Unit – II - Characteristics, starting and testing methods of Induction Motors

1.1.12.1. Lecture-1

Torque Equations

The gross torque Tg developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi\ N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi\ N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

Now $\quad \text{Rotor input} = \frac{\text{Rotor Cu loss}}{s} = \frac{3(I'_2)^2 R_2}{s} \qquad \text{(i)}$

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s\ E_2}{\sqrt{R_2^2 + (s\ X_2)^2}} = \frac{s\ K\ E_1}{\sqrt{R_2^2 + (s\ X_2)^2}}$$

where $\quad K = \text{Transformation ratio} = \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \times \frac{1}{s} = \frac{3\ s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

Also $\quad \text{Rotor input} = 3 \times \frac{s^2\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \times \frac{1}{s} = \frac{3\ s\ K^2 E_1^2 R_2}{R_2^2 + (s\ X_2)^2}$

(Putting me value of I'_2 in eq.(i))

$$\therefore \quad T_g = \frac{\text{Rotor input}}{2\pi\ N_s} = \frac{3}{2\pi\ N_s} \times \frac{s\ E_2^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \text{...in terms of } E_2$$

$$= \frac{3}{2\pi\ N_s} \times \frac{s\ K^2\ E_1^2 R_2}{R_2^2 + (s\ X_2)^2} \qquad \text{...in terms of } E_1$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.

Rotor Torque

The torque T developed by the rotor is directly proportional to:

- (i) rotor current
- (ii) rotor e.m.f.
- (iii) power factor of the rotor circuit

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

or $$T = K E_2 I_2 \cos\phi_2$$

where I_2 = rotor current at standstill
E_2 = rotor e.m.f. at standstill
$\cos\phi_2$ = rotor p.f. at standstill

Note. The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

Starting Torque (Ts)

Let,

E2 = rotor e.m.f. per phase at standstill X2 = rotor reactance per phase at standstill R2 = rotor resistance per phase

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$$\therefore \quad \text{Starting torque, } T_s = K E_2 I_2 \cos\phi_2$$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

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

Generally, the stator supply voltage V is constant so that flux per pole φ set up by the stator is also fixed. This in turn means that e.m.f. E2 induced in the rotor will be constant.

$$\therefore \qquad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It is clear that the magnitude of starting torque would depend upon the relative values of R_2 and X_2 i.e., rotor resistance/phase and standstill rotor reactance/phase.

It can be shown that $K = 3/2\ \pi\ N_s$.

$$\therefore \qquad T_s = \frac{3}{2\pi\ N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

1.1.12.2. Lecture-2

Condition for Maximum Starting Torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase.

$$\text{Now} \qquad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} \qquad \text{(i)}$$

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1\left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2}\right] = 0$$

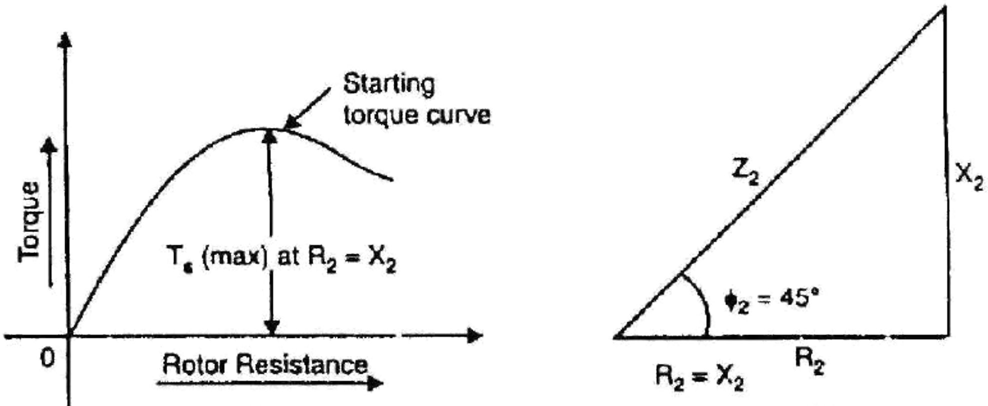
$$\text{or} \qquad R_2^2 + X_2^2 = 2R_2^2$$

$$\text{or} \qquad R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, φ2 = 45° and rotor power factor is 0.707 lagging



(*i*) (*ii*)

Fig. shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when R2 = X2 . If the rotor resistance is increased beyond this optimum value, the starting torque will decrease

1.1.12.3. Lecture-3

Performance Characteristics of Three phase Induction Motor

The equivalent circuits derived in the preceding section can be used to predict the performance characteristics of the induction machine. The important performance characteristics in the steady state are the efficiency, power factor, current, starting torque, maximum (or pull-out) torque.

3.13.1 The complete torque-speed characteristic

In order to estimate the speed torque characteristic let us suppose that a sinusoidal voltage is impressed on the machine. Recalling that the equivalent circuit is the per-phase representation of the machine, the current drawn by the circuit is given by

$$I_s = \frac{V_s}{(R_s + \frac{R'_r}{s}) + j(X_{ls} + X'_{lr})}$$

Where, Vs is the phase voltage phasor and Is is the current phasor. The magnetizing current is neglected. Since this current is flowing through R′r/s, the air-gap power is given by

$$\begin{aligned} P_g &= |I_s|^2 \frac{R'_r}{s} \\ &= \frac{V_s}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})^2} \frac{R'_r}{s} \end{aligned}$$

The mechanical power output was shown to be (1−s)Pg (power dissipated in R′r/s). The torque is obtained by dividing this by the shaft speed ω_m.Thus we have,

$$\frac{P_g(1-s)}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = |I_s|^2 \frac{R'_r}{s\omega_s}$$

where ω_m is the synchronous speed in radians per second and s is the slip. Further, this is the torque produced per phase. Hence the overall torque is given by

$$T_e = \frac{3}{\omega_s} . \frac{V_s^2}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})} . \frac{R'_r}{s}$$

The torque may be plotted as a function of ‘s’ and is called the torque-slip (or torque-speed, since slip indicates speed) characteristic a very important characteristic of the induction machine.

A typical torque-speed characteristic is shown in Fig: 3.18. This plot corresponds to a 3 kW, 4 pole, and 60 Hz machine. The rated operating speed is 1780 rpm

Further, this curve is obtained by varying slip with the applied voltage being held constant. Coupled with the fact that this is an equivalent circuit valid under steady state, it implies that if this characteristic is to be measured experimentally, we need to look at the torque for a given speed after all transients have died down. One cannot, for example, try to obtain this curve by directly starting the motor with full voltage applied to the terminals and measuring the torque and speed dynamically as it runs up to steady speed.

