EE 8401 Electrical Machines - II.

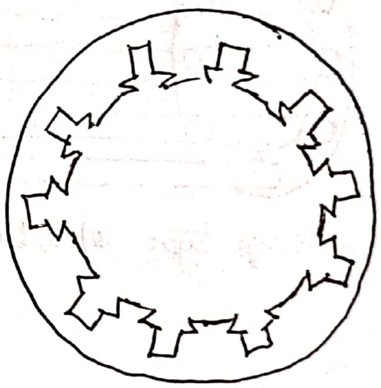
UNIT - 3 Three phase Induction Motors

1. Explain the construction and operation of a 3ϕ Induction Motor:.

Construction

The induction Motor consists of two main parts.

1. Stator → carries 3ϕ stationary winding.
2. Rotor. → which rotates and is connected to the Mechanical load through shaft.



Stator laminations

Stator

1. Stator has a laminated type of construction made up of stampings which are 0.4 to 0.5 mm Thick

2. The stampings are slotted on its periphery to carry stator winding

3. The stampings are insulated from each other to keep the iron loss minimum. The stampings stamped to built stator core

4. The stampings are generally of silicon steel to keep the hysteresis loss minimum.

5. The slots on the periphery of the stator carries a three phase windings

Rotor

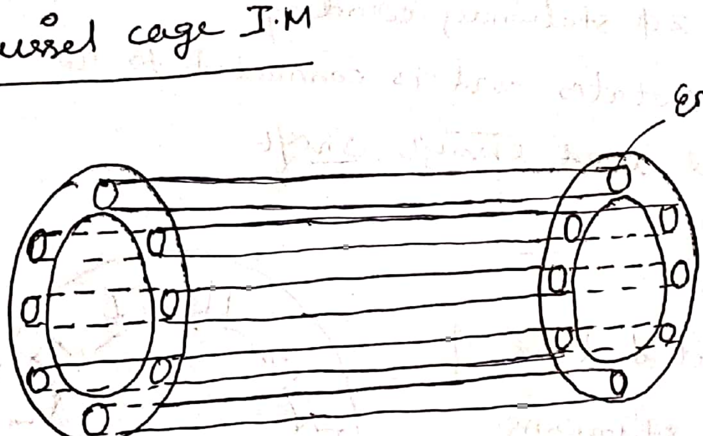
* Rotor is placed inside the stator, also laminated in construction uses cast iron. The rotor conductors or winding is placed in the rotor slots.

Two types are construction are

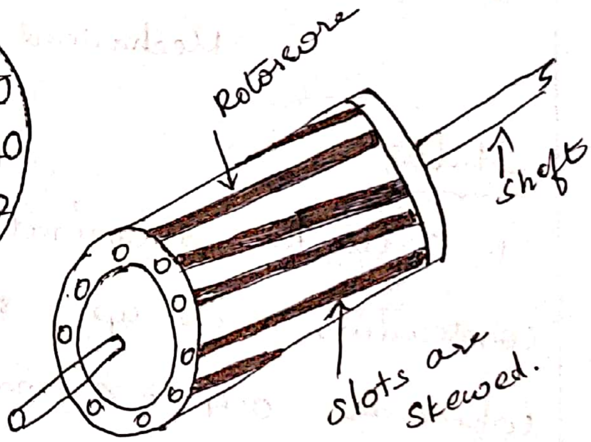
→ Squirrel cage rotor and.

→ slip ring induction motor or wound ring I.M.

1. Squirrel cage I.M



Cage type structure of rotor



The rotor core is cylindrical and slotted on its periphery. The rotor consists of uninsulated copper or aluminium bars called rotor conductors. bars are placed in the slots.

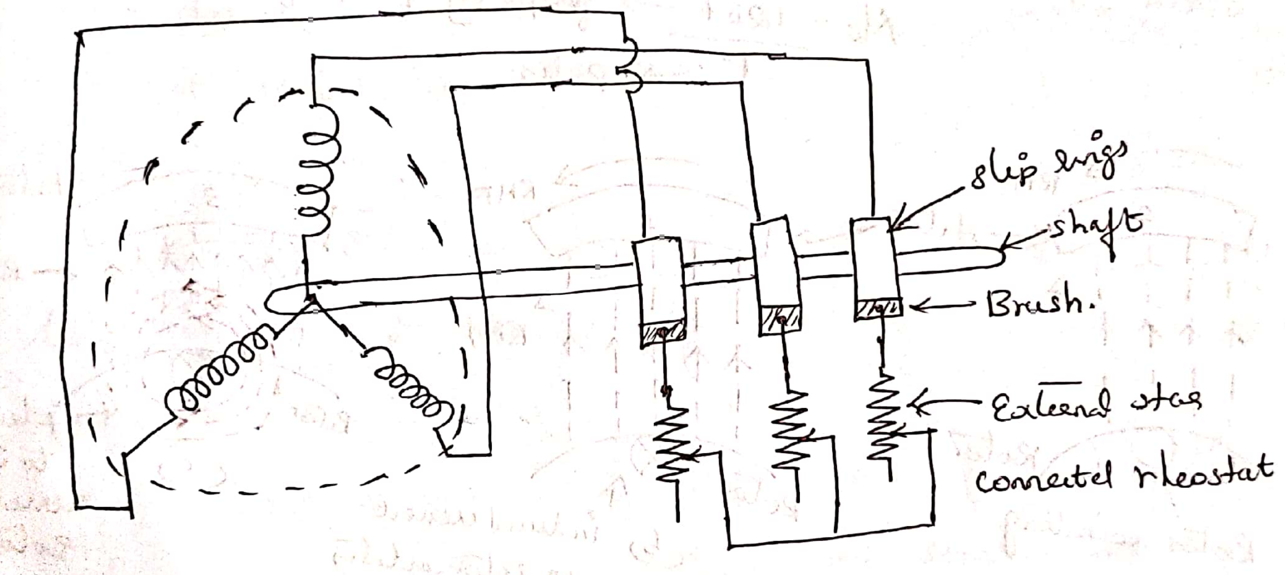
The bars are permanently shorted at each end with the help of conducting copper ring called end ring. The entire structure look like a cage. forming a closed electrical circuit. As the rotor are shorted entire rotor resistance is very very small.

