A LECTURE NOTE
ON
ENERGY CONVERSION
(TH-1)

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Lecture STAGE-II

ELECTRICAL ENGINEERING

GOVT. POLYTECHNIC, MALKANGIRI

CHAPTER-I

Induction Motor

Construction :

The induction motor mainly divided in to two parts.

(1) Stator   (2) Rotor

In case of D. C. Motor basically it is divided into two main parts (i) Yoke (ii) Armature. Yoke is outer & stationary part, similarly the outer portion of the induction motor is known as stator. It is also stationary part of the induction motor. The stator of the induction motor is cylindrical in shape.

The inner part of D. C. Motor i.e., armature is rotating in nature. Similarly the rotating part of the induction motor is known as rotor. The rotor lies inside the stator. It is cylindrical in shape.

Rotor is divided into two types.

(i)   Squirrel cage Rotor

(ii)   Phase wound Rotor or Slip ring Rotor,

Figure shows the disassembled view of an induction motor with squirrel cage rotor.

(a) Stator (b) Rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) terminal box.
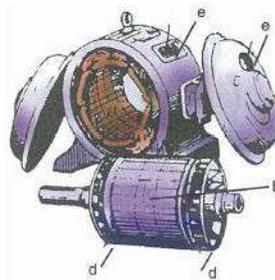

Fig 1.1

Similarly figure shows the disassembled view of a slip ring motor (a) stator (b) rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) Terminal box (g) Slip ring (h) brushes & brush holder.

Production of Rotating Magnetic Field :

When 3 – phase stationary coils are fed with 3 – phase supply, a uniformly rotating magnetic flux of constant magnitude will produce.

It will now be shown that when three – phase winding displaced in space by 120^0, are fed by three phase currents, displaced in time by 120^0, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

The principle of a 3 – phase, two pole stator having three identical windings placed 120^0 space degree apart as shown in fig – 1.2. The flux due to three phase windings is shown in fig 1.3.
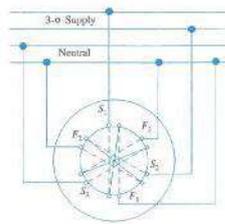
Fig 1.2
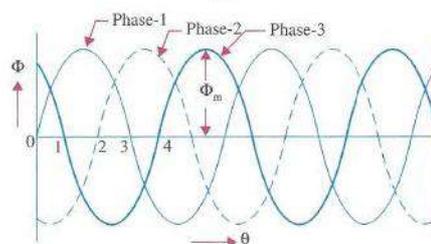
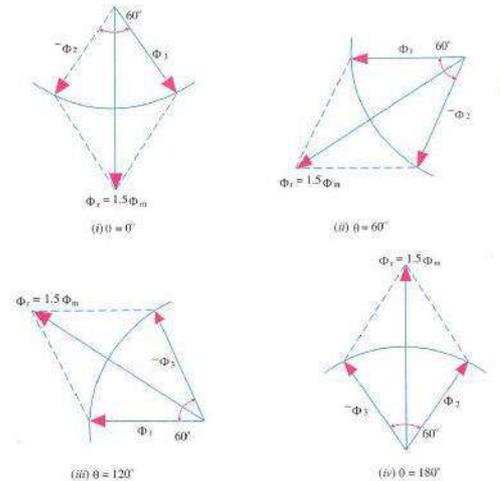

Fig 1.3

Let the maximum value of flux due to any one of the three phases be ϕ_m. The resultant flux ϕ_r, at any instant is given by the vector sum of the individual fluxes ϕ_1, ϕ_2 and ϕ_3 due to three phases. Considering values of ϕ_r at four instants i.e. $1/6^{th}$ time period apart corresponding to points marked 0, 1, 2 & 3.

