UNIT-II

Characteristics, Starting and testing methods of Induction Motors

Torque Equation of Three Phase Induction Motor

The torque produced by three phase induction motor depends upon the following three factors: Firstly the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor, lastly the power factor of rotor of the three phase induction motor. Combining all these factors, we get the equation of torque as-

$$T \propto \phi I_2 \cos\theta_2$$

Where, T is the torque produced by the induction motor, φ is flux responsible for producing induced emf, I_2 is rotor current, $\cos\theta_2$ is the power factor of rotor circuit.

The flux φ produced by the stator is proportional to stator emf E_1. i.e $\varphi \propto E_1$ We know that transformation ratio K is defined as the ratio of secondary voltage (rotor voltage) to that of primary voltage (stator voltage).

$$K = \frac{E_2}{E_1}$$

$$or,\ K = \frac{E_2}{\phi}$$

$$or,\ E_2 = \phi$$

Rotor current I_2 is defined as the ratio of rotor induced emf under running condition , sE_2 to total impedance, Z_2 of rotor side, and total impedance Z_2 on rotor side is given by ,

$$i.e\ I_2 = \frac{sE_2}{Z_2}$$

$$Z_2 = \sqrt{R_2^2 + (sX_2)^2}$$

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

Putting this value in above equation we get, s = slip of induction motor

$$\cos\theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

We know that power factor is defined as ratio of resistance to that of impedance. The power factor of the rotor circuit is Putting the value of flux φ, rotor current I_2, power factor $\cos\theta_2$ in the equation of torque we get

$$T \propto E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$T \propto sE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Combining similar term we get, Removing proportionality constant we get,

$$T = KsE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$This\ comstant\ K = \frac{3}{2\pi n_s}$$

Where, n_s is synchronous speed in r. p. s, $n_s = N_s / 60$. So, finally the equation of torque

$$T = sE_2^2 \times \frac{R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s} N - m$$

becomes, Derivation of K in torque equation. In case of three phase induction motor, there occur copper losses in rotor. These rotor copper losses are expressed as $P_c = 3I_2^2R^2$ We know

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

that rotor current, Substitute this value of I_2 in the equation of rotor copper losses, P_c. So, we

$$P_c = 3R_2 \left(\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \right)^2$$

$$On\ simplifying\ P_c = \frac{3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

get The ratio of $P_2 : P_c : P_m = 1 : s : (1 - s)$ Where, P_2 is the rotor input, P_c is the rotor copper

$$\frac{P_c}{P_m} = \frac{s}{1 - s}$$

$$or\ \ P_m = \frac{(1 - s)P_c}{s}$$

losses, P_m is the mechanical power developed. Substitute the value of Pc in above equation

$$P_m = \frac{1}{s} \times \frac{(1 - s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

$$P_m = \frac{(1 - s)3R_2 s E_2^2}{R_2^2 + (sX_2)^2}$$

$$\omega = \frac{2\pi N}{60}$$

$$or\ P_m = T\frac{2\pi N}{60}$$

we get, On simplifying we get, The mechanical power developed $P_m = T\omega$, Substituting the

$$\frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} = T\frac{2\pi N}{60}$$

$$or\ T = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} \times \frac{60}{2\pi N}$$

value of P_m We know that the rotor speed $N = N_s(1 - s)$ Substituting this value of rotor speed

$$T = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} \times \frac{60}{2\pi N_s(1-s)}$$

in above equation we get, N_s is speed in revolution per minute (rpm) and n_s is speed in revolution per sec (rps) and the relation between the two is Substitute this value of

$$Toeque,\ T = \frac{s\ E_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi N_s}$$

$$or,\ T = KsE_2^2\frac{R_2}{R_2^2 + (sX_2)^2} \qquad \frac{N_s}{60} = n_s$$

N_s in above equation and simplifying it we get Comparing both the equations, we get, constant $K = 3 / 2\pi n_s$

Equation of Starting Torque of Three Phase Induction Motor

Starting torque is the torque produced by induction motor when it starts. We know that at the

$$So,\ slip\ s = \frac{N_s - N}{N_s}\ becomes\ 1$$

start the rotor speed, N is zero. So, the equation of starting torque is easily obtained by simply putting the value of s = 1 in the equation of torque of the three phase induction motor,

$$T = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{3}{2\pi n_s}\ N - m$$

The starting torque is also known as standstill torque.

Maximum Torque Condition for Three-Phase Induction Motor

$$T = \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s}$$

In the equation of torque, The rotor resistance, rotor inductive reactance and synchronous speed of induction motor remain constant. The supply voltage to the three phase induction motor is usually rated and remains constant, so the stator emf also remains the constant. We define the transformation ratio as the ratio of rotor emf to that of stator emf. So if stator emf remains constant, then rotor emf also remains constant. If we want to find the maximum value of some quantity, then we have to differentiate that quantity concerning some variable parameter and then put it equal to zero. In this case, we have to find the condition for maximum torque, so we have to differentiate torque concerning some variable quantity which is the slip, s in this case as all other parameters in the equation of torque remains

$$\frac{dT}{ds} = 0$$

$$T = KsE_2^2 \frac{R_2}{R_2^2 + (sX_2)^2}$$

constant. So, for torque to be maximum Now differentiate the above equation by using division rule of differentiation. On differentiating and after putting the terms equal to zero we

$$s^2 = \frac{R_2^2}{X_2^2}$$

get, Neglecting the negative value of slip we get So, when slip $s = R_2 / X_2$, the torque will be maximum and this slip is called maximum slip Sm and it is defined as the ratio of rotor resistance to that of rotor reactance.

NOTE: At starting S = 1, so the maximum starting torque occur when rotor resistance is equal to rotor reactance.

Equation of Maximum Torque

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

The equation of torque is The torque will be maximum when slip $s = R_2 / X_2$ Substituting the value of this slip in above equation we get the maximum value of torque as,

$$T_{max} = K\frac{{E_2}^2}{2X_2} \quad N - m$$

In order to increase the starting torque, extra resistance should be added to the rotor circuit at start and cut out gradually as motor speeds up.

Conclusion From the above equation it is concluded that

1. The maximum torque is directly proportional to square of rotor induced emf at the standstill.
2. The maximum torque is inversely proportional to rotor reactance.
3. The maximum torque is independent of rotor resistance.

4. The slip at which maximum torque occur depends upon rotor resistance, R_2. So, by varying the rotor resistance, maximum torque can be obtained at any required slip.

Deep Bar Double Cage Induction Motor

Generally in induction motor related operation squirrel cage induction motor is widely used.

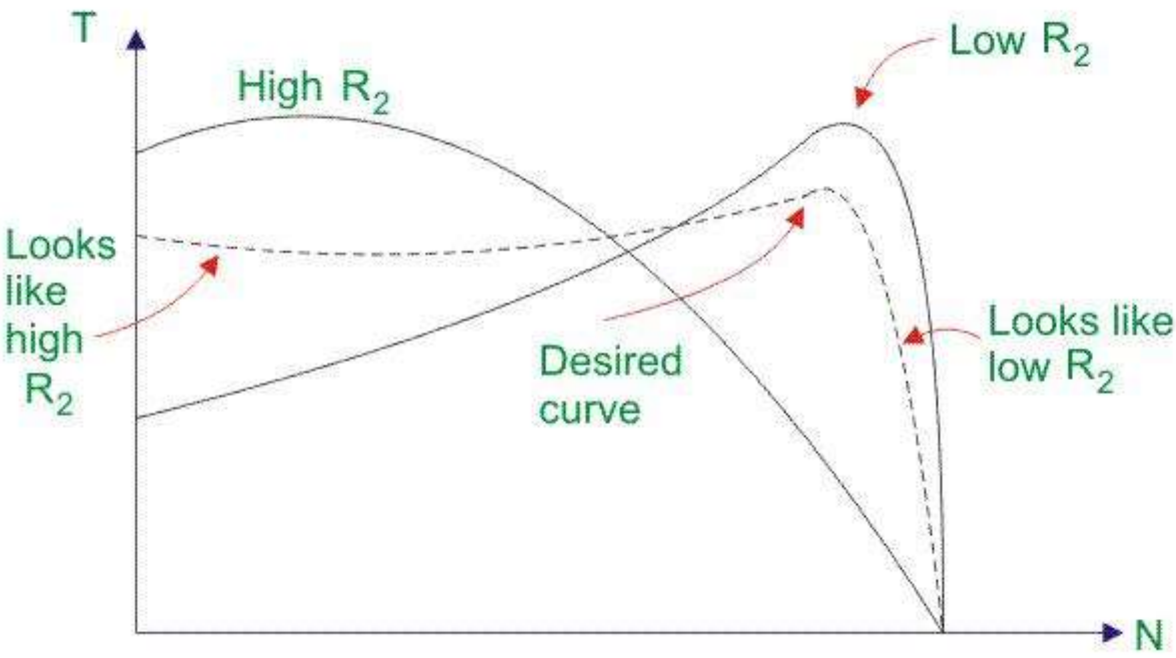
$$T_{st} = \frac{k.\, E_2^2 R_2}{R_2^2 + X_2^2}$$

The starting torque equation of an induction motor is given by Where, R_2 and X_2 are the rotor resistance and inductive reactance at starting respectively, E_2 is the rotor induced EMF and

$$k = \frac{3}{2\pi N_s}$$

N_s is the RPS speed of synchronous stator flux. Here in this equation the starting torque of induction motor T_{sh} is proportional to rotor resistance R_2.

But the thing is that squirrel cage induction motor has very low starting torque due to its rotor resistance of very low value. So to provide a higher value of rotor resistance in squirrel cage induction motor double bar double cage rotor is used in induction motor. The motive is to provide higher value of rotor resistance in such a manner that the rotor with its higher valued resistance provides higher torque and more efficiency.



Why Starting Torque is Poor in Squirrel Cage Induction Motor?

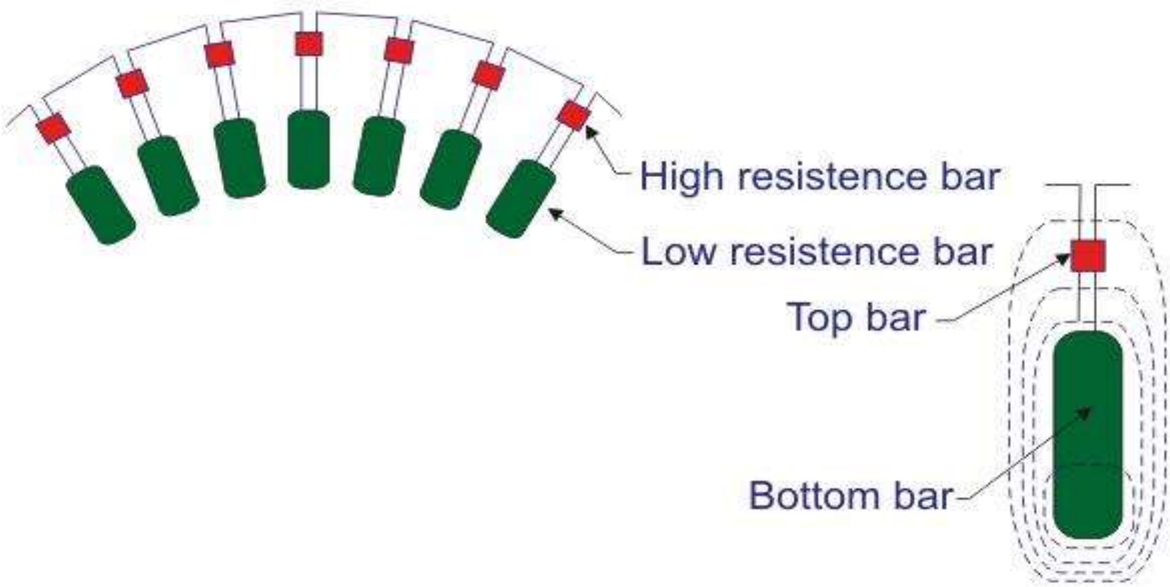
The resistance cannot be varied in squirrel cage rotor as it is possible in slip ring induction motor. The fixed resistance of the rotor of the squirrel cage induction motor is very low. At the starting moment, the induced voltage in the rotor has same frequency as the frequency of the supply. Hence the starting inductive reactance gets higher value at stand still condition. The frequency of the rotor current gets same frequency as the supply frequency at standstill. Now the case is that the rotor induced current in spite of having higher value lags the induced voltage at a large angle.

So this causes poor starting torque at the stand still condition. This torque is only 1.5 times of the full load torque though the induced current is 5 to 7 times of the full load current. Hence, this squirrel cage single bar single cage rotor is not being able to apply against high load. We should go for **deep bar double cage induction motor** to get higher starting torque.

Construction of Deep Bar Double Cage Induction Motor

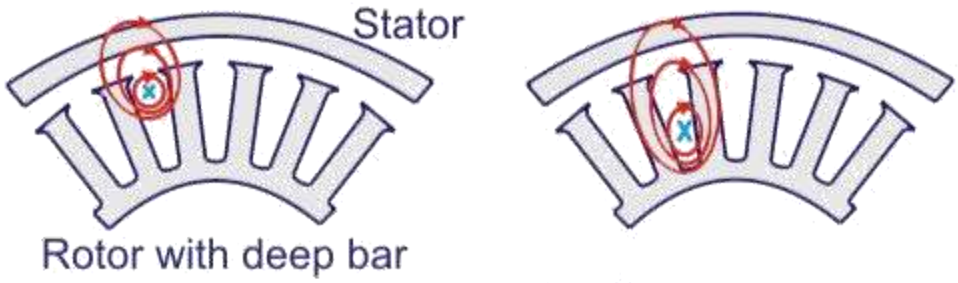
In deep bar double cage rotor bars are there in two layers. Outer layer has the bars of small cross sections. This outer winding has relatively large resistance. The bars are shorted at the both ends. The flux linkage is thus very less. And hence inductance is very low. Resistance in outer squirrel cage is relatively high. Resistance to inductive reactance ration is high.

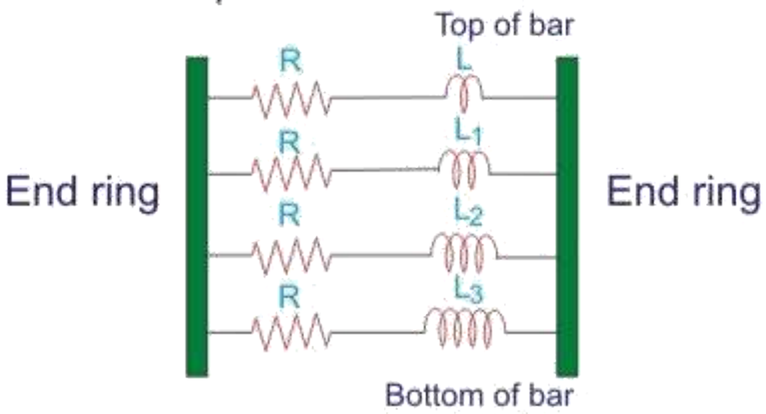
Inner layer has the bars of large cross section comparatively. The resistance is very less. But flux linkage is very high. The bars are thoroughly buried in iron. As flux linkage is high the inductance is also very high. The resistance to inductive reactance ration is poor.



Operational Principle Construction of Deep Bar Double Cage Induction Motor

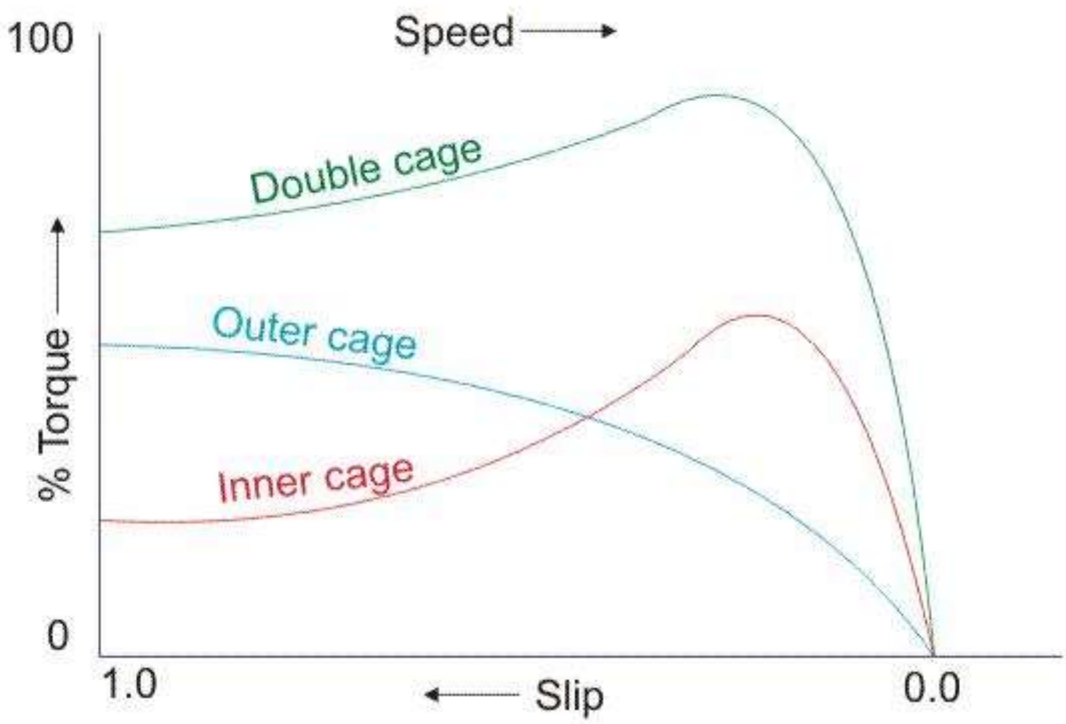
At the stand still condition the inner and outer side bars get induced with voltage and current with the same frequency of the supply. Now the case is that the inductive reactance ($X_L = 2\pi fL$) is offered more in the deep bars or inner side bars due to skin effect of the alternating quantity i.e. voltage and current. Hence the current tries to flow through the outer side rotor bars.