The slots are not arranged parallel to the shaft axis but are skewed.

Advantages of skewing are,

1. A magnetic hum (i.e.) noise get reduced
2. It makes the motor operation smooth
3. Magnetic interlocking get reduced due to skewing.

Slip ring Rotor or Wound Rotor:-



In this type, rotor winding is exactly similar to the stator. The rotor carries a three phase star or delta connected distributed winding, wound for same no. of poles as that of stator.

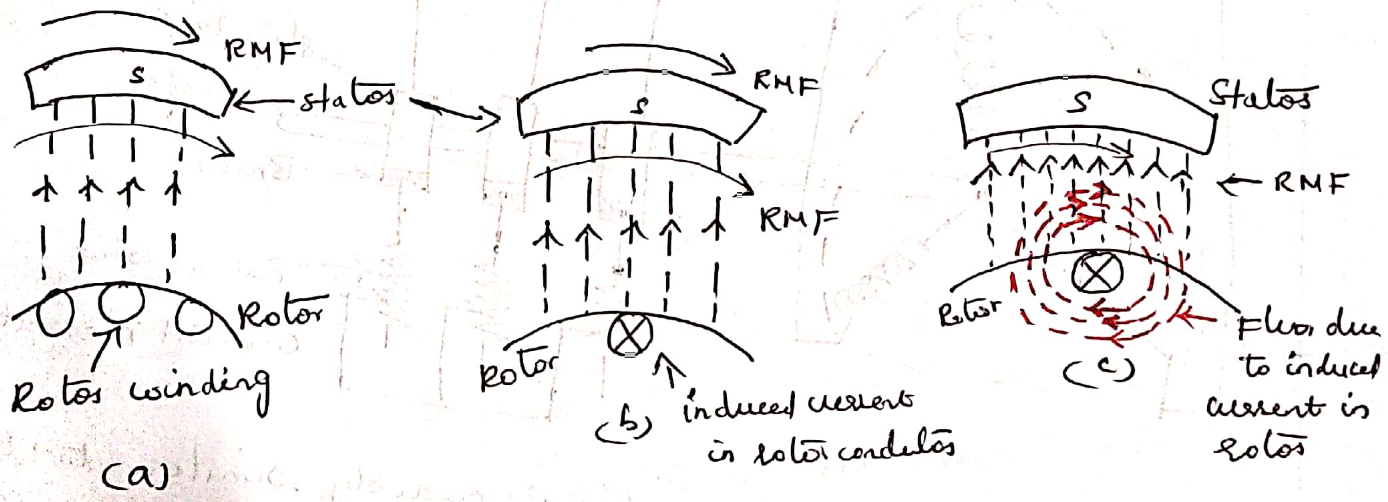
The three ends of 3ϕ windings are connected to the slip rings which is mounted on the same shaft. In this type of rotor

Working Principle :-

Induction motor works on the principle of Electromagnetic Induction.

When a 3ϕ supply is given to the 3ϕ stator winding a rotating magnetic field of constant magnitude is produced. The speed of the rotating magnetic field is synchronous speed Ns.

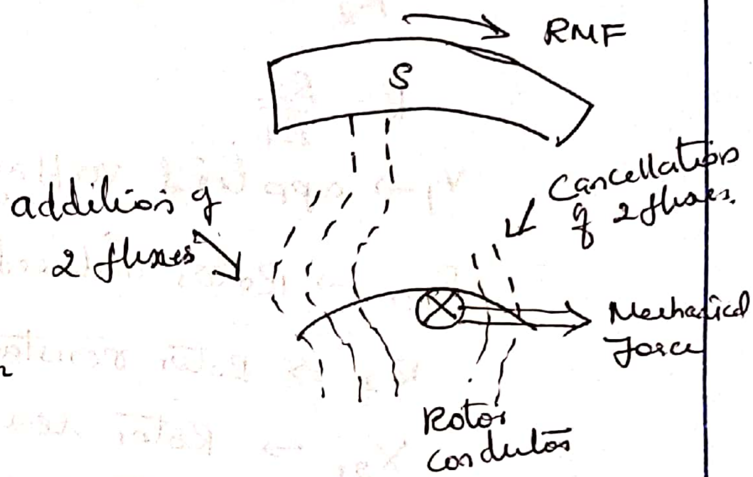
$$N_s = \frac{120f}{P}$$ f → frequency of supply, P → poles.



When supply is given the rotating magnetic field is produced in clockwise as shown in (a) fig.