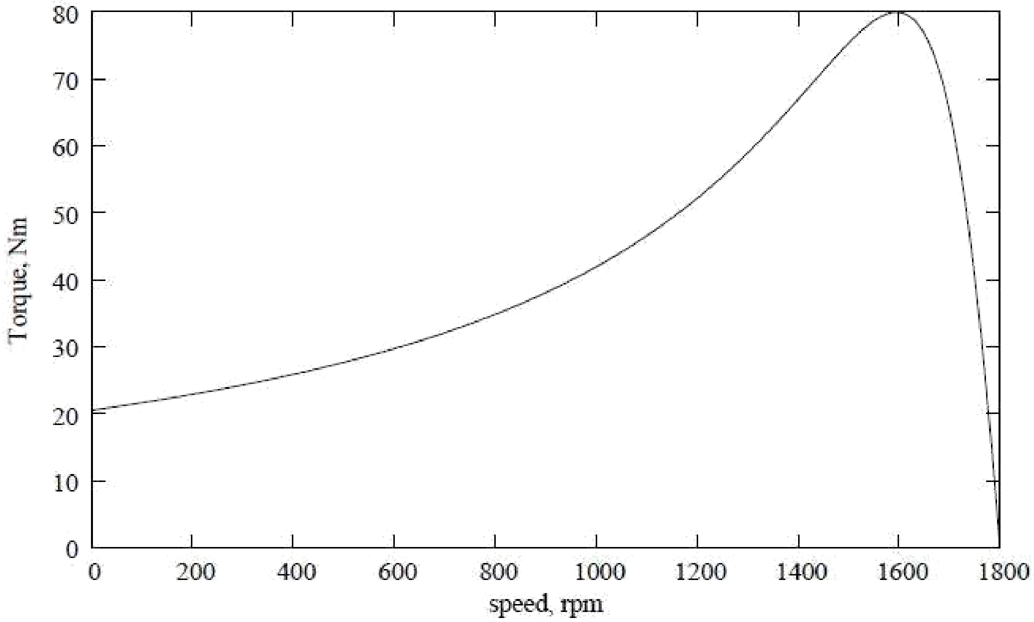


Fig: 3.18

With respect to the direction of rotation of the air-gap flux, the rotor maybe driven to higher speeds by a prime mover or may also be rotated in the reverse direction. The torque-speed relation for the machine under the entire speed range is called the complete speed-torque characteristic. A typical curve is shown in Fig: 3.19 for a four-pole machine, the synchronous speed being 1500 rpm. Note that negative speeds correspond to slip values greater than 1, and speeds greater than 1500 rpm correspond to negative slip. The plot also shows the operating modes of the induction machine in various regions. The slip axis is also shown for convenience.

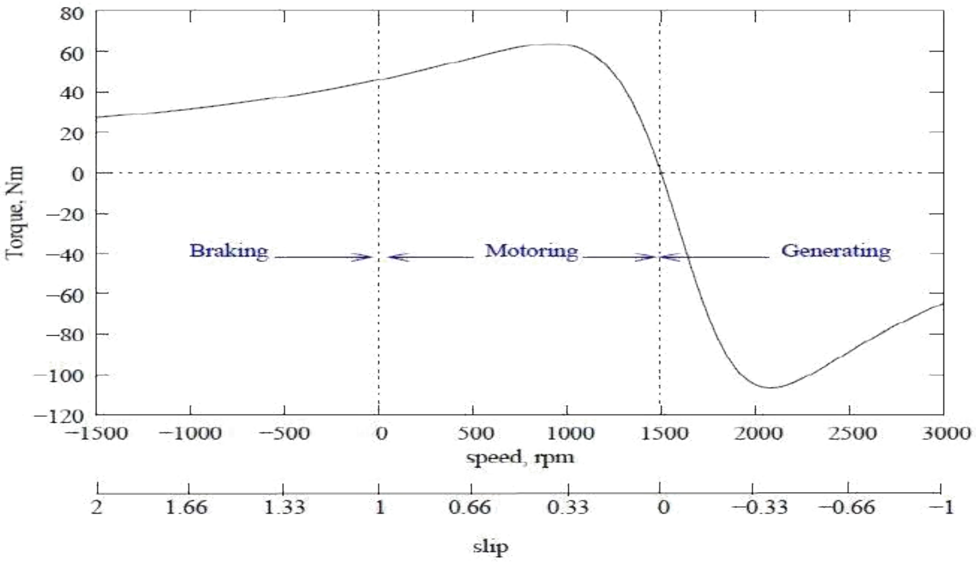


Fig: 3.19

Effect of Rotor Resistance on Speed Torque Characteristic

Restricting ourselves to positive values of slip, we see that the curve has a peak point. This is the maximum torque that the machine can produce, and is called as stalling torque. If the load torque is more than this value, the machine stops rotating or stalls. It occurs at a slip ˆs, which for the machine of Fig: 3.19 is 0.38. At values of slip lower than ˆs, the curve falls steeply down to zero at s = 0. The torque at synchronous speed is therefore zero. At values of slip higher than s = ˆs, the curve falls slowly to a minimum value at s = 1. The torque at s = 1 (speed = 0) is called the starting torque. The value of the stalling torque may be obtained by differentiating the expression for torque with respect to zero and setting it to zero to find the value of ˆs. Using this method, we can write

$$\hat{s} = \frac{\pm R_r'}{\sqrt{R_r'^2 + (X_{ls} + X_{lr}')^2}}$$

Substituting ˆs into the expression for torque gives us the value of the stalling torque ˆ Te,

$$\hat{T}_e = \frac{3V_s^2}{2\omega_s} . \frac{1}{R_s \pm \sqrt{R_s^2 + (X_{ls} + X'_{lr})^2}}$$

The negative sign being valid for negative slip

1.1.12.4. Lecture-4

Double Cage Induction Motor

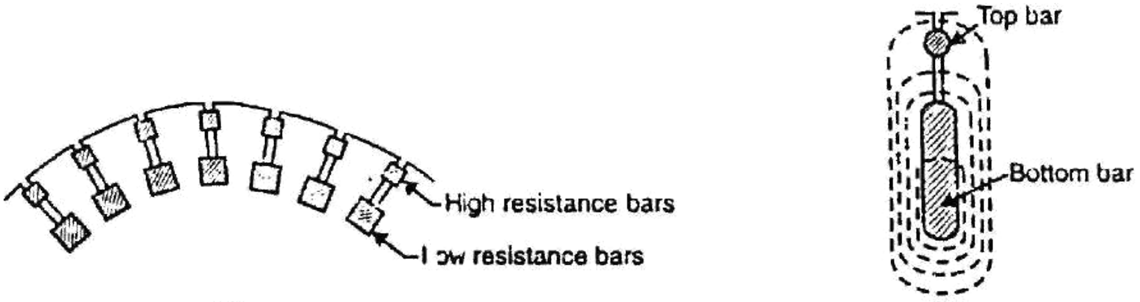
One of the advantages of the slip-ring motor is that resistance may be inserted in the rotor circuit to obtain high starting torque (at low starting current) and then cut out to obtain optimum running conditions. However, such a procedure cannot be adopted for a squirrel cage motor because its cage is permanently short-circuited. In order to provide high starting torque at low starting current, double-cage construction is used.

Construction

As the name suggests, the rotor of this motor has two squirrel-cage windings located one above the other as shown in Fig: 3.38(i).

The outer winding consists of bars of smaller cross-section short- circuited by end rings. Therefore, the resistance of this winding is high. Since the outer winding has relatively open slots and a poorer flux path around its bars [See Fig: 3.38(ii)], it has a low inductance. Thus the resistance of the outer squirrel-cage winding is high and its inductance is low.

The inner winding consists of bars of greater cross-section short-circuited by end rings. Therefore, the resistance of this winding is low. Since the bars of the inner winding are thoroughly buried in iron, it has a high inductance [See Fig: 3.38(ii)].Thus the resistance of the inner squirrel cage winding is low and its inductance is high



(i) (ii)

Fig: 3.38

Working

When a rotating magnetic field sweeps across the two windings, equal e.m.f.s are induced in each.

(i) At starting, the rotor frequency is the same as that of the line (i.e., 50 Hz), making the reactance of the lower winding much higher than that of the upper winding. Because of the high reactance of the lower winding, nearly all the rotor current flows in the high-resistance outer cage winding. This provides the good starting characteristics of a high-resistance cage winding. Thus the outer winding gives high starting torque at low starting current.

(ii) As the motor accelerates, the rotor frequency decreases, thereby lowering the reactance of the inner winding, allowing it to carry a larger proportion of the total rotor current At the normal operating speed of the motor, the rotor frequency is so low (2 to 3 Hz) that nearly all the rotor current flows in the low-resistance inner cage winding. This results in good operating efficiency and speed regulation.