The outer side rotor offers more resistance but poor inductive reactance. The ultimate resistance is somewhat higher than the single bar rotor resistance. he higher valued rotor resistance results more torque to be developed at the starting. When the speed of the rotor of the **deep bar double cage induction motor** increases, the frequency of the induced EMF and current in the rotor gets gradually decreased. Hence the inductive reactance (X_L) in the inner side bars or deep bars gets decreased and the current faces less inductive reactance and less resistance as a whole. Now no need for more torque because the rotor already has arrived to its full speed with running torque.

Speed Torque Characteristics of Deep Rotor IM



Where, R_2 and X_2 are the rotor resistance and inductive reactance at starting respectively, E_2

$$k = \frac{3}{2\pi N_s}$$

is the rotor induced EMF and N_s is the RPS speed of synchronous stator flux and S is the slip of the rotor speed. The above speed-torque graph shows that the higher valued resistance offers higher torque at the stand still condition and the max torque will be achieved at higher valued slip.

Comparison between Single Cage and Double Cage Motors

1. A double cage rotor has low starting current and high starting torque. Therefore, it is more suitable for direct on line starting.
2. Since effective rotor resistance of double cage motor is higher, there is larger rotor heating at the time of starting as compared to that of single cage rotor.
3. The high resistance of the outer cage increases the resistance of double cage motor. So full load copper losses are increased and efficiency is decreased.
4. The pull out torque of double cage motor is smaller than single cage motor.
5. The cost of double cage motor is about 20-30 % more than that of single cage motor of same rating.

Crawling and Cogging of Induction Motor

The important characteristics normally shown by a squirrel cage induction motors are **crawling and cogging**. These characteristics are the result of improper functioning of the motor that means either motor is running at very slow speed or it is not taking the load.

Crawling of Induction Motor

It has been observed that squirrel cage type induction motor has a tendency to run at very low speed compared to its synchronous speed, this phenomenon is known as crawling. The resultant speed is nearly $1/7^{th}$ of its synchronous speed. Now the question arises why this happens? This action is due to the fact that harmonics fluxes produced in the gap of the stator winding of odd harmonics like 3^{rd}, 5^{th}, 7^{th} etc. These harmonics create additional torque fields in addition to the synchronous torque.

The torque produced by these harmonics rotates in the forward or backward direction at $N_s/3$, $N_s/5$, $N_s/7$ speed respectively. Here we consider only 5^{th} and 7^{th} harmonics and rest are neglected. The torque produced by the 5^{th} harmonic rotates in the backward direction. This torque produced by fifth harmonic which works as a braking action is small in quantity, so it can be neglected. Now the seventh harmonic produces a forward rotating torque at synchronous speed $N_s/7$. Hence, the net forward torque is equal to the sum of the torque produced by 7^{th} harmonic and fundamental torque. The torque produced by 7^{th} harmonic reaches its maximum positive value just below 1/7 of N_s and at this point slip is high. At this stage motor does not reach up to its normal speed and continue to rotate at a speed which is much lower than its normal speed. This causes crawling of the motor at just below 1/7 synchronous speed and creates the racket. The other speed at which motor crawls is 1/13 of synchronous speed.

Cogging of Induction Motor

This characteristic of induction motor comes into picture when motor refuses to start at all. Sometimes it happens because of low supply voltage. But the main reason for starting problem in the motor is because of cogging in which the slots of the stator get locked up with the rotor slots. As we know that there is series of slots in the stator and rotor of the induction motor. When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this stage the reluctance of the magnetic path is minimum and motor refuse to start.

This **characteristic of the induction motor** is called cogging. Apart from this, there is one more reason for cogging. If the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage then it causes torque modulation. As a result, of it cogging occurs. This characteristic is also known as magnetic teeth locking of the induction motor.

Methods to overcome Cogging This problem can be easily solved by adopting several measures. These solutions are as follows:

- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

Speed Control of Three Phase Induction Motor

A three phase induction motor is basically a constant speed motor so it's somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low electrical power factor. Before discussing the methods to **control the speed of three phase induction motor** one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas.

Synchronous Speed

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

Where, f = frequency and P is the number of poles

The speed of induction motor is given by, $N = N_s(1-s)$

Where, N is the speed of the rotor of an induction motor, N_s is the synchronous speed, S is the slip. The torque produced by three phase induction motor is given by,

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When the rotor is at standstill slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where, E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

The peed of Induction Motor is changed from Both Stator and Rotor Side. The speed control of three phase induction motor from stator side are further classified as :

- V / f control or frequency control.
- Changing the number of stator poles.
- Controlling supply voltage.
- Adding rheostat in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

- Adding external resistance on rotor side.
- Cascade control method.
- Injecting slip frequency emf into rotor side.

Speed Control from Stator Side

- **V / f Control or Frequency Control**

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

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

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E\ or\ V = 4.44\phi K.T.f\ or\ \phi = \frac{V}{4.44KTf}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage. i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

- **Controlling Supply Voltage**

  The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very small as compared to R_2. So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

ince rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$. The equation above clears that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same, and it is only possible if we increase the slip and if the slip increases the motor will run at a reduced speed. This method of speed control is rarely used because a small change in speed requires a large reduction in voltage, and hence the current drawn by motor increases, which cause overheating of the induction motor.

- **Changing the number of stator poles:**

  The stator poles can be changed by two methods

- **Multiple stator winding method.**
- **Pole amplitude modulation method (PAM)**
- **Multiple Stator Winding Method**

  In this method of speed control of three phase induction motor, we provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. Disadvantages of this method are that the smooth speed control is not possible. This method is more costly and less efficient as two different stator windings are required. This method of speed control can only be applied to squirrel cage motor.
- **Pole Amplitude Modulation Method (PAM)**

  In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

  Let $f_1(\theta)$ be the original mmf wave of induction motor whose speed is to be controlled. $f_2(\theta)$ be the modulation mmf wave. P_1 be the number of poles of induction motor whose speed is to

$$f_1(\theta) = F_1 \sin \frac{P_1\theta}{2}$$

$$f_2(\theta) = F_2 \sin \frac{P_2\theta}{2}$$

  be controlled. P_2 be the number of poles of modulation wave. After modulation resultant mmf

$$F_r(\theta) = F_1 F_2 \sin \frac{P_1\theta}{2} sin \frac{P_2\theta}{2}$$

$$Apply\ formula\ for\ 2 \sin A \sin B = \cos \frac{A-B}{2} - \cos \frac{A+B}{2}$$

$$F_r(\theta) = F_1 F_2 \frac{\cos \frac{(P_1-P_2)\theta}{2} - \cos \frac{(P_1+P_2)\theta}{2}}{2}$$

  wave o we get, resultant mmf wave Therefore the resultant mmf wave will have two different number of poles $i.e\ P_{11} = P_1 - P_2\ and\ P_{12} = P_1 + P_2$Therefore by changing the number of poles we can easily change the speed of three phase induction motor.
- **Adding Rheostat in Stator Circuit**

  In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped .In case of three phase induction motor torque produced is given by $T \propto sV_2^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

Speed Control from Rotor Side

- **Adding External Resistance on Rotor Side**

  In this method of speed control of three phase induction motor external resistance are added

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

  on rotor side. The equation of torque for three phase induction motor is The three-phase induction motor operates in a low slip region. In low slip region term $(sX)^2$ becomes very very small as compared to R_2. So, it can be neglected. and also E_2 is constant. So the equation

$$T \propto \frac{s}{R_2}$$

  of torque after simplification becomes, Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further result in the decrease in rotor speed. Thus by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages :

  - The speed above the normal value is not possible.
  - Large speed change requires a large value of resistance, and if such large value of resistance is added in the circuit, it will cause large copper loss and hence reduction in efficiency.
  - Presence of resistance causes more losses.
  - This method cannot be used for squirrel cage induction motor.

- **Cascade Control Method**

  In this method of speed control of three phase induction motor, the two three-phase induction motors are connected on a common shaft and hence called cascaded motor. One motor is the called the main motor, and another motor is called the auxiliary motor. The three-phase supply is given to the stator of the main motor while the auxiliary motor is derived at a slip frequency from the slip ring of the main motor. Let N_{S1} be the synchronous speed of the main motor. N_{S2} be the synchronous speed of the auxiliary motor. P_1 be the number of poles of the main motor. P_2 be the number of poles of the auxiliary motor. F is the supply frequency. F_1 is the frequency of rotor induced emf of the main motor. N is the speed of set, and it remains same for both the main and auxiliary motor as both the motors are mounted on the common

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$F_1 = S_1 F$$

  shaft. S_1 is the slip of main motor. The auxiliary motor is supplied with same frequency as the

$$F_1 = F_2$$

$$N_{S2} = \frac{120F_2}{P_2} = \frac{120F_1}{P_2}$$

$$N_{S2} = \frac{120S_1F}{P_2}$$

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$We\ get,\ N_{S2} = \frac{120F(N_{S1} - N)}{P_2N_{S1}}$$

$$N = \frac{120F(N_{S1} - N)}{P_2N_{S1}}$$

$$N = \frac{120F}{P_1 - P_2}$$

main motor i.e Now put the value of Now at no load , the speed of auxiliary rotor is almost same as its synchronous speed i.e $N = N_{S2}$ Now rearrange the above equation and find out the value of N, we get, This cascaded set of two motors will now run at new speed having number of poles ($P_1 + P_2$). In the above method the torque produced by the main and auxiliary motor will act in same direction, resulting in number of poles ($P_1 + P_2$). Such type of cascading is called cumulative cascading. There is one more type of cascading in which the torque produced by the main motor is in opposite direction to that of auxiliary motor. Such type of cascading is called differential cascading; resulting in speed corresponds to number of poles ($P_1 - P_2$). In this method of speed control of three phase induction motor, four different speeds can be obtained

- When only main induction motor work, having speed corresponds to $N_{S1} = \frac{120F}{P_1}$.
- When only auxiliary induction motor work, having speed corresponds to $N_{S2} = \frac{120F}{P_2}$.
- When cumulative cascading is done, then the complete set runs at a speed of $N = \frac{120F}{(P_1 + P_2)}$.
- When differential cascading is done, then the complete set runs at a speed of $N = \frac{120F}{(P_1 - P_2)}$.

- **Injecting Slip Frequency EMF into Rotor Side**

When the speed control of three phase induction motor is done by adding resistance in rotor circuit, some part of power called, the slip power is lost as I^2R losses. Therefore the efficiency of three phase induction motor is reduced by this method of speed control. This slip power loss can be recovered and supplied back to improve the overall efficiency of the three-phase induction motor, and this scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit. The injected emf can either oppose the rotor induced emf or aids the rotor induced emf. If it opposes the rotor induced emf, the total rotor resistance increases and hence the speed is decreased and if the injected emf aids the main rotor emf the total decreases and hence speed increases. Therefore by injecting induced emf in the rotor circuit, the speed can be easily controlled. The main advantage of this type of speed control of three phase induction motor is that a wide range of speed control is possible whether it is above normal or below normal speed.

No Load Test of Induction Motor

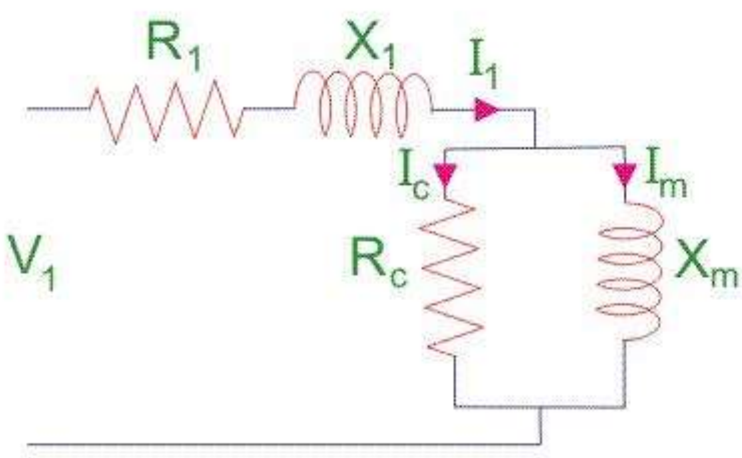
The efficiency of large motors can be determined by directly loading them and by measuring their input and output powers. For larger motors it may be difficult to arrange loads for them. Moreover power loss will be large with direct loading tests. Thus no load and blocked rotor tests are performed on the motors. As the name suggest no load test is performed when rotor rotates with synchronous speed and there is no load torque. This test is similar to the open circuit test on transformer. Actually, to achieve synchronous speed in an induction motor is impossible. The speed is assumed to be synchronized. The synchronous speed can be achieved by taking slip = 0 which creates infinite impedance in the rotor branch.

This test gives the information regarding no-load losses such as core loss, friction loss and windage loss. Rotor copper loss at no load is very less that its value is negligible. Small current is required to produce adequate torque. This test is also well-known as running light test. This test is used to evaluate the resistance and impedance of the magnetizing path of induction motor.

Theory of No Load Test of Induction Motor

The impedance of magnetizing path of induction motor is large enough to obstruct flow of current. Therefore, small current is applied to the machine due to which there is a fall in the stator-impedance value and rated voltage is applied across the magnetizing branch. But the drop in stator-impedance value and power dissipated due to stator resistance are very small in comparison to applied voltage. Therefore, there values are neglected and it is assumed that total power drawn is converted into core loss. The air gap in magnetizing branch in an induction motor slowly increases the exciting current and the no load stator I^2R loss can be recognized.

One should keep in mind that current should not exceed its rated value otherwise rotor accelerates beyond its limit. The test is performed at poly-phase voltages and rated frequency applied to the stator terminals. When motor runs for some times and bearings get lubricated fully, at that time readings of applied voltage, input current and input power are taken. To calculate the rotational loss, subtract the stator I^2R losses from the input power.



Calculation of No Load Test of Induction Motor

Let the total input power supplied to induction motor be W_0 watts.

$$W_0 = \sqrt{3}V_1 I_0 Cos\Phi_0$$

Where, V_1 = line voltage I_0 = No load input current

Rotational loss = $W_0 - S_1$ Where, S_1 = stator winding loss = N_{ph} I^2 R_1 N_{ph} = Number phase The various losses like windage loss, core loss, and rotational loss are fixed losses which can be calculated by

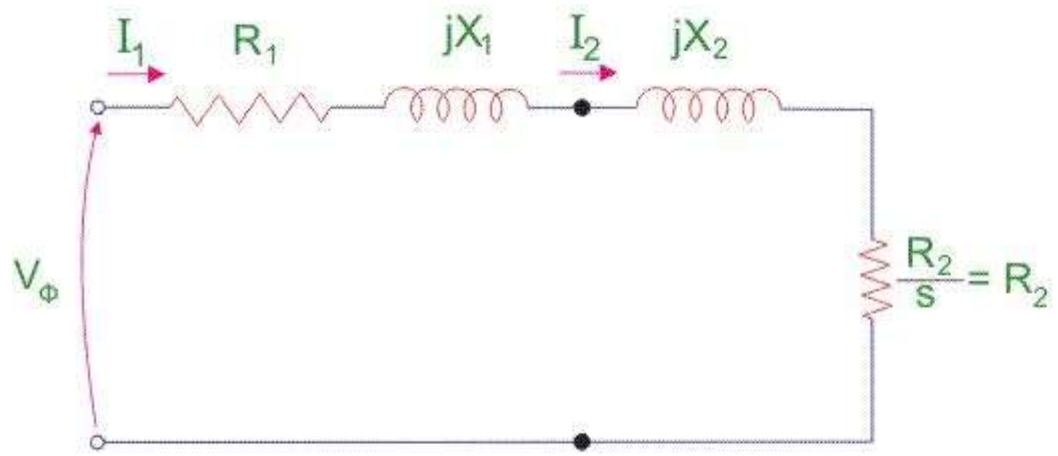
Stator winding loss = $3I_o^2R_1$ Where, I_0 = No load input current R_1 = Resistance of the motor Core loss = $3G_oV^2$

Blocked Rotor Test of Induction Motor

The induction motors are widely used in the industries and consume maximum power. To improve its performance characteristics certain tests have been designed like no-load test and block rotor test, etc. A blocked rotor test is normally performed on an induction motor to find out the leakage impedance. Apart from it, other parameters such as torque, motor, short-circuit current at normal voltage, and many more could be found from this test. Blocked rotor test is analogous to the short circuit test of transformer. Here shaft of the motor is clamped i.e. blocked so it cannot move and rotor winding is short circuited. In slip ring motor rotor winding is short circuited through slip rings and in cage motors, rotors bars are permanently short circuited. The **testing of the induction motor** is a little bit complex as the resultant value of leakage impedance may get affected by rotor position, rotor frequency and by magnetic dispersion of the leakage flux path. These effects could be minimized by conducting a block rotor current test on squirrel-cage rotors.