At this instant rotor is stationary and stator flux is rotating. The RMF cuts the rotor conductors, so, whenever conductor cuts the flux emf is induced in it. As rotor forms a closed circuit the induced emf circulates current through rotor called rotor current as shown in Fig (b)

Any current carrying conductor produces its own flux, so rotor produces its flux as shown in fig (c). The interaction of the flux due to RMF and rotor conductor is shown in fig(d).



On left of rotor conductor two fluxes interact with each are in same direction hence get added have high flux area.

On right side two fluxes cancel each other to produce low flux area so rotor conductor experiences a force from left to right

All the conductors experiences a force as well and rotor experiences a torque and starts rotating.

$N_s \rightarrow$ speed of rotating RMF

$N \rightarrow$ speed of rotor i.e motor speed,

$N_s - N \rightarrow$ Relative speed between two rotating magnetic field and the rotor conductor.

2. Develop an equivalent circuit for 3ϕ I.M. State the difference between exact and approximate equivalent circuit.

In 3ϕ Induction Motor the stator acts a primary & rotor acts as a secondary. When I.M. is treated as a transformer

If E_1 → Induced voltage in stator per phase

E_2 → Rotor induced emf per phase on stand still

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

V_1 → applied voltage per phase to stator.

E_{2r} → Rotor induced emf in running condition

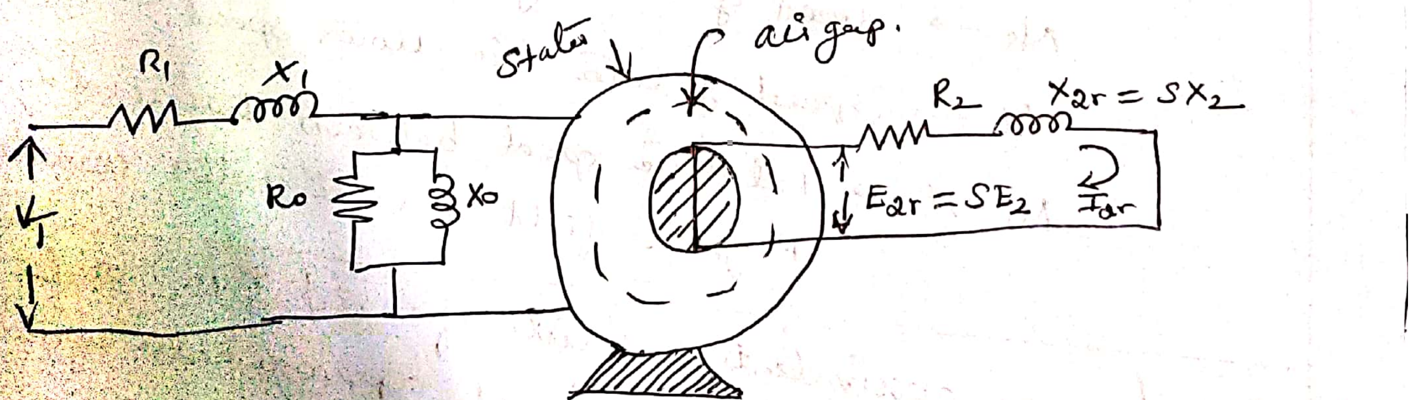
R_2 ⇒ Rotor resistance per phase

X_{2r} → Rotor reactance per phase in running condition

R_1 → stator resistance per phase

X_1 → stator reactance per phase.

When supply is given E_1 emf will induced in the stator and by mutual induction E_2 will be induced in the rotor at stand still. In running condition the induced emf in rotor becomes E_{2r} which is sE_2.



I_c → Active component

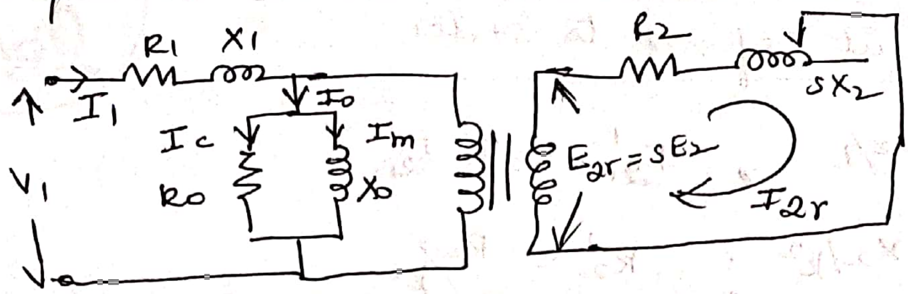
I_m → magnetising component

$\bar{I}_0 = \bar{I}_c + \bar{I}_m$

$R_0 = \frac{V_1}{I_c}$

$X_0 = \frac{V_1}{I_m}$

Equivalent ckt can be represented as.