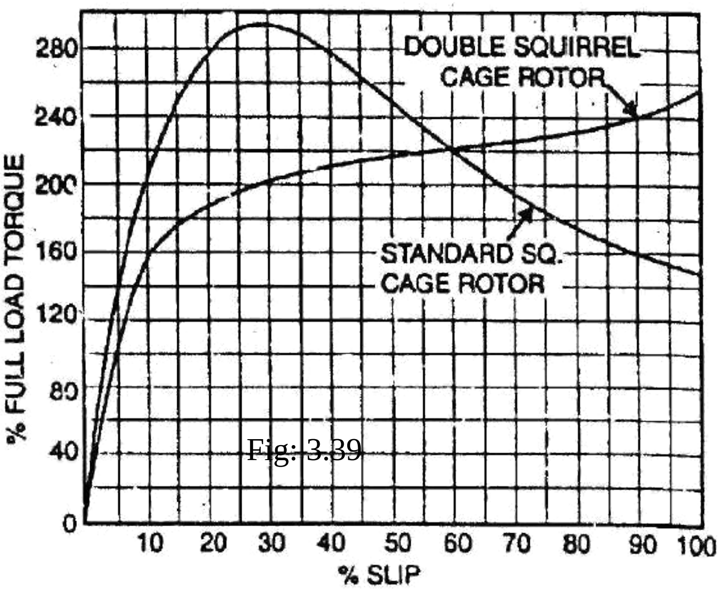


Fig: 3.39

Fig: 3.39 shows the operating characteristics of double squirrel-cage motor. The starting torque of this motor ranges from 200 to 250 percent of full-load torque with a starting current of 4 to 6 times the full-load value. It is classed as a high-torque, low starting current motor

1.1.12.5. *Lecture-5*

Cogging and Crawling of Induction Motor

Crawling of induction motor

Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as crawling of an induction motor.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed

Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Now, 5th harmonic currents will have phase difference of

$5 \times 120 = 600° = 2 \times 360 - 120 = -120°$.

Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of

$7 \times 120 = 840° = 2 \times 360 + 120 = +120°$.

Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7^{th} harmonic torque reaches its maximum positive value just before$1/7^{th}$ of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of its normal speed as shown in Fig: 3.40. *This phenomenon is called as crawling of induction motors*.

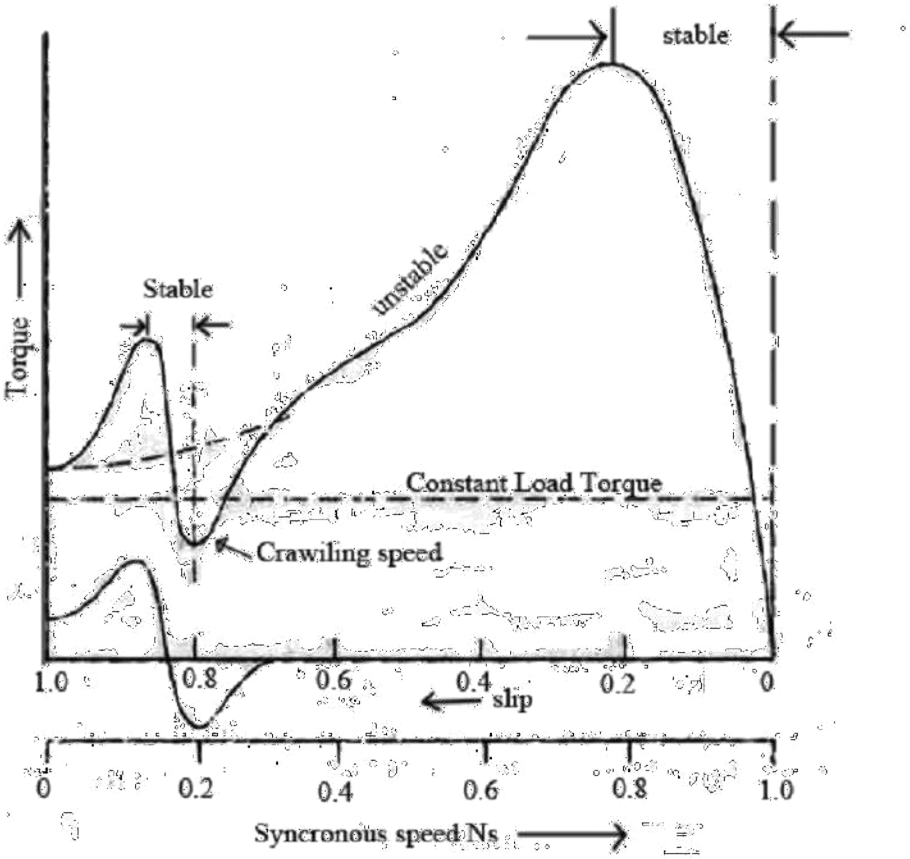


Fig: 3.40

Cogging (Magnetic Locking or Teeth Locking) of induction motor

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum that is why the rotor tends to remain fixed. This phenomenon is called cogging or magnetic locking of induction motor.

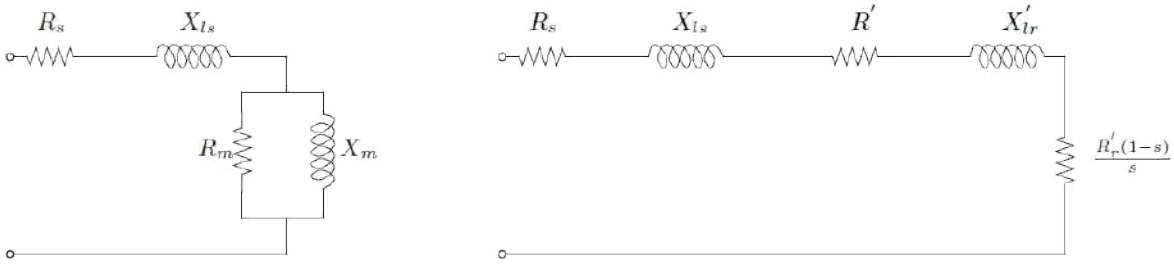
1.1.12.6. Lecture-6

Tests to Determine the Equivalent Circuit Parameters

In order to find values for the various elements of the equivalent circuit, tests must be conducted on a particular machine, which is to be represented by the equivalent circuit. In order to do this, we note the following.

1. When the machine is run on no-load, there is very little torque developed by it. In an ideal case where there is no mechanical losses, there is no mechanical power developed at no-load. Recalling the explanations in the section on torque production, the flow of current in the rotor is indicative of the torque that is produced. If no torque is produced, one may conclude that no current would be flowing in the rotor either. The rotor branch acts like an open circuit. This conclusion may also be reached by reasoning that when there is no load, an ideal machine will run up to its synchronous speed where the slip is zero resulting in an infinite impedance in the rotor branch.
2. When the machine is prevented from rotation, and supply is given, the slip remains at unity. The elements representing the magnetizing branch Rm & Xm are high impedances much larger than R_r' & X_{lr}' in series. Thus, in the exact equivalent circuit of the induction machine, the magnetizing branch may be neglected.

From these considerations, we may reduce the induction machine equivalent circuit of Fig.3.13 & Fig: 3.15 to those shown in Fig: 3.16.



(a) No-load equivalent (b) Blocked rotor equivalent

Fig: 3.16

These two observations and the reduced equivalent circuits are used as the basis for the two most commonly used tests to find out the equivalent circuit parameters — the blocked rotor test and no load test. They are also referred to as the short circuit test and open circuit test respectively in conceptual analogy to the transformer

1. *No-load test*

The behaviour of the machine may be judged from the equivalent circuit of Fig: 3.16 (a). The current drawn by the machine causes a stator-impedance drop and the balance voltage is applied across the magnetizing branch. However, since the magnetizing branch impedance is large, the current drawn is small and hence the stator impedance drop is small compared to the applied voltage (rated value). This drop and the power dissipated in the stator resistance are therefore neglected and the total power drawn is assumed to be consumed entirely as core loss. This can also be seen from the approximate equivalent circuit, the use of which is justified by the foregoing arguments. This test therefore enables us to compute the resistance and inductance of the magnetizing branch in the following manner.