Proof :

Case – 1 : Resultant flux at origin i.e. when $\theta = 0^0$ At that time $\phi_1 = 0$,

$\phi_2 = \phi_m \, Sin < - 120^0 = - \dfrac{\sqrt{3}}{2} \, \phi m \quad \phi_3 = \phi_m \, Sin < - 240^0 = - \dfrac{\sqrt{3}}{2} \, \phi m.$

Fig 1.4

Resultant flux ϕ_r :

As per law of parallerogram

$$\phi_r^2 = \phi_2^2 + \phi_3^2 + 2 \, \phi_2 \cdot \phi_3 \cdot \cos 60^0$$

$$\Rightarrow \phi_r^2 = \left(\dfrac{\sqrt{3}}{2} \phi_m \right)^2 + \left(\dfrac{\sqrt{3}}{2} \phi_m \right)^2 + 2 \cdot \dfrac{\sqrt{3}}{2} \phi_m \cdot \dfrac{\sqrt{3}}{2} \phi_m \dfrac{1}{2}$$

$$\Rightarrow \phi_r^2 = \dfrac{3}{4} \phi_m^2 + \dfrac{3}{4} \phi_m^2 + \dfrac{3}{4} \phi_m^2$$

$$\Rightarrow \phi_r^2 = \dfrac{9}{4} \phi_m^2$$

$$\Rightarrow \phi_r = \dfrac{3}{2} \phi_m$$

$$\Rightarrow \phi_r = 1.5 \, \phi_m$$

Case – II : When $\theta = 60^0$

Therefore $\phi_1 = \phi_m \, Sin < 60^0 = \dfrac{\sqrt{3}}{2} \, \phi_m$

$$\phi_2 = \phi_m \text{ Sin} < -120^0 + 60^0 = \phi_m \text{ Sin} < -60^0 = \frac{-\sqrt{3}}{2} \phi_m$$

and $\phi_3 = \phi_m \text{ Sin} < -240^0 + 60^0 = \phi_m \text{ Sin} < -180 = 0$

case – III   When $\theta = 120^0$

$$\phi_1 = \phi_m \text{ Sin} < 120^0 = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_2 = \phi_m \text{ Sin} < -120^0 + 120^0 = \phi_m \text{ Sin} < 0^0 = 0$$

$$\phi_3 = \phi_m \text{ Sin} < -240^0 + 120^0 = \phi_m \text{ Sin} < -120^0 = \frac{-\sqrt{3}}{2} \phi_m$$

ϕ_r can be calculated as earlier

Similarly $\phi_r = 1.5\phi_m$

Case – IV   When $\theta = 180^0$

$$\phi_1 = \phi_m \text{ Sin} < 180^0 = 0$$

$$\phi_2 = \phi_m \text{ Sin} < -120^0 + 180^0 = \phi_m \text{ Sin} < 60^0 = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_3 = \phi_m \text{ Sin} < -240^0 + 180^0 = \phi_m \text{ Sin} < -60^0 = \frac{-\sqrt{3}}{2} \phi_m$$

Similarly ϕ_r can be calculated as earlier $\phi_r = 1.5 \phi_m$

Hence from the above four cases we can draw a conclusion that the resultant flux (ϕ_r) inside the stator winding at any time = 1.5 ϕm and the resultant flux (ϕ_r) rotates around the stator at syncronous speed.

How the rotor rotates :

The rotor lies inside the stator. There is an air gap in between the stator and rotor. The stator slots are provided with three Phase winding.

When three phase stator windings are fed by a 3-phase supply then a rotating magnetic flux of constant magnitude will produce.

This rotating flux passes through air gap and cuts the stationary conductors on the rotor . There is also a 3-phase rotor winding on the rotor. The stator and rotor windings act as

primary and secondary windings of a 3-phase transformer. The air gap acts as core of the transformer. The fluxes passes from stator to rotor winding through induction principle.

The rotating flux produces an emf in the rotor winding. The rotor winding is closed circuit. Hence current will flow in the rotor conductors. When current will flow it will produce the flux in the air gap. The flux in the rotor winding interacts with the flux in the stator winding there by producing a torque, which is responsible for the rotation of the rotor.

Slip(s) :

The rotor never succeeds in catching up with the stator field. It is really did so, then there would be no relative speed between the two, hence no rotor emf, no rotor current and so no torque to maintain rotation. That in why the rotor runs at a speed which is always less than the speed of the stator field.