I_{2r} = rotor current in running condition

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{sE_2}{\sqrt{R_2^2+(sX_2)^2}}.$$

Representation of Rotor Impedance

$$I_{2r} = \frac{sE_2}{\sqrt{R_2^2+(sX_2)^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2+X_2^2}}.$$

taking R_2/s as;

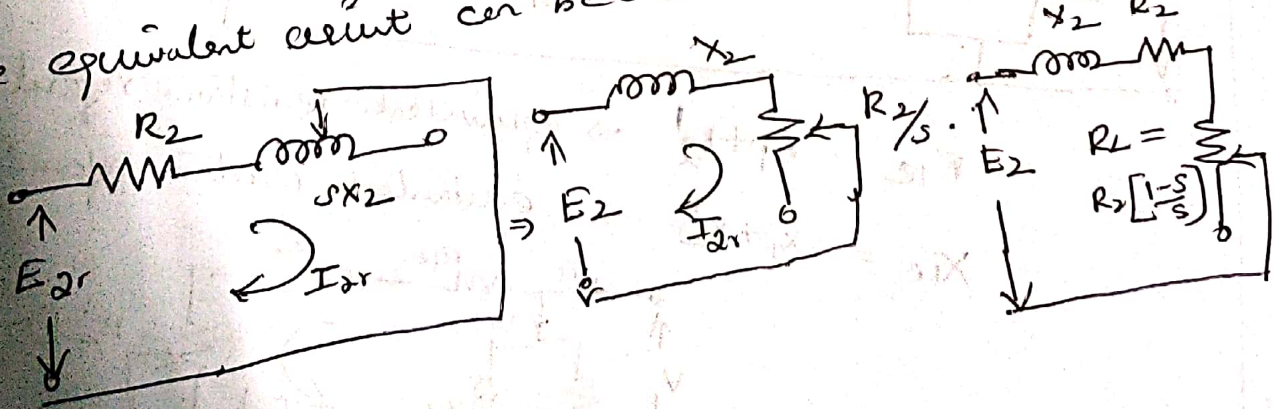
$$\frac{R_2}{s} = R_2 + \frac{R_2}{s} - R_L$$

$$\frac{R_2}{s} = R_2 + R_2\left[\frac{1}{s}-1\right] \Rightarrow R_2 + R_2\left[\frac{1-s}{s}\right]$$

$R_2 \rightarrow$ rotor resistance represents copper loss.

$R_2[1-s)/s$ represents load Resistance R_L.

The equivalent circuit can be shown as,



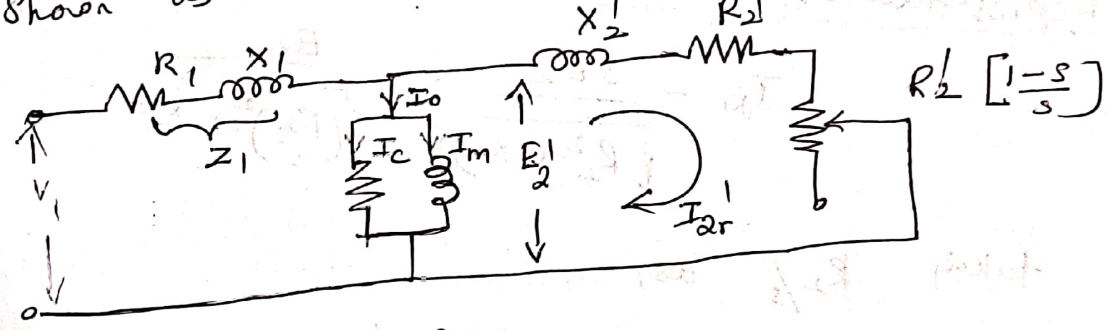
Equivalent circuit referred to stator

$E_2' = E_2/k$, $I_{2r}' = k\, I_{2r}$

$X_2' = X_2/k^2$; $R_2' = R_2/k^2$

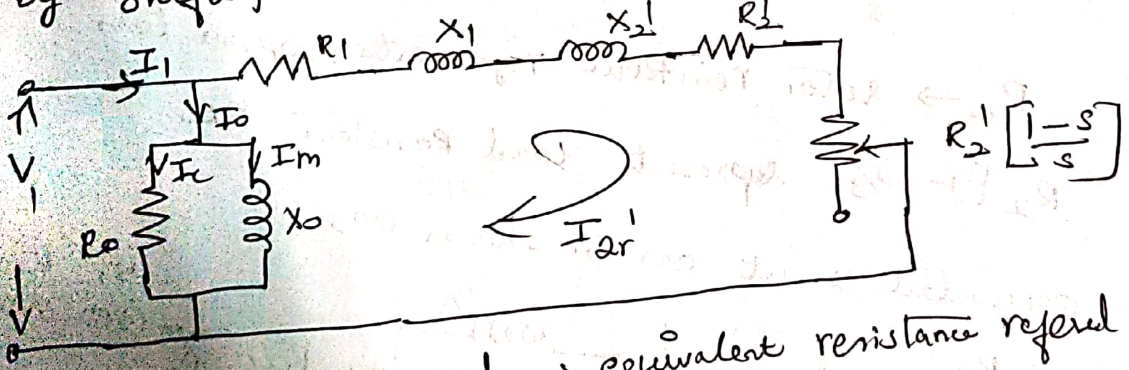
$R_L' = \frac{R_L}{k^2} = R_2' \left[\frac{1-s}{s}\right]$