Let applied voltage $= V_s$. Then current drawn is given by

$$I_s = \frac{V_s}{R_m} + \frac{V_s}{jX_m}$$

The power drawn is given by

$$P_s = \frac{V_s^2}{R_m} \Rightarrow R_m = \frac{V_s^2}{P_s}$$

Vs, Is and Ps are measured with appropriate meters. With R m known by above equation, Xm also can be found. The current drawn is at low power factor and hence a suitable wattmeter should be used.

2. *Blocked-rotor Test*

In this test the rotor is prevented from rotation by mechanical means and hence the name. Since there is no rotation, slip of operation is unity, s = 1. The equivalent circuit valid under these conditions is shown in Fig: 3.16 (b). Since the current drawn is decided by the resistance and leakage impedances alone, the magnitude can be very high when rated voltage is applied. Therefore in this test, only small voltages are applied — just enough to cause rated current to flow. While the current magnitude depends on the resistance and the reactance, the power drawn depends on the resistances.

The parameters may then be determined as follows. The source current and power drawn may be written as -

$$\begin{aligned} I_s &= \frac{V_s}{(R_s + R_r') + j(X_s + X_r')} \\ P_s &= |I_s|^2 (R_s + R_r') \end{aligned}$$

In the test Vs, Is and Ps are measured with appropriate meters. Above equation enables us to compute (Rs + R′r). Once this is known, (Xs + X′r) may be computed from the above equation.

Note that this test only enables us to determine the series combination of the resistance and the reactance only and not the individual values. Generally, the individual values are assumed to be equal; the assumption Rs = R′r, and Xs = X′r suffices for most purposes.

In practice, there are differences. If more accurate estimates are required IEEE guidelines may be followed which depend on the size of the machine.

These two tests determine the equivalent circuit parameters in a ‘Stator-referred’ sense, i.e., the rotor resistance and leakage inductance are not the actual values but what they ’appear to be’ when looked at from the stator. This is sufficient for most purposes as interconnections to the external world are generally done at the stator terminals

1.1.12.7. Lecture-7

Construction of Circle Diagram

Conduct No load test and blocked rotor test on the induction motor and find out the per phase

values of no load current I0, short circuit current ISC and the corresponding phase angles Φ0 and ΦSC. Also find short circuit current ISN corresponding to normal supply voltage. With this data, the circle diagram can be drawn as follows see Fig: 3.17.

- With suitable scale, draw vector OA with length corresponding to I0 at an angle Φ0 from the vertical axis. Draw a horizontal line AB.
- Draw OS equal to ISN at an angle ΦSC and join AS.
- Draw the perpendicular bisector to AS to meet the horizontal line AB at C.
- With C as centre, draw a portion of circle passing through A and S. This forms the circle diagram which is the locus of the input current.
- From point S, draw a vertical line SL to meet the line AB.
- Divide SL at point K so that SK : KL = rotor resistance : stator resistance.
- For a given operating point P, draw a vertical line PEFGD as shown. then PE = output power, EF = rotor copper loss, FG = stator copper loss, GD = constant loss (iron loss + mechanical loss)

To find the operating points corresponding to maximum power and maximum torque, draw tangents to the circle diagram parallel to the output line and torque line respectively. The points at which these tangents touch the circle are respectively the maximum power point and maximum torque point

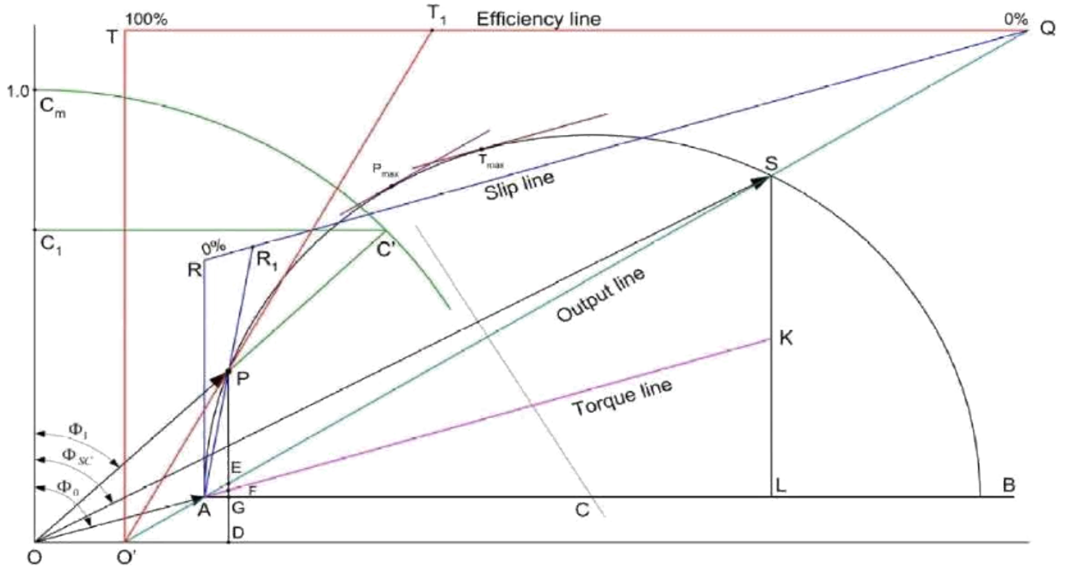


Fig: 3.17 Construction of Circle Diagram

Efficiency line

a. The output line AS is extended backwards to meet the X-axis at O′.
b. From any convenient point on the extended output line, draw a horizontal line QT so as to meet the vertical from O′. Divide the line QT into 100 equal parts.
c. To find the efficiency corresponding to any operating point P, draw a line from O′ to the efficiency line through P to meet the efficiency line at T1. Now QT1 is the efficiency.

Slip Line

1. Draw line QR parallel to the torque line, meeting the vertical through A at R. Divide RQ into equal parts.
2. To find the slip corresponding to any operating point P, draw a line from A to the slip line through P to meet the slip line at R1. Now RR1 is the slip

Power Factor Curve

1. Draw a quadrant of a circle with O as centre and any convenient radius. Divide OCm into 100 equal parts.

2. To find power factor corresponding to P, extend the line OP to meet the power factor curve at C′. Draw a horizontal line C′C1 to meet the vertical axis at C1. Now OC1 represents power factor.

Performance Characteristics of Three phase Induction Motor

The equivalent circuits derived in the preceding section can be used to predict the performance characteristics of the induction machine. The important performance characteristics in the steady state are the efficiency, power factor, current, starting torque, maximum (or pull-out) torque.

The complete torque-speed characteristic

In order to estimate the speed torque characteristic let us suppose that a sinusoidal voltage is impressed on the machine. Recalling that the equivalent circuit is the per-phase representation of the machine, the current drawn by the circuit is given by

$$I_s = \frac{V_s}{(R_s + \frac{R_r'}{s}) + j(X_{ls} + X_{lr}')}$$

Where, Vs is the phase voltage phasor and Is is the current phasor. The magnetizing current is neglected. Since this current is flowing through R′r/s, the air-gap power is given by

$$\begin{aligned} P_g &= |I_s|^2 \frac{R_r'}{s} \\ &= \frac{V_s}{(R_s + \frac{R_r'}{s})^2 + (X_{ls} + X_{lr}')^2} \frac{R_r'}{s} \end{aligned}$$

The mechanical power output was shown to be (1−s)Pg (power dissipated in R′r/s). The torque is obtained by dividing this by the shaft speed ω_m.Thus we have,

$$\frac{P_g(1-s)}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = |I_s|^2 \frac{R_r'}{s\omega_s}$$

where ω_m is the synchronous speed in radians per second and s is the slip. Further, this is the torque produced per phase. Hence the overall torque is given by

$$T_e = \frac{3}{\omega_s} . \frac{V_s^2}{(R_s + \frac{R'_r}{s})^2 + (X_{ls} + X'_{lr})} . \frac{R'_r}{s}$$

The torque may be plotted as a function of 's' and is called the torque-slip (or torque-speed, since slip indicates speed) characteristic a very important characteristic of the induction machine.

