque Developed
vii. Output Power in Hp
viii. Efficiency

This machine has no iron loss resistance, so the equivalent circuit is as follows:



i. Synchronous speed is given by:

$$n_s = \frac{120 f_e}{P}$$

ii. Slip is given by

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

Using the rpm equation,

$$s = (1200-1170)/1200 = 0.025$$

iii. Now, phase current is given by

$$I_1 = \frac{V_1}{Z_{in}}$$

where phase impedance is given by

$$Z_{in} = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2}{s} + jX_2\right)}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}$$

Using the above equation, $Z_{in} = 9.57 + j3.84\ \Omega$

And noting that the machine is delta connected, $V_1 = V_{LL} = 480V$

$$I_1 = 43.1 - j17.4\ A.\ |I_1| = 46.6\ A,\ \theta = -21.9^\circ$$
$$\text{Therefore } I_L = \sqrt{3} \times 46.6 = 80.6\ A$$

iv. Input power is given by:

$$P_{in} = \sqrt{3} V_{LL} I_L \cos\theta = 3V_1 I_1 \cos\theta$$

$$P_{in} = 62.2\ kW$$

v. Airgap power is the input power minus stator losses. In this case the core losses are grouped with rotational loss. Therefore

$$P_{gap} = P_{in} - 3I_1^2 R_1$$

$$P_{gap} = 62.2\ kW - 3 \times 46.6^2 \times 0.461$$
$$P_{gap} = 59.2\ kW$$

vi. Torque developed can be found from $\tau = \frac{P_{gap}}{\omega_s}$

where synchronous speed in radians per second is given by $\omega_s = \frac{4\pi f_e}{p}$

giving $\tau = 471\ Nm$

Vii.Output power in horsepower is the output power in Watts divided by 746. (there are 746 W in one Hp).

$$P_{out} = P_{conv} - P_{rotational}$$

and

$$P_{conv} = (1 - s) P_{gap}$$

Therefore output power in Watts is: $P_{out} = 55.3kW$

Viii. Efficiency is given by

$$\eta = \frac{P_{out}}{P_{in}}$$

$$\eta = 55.3/62.2 = 88.9\%$$

Q. A three-phase, 60-Hz induction motor runs at 890 r/min at no load and at 840 r/min at full load. (a) How many poles does this motor have? (b) What is the slip at rated load? (c) What is the speed at one-quarter of the rated load? (d) What is the rotor's electrical frequency at one-quarter of the rated load?

SOLUTION

(a) This machine has 8 poles, which produces a synchronous speed of

Ns=120f/P = 900 r/min

(b) The slip at rated load is S = {(900 – 840)/900} *100% = 6.67%

(c) The motor is operating in the linear region of its torque-speed curve, so the slip at ¼ load will be 0.25(0.0667) = 0.0167 s

The resulting speed = (1-s) Ns = (1-0.0167) *900 = 885 rpm

(d) The electrical frequency at ¼ load = 0.0167*60 Hz =1.00 Hz

Q. A 208-V, 60 Hz, six-pole Y-connected 25-hp design class A induction motor is tested in the laboratory, with the following results:

No load: 208 V, 22.0 A, 1200 W, 60 Hz

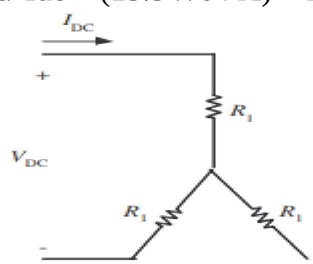
Locked rotor: 24.6 V, 64.5 A, 2200 W, 15 Hz

DC test: 13.5 V, 64 A

Find the equivalent circuit of this motor

Soln:

From the DC test, Vdc/ Idc = (13.5V/64 A) = 2R_1 ⇒ R1 = 0.105 Ω



In the no-load test, the line voltage is 208 V, so the phase voltage is 120 V. Therefore

Z = Xl + Xm = Vph/ Iph = $(208/\sqrt{3})/22$ = 5.45 ohm @ 60Hz

In the locked-rotor test, the line voltage is 24.6 V, From the locked-rotor test at 15 Hz,

Z= R+jX = V ph/ Iph = $(24.6/\sqrt{3})/64.5$ = 0.2202 ohms

And, Pin =$\sqrt{3}$ VL Il cosΘ

Θ = (2200)/($\sqrt{3}$*24.6*64.5)=36.8 degree

So, Req= Z cosΘ = 0.176 ohm

R1 + R2 = 0.176

From DC test, R1 = 0.105 Ω so, R2 = 0.071 ohm

And, Xeq= Z sin Θ = 0.132 ohm at !5 HZ

So, at 60Hz X = (60/15) * 0.132 =0.528 ohms

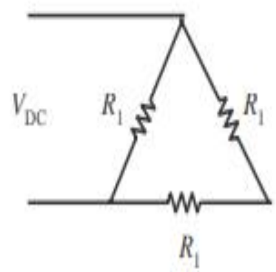
For class A I.M this reactance is assumed to be divided equally between rotor and stator.

X1 =X2 = 0.264 ohms

Xm = 5.45 – 0.264 = 5.186 ohms

A dc test is performed on a 460-V Δ-connected 100-hp induction motor. If V_{DC} = 24 V and I_{DC} = 80 A, what is the stator resistance R_1? *Why is this so?*

SOLUTION If this motor's armature is connected in delta, then there will be two phases in parallel with one phase between the lines tested.



Therefore, the stator resistance R_1 will be

$$\frac{V_{DC}}{I_{DC}} = \frac{R_1(R_1+R_1)}{R_1+(R_1+R_1)} = \frac{2}{3}R_1$$

$$R_1 = \frac{3}{2}\frac{V_{DC}}{I_{DC}} = \frac{3}{2}\frac{24\text{ V}}{80\text{ A}} = 0.45\ \Omega$$

Q. The test data on a 208-V, 60-Hz, 4-pole, Y-connected, three-phase induction motor rated at 1710 rpm are as follows:

The stator resistance (dc) between any two terminals = 2.4 ohms

No-Load Test 450 W 1.562 A 208 v

Blocked-Rotor Test 59.4 w 2.77 A 27 V
Friction and windage loss = 18 W
Compute the equivalent circuit parameters of the motor.
SOLUTION
For a Y-connected motor,
the per-phase resistance of the stator winding is R1 = 2.4/2 = 1.2 ohms
No-load test: Woc =450/3 = 150 W
P fric+wind = 18/3= 6W
Poc = 150 - 6 = 144 W
Voc =208/$\sqrt{3}$ = 120 V
Ioc = 1.562 A
The core-loss resistance is Rc= {(120)^2}/144 = 100ohms
The apparent power input (per phase) is So, = V*I = 120 * 1.562 = 187.44 VA
Thus, the power factor is cosΦ = Woc/ Soc = 150/187.44 = 0.8
The magnetization current: Im = Io sin Φ = 1.562 */ 0.6 = 0.937 A
Xm = Voc/ Im = 120/0.937 = 128ohm

Blocked-rotor test:
Vb, = 27/$\sqrt{3}$ = 15.588 V
Pb = 59.4/3 = 19.8 W
Ib = 2.77A
Re = (19.8)/(2.77)^2 = 2.58 ohm
R2 = Re – R1 = 2.58 – 1.2 = 1.38 ohm
Ze = 15.588/2.77 = 5.267 ohms
So Xe =$\sqrt{Z^2 - R^2}$ = 5 ohms
Thus, X1 = X2 = 2.5 ohms