So equivalent circuit referred to stator shown as



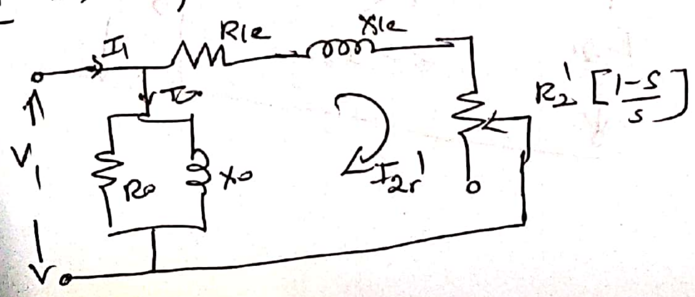
Approximate equivalent circuit

Approximate equivalent circuit can be drawn by shifting the exciting circuit to the left of R_1 & X_1



$R_{1e} = R_1 + R_2'$ ⇒ equivalent resistance referred to stator $= R_1 + R_2/k^2$

$X_{1e} = X_1 + X_2'$ → equivalent reactance referred to stator $= X_2 + X_2/k^2$



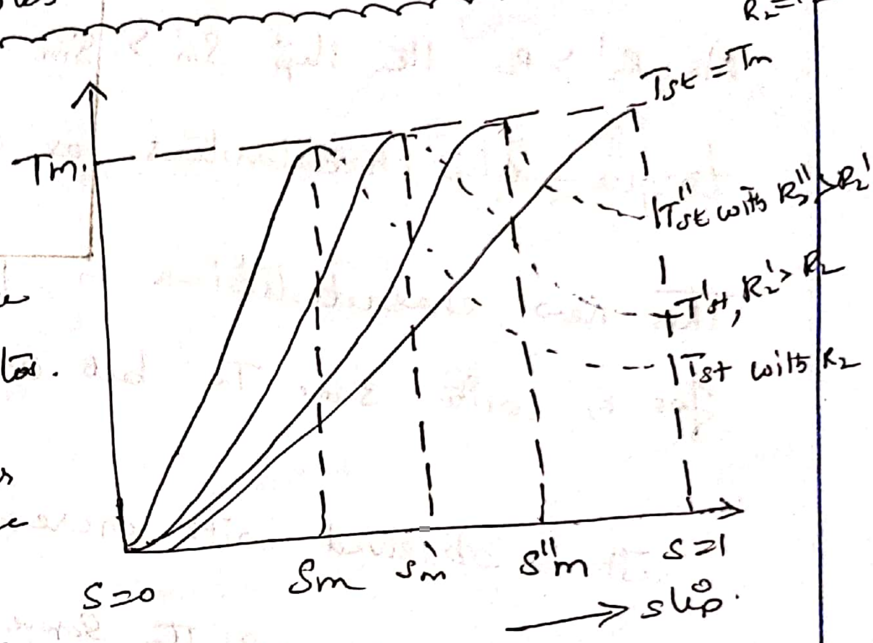
$\bar{I_1} = \bar{I_0} + \bar{I_{2r}'}$

$\bar{I_0} = \bar{I_c} + \bar{I_m}$

23. Draw the torque slip characteristics of an Induction motor for varying frequency stator voltage and rotor resistance.

(i) **Effect of change in rotor Resistance on Torque:-**

In slip ring induction motor external resistance can be added in the rotor.



R_2 = Rotor resistance per phase

Torque $T \propto \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2}$

R_2' = New rotor resistance

$$T' \propto \frac{s E_2^2 R_2'}{R_2'^2 + (sX_2)^2}$$

s = 1, R_2 and R_2' can be rewritten as

$$T_{st} \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2}, \quad T'_{st} \propto \frac{E_2^2 R_2'}{R_2'^2 + X_2^2}$$

Max Torque. $T_m \propto \frac{E_2^2}{2X_2}$

For R_2, $S_m = \frac{R_2}{X_2}$ where T_m occurs

$$S'_m = \frac{R_2'}{X_2}$$

As $R_2' > R_2$ the slip $S_m' > S_m$. Due to this we get a new torque - slip characteristics for rotor Resistance R_2'

This new characteristics is parallel to the characteristics for R_2 with same T_m but occuring at S'_m

It is observed with increase in resistance the max torque remains the same and the starting torque can be increased.

Effect of change in Voltage and frequency

Case 1. Halving the applied voltage, keeping frequency normal

When the motor is running with slip s, the torque is

$$T = \frac{K_s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$

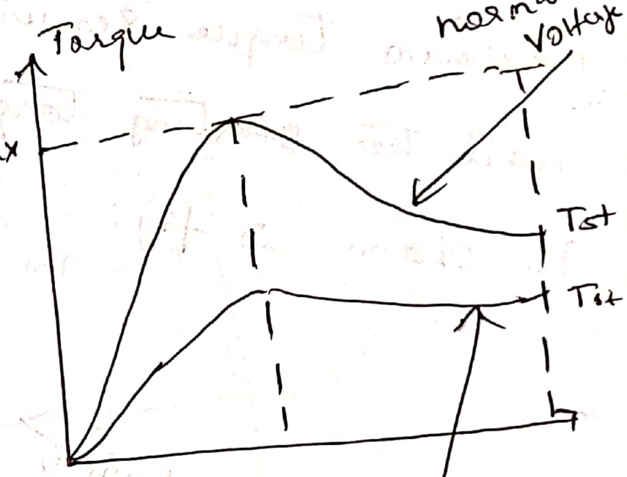
Now standstill e.m.f. E_2 is proportional to the supply voltage

$$T = \frac{k' s V^2 R_2}{R_2^2 + (sX_2)^2}$$ where k' is another constant

On full load, slip s is very small hence $(sX_2)^2 << R_2^2$,

$$T = \frac{k' s V^2 R_2}{R_2^2} = \frac{k' s V^2}{R_2}$$

$$\boxed{T \propto sV^2}$$



If the supply is made half the torque will reduce by the factor (1/4), is the running condition.