A typical torque-speed characteristic is shown in Fig: 3.18. This plot corresponds to a 3 kW, 4 pole, and 60 Hz machine. The rated operating speed is 1780 rpm

Further, this curve is obtained by varying slip with the applied voltage being held constant. Coupled with the fact that this is an equivalent circuit valid under steady state, it implies that if this characteristic is to be measured experimentally, we need to look at the torque for a given speed after all transients have died down. One cannot, for example, try to obtain this curve by directly starting the motor with full voltage applied to the terminals and measuring the torque and speed dynamically as it runs up to steady speed.

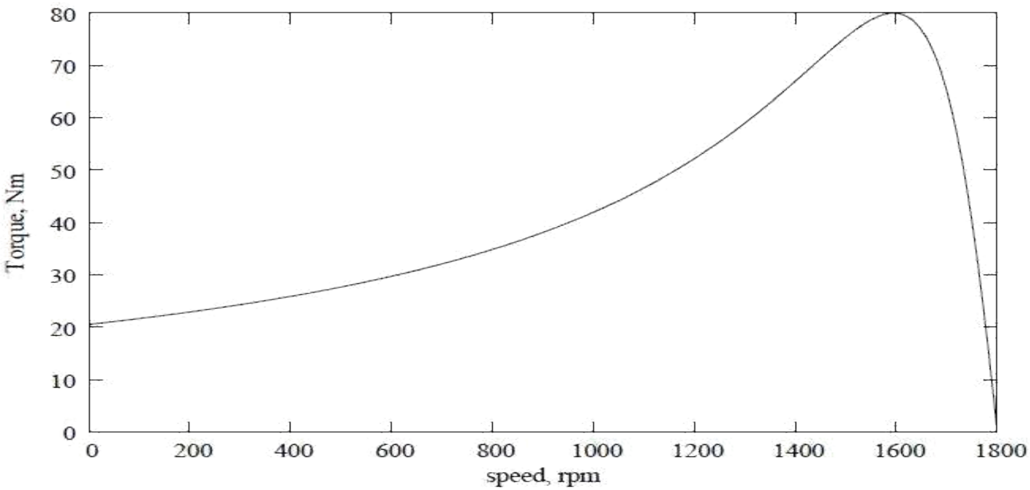


Fig: 3.18

With respect to the direction of rotation of the air-gap flux, the rotor maybe driven to higher speeds by a prime mover or may also be rotated in the reverse direction. The torque-speed relation for the machine under the entire speed range is called the complete speed-torque characteristic. A typical curve is shown in Fig: 3.19 for a four-pole machine, the synchronous speed being 1500 rpm. Note that negative speeds correspond to slip values greater than 1, and speeds greater than 1500 rpm correspond to negative slip. The plot also shows the operating modes of the induction machine in various regions. The slip axis is also shown for convenience

1.1.12.8. Lecture-8

Starting of Three Phase Induction Motor

The induction motor is fundamentally a transformer in which the stator is the primary and the rotor is short-circuited secondary. At starting, the voltage induced in the induction motor rotor is maximum ($s = 1$). Since the rotor impedance is low, the rotor current is excessively large. This large rotor current is reflected in the stator because of transformer action. This results in high starting current (4 to 10 times the full-load current) in the stator at low power factor and consequently the value of starting torque is low. Because of the short duration, this value of large current does not harm the motor if the motor accelerates normally.

However, this large starting current will produce large line-voltage drop. This will adversely affect the operation of other electrical equipment connected to the same lines. Therefore, it is desirable and necessary to reduce the magnitude of stator current at starting and several methods are available for this purpose.

Methods of Starting Three Phase Induction Motors

The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are:

(i) Direct-on-line starting

(ii) Stator resistance starting

(iii) Autotransformer starting

(iv) Star-delta starting

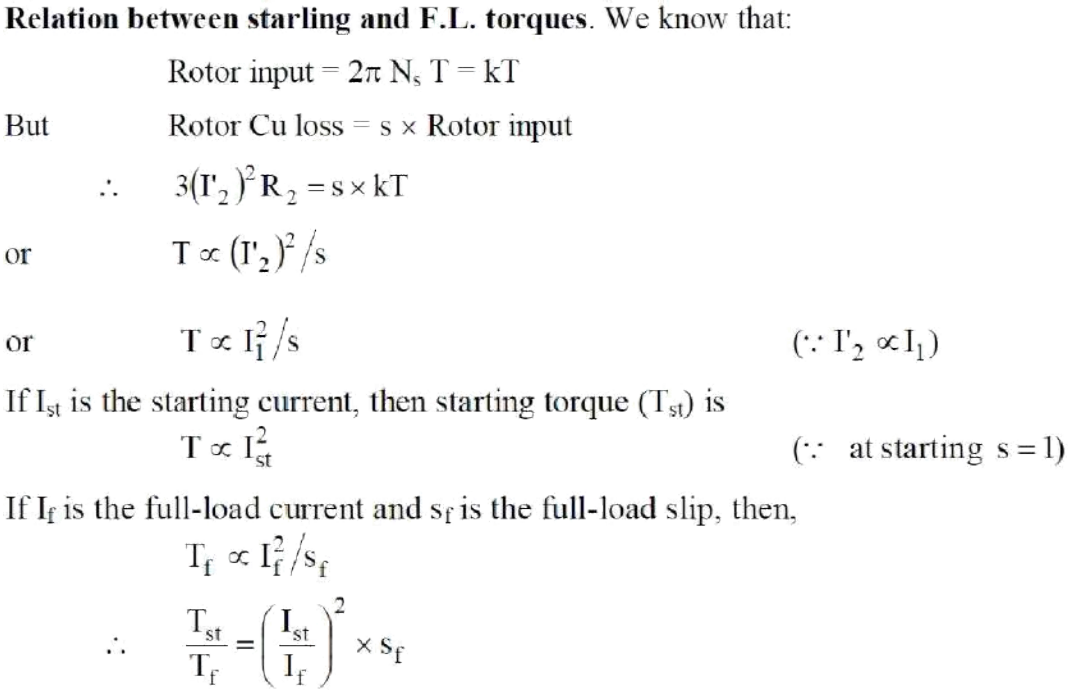
(v) Rotor resistance starting

Methods (i) to (iv) are applicable to both squirrel-cage and slip ring motors. However, method (v) is applicable only to slip ring motors. In practice, any one of the first four methods is used for starting squirrel cage motors, depending upon, the size of the motor. But slip ring motors are invariably started by rotor resistance starting.

Except direct-on-line starting, all other methods of starting squirrel-cage motors employ reduced voltage across motor terminals at starting.

(i) Direct-on-line starting

This method of starting in just what the name implies—the motor is started by connecting it directly to 3-phase supply. The impedance of the motor at standstill is relatively low and when it is directly connected to the supply system, the starting current will be high (4 to 10 times the full-load current) and at a low power factor. Consequently, this method of starting is suitable for relatively small (up to 7.5 kW) machines.