Process of Testing of Blocked Rotor Test of Induction Motor

In the blocked rotor test, it should be kept in mind that the applied voltage on the stator terminals should be low otherwise normal voltage could damage the winding of the stator. In block rotor test, the low voltage is applied so that the rotor does not rotate and its speed becomes zero and full load current passes through the stator winding. The slip is unity related to zero speed of rotor hence the load resistance becomes zero. Now, slowly increase the voltage in the stator winding so that current reaches to its rated value. At this point, note down the readings of the voltmeter, wattmeter and ammeter to know the values of voltage, power and current. The test can be repeated at different stator voltages for the accurate value.



Calculations of Blocked Rotor Test of Induction Motor

Resistance and Leakage Reactance Values

In blocked rotor test, core loss is very low due to the supply of low voltage and frictional loss is also negligible as rotor is stationary, but stator cupper losses and the rotor cupper losses are reasonably high. Let us take denote copper loss by W_{cu}.

$$W_{cu} = W_s - W_c$$

Therefore, Where, W_c = core loss $W_{cu} = 3I^2 R_{01}$

Where, R_{01} = Motor winding of stator and rotor as per phase referred to stator. Thus,

$$R_{01} = \frac{W_{cu}}{3I_s^2} \ldots\ldots\ldots\ldots(1)$$

Now let us consider I_s = short circuit current V_s = short circuit voltage Z_0 = short circuit impedance as referred to stator

$$Z_{01} = \frac{short\ circuit\ voltage\ per\ phase}{short\ circuit\ current} = \frac{V_s}{I_s} \ldots\ldots\ldots\ldots(2)$$

Therefore, X_{01} = Motor leakage reactance per phase referred to stator can be calculated as

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Stator reactance X_1 and rotor reactance per phase referred to stator X_2 are normally assumed

$$X_1 = X_2 = \frac{X_{01}}{2}$$

equal. Therefore, Similarly, stator resistance per phase R_1 and rotor resistance per phase referred to stator R_2 can be calculated as follows: First some suitable test are done on stator windings to find the value of R_1 and then to find R_2 subtract the R_1 from R_{01} $R_2 = R_{01} - R_1$

Short Circuit Current for Normal Supply Voltage

To calculate short circuit current I_{sc} at normal voltage V of the stator, we must note short-circuit current I_s and low voltage V_s applied to the stator winding.

$$I_{sc} = I_s\left(\frac{V}{V_s}\right)$$

Circle Diagram of Induction Motor

The **circle diagram of an induction motor** is very useful to study its performance under all operating conditions. The "CIRCLE DIAGRAM" means that it is figure or curve which is drawn has a circular shape. As we know, the diagrammatic representation is easier to understand and remember compared to theoretical and mathematical descriptions. Actually, we do not have that much time or patience to go through the writings so we prefer diagrammatic representation. Also, it is very easy to remember the things which are shown in picture. As we know, "A PICTURE IS WORTH 1000 WORDS". This also holds good here and we are to draw circle diagram in order to compute various parameters rather than doing it mathematically.

Importance of Circle Diagram

The diagram provides information which is not provided by an ordinary phasor diagram. A phasor diagram gives relation between current and voltage only at a single circuit condition. If the condition changes, we need to draw the phasor diagram again. But a circle diagram may be referred to as a phasor diagram drawn in one plane for more than one circuit conditions. On the context of induction motor, which is our main interest, we can get information about its power output, power factor, torque, slip, speed, copper loss, efficiency etc. in a graphical or in a diagrammatic representation.

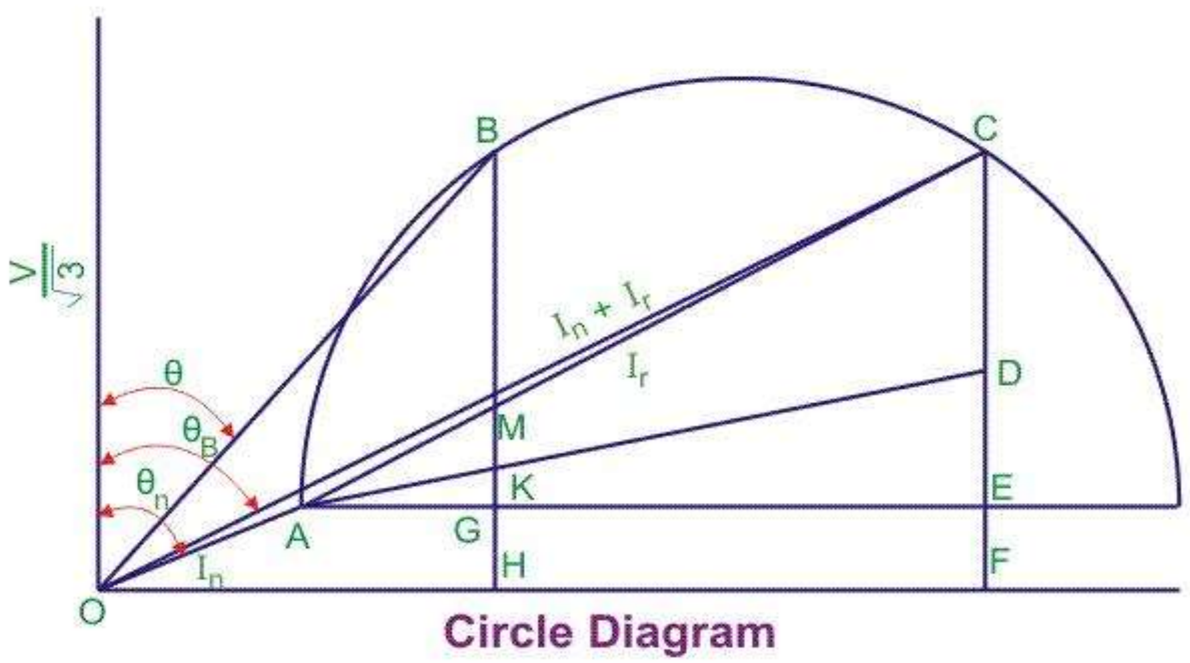
Test Performed to Compute Data Required for Drawing Circle Diagram

We have to perform no load and blocked rotor test in an induction motor. In no load test, the induction motor is run at no load and by two watt meter method, its total power consumed is calculated which is composed of no load losses only. Slip is assumed to be zero. From here no load current and the angle between voltage and current required for drawing circle diagram is calculated. The angle will be large as in the no load condition induction motor has high inductive reactance.

In block rotor test, rotor is blocked which is analogous to short circuiting secondary of a transformer. From this test, we need to calculate short circuit current and the lag angle between voltage and current for drawing circle diagram. Also, we need rotor and stator copper loss.

Procedure to Draw the Circle Diagram

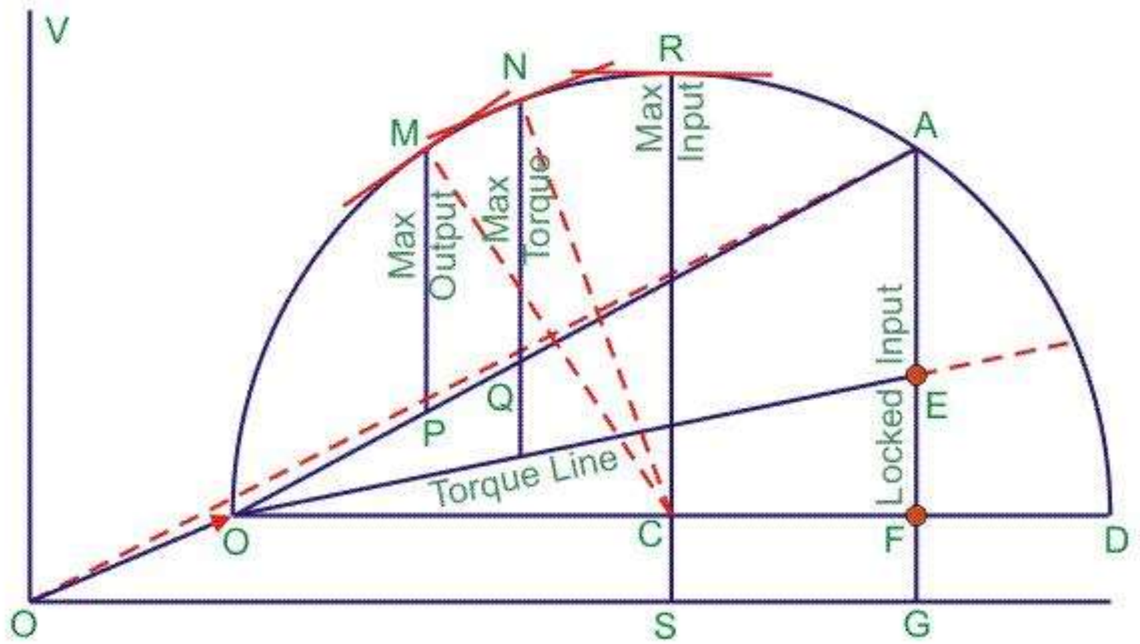
We have to assume a suitable before drawing it. This assumption is done according to our convenience.



1. The no load current and the no load angle calculated from no load test is plotted. This is shown by the line OA, where Θ_0 is the no load power factor angle.
2. The short circuit current and the angle obtained from block rotor test is plotted. This is shown by the line OC and the angle is shown by Θ_B.
3. The right bisector of the line AC is drawn which bisects the line and it is extended to cut in the line AE which gives us the centre.
4. The stator current is calculated from the equivalent circuit of the induction motor which we get from the two tests. That current is plotted in the circle diagram according to the scale with touching origin and a point in the circle diagram which is shown by B.
5. The line AC is called the power line. By using the scale for power conversion that we have taken in the circle diagram, we can get the output power if we move vertically above the line AC to the periphery of the circle. The output power is given by the line MB.

6. The total copper loss is given by the line GM.
7. For drawing the torque line, the total copper loss should be separated to both the rotor copper loss and stator copper loss. The line DE gives the stator copper loss and the line CD gives the rotor copper loss. In this way, the point E is selected.
8. The line AD is known as torque line which gives the torque developed by induction motor.

Maximum Quantities from Circle Diagram



Maximum Output Power

When the tangent to the circle is parallel to the line then output power will be maximum. That point M is obtained by drawing a perpendicular line from the center to the output line and extending it to cut at M.

Maximum Torque

When the tangent to the circle is parallel to the torque line, it gives maximum torque. This is obtained by drawing a line from the center in perpendicular to the torque line AD and extending it to cut at the circle. That point is marked as N.

Maximum Input Power

It occurs when tangent to the circle is perpendicular to the horizontal line. The point is the highest point in the circle diagram and drawn to the center and extends up to S. That point is marked as R.

Conclusion of Circle Diagram

This method is based on some approximations that we have used in order to draw the circle diagram and also, there is some rounding off of the values as well. So there is some error in this method but it can give good approximate results. Also, this method is very much time consuming so it is drawn at times where the drawing of circle diagram is absolutely necessary. Otherwise, we can go for mathematical formulas or equivalent circuit model in order to find out various parameters.

Losses and Efficiency of Induction Motor

There are two types of losses occur in three phase induction motor. These losses are,

1. Constant or fixed losses,
2. Variable losses.

Constant or Fixed Losses

Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor. These losses are further classified as-

1. Iron or core losses,
2. Mechanical losses,
3. Brush friction losses.

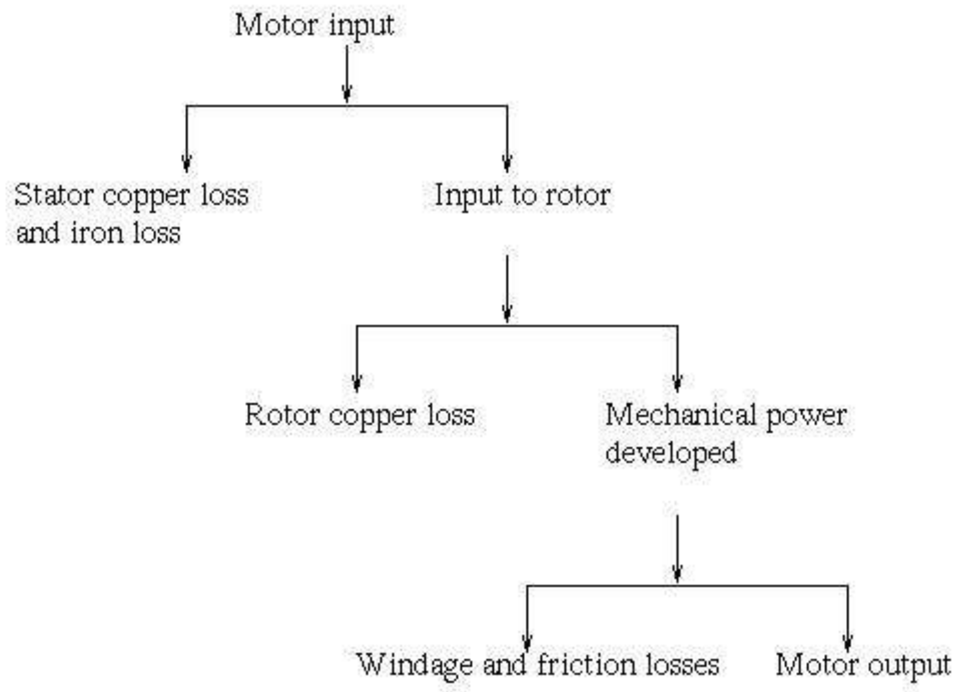
Iron or Core Losses

Iron or core losses are further divided into hysteresis and eddy current losses. Eddy current losses are minimized by using lamination on core. Since by laminating the core, area decreases and hence resistance increases, which results in decrease in eddy currents. Hysteresis losses are minimized by using high grade silicon steel. The core losses depend upon frequency of the supply voltage. The frequency of stator is always supply frequency, f and the frequency of rotor is slip times the supply frequency, (sf) which is always less than the stator frequency. For stator frequency of 50 Hz, rotor frequency is about 1.5 Hz because under normal running condition slip is of the order of 3 %. Hence the rotor core loss is very small as compared to stator core loss and is usually neglected in running conditions.

Mechanical and Brush Friction Losses

Mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses are zero at start and with increase in speed these losses increases. In three phase induction motor the speed usually remains constant. Hence these losses almost remains constant.

Variable Losses



These losses are also called copper losses. These losses occur due to current flowing in stator and rotor windings. As the load changes, the current flowing in rotor and stator winding also changes and hence these losses also changes. Therefore these losses are called variable losses. The copper losses are obtained by performing blocked rotor test on three phase induction motor. The main function of induction motor is to convert an electrical power into mechanical power. During this conversion of electrical energy into mechanical energy the power flows through different stages.

This power flowing through different stages is shown by power flow diagram. As we all know the input to the three phase induction motor is three phase supply. So, the three phase supply is given to the stator of three phase induction motor. Let, P_{in} = electrical power supplied to the stator of three phase induction motor, V_L = line voltage supplied to the stator of three phase induction motor, I_L = line current, Cosφ = power factor of the three phase induction motor. Electrical power input to the stator, $P_{in} = \sqrt{3}V_L I_L \cos\varphi$ A part of this power input is used to supply stator losses which are stator iron loss and stator copper loss. The remaining power i.e (input electrical power – stator losses) are supplied to rotor as rotor input. So, rotor input $P_2 = P_{in}$ – stator losses (stator copper loss and stator iron loss). Now, the rotor has to convert this rotor input into mechanical energy but this complete input cannot be converted into mechanical output as it has to supply rotor losses. As explained earlier the rotor losses are of two types rotor iron loss and rotor copper loss. ince the iron loss depends upon the rotor frequency, which is very small when the rotor rotates, so it is usually neglected. So, the rotor has only rotor copper loss. Therefore the rotor input has to supply these rotor copper losses. After supplying the rotor copper losses, the remaining part of Rotor input, P_2 is converted into mechanical power, P_m.

Let P_c be the rotor copper loss, I_2 be the rotor current under running condition, R_2 is the rotor resistance, P_m is the gross mechanical power developed. $P_c = 3I_2^2R_2$ $P_m = P_2 - P_c$ Now this mechanical power developed is given to the load by the shaft but there occur some mechanical losses like friction and windage losses. So, the gross mechanical power developed has to be supplied to these losses. Therefore the net output power developed at the shaft, which is finally given to the load is P_{out}. $P_{out} = P_m$ – Mechanical losses (friction and windage losses). P_{out} is called the shaft power or useful power.