The slip at which Tmax occurs remains same but the value of Tmax reduces. as show in fig.

Case 2: Halving both the applied voltage and frequency

For an induction motor, the air gap flux is given by

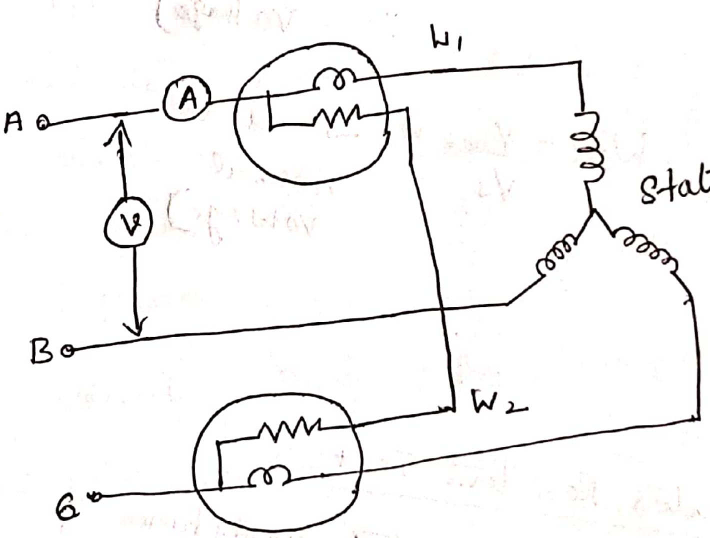
$$\phi_g = \frac{1}{4.44 k_1 T_{ph1}} \left(\frac{V}{f}\right)$$

Circle Diagram of 3φ Induction Motor

The circle diagram of a 3φ induction motor is the graphical representation of the equivalent circuit. All the information that can be obtained from its equivalent circuit can also be obtained from the circle diagram.

Following test data required to draw circle diagram.

No Load Test



Open ckt test is conducted on the 3φ I.M. to determine No load current I_0, power factor $\cos\phi_0$, windage and friction losses, no load copper losses ($I_0^2 R$), no load power input P_0.

$$W_0 = \sqrt{3}\, V_L I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_0}{\sqrt{3}\, V_L I_0}$$

$$I_w = I_0 \cos\phi_0$$

$$I_\mu = I_0 \sin\phi_0$$

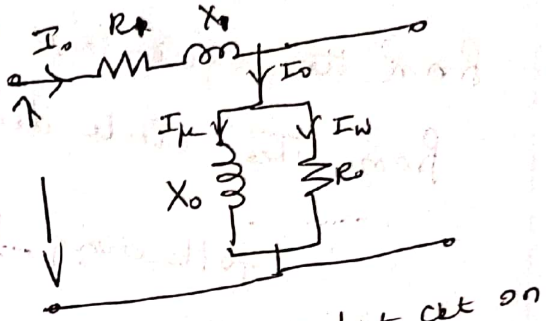
$$R_0 = \frac{V_L/\sqrt{3}}{I_w}$$

$$X_0 = \frac{V_L/\sqrt{3}}{I_\mu}$$

Blocked Rotor Test

This test is conducted to determine the short circuit current (I_{sc}) with rated current drawn by the stator, power factor on short circuit & equivalent Resistance (R_{01}) & reactance X_{01} referred to stator side.

$$W_{sc} = \sqrt{3} V_s I_s \cos\phi_{sc}$$

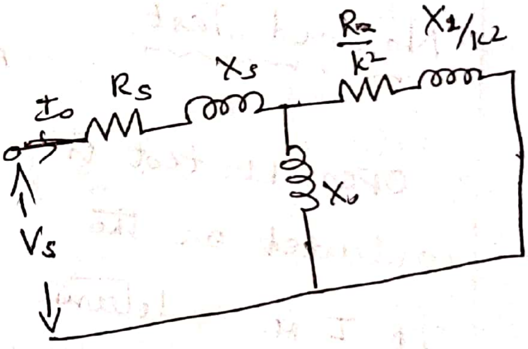


$$\cos\phi_{sc} = \frac{W_{sc}}{V_s I_s}$$

$$I_{SN} = \left(\frac{V}{V_s}\right)^2 \cdot I_s$$ (current at normal voltage)

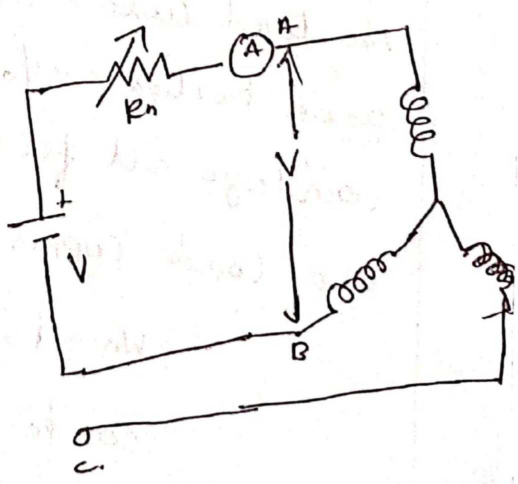
Equivalent ckt on No load

$$W_{SN} = \frac{V}{V_s} \times W_s$$ [Power at normal voltage]



(3) Stator Resistance Test

Using this test resistance of the stator winding resistance is determined



The total resistance of the two winding is measured & value is divided by 2. from the resistance value is multiplied by 1.25 to obtain actual resistance.