The difference between synchronous speed N_s to the actual speed of the totor N_r is known as slip speed.

Slip speed $= N_s - N_r$.

Slip (s) or % of Slip (s) $= \dfrac{N_s - N_r}{N_s} \times 100$

$\Rightarrow S = \dfrac{N_s - N_r}{N_s}$

$\Rightarrow N_s - N_r = SN_s$

$\Rightarrow N_s - SN_s = N_r$

$\Rightarrow N_s(1-S) = N_r$

Therefore Rotor speed $N_r = N_s (1-S)$

Frequency of Rotor Current :

When the rotor is stationary, the frequency of rotor current is the same as the supply frequency. But when the rotor starts revolving, then the frequency depends upon the relative speed. Let the frequency of the rotor current be f'

Hence $\qquad N_s - N_r = = \dfrac{120 f'}{P}$

As $N_s = = \dfrac{120f}{P}$

$\Rightarrow \dfrac{N_s - N_r}{N_s} = \dfrac{120f'}{P} \times \dfrac{P}{120f}$

$\Rightarrow S = \dfrac{f'}{f}$

Therefore $f' = Sf$

Hence Rotor frequency = slip x supply frequency

<u>Torque of an Induction Motor :</u>

The torque of an induction motor is the torque produced at the rotor. Hence $T = T_r$ where T_r is the rotor torque.

In case of D.C. motor torque = Armature Torque = T_a

$$T_a = 0.159\phi Z I_a \left(\dfrac{P}{A}\right) \text{N·m}$$

There fore $T_a = K\phi I_a$

[Where 0.159, Z, P and A are all constants)

Where ϕ is the flux produced by the filed winding which is pulsating in nature.

Similarly in case of an induction motor the torque is also proportional to the product of flux produced in stator and rotor current.

However there is another factor which is to be taken is power factor. Because in this case both flux and current are alternating in nature.

Therefore $T_r \propto \phi I_2 \cos \phi_2$

Where I_2 – Rotor Current

$\quad\quad \phi$ - flux produced in the stator.

$\quad\quad \phi_2$ – The phase angle between rotor emf and rotor current (E_2 and I_2)

$\quad\quad$ As $\phi \propto E_2$

Therefore $\quad\quad T_r = T \propto E_2 I_2 \cos \phi_2$

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

Starting Torque :

The torque developed by the motor at the instant of starting is called starting torque.

Let E_2 = Rotor emf per phase at stand still

R_2 = Rotor resistance / phase

X_2 = Rotor reactance / phase at stand still

$Z_2 = \sqrt{R_2^2 + X_2^2}$ = Rotor impedance / phase at stand still

Then $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$, $\cos \phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$

Stand still or starting torque $T_{st} = K\, E_2\, I_2 \cos \phi_2$

Or $T_{st} = K\, E_2 \cdot \dfrac{E_2}{\sqrt{R_2^2 + R_2}} \cdot \dfrac{R_2}{\sqrt{R_2^2 + R_2}} = \dfrac{K\, E_2^2\, R_2}{R_2^2 + R_2}$

If supply voltage V remains constant, then the flux ϕ and hence E_2 remain constant.

Therefore $T_{st} = K_1 \dfrac{R_2}{R_2^2 + X_2^2}$

$\Rightarrow T_{st} = K_1 \dfrac{R_2}{Z_2^2}$

Starting Torque of a Squirrel – cage Induction Motor :

The resistance of a squirrel cage motor is fixed and small as compared to its reactance which is very large especially at the start because at stand still, the frequency of the rotor currents equal the supply frequency. Hence the starting current I_2 of the rotor, though very large in magnitude, laggs by a very large angle E_2, with the result that the starting torque per ampere is very poor. Hence, such motors are not useful where the motor has to start against heavy loads.

Starting Torque of a slip-ring motor :

The starting torque of such motor is increased by improving its power factor by adding external resistance in the rotor circuit from the star connected rheostat, the rheostat resistance

being progressively cut out as the motor gathers speed. Addition of external resistance, however increases the rotor impedance and so reduces the rotor current. At first, the effect of improved power factor predominates the current–decrearing effect of impedance. Hence, starting torque is increased. But after a certain point, the effect of increased impedance predominates the effect of improved power factor and so the torque starts decreasing.