Relation between starling and F.L. torques. We know that:

$$\text{Rotor input} = 2\pi N_s T = kT$$

But $$\text{Rotor Cu loss} = s \times \text{Rotor input}$$

$$\therefore \quad 3(I'_2)^2 R_2 = s \times kT$$

or $$T \propto (I'_2)^2 / s$$

or $$T \propto I_1^2 / s \qquad (\because I'_2 \propto I_1)$$

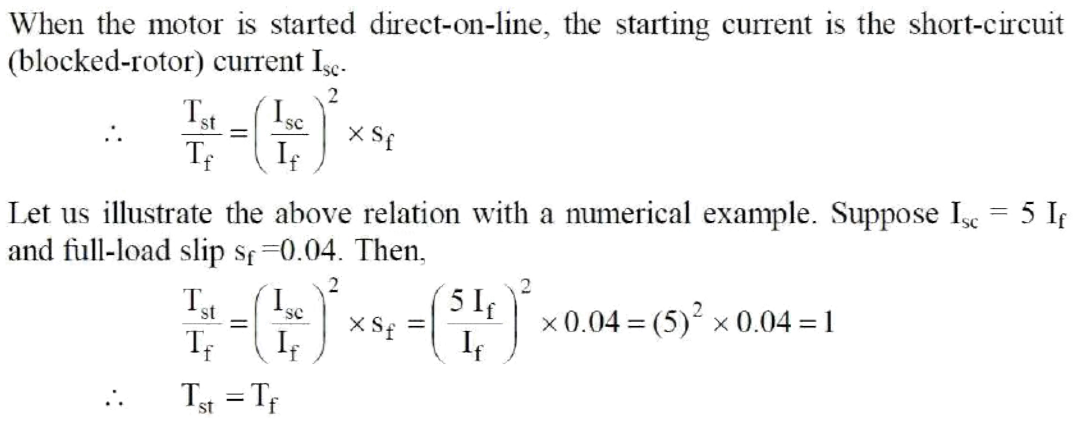
If I_{st} is the starting current, then starting torque (T_{st}) is

$$T \propto I_{st}^2 \qquad (\because \text{ at starting } s = 1)$$

If I_f is the full-load current and s_f is the full-load slip, then,

$$T_f \propto I_f^2 / s_f$$

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$



When the motor is started direct-on-line, the starting current is the short-circuit (blocked-rotor) current I_{sc}.

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

Let us illustrate the above relation with a numerical example. Suppose $I_{sc} = 5\, I_f$ and full-load slip $s_f = 0.04$. Then,

$$\frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f = \left(\frac{5\, I_f}{I_f}\right)^2 \times 0.04 = (5)^2 \times 0.04 = 1$$

$$\therefore \quad T_{st} = T_f$$

Note that starting current is as large as five times the full-load current but starting torque is just equal to the full-load torque. Therefore, starting current is very high and the starting torque is comparatively low. If this large starting current flows for a long time, it may overheat the motor and damage the insulation.

(ii) Stator resistance starting

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 see Fig: 3.23.

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.

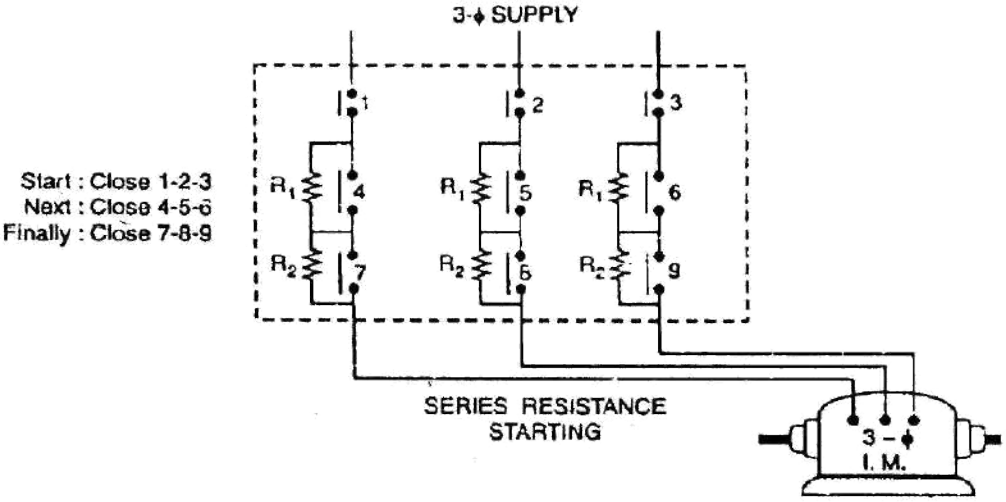


Fig: 3.23

Relation between starting and F.L. torques.

Let V be the rated voltage/phase. If the voltage is reduced by a fraction x by the insertion of resistors in the line, then voltage applied to the motor per phase will be xV.

So,

$$I_{st} = x\, I_{sc}$$

Now $$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$

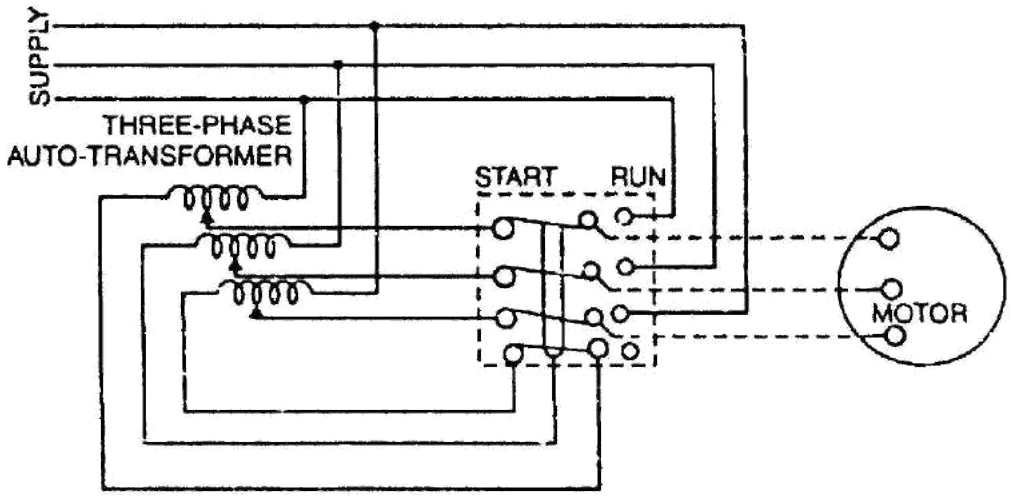
or $$\frac{T_{st}}{T_f} = x^2\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

Thus while the starting current reduces by a fraction x of the rated-voltage starting current (Isc), the starting torque is reduced by a fraction x2 of that obtained by direct switching. The reduced voltage applied to the motor during the starting period lowers the starting current but at the same time increases the accelerating time because of the reduced value of the starting torque. Therefore, this method is used for starting small motors only.

(iii) Autotransformer starting

This method also aims at connecting the induction motor to a reduced supply at starting and then connecting it to the full voltage as the motor picks up sufficient speed. Fig: 3.24 shows the circuit arrangement for autotransformer starting. The tapping on the autotransformer is so set that when it is in the circuit, 65% to 80% of line voltage is applied to the motor.