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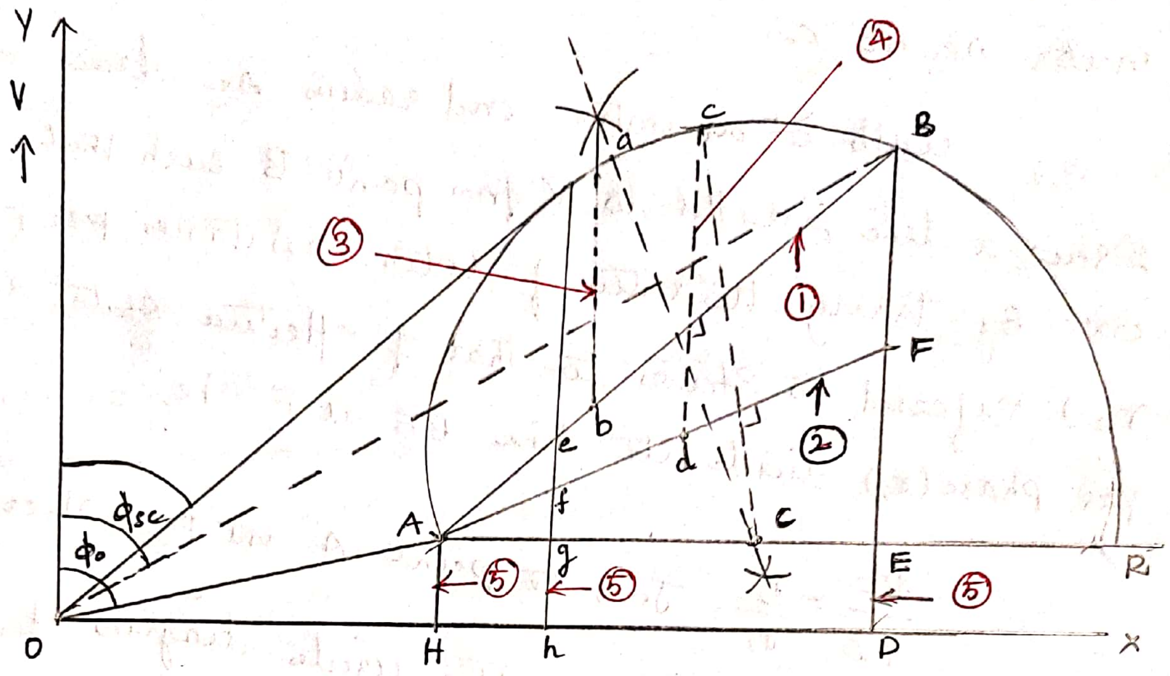
Construction of circle diagram



1. The value of ϕ_0 and I_0 can be calculated from no-load test. Hence the vector OA for no-load current I_0 is drawn by an angle ϕ_0 lagging with the applied voltage phasor V and is shown in figure.

The short circuit current I_{SN} corresponding to normal voltage and power factor angle ϕ_{sc} can be found out from the blocked rotor test or stator resistance test.

This current is represented by the vector OB making angle ϕ_{sc} with the voltage phasor. Join the points A and B where the vector AB represents the rotor current I_2 as referred to stator.

Now draw OX and AR perpendicular to the phasor V. Draw the perpendicular bisector of AB such that it meets AR at C.

with 'C' as centre and radius AC draw a circle

Draw a line parallel to V from point B such that it cuts OX. By taking the ratio of rotor Resistance per phase (r_2) referred to stator to that of effective stator resistance per phase (r_1) divide the line BE at F. ie,

$$\frac{BF}{FE} = \frac{r_2}{r_1}$$ Join the point A and F where AF represents the torque line. The circle diagram of a 3φ induction motor along with its specifications is shown.

Specification

AB = Output line
AF = Torque line
ab = Maximum power output
cd = Maximum torque
ED = AH = gh = Fixed loss.

Now, for any operating point (ie) when the motor is running, taking current as OI and by drawing a perpendicular Ih on OX, the entire performance of the motor can be obtained.

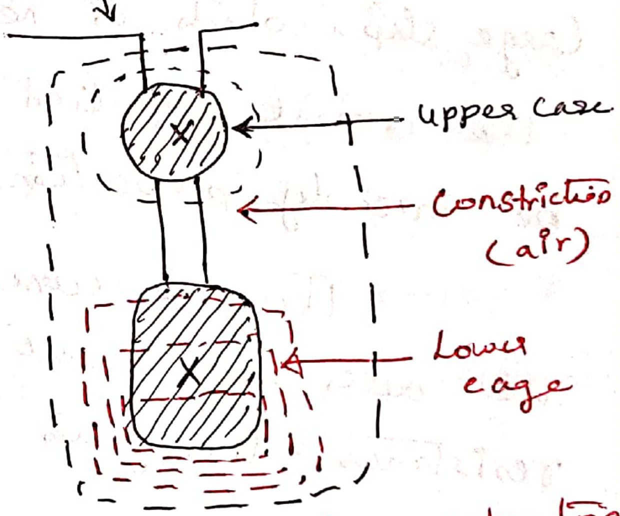
OI = I/p current
eI = Power output
ef = Rotor ohmic loss
fg = stator ohmic loss
gh = friction windage and core loss
Ih = power input

$\frac{It}{Ws}$ = Torque , $\frac{et}{It}$ = slip.