Condition for maximum starting Torque :

As starting torque $T_{st} = \dfrac{K_2 R_2}{R_2^2 + X_2^2}$

From mathematics we know that differentiation of a maximum quantity = 0

$D(T_{st}) = 0$, when $T_{st} =$ Maximum starting Torque

Therefore $\dfrac{d(T_{st})}{dR_2} = 0$

$\Rightarrow \dfrac{d}{dR_2}\left(\dfrac{K_2 R_2}{R_2^2 + X_2^2}\right) = 0$

$\Rightarrow K_2 \dfrac{d}{dR_2}\left(\dfrac{R_2}{R_2^2 + X_2^2}\right) = 0$

$\Rightarrow \dfrac{d}{dR_2}\left(\dfrac{R_2}{R_2^2 + X_2^2}\right) = 0$

$\Rightarrow \dfrac{\left(R_2^2 + X_2^2\right)\cdot \dfrac{d}{dR_2}\cdot R_2 \;-\; R_2 \dfrac{d}{dR_2}\left(R_2^2 + X_2^2\right)}{\left(R_2^2 + X_2^2\right)^2} = 0$

$\Rightarrow R_2^2 + X_2^2 \cdot 1 - R_2\left(2R_2 + 0\right) = 0$

$\Rightarrow R_2^2 + X_2^2 - 2R_2^2 = 0$

$\Rightarrow X_2^2 = R_2^2$

$\Rightarrow R_2 = X_2$

Hence the starting torque will be maximum when Rotor resistance = Rotor Reactance.

Rotor EMF and Rotor reactance under running condition :

Rotor EMF : Let E_2 = Stand still rotor EMF / phase

X_2 = Stand still rotor reactance / phase

When rotor starts rotating, the relative speed between rotor and rotating flux in the stator starts decreasing.

$$\text{Slip (s)} = \frac{N_s - N_r}{N_s}$$

The rotor induced emf is directly proportional to this relative speed

i.e. $E_r \propto (N_s - N_r) \, E_2$

$$\Rightarrow E_r = K (N_s - N_r) \, E_2$$

$$\Rightarrow E_r = \frac{N_s - N_r}{N_s} \cdot E_2$$

Therefore $E_r = SE_2$

Rotor Reactance :

The frequency of the rotor current

$f_r = sf$

Therefore $X_r = 2\pi s f_r L$

$$\Rightarrow X_r = 2\,\pi s f L$$

$$\Rightarrow X_r = S\,(2\pi f L)$$

Therefore $X_r = S\,X_2$

Torque under running conditions :

As we know that starting torque $T_{st} = KE_2 I_2 \cos \phi_2$

Therefore $T_{st} \propto E_2 \, I_2 \cos \phi_2$

So the torque under running condition $T_r \propto E_r \, I_r \cos \phi_r$

Where E_r = Rotor EMF/Phase under running condition

I_r = Rotor Current/Phase under running condition

A_s $E_r \propto \phi$

Therefore $T_r \propto \phi \, I_r \cdot \cos \phi_r$

$$I_r = \frac{E_r}{Z_r} \qquad\qquad \text{But } Z_r = R_2 + j\,X_r = R_2 + j\,SX_2$$

$$\text{Cos } \phi_r = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}} \text{ and } I_r = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Therefore running torque $T_r \propto E_r\, I_r$ as ϕ_r

Therefore $T_r \propto \phi\, \dfrac{SE_2}{\sqrt{R_2^2 + (S \cdot X_2)^2}} \cdot \dfrac{R_2}{\sqrt{R_2^2 + (S \cdot X_2)^2}}$

$\Rightarrow \qquad T_r \propto \phi\, \dfrac{SE_2 R_2}{R_2^2 + (S \cdot X_2)^2}$

$\Rightarrow \qquad$ As $E_2 \propto \phi$

Otenu $T_r \propto \dfrac{SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$

Therefore $T_r = \dfrac{K_1 SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$

Torque under stand still condition :

$N_r = 0$ at stand still condition

$$S = \frac{N_s - 0}{N_s} = 1$$

Therefore torque under stand still condition

$$Tr = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition for maximum Torque under running condition :

The torque of a rotor under running condition

$$T_r = \frac{K_1 SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$$

The conditions for maximum torque may be obtained by differentiating the above equation w.r.t slip (s) and then putting it equal to zero.