Efficiency of Three Phase Induction Motor

Efficiency is defined as the ratio of the output to that of input, $Efficiency,\ \eta = \frac{output}{input}$

Rotor efficiency of the three phase induction motor , $= \frac{rotor\ output}{rotor\ input}$ = Gross mechanical power developed / rotor input $= \frac{P_m}{P_2}$

Three phase induction motor efficiency, $= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$

Three phase induction motor efficiency $\eta = \frac{P_{out}}{P_{in}}$

Advantages and Disadvantages of Induction Motor

Advantages of Induction Motor

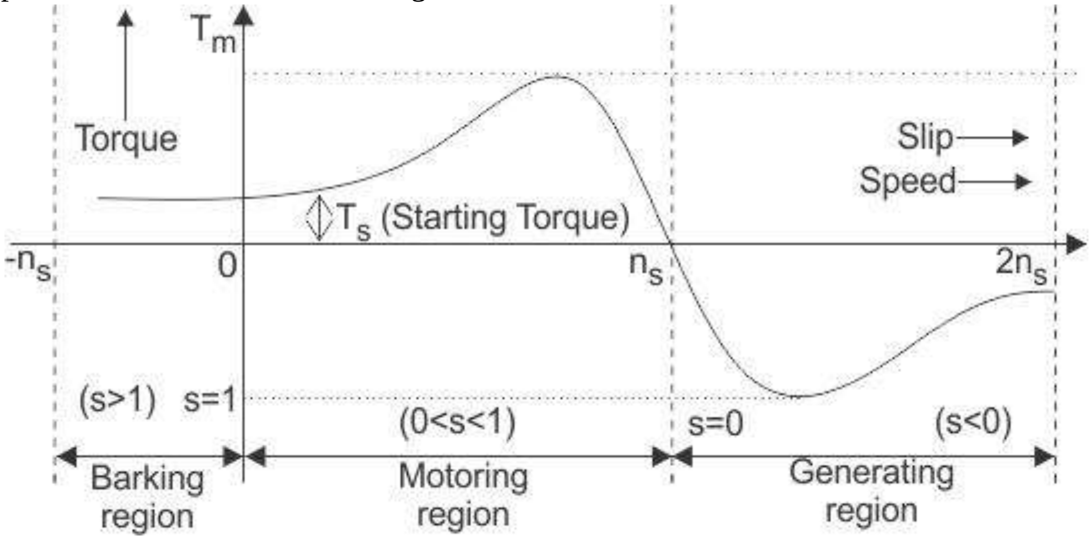
1. The most important **advantage of an induction motor** is that its construction is quite simple in nature. The construction of the Stator is similar in both Synchronous motors as well as induction motors. However, a slip ring is required to feed DC Supply to the Rotor in the case of a Synchronous Generator. These Slip rings are not required in a Squirrel cage induction motor because the windings are permanently short circuited. When compared with a DC Motor, the induction motor does not have Brushes and hence, maintenance required is quite low. This leads to a simple construction.
2. The working of the motor is independent of the environmental condition. This is because the induction motor is Robust and mechanically strong.
3. A Squirrel cage induction motor does not contain Brushes, Slip rings and Commutators. Due to this reason, the cost of the motor is quite low. However, Slip Rings are used in Wound type induction motor to add external resistance to the rotor winding.
4. Due to the absence of Brushes, there are no sparks in the motor. It can also be operated in hazardous conditions.
5. Unlike synchronous motors, a 3 phase induction motor has a high starting torque, good speed regulation and reasonable overload capacity.
6. An induction motor is a highly efficient machine with full load efficiency varying from 85 to 97 percent.

Disadvantages of Induction Motor

1. A single phase induction motor, unlike a 3 phase induction motor, does not have a self starting torque. Auxiliaries are required to start a single phase motor.
2. During light load conditions, the power factor of the motor drops to a very low value. This is because during the start, the motor draws a large magnetising current to overcome the reluctance offered by the air gap between the Stator and the Rotor. Also, the induction motor will take very less current from the supply main. The vector sum of Load current and Magnetising current lags the voltage by around 75-80 degrees and hence, the power factor is low. Due to high magnetising current, the copper losses of the motor increase. This in turn leads to decrease in the efficiency of the motor.
3. Speed control of an induction motor is very difficult to attain. This is because a 3 phase induction motor is a constant speed motor and for the entire loading range, the change in speed of the motor is very low.
4. Induction motors have high input surge currents, which are referred to as Magnetising Inrush currents. This causes a reduction in voltage at the time of starting the motor.
5. Due to poor starting torque, the motor cannot be used for applications which require high starting torque.

Starting Methods for Polyphase Induction Machine

In this article we are going to discuss various ***methods of starting three phase induction motor***. Before we discuss this, it is very essential here to recall the torque slip characteristic of the three phase induction motor which is given below.



From the torque slip characteristic it is clear that at the slip equals to one we have some positive starting torque hence we can say that the three phase induction motor is self starting machine, then why there is a need of starters for three phase induction motor? The answer is very simple.

If we look at the equivalent circuit of the three phase induction motor at the time of starting, we can see the motor behaves like an electrical transformer with short circuited secondary winding, because at the time of starting, the rotor is stationary and the back emf due to the rotation is not developed yet hence the motor draws the high starting current. So the reason of using the starter is clear here. We use starters in order to limit the high starting current. We use different starters for both the type of three phase induction motors. Let us consider first squirrel cage type of induction motor. In order to choose a particular type of starting method for the squirrel cage ype of induction motor, we have three main considerations and these are,

(a) A particular type of starter is selected on the basis of power capacity of the power lines. **(b)** The type of starter selected on the basis of the size and the design parameters of the motor. **(c)** The third consideration is the type of load on the motor (i.e. the load may be heavy or light). We classify starting methods for squirrel cage induction motor into two types on the basis of voltage. The two types are (i) Full voltage starting method and (ii) reduced voltage method for starting squirrel cage induction motor. Now let us discuss each of these methods in detail.

Full Voltage Starting Method for Squirrel Cage Induction Motor

In this type we have only one method of starting.

Direct on Line Starting Method

This method is also known as the **DOL method for starting the three phase squirrel cage induction motor**. In this method we directly switch the stator of the three phase squirrel cage induction motor on to the supply mains. The motor at the time of starting draws very high starting current (about 5 to 7 times the full load current) for the very short duration. The amount of current drawn by the motor depends upon its design and size. But such a high value of current does not harm the motor because of rugged construction of the squirrel cage induction motor.

Such a high value of current causes sudden undesirable voltage drop in the supply voltage. A live example of this sudden drop of voltage is the dimming of the tube lights and bulbs in our homes at the instant of starting of refrigerator motor. Now let us derive the expression for starting torque in terms of full load torque for the direct online starter. We have various quantities that involved in the expression for the starting torque are written below: We define T_s as starting torque T_f as full load torque I_f as per phase rotor current at full load I_s as per phase rotor current at the time of starting s_f as full load slip s_s as starting slip R_2 as rotor resistance W_s as synchronous speed of the motor Now we can directly write the expression for torque of induction motor as

$$T = \frac{1}{W_s} I^2 \frac{r}{s}$$

From the help of the above expression we write the ratio of starting torque to full load torque as

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f$$

Here we have assumed that the rotor resistance is constant and it does not vary with the frequency of the rotor current.

Reduced voltage method for starting squirrel cage induction motor

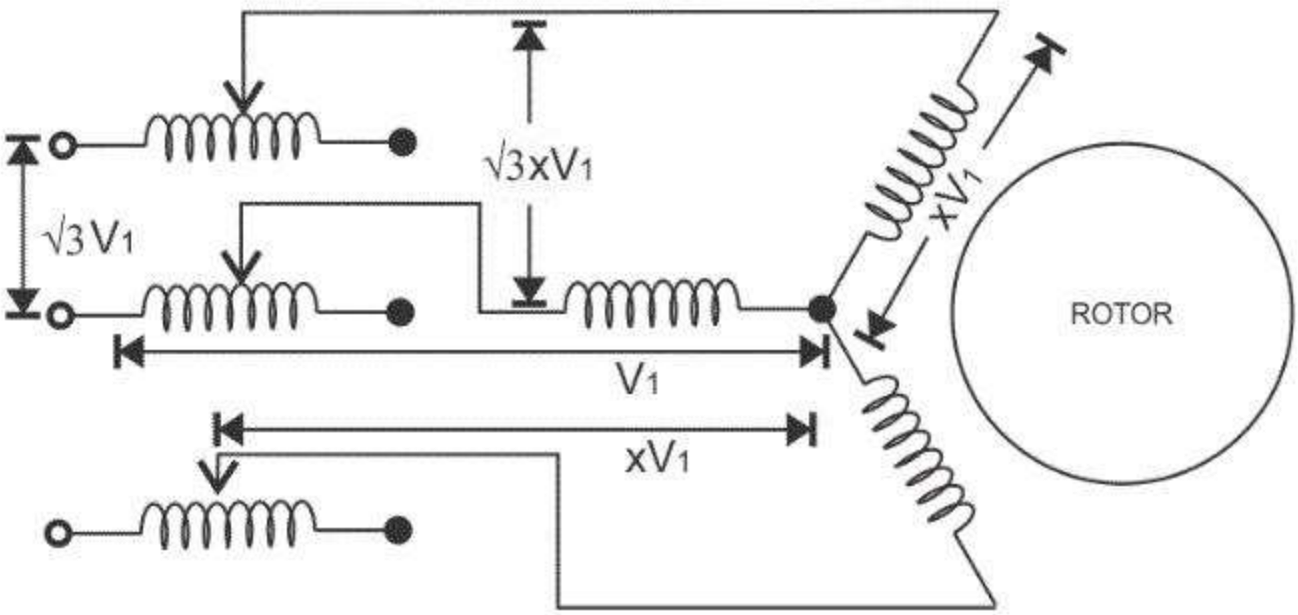
In reduced voltage method we have three different type of starting method and these are written below:

1. Stator resistor starting method
2. Auto transformer staring method
3. Star delta starting method

Now let us discuss each of these methods in detail.

Stator Resistor Starting Method

Given below is the figure for the starting resistor method:



In this method we add resistor or a reactor in each phase as shown in the diagram (between the motor terminal and the supply mains).Thus by adding resistor we can control the supply voltage. Only a fraction of the voltage (x) of the supply voltage is applied at the time of starting of the induction motor. The value of x is always less than one. Due to the drop in the voltage the starting torque also decreases. We will derive the expression for the starting torque in terms of the voltage fraction x in order to show the variation of the starting torque with the value of x. As the motor speeds up the reactor or resistor is cut out from the circuit and finally the resistors are short circuited when the motor reaches to its operating speed. Now let us derive the expression for starting torque in terms of full load torque for the stator resistor starting method. We have various quantities that involved in the expression for the starting torque are written below: we define T_s as starting torque T_f as full load torque I_f as per phase rotor current at full load I_s as per phase rotor current at the time of starting s_f as full load slip s_s as starting slip R_2 as rotor resistance W_s as synchronous speed of the motor Now we can directly write the expression for

$$T = \frac{1}{W_s} \times I^2 \frac{r}{s}$$

torque of the induction motor as From the help of the above expression we

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \cdots\cdots (i)$$

write the ratio of starting torque to full load torque as Here we have assumed that the rotor resistance is constant and it does not vary with the frequency of the rotor current. From the above equation we can have the expression for the starting torque in terms of the full load torque. Now at the time of starting the per phase voltage is reduced to xV_1, the per phase starting current is also reduced to xI_s. On substituting the value of I_s as xI_s in

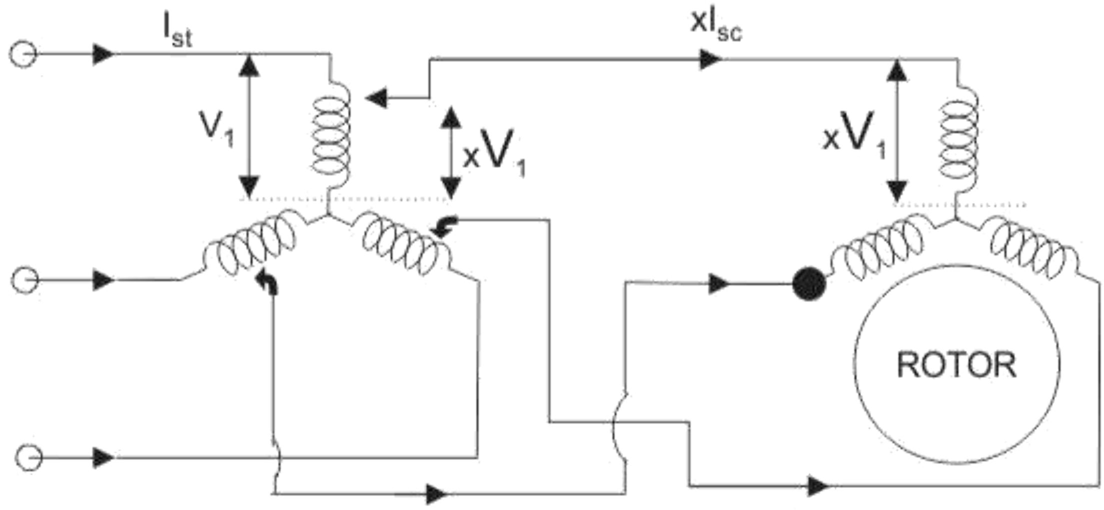
$$\frac{T_s}{T_f} = \left(\frac{xI_s}{I_f}\right)^2 \times s_f$$

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \times x^2$$

equation 1. We have This shows the variation of the starting torque with the value of x. Now there are some considerations regarding this method. If we add series resistor then the energy losses are increased so it’s better to use series reactor in place of resistor because it is more effective in reducing the voltage however series reactor is more costly than the series resistance.

Auto Transformer Starting Method

As the name suggests in this method we connect auto transformer in between the three phase power supply and the induction motor as shown in the given diagram:



Pertaining to Auto-Transfer Starting

The auto transformer is a step down transformer hence it reduces the per phase supply voltage from V_1 to xV_1.The reduction in voltage reduces current from I_s to xI_s. After the motor reaches to its normal operating speed, the auto transformer is disconnected and then full line voltage is applied. Now let us derive the expression for starting torque in terms of full load torque for the auto transformer starting method. We have various quantities that involved in the expression for the starting torque are written below: We define T_s as starting torque T_f as full load torque I_f as per phase rotor current at full load I_s as per phase rotor current at the time of starting s_f as full load slip s_s as starting slip R_2 as rotor resistance W_s as synchronous speed of the motor Now we can directly write the expression for torque of the induction motor as

$$T = \frac{1}{W_s} \times I^2 \frac{r}{s}$$

From the help of the above expression we write the ratio of starting torque to full load torque as

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \cdots\cdots (i)$$

Here we have assumed that the rotor resistance is constant and it does not vary with the frequency of the rotor current. From the above equation we can have the expression for the starting torque in terms of the full load torque. Now at the time of starting the per phase voltage is reduced to xV_1, the per phase starting current is also reduced to xI_s. On substituting the value of I_s as xI_s in equation 1. We have

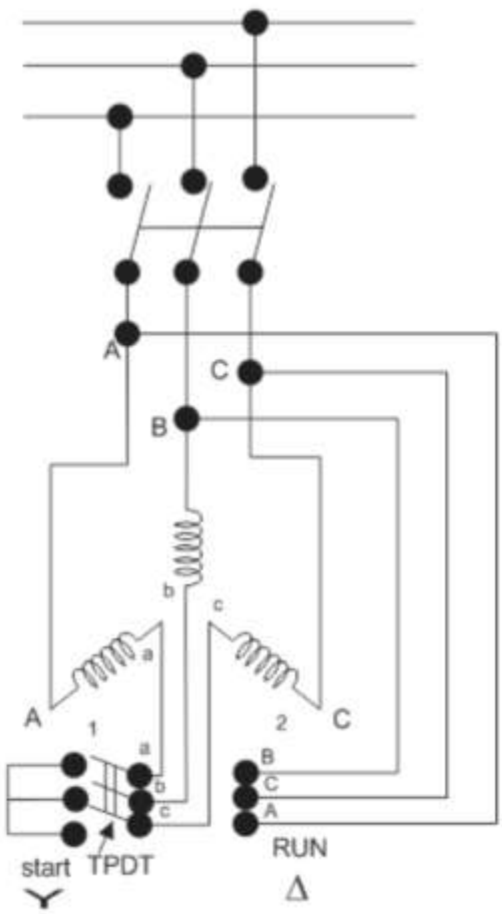
$$\frac{T_s}{T_f} = \left(\frac{xI_s}{I_f}\right)^2 \times s_f$$

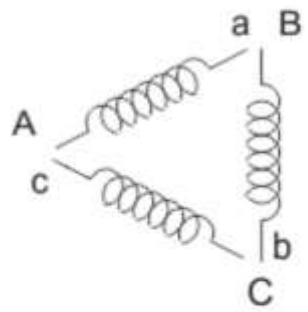
$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \times x^2$$

This shows the variation of the starting torque with the value of x.