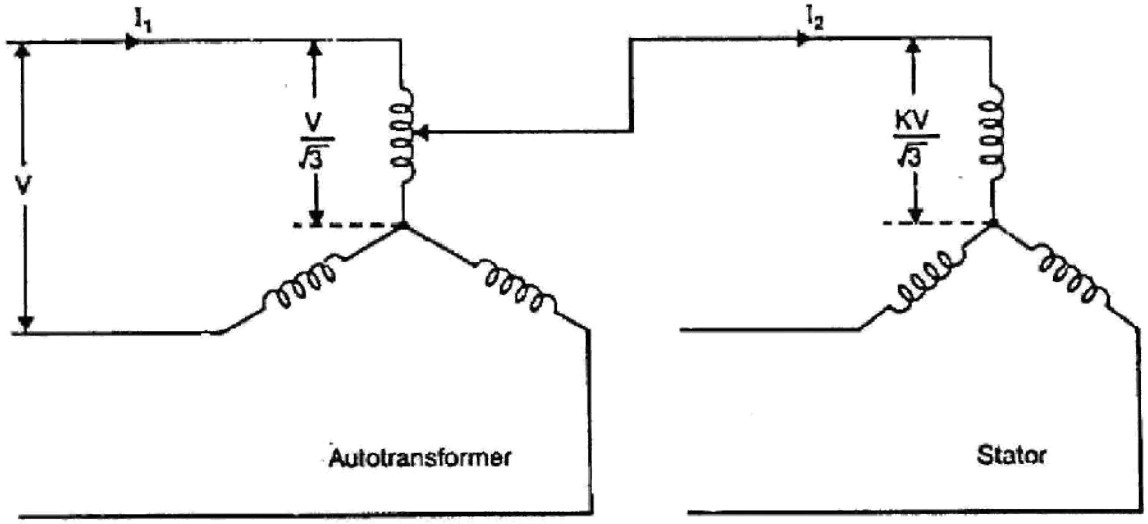
At the instant of starting, the change-over switch is thrown to “start” position. This puts the autotransformer in the circuit and thus reduced voltage is applied to the circuit. Consequently, starting current is limited to safe value. When the motor attains about 80% of normal speed, the changeover switch is thrown to “run” position. This takes out the autotransformer from the circuit and puts the motor to full line voltage. Autotransformer starting has several advantages viz low power loss, low starting current and less radiated heat. For large machines (over 25 H.P.), this method of starting is often used. This method can be used for both star and delta connected motors



Relation between starting And F.L. torques. Consider a star-connected squirrel-cage induction motor. If V is the line voltage, then voltage across motor phase on direct switching is $V/\sqrt{3}$ and starting current is $I_{st} = I_{sc}$. In case of autotransformer, if a tapping of transformation ratio K (a fraction) is used, then phase voltage across motor is $KV/\sqrt{3}$ and $I_{st} = K\,I_{sc}$,

Now $$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = \left(\frac{K\,I_{sc}}{I_f}\right)^2 \times s_f = K^2\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

$$\therefore \quad \frac{T_{st}}{T_f} = K^2\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$



The current taken from the supply or by autotransformer is I1 = KI2 = K^2Isc. Note that motor current is K times, the supply line current is K^2 times and the starting torque is K^2 times the value it would have been on direct-on-line starting.

(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: 3.26.

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”3 position which connects the stator

windings in star. Therefore, each stator phase gets 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 $\left(1/\sqrt{3}\right)^2$ or 1/3 times the value it would have with Δ-connection. This is rather a large reduction in starting torque.

(b) The reduction in voltage is fixed.

This method of starting is used for medium-size machines (upto about 25 H.P.)

Relation between starting and F.L. torques. In direct delta starting,

Starting current/phase, $I_{sc} = V/Z_{sc}$ where V = line voltage

Starting line current $= \sqrt{3}\ I_{sc}$

In star starting, we have,

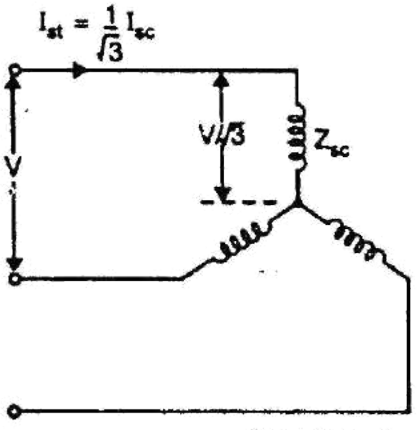
Starting current/phase, $I_{st} = \dfrac{V/\sqrt{3}}{Z_{sc}} = \dfrac{1}{\sqrt{3}} I_{sc}$

Now $$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = \left(\frac{I_{sc}}{\sqrt{3} \times I_f}\right)^2 \times s_f$$

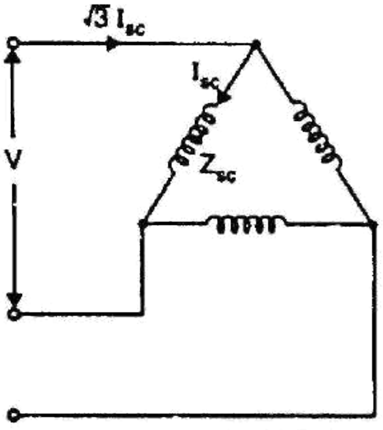
or $$\frac{T_{st}}{T_f} = \frac{1}{3}\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

where I_{sc} = starting phase current (delta)

I_f = F.L. phase current (delta)



Star (Stator)

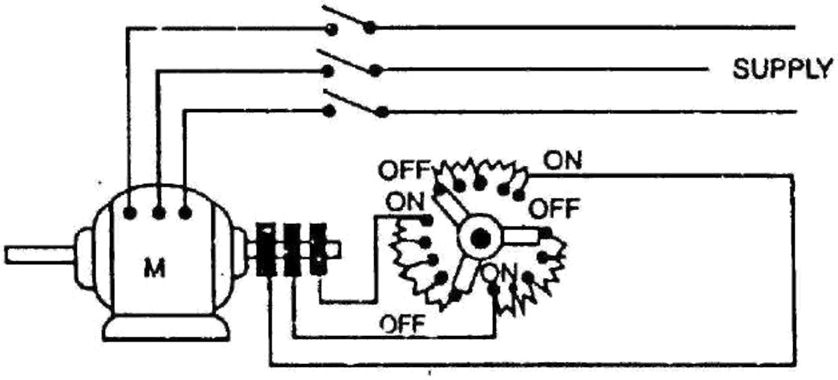


Delta (Stator)

Note that in star-delta starting, the starting line current is reduced to one-third as compared to starting with the winding delta connected. Further, starting torque is reduced to one-third of that obtainable by direct delta starting. This method is cheap but limited to applications where high starting torque is not necessary e.g., machine tools, pumps etc.

Starting of Slip-Ring Induction Motors

Slip-ring motors are invariably started by rotor resistance starting. In this method, a variable star-connected rheostat is connected in the rotor circuit through slip rings and full voltage is applied to the stator winding as shown in Fig: 3.27



At starting, the handle of rheostat is set in the OFF position so that maximum resistance is placed in each phase of the rotor circuit. This reduces the starting current and at the same time starting torque is increased.