Let $Y = \dfrac{1}{T_r}$ (For to make the differentiation easy)

Therefore $Y = \dfrac{R_2^2 + (SX_2)^2}{K_1 SE_2^2 R_2}$

$\Rightarrow Y = \dfrac{R_2}{K_1 SE_2^2} + \dfrac{SX_2^2}{K_1 E_2^2 R_2}$

For maximum torque under running condition $\dfrac{dY}{dS} = 0$

$\Rightarrow \dfrac{d}{dS}\left(\dfrac{R_2}{K_1 SE_2^2}\right) + \dfrac{d}{dS}\left(\dfrac{SX_2^2}{K_1 E_2^2 R_2}\right) = 0$

$\Rightarrow \dfrac{d}{dS}\left(\dfrac{R_2}{SE_2^2}\right) + \dfrac{d}{dS}\left(\dfrac{SX_2^2}{E_2^2 R_2}\right) = 0$

$\Rightarrow \dfrac{\dfrac{dR_2}{dS}\cdot SE_2^2 - R_2 \dfrac{d}{dS}(SE_2^2)}{(SE_2^2)^2} + \dfrac{\dfrac{d}{dS}(SE_2^2)\cdot E_2^2 R_2 - \dfrac{d}{dS}E_2^2 R_2 \cdot (SX_2^2)}{(E_2^2 R_2)^2} = 0$

$\Rightarrow \dfrac{0 - \cdot E_2^2 R_2}{S^2 E_2^4} + \dfrac{X_2^2 E_2^2 R_2 - 0}{E_2^4 R_2^2} = 0$

$\Rightarrow \dfrac{-R_2 E_2^2}{S^2 E_2^4} + \dfrac{X_2^2}{E_2^2 R_2} = 0$

$\Rightarrow \dfrac{R_2}{S^2 E_2^2} = \dfrac{X_2^2}{E_2^2 R_2}$

$\Rightarrow \dfrac{R_2}{S^2} = \dfrac{X_2^2}{R_2}$

$\Rightarrow R_2^2 = S^2 X_2^2$

Therefore $\boxed{R_2 = SX_2}$

Hence the torque under running condition will be maximum when $R_2 = SX_2$

As the torque under running condition

$$T_r = \dfrac{K_1 SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Putting the value $R_2 = SX_2$

Therefore $T_r = T_r(max) = \dfrac{K\,SE_2^2 \cdot SX_2}{\left(SX_2\right)^2 + \left(SX_2\right)^2}$

$\Rightarrow T_r(max) = \dfrac{KS^2E_2^2X_2}{2S^2X_2^2} = \dfrac{K\,E_2^2}{2X_2}$

Hence $\boxed{T_r(max) = \dfrac{K\,E_2^2}{2X_2}}$

Relation between full load Torque and Maximum Torque :

As Torque $(T) = \dfrac{K_1\,SE_2^2\,R_2}{R_2^2 + \left(SX_2\right)^2}$

E_2 is practically constant

Hence $T = \dfrac{K_2\,SR_2}{R_2^2 + \left(SX_2\right)^2}$

Therefore $T \propto \dfrac{SR_2}{R_2^2 + \left(SX_2\right)^2}$

Taking full load slip as S_f at full load torque T_f

Therefore $T_f \propto \dfrac{S_f R_2}{R_2^2 + \left(SX_2\right)^2}$ .... (I)

As $T_{max} = \dfrac{K\,E_2^2}{2X_2}$

$T_{max} \propto \dfrac{1}{2X_2}$ .... (II)

$\dfrac{(i)}{(ii)} = \dfrac{T_f}{T_{max}} = \dfrac{S_f\,R_2}{R_2^2 + \left(S_f X_2\right)^2} \times \dfrac{2X_2}{1}$