Star-Delta Starting Method

Connection diagram is shown below for star delta method,





Star Delta

This method is used for the motors designed to operate in delta connected winding. The terminals are marked for the phases of the stator are shown above. Now let us see this method works. The stator phases are first connected to the star by the help of triple pole double throw switch (TPDT switch) in the diagram the position is marked as 1 then after this when the steady state speed is reached the switch is thrown to position 2 as shown in the above diagram. Now let analyse the working of the above circuit. In the first position the terminals of the motor are short circuited and in the second position from the diagram the terminal a, b and c are respectively connected to B, C and A. Now let us derive the expression for starting torque in terms of full load torque for the star delta starting method. We have various quantities that involved in the expression for the starting torque are written below T_f as full load torque T_s as starting torque I_f as per phase rotor current at full load I_s as per phase rotor current at the time of starting s_f as full load slip s_s as starting slip R_2 as rotor resistance W_s as synchronous speed of the motor Now we can directly write the expression for torque of the induction motor as

$$T = \frac{1}{W_s} \times I^2 \frac{r}{s}$$

From the help of the above expression we write the ratio of starting torque to full load torque as

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \cdots\cdots(ii)$$

Here we have assumed that the rotor resistance is constant and it does not vary with the frequency of the rotor current. Let us assume the line voltage to be V_l then the per phase starting current when connected in star position is I_{ss} which is given by

$$I_{ss} = \frac{V_l}{\sqrt{3} \times Z}$$

When stator is in delta connected position we have starting current

$$I_{sd} = \frac{V_l}{Z} \; clearly, \; I_{sd} = \sqrt{3} \times I_{ss} \; and \; I_{fd} = I_{ss}$$

$$\frac{T_s}{T_f} = \frac{1}{3} \left(\frac{I_{sd}}{I_{fd}}\right)^2 \times s_f \cdots\cdots(iii)$$

From the above equation we have This shows that the reduced voltage method has an advantage of reducing the starting current but the disadvantage is that all these methods of reduced voltage causes the objectionable reduction in the starting torque.

Starting Methods of Wound Rotor Motors

We can employ all the methods that we have discussed for starting of the squirrel cage induction motor in order to start the wound rotor motors. We will discuss the cheapest method of starting the wound rotors motor here.

Addition of External Resistances in Rotor Circuit

This will decrease the starting current, increases the starting torque and also improves the power factor. The circuit diagram is shown below: In the circuit diagram, the three slip rings shown are connected to the rotor terminals of the wound rotor motor. At the time of starting of the motor, the entire external resistance is added in the rotor circuit. Then the external rotor resistance is decreased in steps as the rotor speeds up, however the motor torque remain maximum during the acceleration period of the motor. Under normal condition when the motor develops load torque the external resistance is removed. **After completing this article, we are able to compare induction motor with synchronous motor. Point wise comparison between the induction motor and synchronous motor is written below,** (a) Induction motor always operates at lagging power factor while the synchronous motor can operate at both lagging and leading power factor. (b) In an induction motor the value of maximum torque is directly proportional to the square of the supply voltage while in case of synchronous machine the maximum torque is directly proportional to the supply voltage. (c) In an induction motor we can easily control speed while with synchronous motor, in normal condition we cannot control speed of the motor. (d) Induction motor has inherent self starting torque while the synchronous motor has no inherent self starting torque. (e) We cannot use induction motor to improve the power factor of the supply system while with the use of synchronous motor we can improve the power factor of the supply system. (f) It is a singly excited machine means there is no requirement of dc excitation while the synchronous motor is doubly excited motor means there is requirement of separate dc excitation. (g) In case of induction motor on increasing the load the speed of the motor decreases while with the speed of the synchronous motor remains constant.

Unit 2:-

Torque equation of 3-phase induction motor:-

Rotor copper loss = $s P_2$

$$P_2 = \frac{\text{Rotor copper loss}}{s}$$

$$P_2 = \frac{3 I_{2r}^2 R_2}{s}$$ → 3-ϕ cu loss.

$$I_{2r} = \frac{s E_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$P_2 = \frac{3 \left[\frac{s E_2}{\sqrt{R_2^2 + (sX_2)^2}} \right]^2 R_2}{s}$$

$$P_2 = \frac{3 s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$

$$P_2 = \frac{2 \pi N_s T}{60}$$

∴ Equating.

$$\frac{2 \pi N_s T}{60} = \frac{3 s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$

Torque $T = \frac{3 \times 60}{2\pi N_s} \times \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$

$$T = K . \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2} \rightarrow (1)$$

if $S = 1$

$$T_{st} = K . \frac{E_2^2 R_2}{R_2^2 + X_2^2} \rightarrow (A)$$

→ stand still to sque.

T_{st} is the starting torque of 3-phase induction motor.

condition for maximum torque:-

Differentiate eq (1) with "r/s" to slip "s" and equate it to zero.

$$\frac{dT}{ds} = 0$$

$$\frac{dT}{ds} = \frac{d}{ds}\left[\frac{K S E_2^2 R_2}{R^2 + (S X_2)^2}\right] \qquad \frac{d}{ds}\left(\frac{u}{v}\right) = \frac{uv' - vu'}{v^2}$$

$$\frac{dT}{ds} = K E_2^2 R_2 \left[\frac{s(0 + 2(s X_2) X_2 - [R_2^2 + (s X_2)^2] 1}{[R^2 + (s X_2)^2]^2}\right] = 0$$

$$\frac{dT}{ds} = 2 s^2 X_2^2 - R_2^2 - s^2 X_2^2 = 0.$$

$$s^2 X_2^2 = R_2^2$$

$$R_2 = S X_2 \rightarrow (2)$$

This is the condition to get maximum torque.

Substitute eqn (2) with eqn (1)

$$T_{max} = K . \frac{S E_2^2 (S X_2)}{(S X_2)^2 + (S X_2)^2}$$

$$= \frac{K E_2^2 S^2 X_2}{2 (S X_2)^2}$$

$$= \frac{K E_2^2 S^2 (X_2)}{2 \times S^2 \times (X_2^2)}$$

$$T_{max} = \frac{K}{2} \frac{E_2^2}{X_2}.$$

$$T_{max} = \frac{K E_2^2}{2 X_2}$$

Note :-

1. Starting torque and running torque [Eq. (1) & And Eq. (A)] Both are depends on Rotor Resistance (R_2).

2. But maximum torque does not depends on Rotor Resistance (R_2).

3. maximum torque depends on Rotor reactance. (X_2).

maximum torque condition

$$R_2 = S\, X_2$$

The slip at which maximum torque occurs is "Sm"

$$S_m = \frac{R_2}{X_2}$$

Torque slip characteristics:-

$$T = \frac{K\, S\, E_2^2 R_2}{R_2^2 + (S X_2)^2} \quad \{0 \le slip \le 1\}.$$

To draw the torque slip characteristics, we have two slip region cases.

case i:- low values of slip. [near to zero].

case ii:- High values of slip [near to one].

Case i :- Low values of slip:-

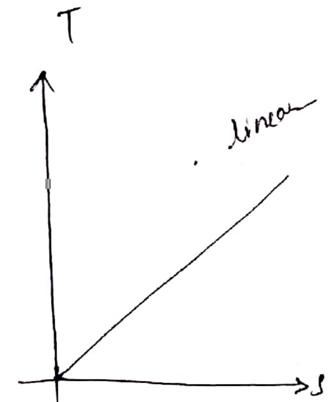
Here s value is low then s^2 value is very very small, ~~Hence~~

$$(S X_2)^2 <<< R_2$$

Hence neglecting $(S X_2)^2$ value

$$\therefore T = \frac{K \cdot S\, E_2^2 R_2}{R_2^2}$$

$$\therefore T \propto S$$



$$s = \frac{N_s - N_r}{N_s}$$

$N_r \downarrow \rightarrow s \uparrow$

Load $\propto s \propto \frac{1}{N_r}$

$\therefore$ Torque increases, slip increases

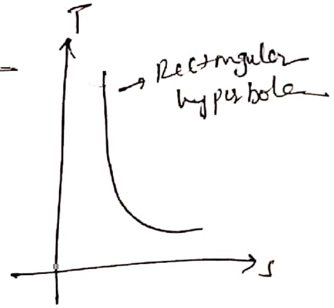
Case iii:- High value of slip.

then s is high, s^2 becomes very very high.

$\therefore (s x_2)^2 >> R_2$

Neglecting R_2

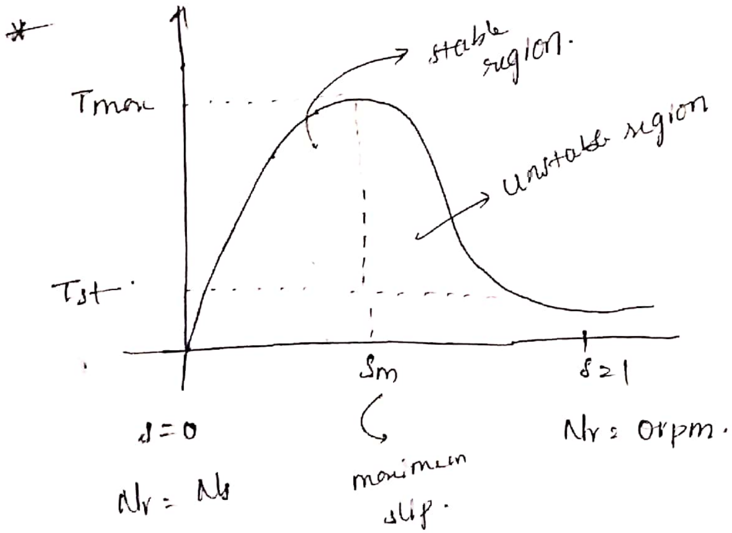
$$\therefore T = \frac{K s E_2^2 R_2}{s^2 x_2^2}$$



$$\therefore T \propto \frac{1}{s}$$

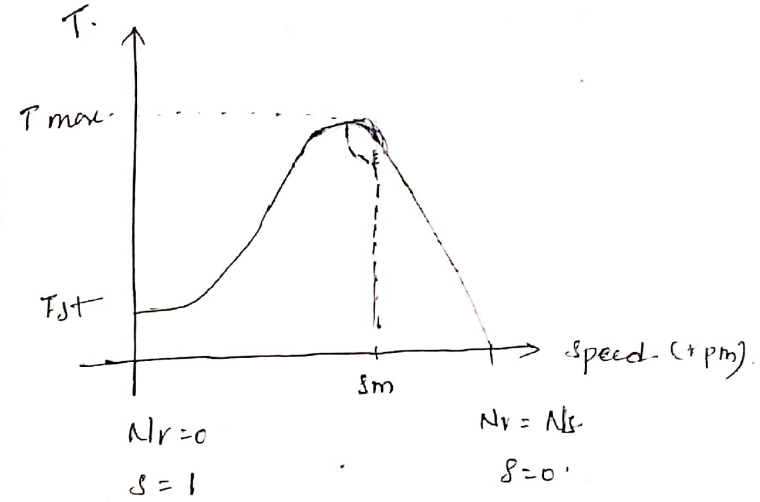
then Torque increases, Slip decreases.

*



* Induction motor always operated in stable region.

Torque - speed characteristics:-

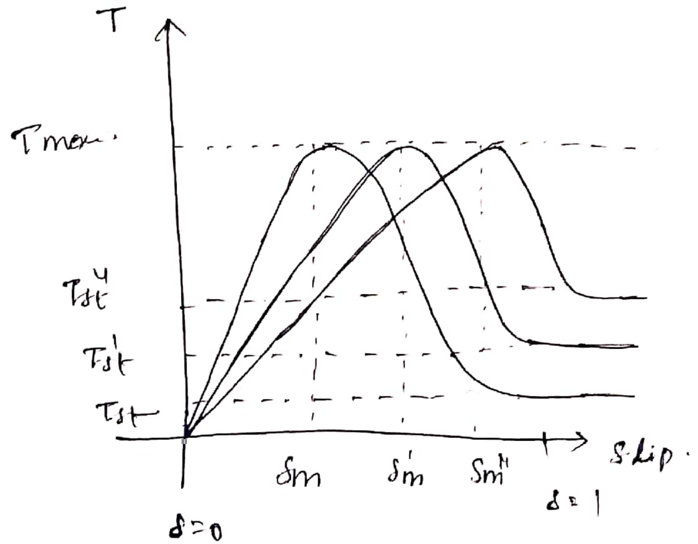


* Effect of rotor resistance on torque slip characteristics:-

$R_2 < R_2' < R_2''$

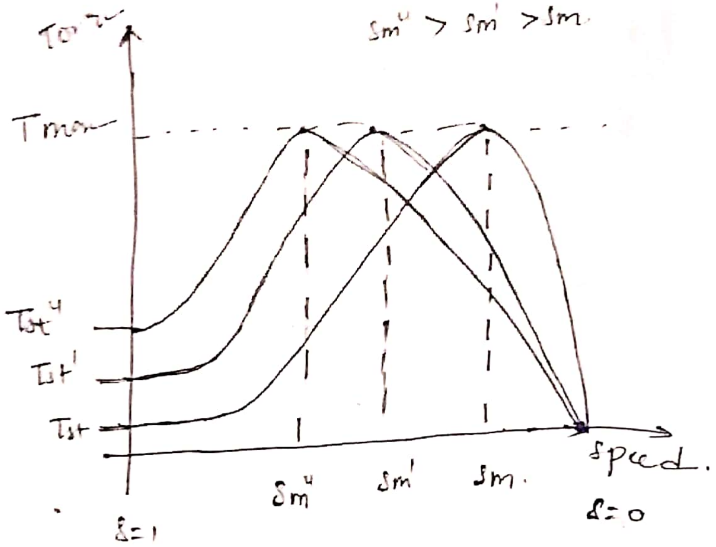
$Sm = \frac{R_2}{X_2}$; $Sm' = \frac{R_2'}{X_2}$; $Sm'' = \frac{R_2''}{X_2}$

$Sm < Sm' < Sm''$



Effect of Rotor resistance on Torque speed characteristics $T_{st}'' > T_{st}' > T_{st}$

$s_m'' > s_m' > s_m$



Relation b/w full load torque, maximum torque and starting torque

$$T_{fl} = \frac{K s_f E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

s_f - full load slip.

$$T_{st} = \frac{K \cdot E_2^2 R_2}{R_2^2 + X_2^2}$$

s_m : slip at maximum torque

$$s_m = \frac{R_2}{X_2}$$

$$T_{max} = \frac{K E_2^2}{2 X_2}$$

$$\frac{T_{fl}}{T_{max}} = \frac{\dfrac{K s_f E_2^2 R_2}{R_2^2 + (s_f X_2)^2}}{\dfrac{K \cdot E_2^2}{2 X_2}}$$

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

$$= \frac{s_f\, 2 X_2 R_2}{X_2^2\left[\left(\frac{R_2}{X_2}\right)^2 + s_f^2\right]}$$

$$= \frac{s_f\, 2\, (R_2/X_2)}{\left(\frac{R_2}{X_2}\right)^2 + s_f^2}$$

$$\boxed{\frac{T_{fl}}{T_{max}} = \frac{2 s_m s_f}{s_m^2 + s_f^2}}$$

Now.

$$\frac{T_{st}}{T_{max}} = \frac{\dfrac{K E_2^2 R_2}{R_2^2 + X_2^2}}{\dfrac{K \cdot E_2^2}{2 X_2}}$$

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

$$= \frac{2 X_2 R_2}{X_2^2\left[\left(\frac{R_2}{X_2}\right)^2 + 1\right]}$$

$$\frac{T_{st}}{T_{max}} = \frac{2\,(R_2/X_2)}{(\frac{R_2}{X_2})^2+1}$$

$$\boxed{\frac{T_{st}}{T_{max}} = \frac{2\,S_m}{S_m^2+1}}$$

$$\boxed{\frac{T_{fL}}{T_{st}} = \frac{S_f\,(S_m^2+1)}{S_f^2+S_m^2}}$$

Note:-

1. $\frac{T_{fL}}{T_{max}} = \frac{2\,S_f\,S_m}{S_f^2+S_m^2}$

2. $\frac{T_{st}}{T_{max}} = \frac{2\,S_m}{S_m^2+1}$

3. $\frac{T_{fL}}{T_{st}} = \frac{S_f\,(S_m^2+1)}{S_f^2+S_m^2}$

1) The rotor resistance & stand still reactance per phase of a 3-phase (slip) Induction are 0.02 Ω & 0.1 Ω. what should be the value of the of the external resistance per phase in the rotor circuit to give maximum torque at starting.

Sol:-

Rotor resistance = 0.02 Ω = R_2

stand still reactance = X_2 = 0.1 Ω

$\boxed{T_{st} = T_{max}}$ given condition (when external resistance is added to rotor circuit).

① $\frac{T_{st}}{T_{max}} = \frac{2S_m}{S_m^2+1}$

$1 = \frac{2S_m}{S_m^2+1}$

$S_m^2+1 = 2S_m$

$S_m^2 - 2S_m + 1 = 0$

$(S_m-1)^2 = 0$

$S_m = 1$

$\frac{R_2'}{X_2} = 1$ by given condition

$R_2' = R_2 + R_{external}$

$\frac{R_2 + R_{ext}}{X_2} = 1$

$R_2 + R_{ext} = X_2$

$R_{ext} = X_2 - R_2$

$R_{ext} = 0.1 - 0.02$

$\boxed{R_{ext} = 0.08\ \Omega}$

Eqn ① is possible when some external resistance is added to rotor circuit

2) A 6 pole, 50 Hz, 3-phase induction motor has rotor resistance & stand still reactance of 0.03 Ω & 0.1 Ω per phase. Calculate the value of external resistance to be connected in the rotor circuit to get 80% of maximum torque at starting.