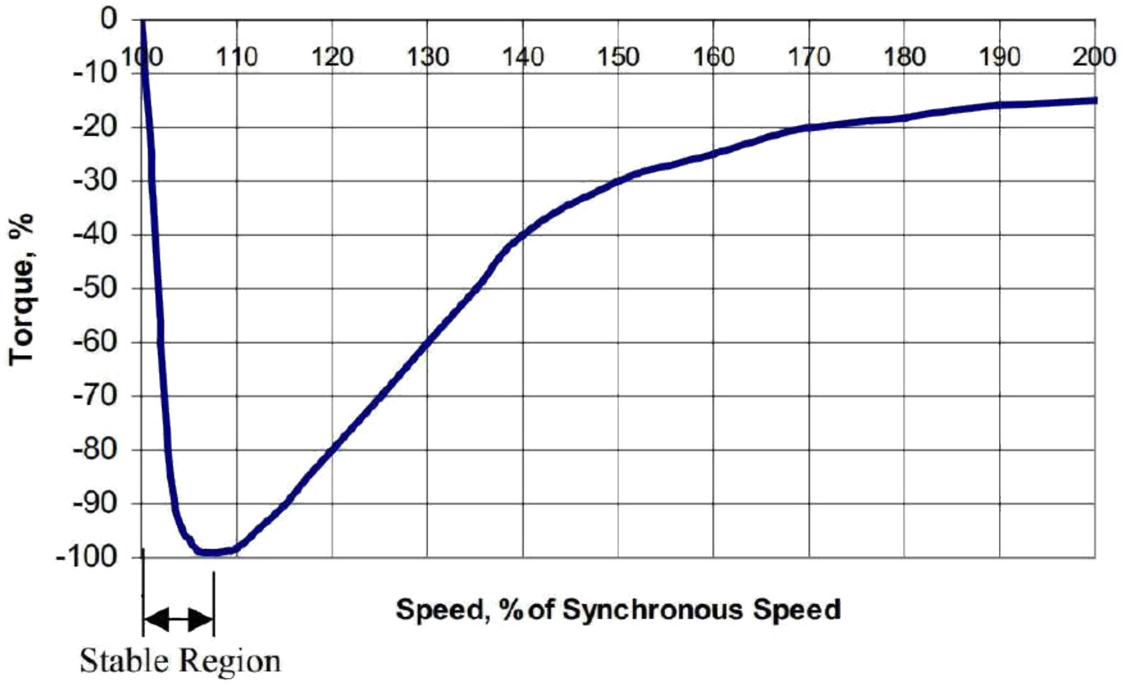
As the motor picks up speed, the handle of rheostat is gradually moved in clockwise direction and cuts out the external resistance in each phase of the rotor circuit. When the motor attains normal speed, the change-over switch is in the ON position and the whole external resistance is cut out from the rotor circuit

1.1.12.9. Lecture-9

Induction Generator

When a squirrel cage induction motor is energized from a three phase power system and is mechanically driven above its synchronous speed it will deliver power to the system. An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. Typical speed torque characteristic of induction generator is shown in Fig: 3.41



Now for example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM. If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc. Since the induction generator is actually an induction motor being driven by a prime mover, it has several advantages.

It is less expensive and more readily available than a synchronous generator.

It does not require a DC field excitation voltage.

It automatically synchronizes with the power system, so its controls are simpler and less expensive.

The principal disadvantages of an induction generator are listed below

1. It is not suitable for separate, isolated operation
2. It consumes rather than supplies magnetizing KVAR
3. It cannot contribute to the maintenance of system voltage levels (this is left entirely to the synchronous generators or capacitors)
4. In general it has a lower efficiency.

Induction Generator Application

As energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.

Because of their simplicity and small size per kilowatt of output power, induction generators are also favoured very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer’s total power needs. In such operation, the power system can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction

1.1.13. Test Questions

h. Fill in the blanks type of questions <Minimum of ten>
i. Multiple choice questions <Minimum of ten>
j. True or False questions <Minimum of ten>

1.1.14. Review Questions

Short Answer Type Questions

1. What are the advantages of auto transformer starting?
2. What are the advantages of slip ring Im over squirrel cage IM?
3. What is meant by cascade operation?
4. Discuss about direct online starting of an IM?
5. How do changes in supply voltages and frequency affect the performance of an IM?
6. Why no-load current of an Induction motor is much higher than that of an equivalent transformer?
7. In what ratio line current and starting torque is reduced with star-delta starting?
8. On what factors does the speed of an Induction motor depends?
9. Why the induction generator is often called as asynchronous generator?
10. What is the application for Induction generators?

Essay type questions

1. With neat diagram discuss the various tests to be conducted on 3phase IM to plot the circle diagram.
2. Compare DOL starter, Auto transformer starter & Rotor resistance starter with relate to the following: (i) starting current (ii) starting torque.
3. Calculate the minimum torque. Assume stator and rotor copper losses equal at standstill.
4. Describe the speed control of IM by rotor resistance control method. How this method of speed control is different from stator side speed control methods
5. Compare the speed control of 3phase IM by rotor resistance control & variable frequency control

6. What happens if the emf is injected to the rotor circuit 0f inducti0n motor?
7. With the help of experimental circuit, describe how the equivalent circuit parameters are determined by no load and blocked rotor tests on 3 phase Induction motor.

8. With the help of a neat diagram, describe the working of a star - delta starter

9. Discuss the working principle of Induction generator.
10. Mention the advantages and disadvantages of Induction generator.

Analytical and numerical problems

1. A cage IM when started by means of a star-Delta starter takes 180 % of full load current & develops 35 % of full load torque at starting. Calculate the starting current & torque in terms of full load torque when started by means of an auto transformer with 75 % tapping.
2. A 3-phase, 400V induction motor has the following test readings:-No-load:- 400V, 1250W, 9 A Short circuit:- 150V, 4KW,38 A Draw the circle diagram. If the normal rating is 14.9 KW, find from the circle diagram, the full load value of current, power factor and slip.
3. A 4 pole, 50 Hz, wound rotor IM has a rotor resistance of 0.56 ph and runs at 1430 rpm at full load. Calculate the additional resistance per phase to be inserted in the rotor circuit to lower the speed to 1200 rpm, if the torque remains constant.
4. Two 50Hz, 3 phase induction motors having six and four poles respectively are cumulatively cascaded, the 6 pole motor being connected to the main supply. Determine the frequencies of the rotor currents and the slips refereed to each stator field if the set has a slip of 2%.

5. A 3 phase, 6 pole 50Hz induction motor when fully loaded, runs with a slip of 3%. Find the value of resistance necessary in series per phase of the rotor to reduce the speed by 10%. Assume that the resistance of the rotor per phase is 0.2 ohm.
6. Two slip ring IMs having 10 & 6 poles respectively are mechanically coupled.
   - I. Calculate the possible speed when first motor is supplied from a 50 Hz supply line.
   - II. Calculate the ratio of power shared by the two motors.
   - III. If the smallest possible speed is to be attained independently by each machine,
   - IV. Calculate the frequency of the voltage to be injected in the rotor circuit.

7. A 6 pole, 50 Hz, 3 phase induction motor is running at 3 percent slip when delivering full load torque. It has standstill rotor resistance of 0.2 ohm and reactance of 0.4 ohm per phase. Calculate the speed of the motor if an additional resistance of 0.6 ohm per phase is inserted in the rotor circuit. The full load torque remains constant.
8. Two 50 Hz, 3 phase Induction motors having six and four poles respectively are cumulatively cascaded, the 6 pole motor being connected to the main supply. Determine the frequency of the rotor currents and the slips referred to each stator field if the set has a slip of 2%.

9. A 50 KVA, 400V, 3 phase, 50 Hz squirrel cage Induction motor has full load slip of 5%. Its standstill impedance is 0.866 ohms per phase. It is started using a tapped auto transformer. If the maximum allowable supply current at the time of starting is 100A, calculate the tap position and the ratio of starting torque to full load.
10. A three-phase delta-connected cage type induction, motor when connected directly to a 400 V, 50Hz supply, takes a starting current of 100 A, in each stator phase. Calculate
    I. The line current for `direct--on-line' starting.
    II. Line and phase starting currents for star-delta starting

1.1.15. *Skill Building Exercises/Assignments*

Eg:- -Prepare a model of something
-Trace something
-Prepare a report on something etc.,

1.1.16. *Previous Questions (Asked by JNTUK from the concerned Unit)*

1.1.17. *GATE Questions (Where relevant)*

1.1.18. *Interview questions (which are frequently asked in a Technical round - Placements)*

1.1.19. *Real-Word (Live) Examples / Case studies wherever applicable*

1.1.20. Suggested “Expert Guest Lectures” (both from in and outside of the campus)

1.1.21. Literature references of Relevant NPTEL Videos/Web/You Tube videos etc.

1.1.22. Any Lab requirements; if so link it to Lab Lesson Plan.

1.1.23. Reference Text Books / with Journals Chapters etc.