$\dfrac{T_f}{T_{max}} = \dfrac{2S_f R_2 X_2}{R_2^2 + \left(S_f X_2\right)^2}$

Dividing X_2^2 on both side

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2S_f \dfrac{R_2}{X_2}}{\dfrac{R_2^2}{X_2^2} + S_f^2}$$

Taking $\dfrac{R_2}{X_2} = a$

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2aS_f}{a^2 + S_f^2}$$

In general $\dfrac{\text{operating Torque}}{\text{Maximum Torque}} = \dfrac{2as}{s^2 + a^2}$

s – operating slip

Relation between starting Torque and Maximum Torque :

As $T_{st} = K \dfrac{R_2}{R_2^2 + X_2^2}$

$$\Rightarrow T_{st} \ \alpha \ \frac{R_2}{R_2^2 + X_2^2} \qquad \dots\dots\dots\dots\dots (i)$$

But $T_{max} \ \alpha \ \dfrac{1}{2X_2} \qquad \dots\dots\dots\dots\dots (ii)$

$$\frac{(i)}{(ii)} = \frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2 + X_2^2} \times \frac{2X_2}{1}$$

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

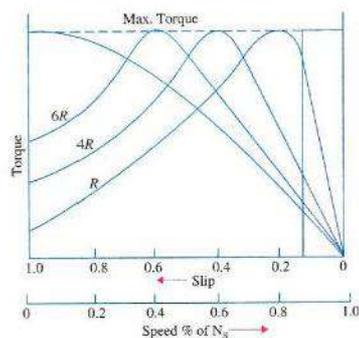$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\dfrac{2R_2 X_2}{X_2^2}}{\dfrac{R_2^2}{X_2^2} + \dfrac{X_2^2}{X_2^2}}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\dfrac{2R_2}{X_2}}{\left(\dfrac{R_2}{X_2}\right)^2 + 1}$$

$$\Rightarrow \boxed{\frac{T_{st}}{T_{max}} = \frac{2a}{a^2 + 1}}$$

Relation between Torque and slip :

As Torque $(T) = \dfrac{KSE_2^2 R_2}{R_2^2 + (SX_2)^2}$

Taking Torque in Y axis and slip in X axis

Fig. 1.5

At origin i.e. $S = 0$, torque $T = 0$

Therefore the curve starts from origin. At normal speed, closed to synoronism that is when N_r is very near to N_s, then slip is very nearly equal to zero.

Therefore $SX_2 << R_2$

$$\Rightarrow \quad T \quad \alpha \quad \frac{SE_2^2 R_2}{R_2^2} \qquad \{\text{Neglecting } (SX_2)^2\}$$

(Taking supply voltage constant so E_2 is also constant)

$$\Rightarrow \quad T \quad \alpha \quad \frac{S}{R_2}$$

For a particular induction motor R_2 is constant.

Hence $T \quad \alpha \quad S$

Therefore low valve of slip, torque is directly proportional to slip. Hence the curve is straight line for low valve of slip.

As slip increases the torque also increases and becomes maximum when $= R_2 = SX_2$

i.e. $S = \dfrac{R_2}{X_2}$

As the slip further increases (SX_2) becomes higher compare to R_2.

Hence R_2 can be neglected in compare to (SX_2)

$$\Rightarrow T\alpha \ \frac{S}{(SX_2)^2}$$

$$\Rightarrow T\alpha \ \frac{1}{SX_2^2}$$

Taking X_2 is constant for a particular induction motor

Therefore $T \ \alpha \ \dfrac{1}{S}$

So beyond the point of maximum torque any further increase in slip, results in decrease of torque.

Method of standing of Induction Motor

The operation of the squirrel cage induction motor is similar to transformer having short circuited on the secondary side.

Due to short circuited on the rotor circuit it will take heavy current when it is directly switched on. Generally when direct switched, take five to seven times of their full load current. This initial excessive current is objectionable, because it will produce large line voltage drop.