Sol:

$R_2 = 0.03\ \Omega$

$X_2 = 0.1\ \Omega$

By given condition

$T_{st} = 0.8 \times T_{max}$

We know that

$$\frac{T_{st}}{T_{max}} = \frac{2S_m}{S_m^2+1}$$

$$\frac{0.8\, T_{max}}{T_{max}} = \frac{2S_m}{S_m^2+1}$$

$0.8\times(S_m^2+1) = 2S_m$

$0.8\, S_m^2 + 0.8 - 2S_m = 0$

$S_m = 2$ & 0.5

$0 \le S < 1$

$\therefore S_m = 0.5$

$S_m = \frac{R_2'}{X_2}$

$R_2' = R_2 + R_{ext}$.

$$\frac{R_2 + R_{ext}}{X_2} = 0.5$$

$R_2 + R_{ext} = (0.5 \times X_2) - R_2$

$= (0.5\times 0.1) - 0.03$

$R_{ext} = 0.02\ \Omega$

3) A ... connected induction motor runs at 660 V, 50 Hz. It has a slip ring rotor resistance of 0.03 Ω and stand still reactance of 0.5 Ω per phase. Calculate:

i) The speed at maximum torque.

ii) The ratio of full load torque to maximum torque.

Full load speed is 495 rpm.

Sol:

$R_2 = 0.03\ \Omega$

$X_2 = 0.5\ \Omega$

$$S_m = \frac{R_2}{X_2} = \frac{0.03}{0.5}$$

$S_m = 0.06.$

$$N_s = \frac{120 f}{P} = \frac{120\times 50}{12}$$

$N_s = 500$ rpm

$$S_m = \frac{N_s - N_{r\,max}}{N_s}$$

$$0.06 = \frac{500 - N_{r\,max}}{500}$$

$0.06\times 500 = 500 - N_{rm}$

$N_{r\,max} = 500 - (500\times 0.06)$

$= 470$ rpm

Speed at maximum torque $= 470$ rpm.

$$\frac{T_{fl}}{T_{max}} = \frac{2 S_m S_f}{S_m^2 + S_f^2}$$

$$S_f = \frac{N_s - 495}{N_s}$$

$$S_f = \frac{500 - 495}{500}$$

$S_f = 0.01$

$$\frac{T_{fl}}{T_{m}} = \frac{2(0.06)(0.01)}{(0.06)^2 + (0.01)^2}$$

$= 0.324$

4) A 4 pole, 50 Hz, 7.46 K.W 3-phase induction motor is supplied by rated voltage & rated frequency, a starting torque of 160% and maximum torque of 200% of full load torque. Determine

i, full load speed

ii, speed at maximum torque

$P = 4$

$f = 50\ Hz$

$T_{st} = 1.6 \times T_f \rightarrow (A)$

$T_{max} = 2 \times T_f \rightarrow B$

$P_{out} = 7.46\ kW$

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

$= 1500\ rpm.$

$\frac{T_{FL}}{T_{max}} = \frac{2 S_f S_m}{S_f^2 + S_m^2} \rightarrow (1)$

$\frac{T_{st}}{T_{max}} = \frac{2 S_m}{S_m^2 + 1} \rightarrow (2)$

$\frac{T_{fL}}{T_{st}} = \frac{S_f (S_m^2 + 1)}{S_f^2 + S_m^2} \rightarrow (3)$

from (1) & (A)

$0.625 = \frac{S_f (S_m^2 + 1)}{S_f^2 + S_m^2}$

$0.5 = \frac{2 S_f S_m}{S_f^2 + S_m^2}$

$S_f^2 + S_m^2 = \frac{S_f (S_m^2 + 1)}{} \times 1.6$

$S_f^2 + S_m^2 = 2 \times 2 S_f S_m$

$S_f (S_m^2 + 1) \times 1.6 = 4 \times S_f S_m$

$4 S_m = 1.6 [S_m^2 + 1]$

$1.6 S_m^2 - 4 S_m + 1.6 = 0.$

$S_m = 2.21 / 0.508$

$\therefore S_m = 0.5$

$S_m = 0.5$

$0.5 = \frac{2 S_f S_m}{S_f^2 + S_m^2}$

$0.5 = \frac{2 \times S_f \times 0.5}{S_f^2 + (0.5)^2}$

$0.5 [S_f^2 + 0.25] = 2 S_f \times 0.5$

$S_f^2 - 2 S_f + 0.25 = 0.$

$S_f = 1.86 / 0.13$

$S_f = 0.13$

$S_f = \frac{N_s - N_{rf}}{N_s}.$

$0.13 = \frac{1500 - N_{rf}}{1500}$

$1500 - N_{rf} = 0.13 \times 1500$

$N_{rf} = 1500 - (0.13 \times 1500)$

$N_{rf} = 1305\ rpm$

speed at full load.

$S_m = \frac{N_s - N_m}{N_s}$

$N_m = 1500 -$

$= 1500 - (0.5 \times 1500)$

$N_{max} = 750\ rpm$

This is speed at maximum torque

5) A 3-phase 4 pole 50 Hz motor has a slip ring rotor with a resistance & stand still reactance of 0.04 Ω per phase & 0.3 Ω per phase. Find the amount of resistance inserted in the rotor to obtain full load torque at starting. The full load slip is 4%.

$R_2 = 0.04\ \Omega$

$X_2 = 0.03\ \Omega$

$P = 4$

$f = 50\ Hz$ $\quad s_f = 0.04$

$T_{fl} = T_{st}$

$$\frac{T_{fl}}{T_{st}} = \frac{s_f(s_m^2+1)}{s_f^2 + s_m^2}$$

$$s_m = \frac{R_2}{X_2} = \frac{0.04}{0.03}$$

$s_m = 0.133$

$$\frac{T_{fl}}{T_{st}} = \frac{0.04(0.133^2+1)}{(0.04)^2+(0.133)^2}$$

$$\frac{T_{fl}}{T_{st}} = 2.07$$

$$1 = \frac{s_f(s_m^2+1)}{s_f^2+s_m^2}$$

$s_f^2 + s_m^2 = s_f(s_m^2+1)$

$(0.04)^2 + s_m^2 = (0.04)(s_m^2+1)$

$s_m^2 + (0.04)^2 = 0.04 s_m^2 + 0.04$

$s_m^2(1-0.04) + (0.04)^2 - 0.04 = 0$

$s_m^2(0.96) = 0.0384$

$$s_m^2 = \frac{0.0384}{0.96}$$

$s_m^2 = 0.04$

$s_m = 0.2$

$$s_m = \frac{R_2 + R_{ext}}{X_2}$$

$$0.2 = \frac{R_2 + R_{ext}}{X_2}$$

$R_2 + R_{ext} = 0.2 \times 0.3$

$R_2 + R_{ext} = 0.06$

$R_{ext} = 0.06 - R_2$

$= 0.06 - 0.04$

$R_{ext} = 0.02$

$R_{ext} = 0.02\ \Omega$ per phase

Note! –

We can not take $s_m = \frac{R_2}{X_2} = \frac{0.04}{0.3}$. Because its value of s_m is before adding external resistance in rotor.

6) 3-phase.

R_s, X_s } stator parameters [From equivalent circuit 5th step].

R_r', X_r', X_m } Rotor parameters

R_o → is neglected

$$Z_{eq} = (R_s + jX_s) + \frac{\left[\frac{R_r'}{s} + jX_r'\right] jX_m}{\frac{R_r'}{s} + jX_r' + jX_m} \quad \rightarrow (A)$$

Input current $I_s(ph) = \frac{V_{ph}}{Z_{eq}}$

Eqn (A) is for full load.

If you want starting impedance substitute $S = 1$.

1) A 4 pole, 230V, 60Hz star connected 3-phase induction motor has $R_s = 0.9\Omega$, $R_r' = 0.5\Omega$, $X_s = 1.5\Omega$, $X_r' = 0.8\Omega$ and $X_m = 40\Omega$. At under full load, the motor operates at 1728 rpm. And has rotational loss of 200W. Find

i) power factor
ii) stator copper loss
iii) rotor copper losses
iv) Output power
v) Output torque
vi) full load efficiency.

Sol:

$V_L = 230V$
$R_s = 0.9\Omega$
$R_r' = 0.5\Omega$
$X_s = 1.5\Omega$
$X_r' = 0.8\Omega$
$X_m = 40\Omega$
rotational loss = 200W.

$N_s = \frac{120f}{P} = \frac{120 \times 60}{4}$

$N_s = 1800$ rpm.

$S = \frac{N_s - N_r}{N_s}$

$= \frac{1800 - 1728}{1800}$

$S = 0.04$ or 4%

$$Z_{eq} = (R_s + jX_s) + \frac{\left[\frac{R_r'}{s} + jX_r'\right] jX_m}{\frac{R_r'}{s} + jX_r' + jX_m}$$

$$= (0.9 + j1.5) + \frac{\left(\frac{0.5}{0.04} + j0.8\right)(j40)}{\frac{0.5}{0.04} + j0.8 + j40}$$

$$= (0.9 + j1.5) + \frac{(12.52\angle 3.66)(40\angle 90)}{(12.52\angle 3.66) + 40\angle 90}$$

$$Z_{eq} = (13.16\angle 26.56°)\,\Omega$$

$V_{ph} = \frac{V_L}{\sqrt{3}}$

$V_{ph} = 132.79\angle 0^\circ$ V

$I_s = \frac{V_{ph}}{Z_T}$

$= \frac{132.79\angle 0^\circ}{13.162\angle 26.56^\circ}$

$I_s = 10.08\angle -26.56$ A

$\cos\phi = \cos(26.56) = 0.89$ lag

Stator input power P_{in}

$P_{in} = \sqrt{3}\, V_L I_L \cos\phi$

$= (\quad)(10.08\angle -26.56^\circ)$

iii, Stator copper loss

$= 3 I_1^2 R_1$

$= 3 (10.088)^2 (0.9)$

$= 274.8$ W

$P_{in} = \sqrt{3} \times V_L \times I_s \cos\phi$

$= \sqrt{3} \times 230 \times 10.088 \times 0.89$

$P_{in} = 3.59$ kW

Stator output $= P_2$

P_2 = Rotor input

$P_2 = P_{in}$ − Stator cu.l

$= 3.59 \times 10^3 - 274.8$

$P_2 = 3295.2$ W

Rotor copper loss $= P_2 \times s$

$= 3295.2 \times 0.04$

$= 131.808$

$P_m = P_2 - 131.808$

$P_m = 3163.4$ W

$P_{out} = P_m$ − Rotational loss

$= 3163.4 - 200$

$P_{out} = 2963.4$ W

$= 2.96$ kW

$P_{out} = \frac{2\pi N T}{60}$

$T = \frac{P_{out} \times 60}{2\pi \times N_r}$

$= \frac{2963.4 \times 60}{2 \times \pi \times 1728}$

$T_{sh} = 16.37$ N-m

$P_m = \frac{2\pi N_s T_d}{60}$

$T_d = \frac{P_m \times 60}{2\pi \times N_s}$

$= \frac{3163.4 \times 60}{2\pi \times 1800}$

$T_d = 16.78$ N-m.

Full load efficiency $= \eta$

$\eta = \frac{P_{out}}{P_{in}} \times 100$

$= \frac{2.96}{3.57} \times 100$

$\boxed{\eta = 82.91\%}$

\# for output torque we N_r. (P_{out})

\# for developed torque we N_s (P_m)

2) A 4 pole, 210V, 60 Hz star connected induction motor has $R_s = 1\Omega$, $R_r' = 0.5\Omega$, $X_s = 1.9\Omega$, $X_r' = 0.8\Omega$ and $X_m = 40\Omega$.

Find

i, starting current

ii, starting torque

$V_{ph} = E_2$

Sol:

$R_s = 1\Omega$

$R_r' = 0.5\Omega$.

$X_s = 1.9\Omega$

$X_r' = 0.8\Omega$

$X_m = 40\Omega$.

For starting impedance s=1

$$Z = (R_s + jX_s) + \frac{(R_r' + jX_r')(jX_m)}{R_r' + jX_r' + jX_m}$$

$$= (1+j1.9) + \frac{(0.5+0.8j)(40j)}{(0.5+0.8j)(40j)}$$

$$= (1+j1.9j) + (0.924\angle 58.69°)$$

$V_L = 210V$.

$$Z = 3.07\angle 61.17\ \Omega$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{210}{\sqrt{3}}$$

$V_{ph} = 121.24\ V$.

$$I_s = \frac{V_{ph}}{Z} = \frac{121.24\angle 0°}{3.07\angle 61.17°}$$

$$I_s = 39.49\angle -61.17°\ A$$

* I_s = (30-40)% full load current. *

starting torque

$$T_{st} = \frac{K \cdot E_2^2 R_2}{R_2^2 + X_2^2}.$$

$$K = \frac{180}{2\pi N_s}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 60}{4}.$$

$N_s = 1800$ rpm.

$$K = \frac{180}{2\pi \times 1800}$$

$K = 0.0159$.

~~$E_2 = V_{ph}$~~, → $E_2 = V_{ph}$; $R_2 = R_r'$; $X_2 = X_r'$

T_{st} = ~~0.0159×~~

$$T_{st} = K\frac{E_2^2 R_r'}{R_r'^2 + X_r'^2}$$

$$= \frac{0.0159 \times (121.24)^2 \times 0.5}{(0.5)^2 + (0.8)^2}$$

$$= \frac{\text{~~0.9638~~}}{\text{~~0.89~~}}$$

= ~~1.086 N-m~~

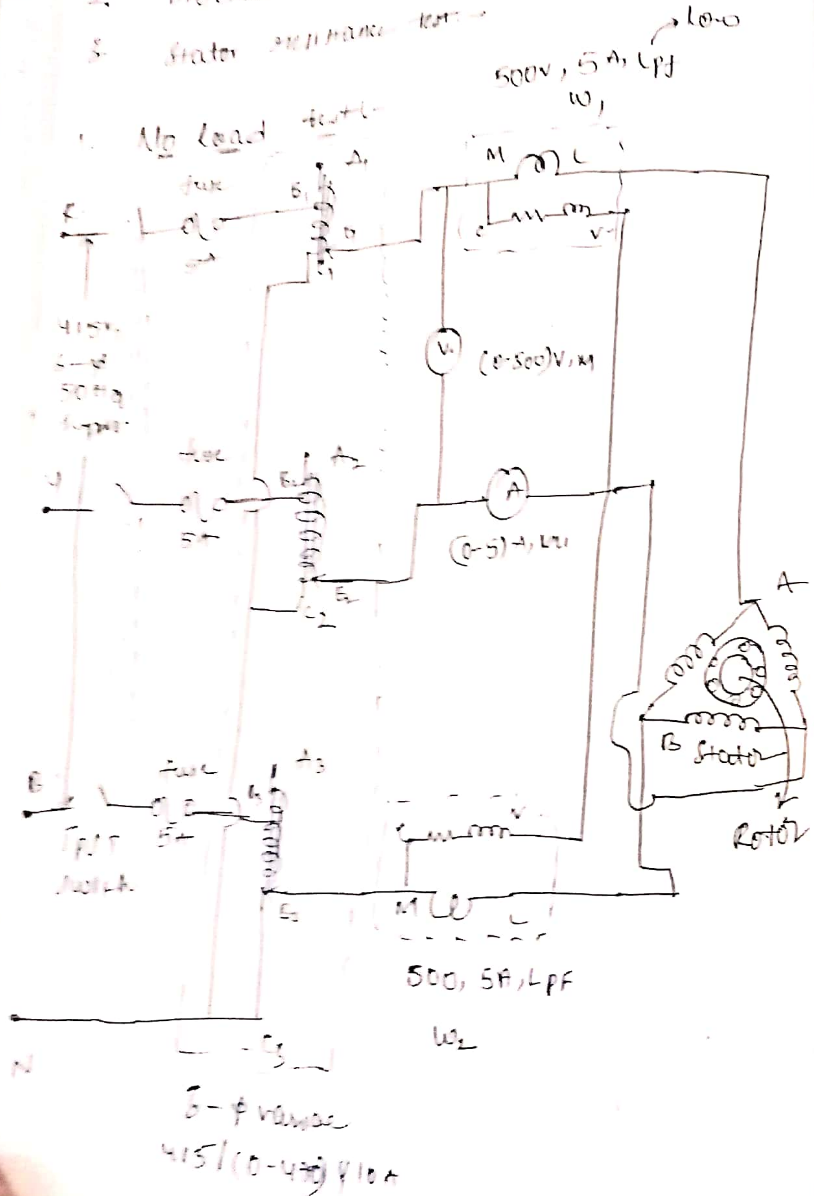
$$= \frac{116.8581}{0.89}.$$

T_{st} = 131.30 N-m

Different test on 3 phase Induction motor

1. No load test → OC test → constant loss
2. Blocked rotor test → SC test → copper loss
3. Stator resistance test →

1. No load test:-



V_{oc} (l) → No load line voltage.

I_o → No load line current

P_o → No load power → constant loss.

V_{oc} (ph) → No load phase voltage

$$P_o = W_1 + W_2$$

$$P_o = \sqrt{3}\, V_{oc}\, I_o \cos\phi_o.$$

$$\cos\phi_o = \frac{P_o}{\sqrt{3}\, V_{oc}(l)\, I_o}$$

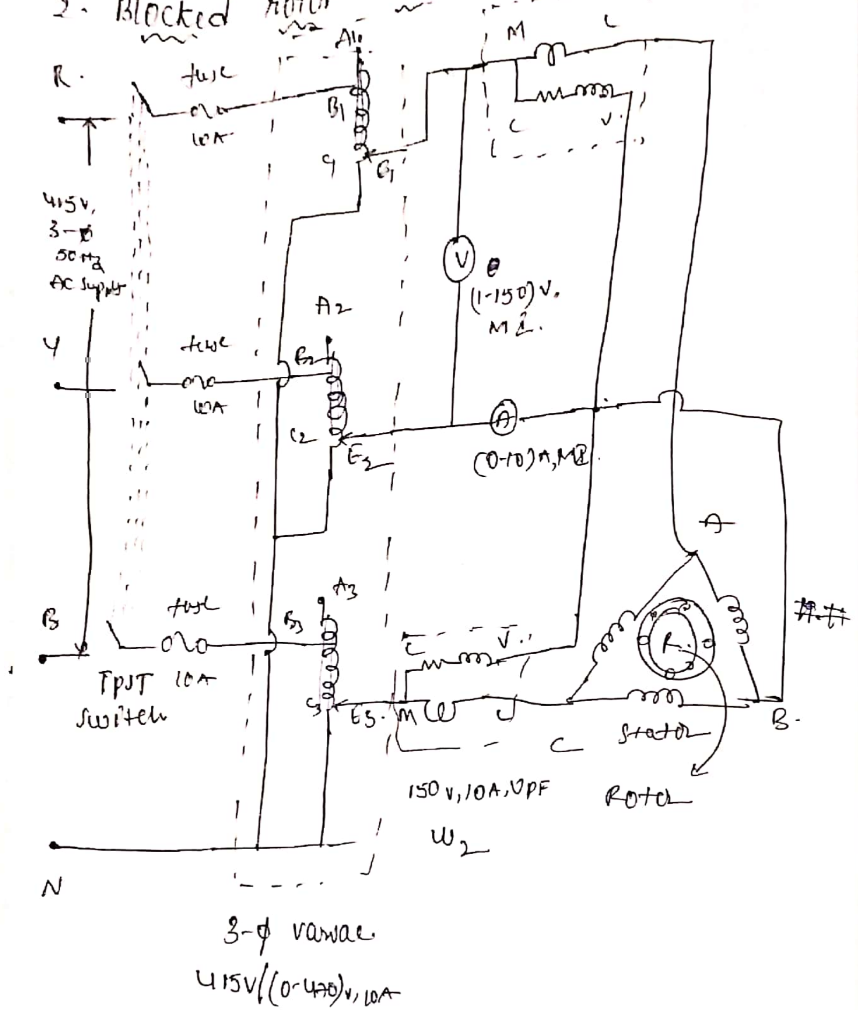
$$I_w = I_o \cos\phi_o$$

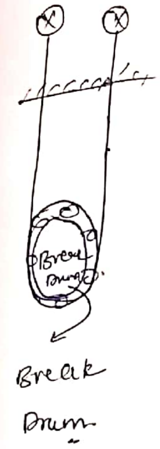
$$I_\mu = I_o \sin\phi_o.$$

$$R_o = \frac{V_{oc}\ (ph)}{I_w.}$$

$$X_{om} = \frac{V_{oc}\ (ph)}{I_\mu.}$$

2. Blocked rotor test :-





V_{sc} (L) - short circuited line voltage (10 - 20% of rated voltage

I_{sc} - short circuited current

P_{sc} = copper loss
short circuited power

$P_{sc} = W_1 + W_2$

$$Z_{eq} = \frac{V_{sc}\,(ph)}{I_{sc}}$$

$$P_{sc} = 3\, I_{sc}^2 R_{eq}$$

$$R_{eq} = \frac{P_{sc}}{3\, I_{sc}^2} \quad (\text{Rotor} + \text{stator } R)$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} \quad (\text{Rotor} + \text{stator } X)$$

$$R_{eq} = R_1 + R_2'$$

$$R_2' = R_{eq} - R_1$$

$$X_1 = X_2' = \frac{X_{eq}}{2}$$

Construction of circle diagram:-

No load test

V_{oc} , I_0 , P_0

$$\cos\phi_0 = \frac{P_0}{\sqrt{3}\, V_{oc}\, I_0}$$

$$\phi_0 = \cos^{-1}\left\{\frac{P_0}{\sqrt{3}\, V_{oc}\, I_0}\right\}$$

$\phi_0 = (70-80^\circ)$

Blocked test

V_{sc} a, I_{sc} , P_{sc}

W_{sc} (or) $P_{sc} = \sqrt{3}\, V_{sc}\, I_{sc} \cos\phi_{sc}$

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

$$\phi_{sc} = \cos^{-1}\left\{\frac{P_{sc}}{\sqrt{3}\, V_{sc}\, I_{sc}}\right\}$$

$$I_{SCN} = I_{sc}\left[\frac{\text{Rated voltage}}{V_{sc}}\right]$$

I_{SCN} = Normalised Short circuited current

Construction:-

Step 1:- With origin 'O' draw I_0 line with an angle of ϕ_0 with voltage axis. end point of I_0 line is marked as 'O''

Step 2:- With origin 'O' draw I_{SCN} line with an angle of ϕ_{sc} with voltage axis. The end point of I_{SCN} line is marked as point 'A'

Step 3:- Draw a parallel to x-axis from origine 'O''.

Step 4:- Joint the point (O' & A). That line is named as Output line.

Step 5:- Draw a line from point 'A' which is parallel to voltage axis, it cuts the x-axis parallel line at 'B'.

Step 6:- measure the length 'AB' locate a point on AB line, which is exactly having half of length from both A & B. H is a mid point of AB line.

Now join the point O' & H, it makes a line O'H called Torque line

AH = rotor copper loss

BH = stator copper loss.

FB = fixed loss or constant loss.

Step 7:- Draw a perpendicular bisector to O'A line. The bisector cuts the x-axis parallel line at point 'C'.

'C' be the center point.

Step 8:- Taking as a centre ... with length O'C as a Radius draw a semi circle which cuts parallel line at 'D'.

W_{scN} (or) $P_{scN} = W_{sc}\left[\frac{\text{Rated voltage}}{V_{sc}}\right]^2$

$\text{power scale} = \frac{W_{scN}}{\text{length of AF}}$

We have to mark a point S from 'A'

$\therefore \text{length of AS} = \frac{\text{power scale}}{\text{KVA}}$

Step 9:-

∴ Draw a length "AS" from point A to S parallel to voltage axis or along AF line.

Step 10:- Draw a parallel line from point 'S' to voltage axis side which is parallel to output line (O'A) it cuts the semi circle at point P.

OP = full load current.

Step 11:- Draw a parallel line to voltage axis from point P to x-axis. It cuts Isc line at E, & Torque line at point K. on x-axis at G at L.

1) Draw a circle diagram of a star connected 20Hp, 400V, 50Hz induction motor a has the following data.

No load test:- 400V, 9A, power factor = 0.2 lag

Block test:- 200V, 50A, power factor = 0.4 lag.

From the circle diagram find,

i, line current, power factor and efficiency on full load

ii, full load slip

From No Load test

$\cos\phi_0 = 0.2$

$\phi_0 = \cos^{-1}(0.2)$

$\phi_0 = 78.46$

$I_0 = 9\ A$

| I_0 in cm = 1.8 |

Blocked test

$I_{sc} = 50\ A$

$\cos\phi_{sc} = 0.4$

$\phi_{sc} = \cos^{-1}(0.4)$

$\phi_{sc} = 66.42$

$I_{scN} = I_{sc}\left[\frac{400}{200}\right]$

$= 50[2]$

$= 100\ A$

| 1cm = 5A |

$R_2 = SRP_2$

$S = \frac{R_2 f}{P_2 f}$

$\frac{0.2}{6}$

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

$= \sqrt{3} \times 200 \times 50 \times 0.4$

$W_{sc} = 6928W$

| AD = 8.3cm. → from G |

$W_{scN} = W_{sc}\left[\frac{\text{rated voltage}}{V_{sc}}\right]^2$

$= 6928 \times \left[\frac{400}{200}\right]^2$

$W_{scN} = 27712.8.$

$= 27.71 k.w$

W_{scN} = length of AD.

$\frac{27.71 \times 10^3}{8.3} \times$

for 1cm = 3.329 KW

Pout = 20Hp

$= 20 \times 746$

Pout = 14.92 k.w

Pout for 1cm = $\frac{14.92}{3.39}$

= 4.46cm

$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{PT}{PLD}$

$= \frac{4.6}{5.7} \times 100$

= 80.70

line current

= length of OP × current scale

= 6.6 × 5 = 33A

ED: constant loss

i.e

constant loss = ED × 3.29kw

= 0.4 × 3.29

= 1.31kw.

Stator cu lost = QR = 0.3cm

= 0.3 × 3.29kw

= 980 W.

rotor cu loss = TQ

= 0.3 × 3.29

= 980W

S Rotor cu loss = SP_2

$S = \frac{\text{Rotor cu loss}}{P_2}$

980W

P_2 = PT × 3.29.

= 4.6 × 3.29

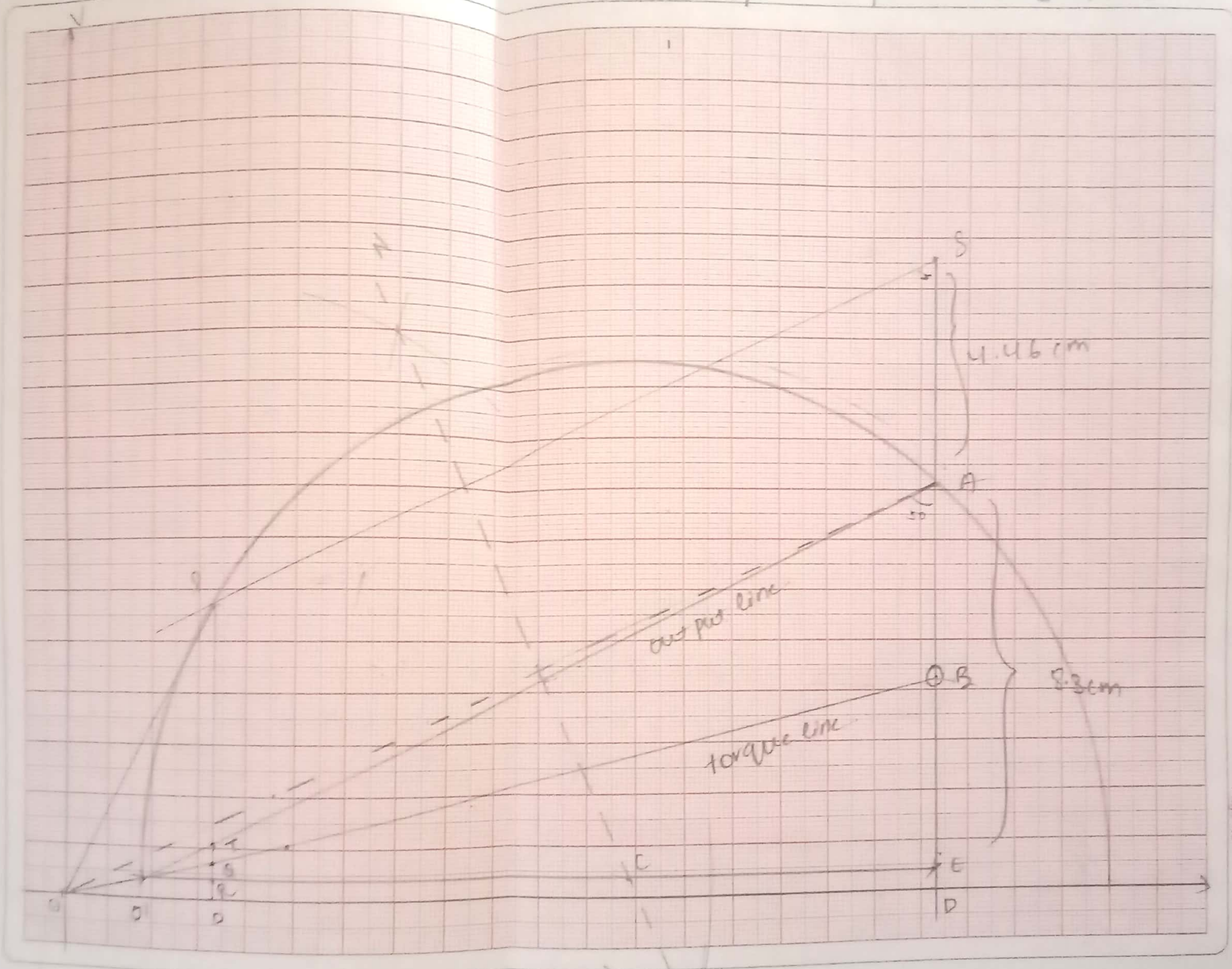
= 15.134 k.w

$S = \frac{980}{15.134 \times 10^3}$

S = 0.06

$I_0 = 1.8$ / 78.16 | CS - 1cm = 5A

I_{scv} = 20cm | 66.42 | PS - 1cm = 3.29 kW



$W_{SCN} = W_{SC} \left(\frac{200}{100}\right)^2$

$= ~~3050~~\ ~~1700~~$

$= 1700 \times 4$

$= 6.8 \times 10^3 \, W$

$W_{SCN} = 6.8 \, kW$

∴ from graph

AB = 7.9 cm

∴ 6.8 kW = 7.9 cm

$1 cm = \frac{6.8}{7.9}$

1 cm = 0.860 k.W (PS)

Pout = 5 HP.

= 5 × 746

= 3.730 k.W.

$P_{out} \text{ in cm} = \frac{3.730}{0.860}$

Pout/1 cm = 4.33 k.W

constant loss = ST

= ST × ~~RS~~ P_{fs}

= 0.4 × 0.860 =

= 0.344 kW

Stator copper loss = SP

= ~~R~~ SP × P_s

= 0.35 × 0.860

= 0.301 kW

Rotor cu loss = RQ ∴

= RQ × P_s

= 0.35 × 0.867

= ~~3.03 kW~~

= 0.301 kW

i) ~~cos~~ φ = 32.2°

cos φ = ~~0.832~~ 0.84

ii) P_L = PO × P_s

= 6.9 × 2.5

= 17 k.W.

iv) $S = \frac{RQ}{~~RQ~~} \frac{RQ}{QR}$

$= \frac{0.3}{4.9} = 0.06$

iv) $\eta = \frac{~~\varphi~~ 4.2}{5.7} \cdot \frac{PG}{PQT}$

= 73.68%

---

i) max I/P power = xx' × 0.860

= 10.6 × 0.860

= 9.116 k.W.

ii) max O/P = yy' × 0.860

= 6.6 × 0.860

= ~~5.676~~ k.W

iii) max Torque = ~~zz'~~ × 0.86

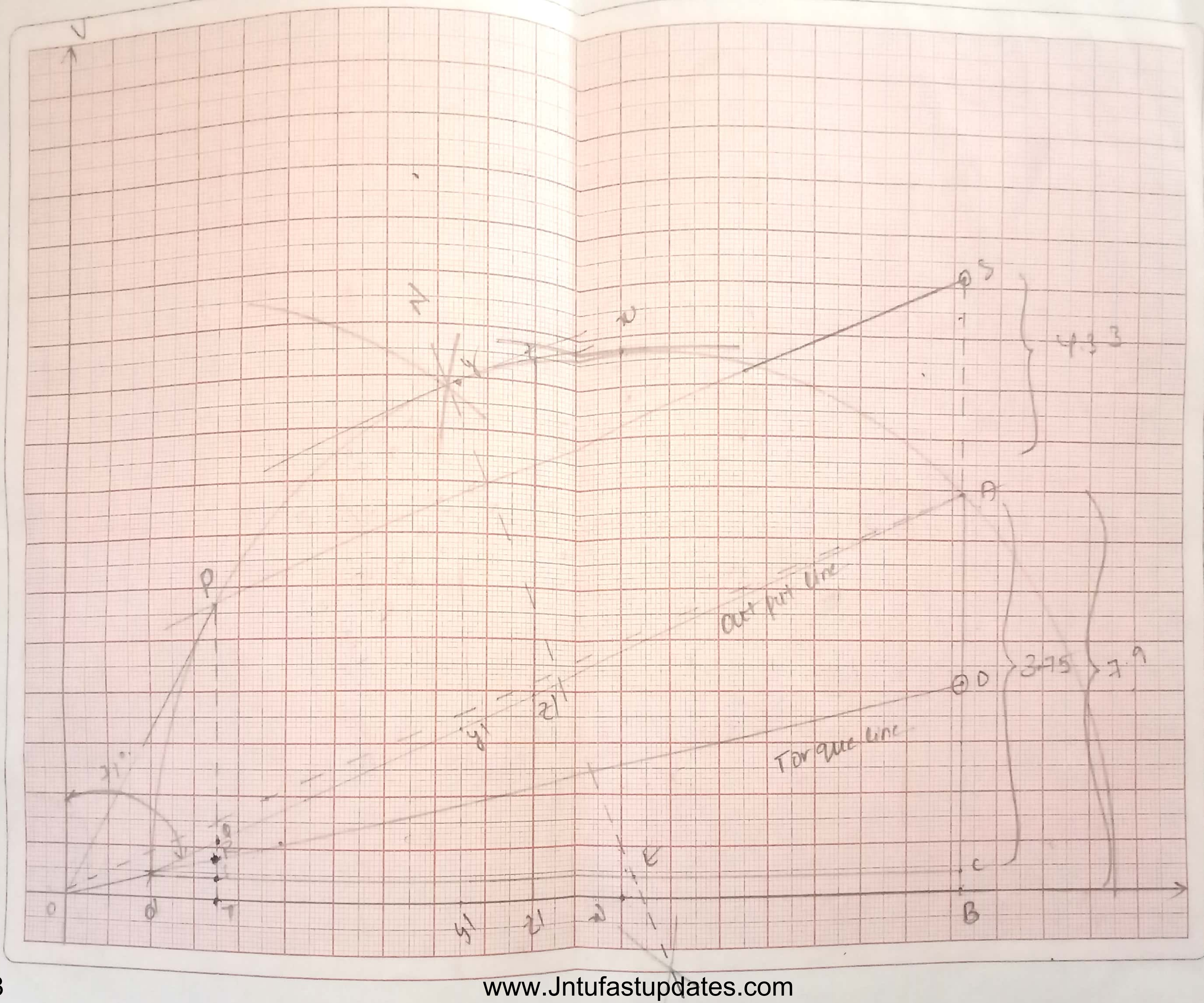
5.6 × 0.860

= 4.816 kW

$i_0 = 2cm/78.34°$ | Rotor cu loss = RQ = 3.5

i_{SCN} = 28.8cm/67.82 | C.S - 1cm = 25A

P.S - 0.860 kV



Draw the circle diagram from No load & blocked rotor test of a 3-φ, 14.92 kW, 400V, 6 pole induction motor - has the following test results.