Hence it is not advisable to start directly motors of rating above 5 KW. But the starting torque of an induction motor can be improved by increasing the resistance of the rotor circuit. This is easily feasible in the case of slip ring induction motor but not in the case of squirrel cage motors. However, in their case, the initial in rush of current is controlled by applying a reduced voltage to the stator during the starting period, full normal voltage being applied when the motor has run up to speed.

Method of Starting of Squirrel Cage Motor :

(1)   Resistors Method

(2)   Star – Delta Method

(3)   Auto transformer Method

In the above methods, the supply voltage to the squirrel cage motor is reduced during starting.

1)   Resistor Method :
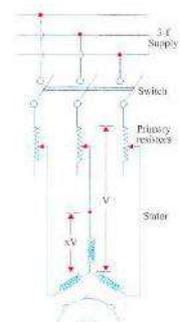
In this method the resistors are connected in series with the stator phases, to give reduced voltage to the stator winding.

When resistors are connected in series with the stator phases, the current in the stator phases will reduce. If the voltage applied across the motor terminals is reduced by 50%, starting current is reduced by 50%.

Fig 1.6

When the motor starts running the resistances in the circuit is gradually cut out and full voltage is applied to the stator circuit. This method is useful for the smooth starting of small machines only.

2)   Star – Delta Starter :

This method is used in the case of motors which are built to run normally with a delta connected stator winding. It consists of a two way switch which connects the motor in star for starting and then in delta for normal running.

At starting, when star connected, the applied voltage over each motor phases is reduced by a factor $1/\sqrt{3}$. Hence during starting, when motor is star connected it takes $1/\sqrt{3}$ times as much as starting current.
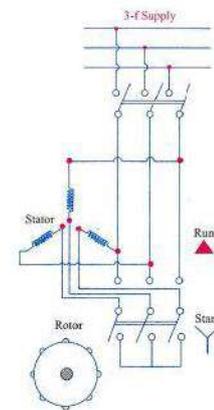
Fig 1.7

When the motor catches the speed 80% of its normal speed switch is changed to delta positions at that time $V_L = V_{ph}$.

Auto Transformer Method :

This starter is popularly known as auto starter in auto transformer the secondary side gets less voltage in compare to primary side.

As shown in the figure, at starting condition, a reduced voltage is applied across the mo terminals. When the motor catches the speed 80% of its normal speed, connections are changed to running position, then full supply voltage is applied across the motor.
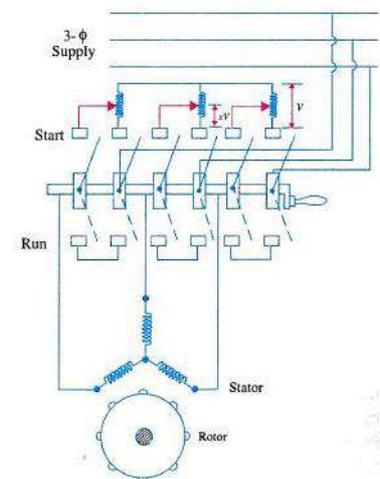
Fig 1.8

Most of the auto starters are provided with 3 – sets of taps so as to reduced the voltage to 80, 65 or 50 percent of line voltage.

Slip ring Motor :

Rotor Rheostat Method :

These motors are practically always started with full line voltage applied across the stator terminals. The value of starting current is adjusted by introducing a variable resistance in the rotor circuit.
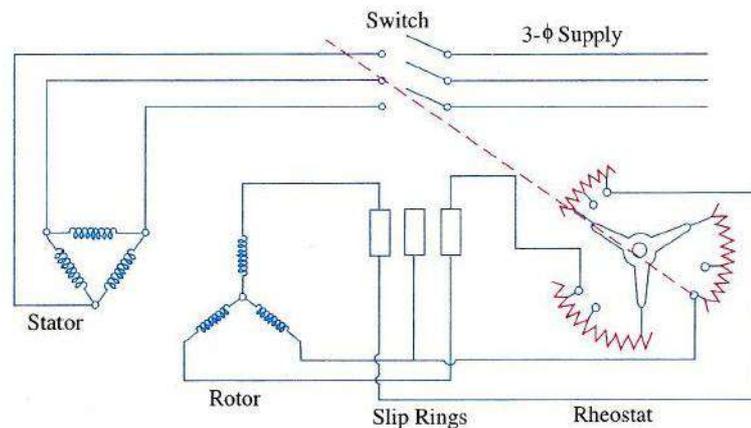
Fig 1.9

The controlling resistance is in the form of a rheostat, connected in star, the resistance being gradually cut – out of the rotor circuit, as the motor gathers speed

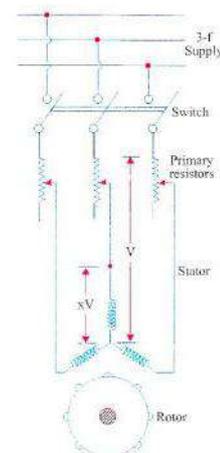**Speed Control of Induction Motor :**

The speed of an induction motor can be changed under two main headings.

    (i)   Control from stator side

    (ii)   Control from Rotor side

(i)   **Control from stator side :**

    (a)   By changing the applied voltage

    (b)   By changing the applied frequency

    (c)   By changing the no of stator poles.

(ii)   **Control from Rotor side :**

(a)   Rotor Rheostatic Control

(b)   Cascade operation   **Fig 1.10**

(c)   By injecting emf in the rotor circuit

By changing applied voltage :

This method is the easiest way for controlling speed of an induction motor. But this method is rarely used for the following reasons.

(i) A large change in voltage is required for a small change in speed.

(ii) Due to the connection of resistances in the stator phases, large power loss occurs at the resistors.

When the resistances are added in the stator circuit, voltage across the stator phase decreases.

$$\text{As torque (T)} = \frac{KV^2 R_2}{R_2^2 + X_2^2}$$

$$\Rightarrow \text{Torque } T = K_1 V^2$$

$$\Rightarrow T \propto V^2$$

The torque depends on the supply voltage on the stator terminals, when V will decrease T will decrease hence speed will decrease.

By Charging the number of stator poles :

This method is easily applicable to squirrel cage motors because the squirrel cage rotor adopts it self to any reasonable number of stator poles.

The change in number of stator poles is achieved by having two more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different synchronous speed.

Rotor Rheostatic Control :

This method is applicable to slip ring motors alone. The motor speed is reduced by introducing an external resistance in the rotor circuit.
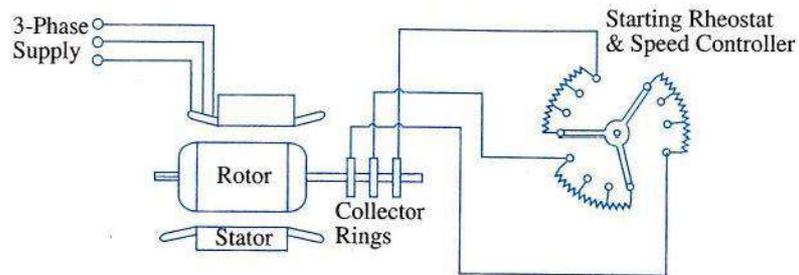
Fig 1.11

For this purpose the rotor starter may be used.

As torque (T) α $\dfrac{S}{R_2}$

By increasing the motor resistance torque will decrease. Hence speed will decrease.

Motor Enclosures :

Enclosed and semi-enclosed motors are practically identical with open motors in mechanical construction and in their operating characterstics. Many different types of frames or enclosures are available to suit particular requirements. Some of the common type of enclosures are given below.

(i)   Totally enclosed, Non ventilated type.

(ii)   Splash – Proof type

(iii) Totally enclosed, Fan cooled type.

(iv)   Cowl covered motor

(v)   Protected Type

(vi)   Drip – Proof Motors

(vii) Self (Pipe) Ventilated Type

(viii) Separately (Forced) Ventilated Type.

Induction Generator :

When the rotor of an induction motor runs faster than its synchronous speed at that time the induction motor runs as a generator called Induction generator. It converts the mechanical energy it receives into electrical energy is released by the stator.