No load test :- 400V, 11A, pf = 0.2

Blocked rotor test = 100V, 25A, pf = 0.4

Rotor culoss at stand still condition is half of total culoss. find

1, line current, slip, efficiency, pf, Max torque

No load test

$I_0 = 11A$

$\cos\phi_0 = 0.2$

$\phi_0 = 78.46$

$I_0 = 11A$

$I_0 = \frac{11}{5} = 2.2\ cm$

$W_{sc} = \sqrt{3}\, V_{sc} I_{sc} \times 0.4$

$= \sqrt{3} \times 100 \times 25 \times 0.4$

$W_{sc} = 1.732\ kW$

$W_{scN} = W_{sc}\left[\frac{V_2}{V_{sc}}\right]^2$

$= 1.732 [4]^2$

$W_{scN} = 27.712\ kW$

Blocked rotor test

$I_{sc} = 25A$

$\cos\phi_{sc} = 0.4$

$\phi_{sc} = 66.42$

$I_{scN} = I_{sc}\left[\frac{\text{Rated } V}{V_{sc}}\right]$

$= 25\left[\frac{400}{100}\right]$

$= 100\ A$

1cm = 5Am (C.S.)

$I_{scn} = \frac{100}{5} = 20\ cm$

O/P = 14.92 kW

AB = 8.3 cm → q.

14.92 kW = 8.3 cm

1cm = 1.797 kW (P.S.)

AB = 8.3 cm — q.

27.71 = 8.3

1cm = $\frac{27.71}{8.3}$ = 3.33 kW

1cm = 3.33 kW

O/P $\frac{14.92}{3.33} = 4.480$

1) Line current = OP × C.S.

16.5 × 5 = 82.5 A

Length of rotor input power = full load torque.

Rotor culoss = 0.3 × 3.33 ~~1.33~~

~~1.33 kw~~ 0.53 kW

$S = \frac{R.cu}{P_2} = \frac{0.99}{4.6 \times 3.3}$ ~~×100~~

$= 6.5\%$

$Pf = \cos\phi = \cos 32.5$

$= 0.84$ lag.

$\eta = \frac{PQ}{PQ} = \frac{30.4}{56}$

$= 80\%$

$x x' = 7.9$ max Torque

$7.9 \times 3.33 = 26.07$

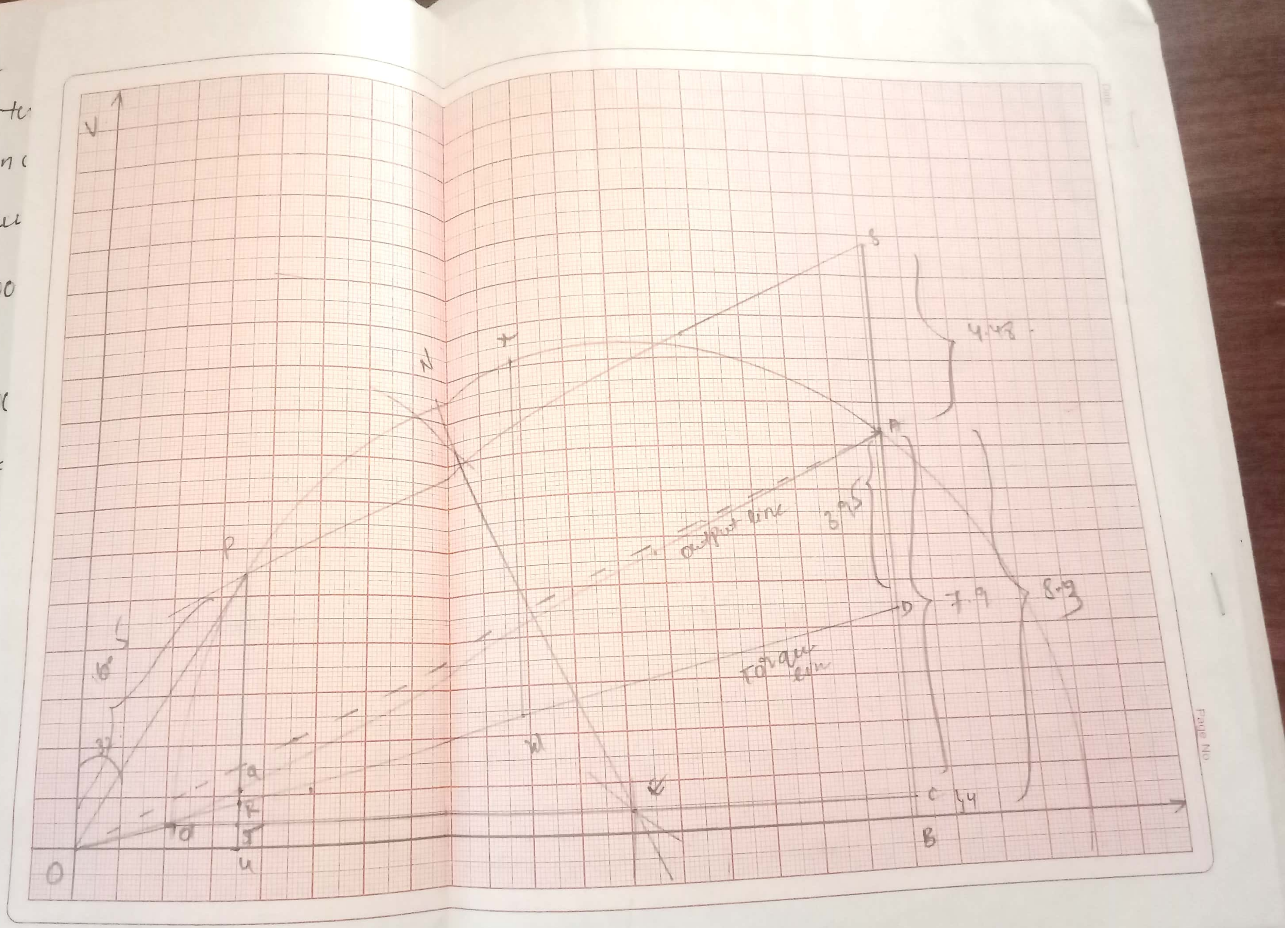
7.9 × 3.33 max. Torque value in terms of S.Watt.

$\frac{7.9}{4.5} = 1.75 = \frac{RR'}{PR}$

maximum torque in terms of full load torque

Synchronous watt × $\frac{2\pi}{N_s}$ = N-m

Synchronous Torque


V
P
N
X
S
A
D
C
B
O
output line
Torque line
4.48
3.95
7.9
8.9
4.4

4) Draw the circle diagram for a 5.6 kw, 400v, 3-φ, 4 pole slipring induction motor has the following test data.

No load test:- 400v, 6A, pf = 0.087

Blocked rotor test:- 100v, 12A, 720 watts.

Determine,
full load current, full load slip, full load pf, maximum output & input power, ratio of max. torque to full load torque.

No load test:-

$I_0 = 6A$

$\cos\phi_0 = 0.087$

$\phi_0 = 85.00$

1 cm = 3A (C.S)

$\frac{48}{3} = 16cm$

$I_{SCN} = 16cm$

$I_0 = \frac{6A}{3}$

$I_0 = 2cm$

$V_{sc} = 100V$

$I_{sc} = 12A$

$W_{sc} = 720$ watts

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

$\cos\phi_{sc} = \frac{720}{\sqrt{3} \times 100 \times 12}$

$\cos\phi_{sc} = 0.34$

$\phi_{sc} = 69.73$

$I_{SCN} = I_{sc}\left(\frac{V_L}{V_{sc}}\right)$

$= 12\left[\frac{400}{100}\right]$

$I_{SCN} = 48A$

$W_{SCN} = W_{sc}\left[\frac{V_L}{V}\right]^2$

$= 720[4]^2$

$W_{SCN} = 11.52$ k.w.

AB = 5.3 cm.

~~W_{sc} = 720 w.~~

720 = 5.3

W_{SCN} = 11.52 k.w

11.52 = 5.3 cm.

1cm = 2.173 k.w. P(o)

~~1cm = 217.35 W~~ (PS)

Pout = 5.6 kw

= 5600 w.

Lout = $\frac{5600}{2.17}$ = 25.76 cm

Lout = 2.577 cm.

i) line current = OP

OP = 4.2 cm

OP = 4.2 × 3 =

I_L = 12.6A

iii) $\cos\phi$ = 40

$\cos\phi$ = 0.766

v) $\frac{T_{max}}{F.T_{or}} = \frac{6.3cm}{2.9} = \frac{xx}{PF}$

$\frac{T_{max}}{T_{fullload}} = 2.12$

max power = gq' = 5cm

max input = MO' or MC = 7.5

$\frac{max\ P_{out}}{max\ P_{in}} = \frac{5}{7.5} = 0.66$

max Pout = 0.66 × 2.173
= 1.434 k.w

max Pin = 7.5 × 2.173
= 16.297 k.w.

$R_{cu} = S \times P_2$

$S = \frac{R_{cu} - Rotor}{P_2}$

$= \frac{GF}{EP}$

$= \frac{0.15}{2.8}$

S = 0.05

circle diagram for a ...

4 po...

wrong t...

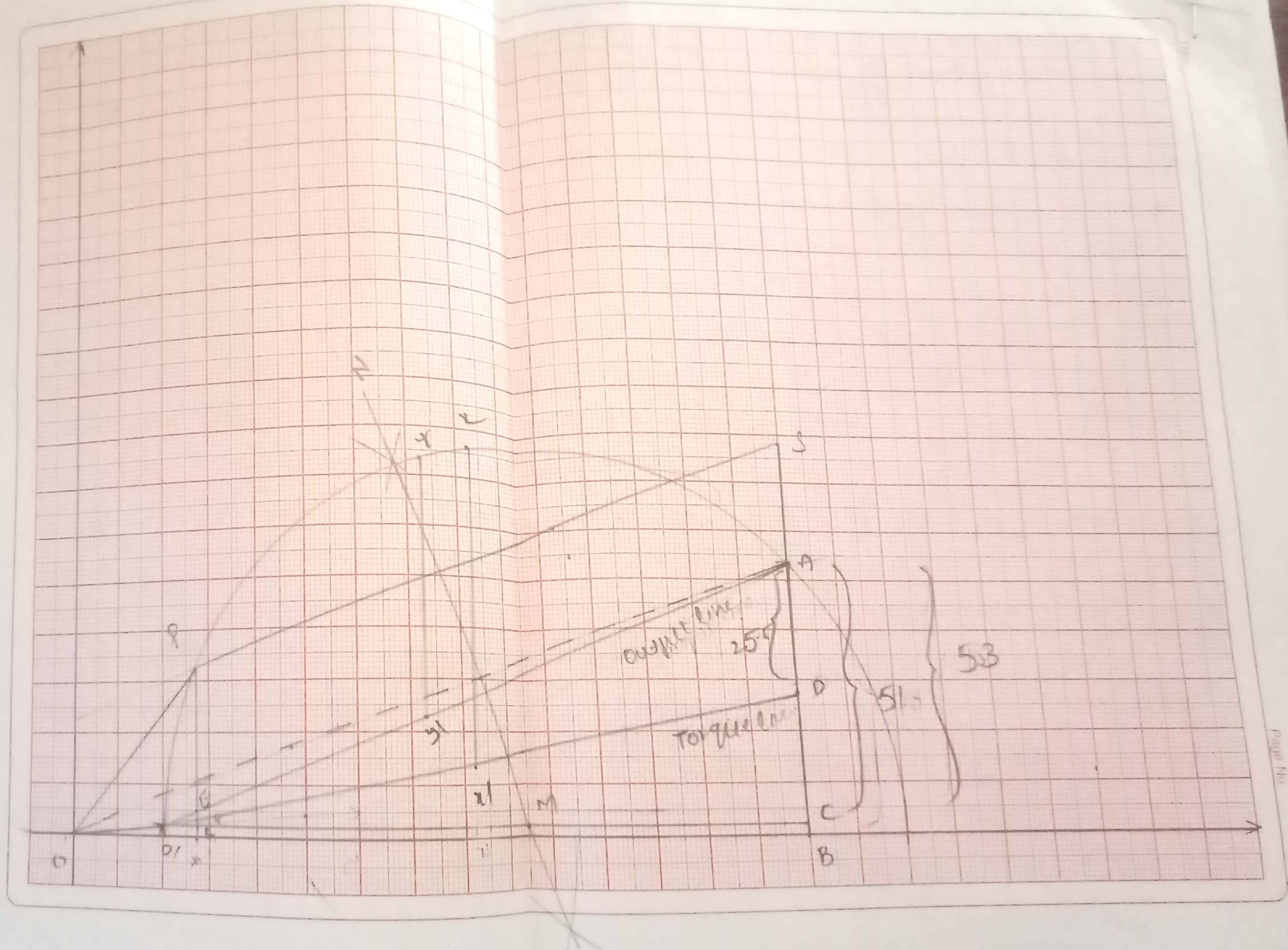
400V

100V,

current,

, ma...

...ric of



 $\cos\phi_{sc} = 0.34$.

S = Rcu − Rotor

Double cage induction motor:-

$T_{st} = k \dfrac{E_2^2 R_2}{R_2^2 + (X_2)^2}$ $s = 1$

$I_{2r} = \dfrac{s E_2}{\sqrt{R_2^2 + (sX_2)^2}}$

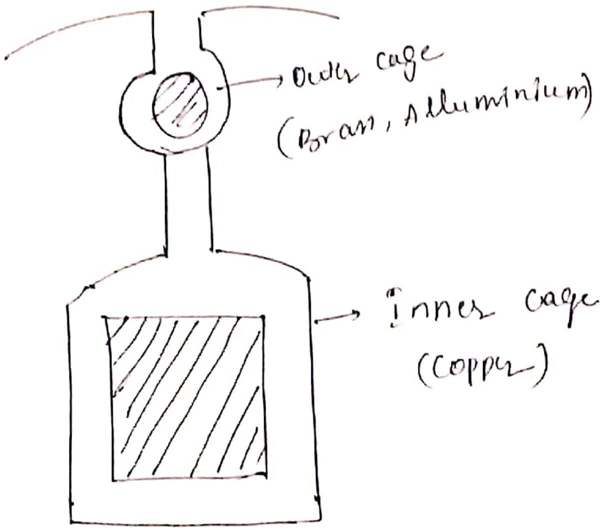
$I_2 = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$

$I_2^2 R_2 \uparrow$; $\eta \downarrow$

$\phi = B \cdot A \downarrow$

$X = 2\pi f L \uparrow$

$f_2 = s f_1$



$\phi = B \cdot A \downarrow$

$X = 2\pi f L \uparrow$ (inner cage)