$\frac{Ih}{Oh}$ = power factor & $\frac{eI}{Ih}$ = Efficiency

Hence, the characteristic of an Induction motor can be determined theoretically from its circle diagram by using the data from no-load, blocked rotor & stator resistance tests.

5. Explain the speed torque characteristics of double cage induction motor with a neat diagram.



Double cage rotor construction

Construction of Double Cage Rotor:-

In double cage rotor induction motor, the stator is similar to that of ordinary induction motor. The only difference is in the rotor construction. The rotor of double cage induction motor is constructed by using two sets of squirrel cage windings which are provided on the rotor separated by narrow slit or construction.

The upper cage or the starting cage which is very close to the air gap is made of high resistivity materials such as aluminium, bronze etc.

Scanned with CamScanner

Lower cage made up of copper. the cross section of upper cage is smaller than the lower cage and hence the resistance of upper cage is higher than that of lower cage. the diagram is shown in fig.

Double cage induction motor has two cages on the same rotor, a high resistance and low reactance bars on outer cage and low resistance and high reactance bar on inner cage.

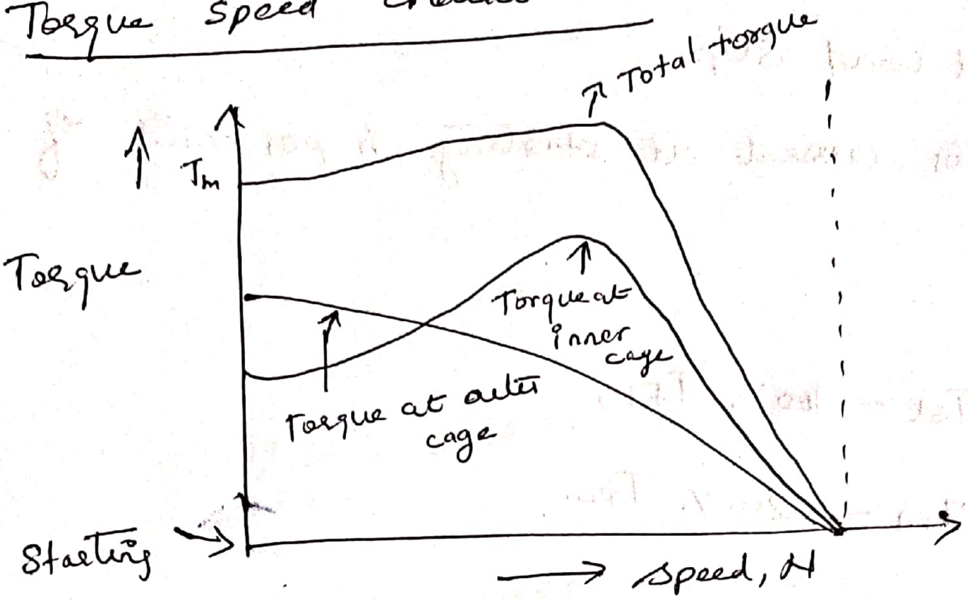
The frequency of rotor current is high due to large slip, which is nearly equal to supply frequency the current supplied to inner cages of rotor will be inversely proportional to their impedances.

Thus the current in the inner cage is small but the outer cage current is enclosed which has a high resistance. This gives good starting torque

when the speed of the motor is increased the frequency of the rotor current gets decreased. Thus the leakage reactance of inner cage is reduced when the motor is running at full speed.

Therefore the reactance of both of the cages become too small and the current is divided in the ratio of resistances.

Torque speed characteristics.



The figure shows the torque speed characteristics of double cage induction motor. The outer cage provides a high starting torque whereas the inner cage helps in obtaining the sufficient speed at the normal running condition.

Hence both the characteristics combined to provide an excellent torque-speed characteristics curve.

Due to this characteristics double cage induction motor is also known as low starting current, high starting torque, low slip motor.

6. A 3 phase induction motor has a starting torque of 100% and a maximum torque of 200% of the full load torque. Determine

(i) slip at which maximum torque occurs

(ii) full load slip

(iii) Rotor current at starting in per unit of full

Solution

Given $T_{st} = 100\%\ T_{FL}$,

$T_m = 200\%\ T_{FL}$.

$$\frac{T_{st}}{T_m} = \frac{T_{FL}}{2T_{FL}} = \frac{1}{2} = 0.5.$$

$$\frac{T_{st}}{T_m} = \frac{2S_m^2}{S_m[1+S_m^2]} = \frac{2S_m}{1+S_m^2} = 0.5$$

$$\Rightarrow 0.5S_m^2 - 2S_m + 0.5 = 0.$$

$$\frac{-b \pm \sqrt{b^2-4ac}}{2a} \Rightarrow \frac{+2 \pm \sqrt{2^2 - 4\times0.5\times0.5}}{2\times0.5}$$

$$S_m = 3.76,\ 0.2679$$

(i) slip at which T_m occurs $S_m = 0.2679$

$= 26.79\%$

(ii) $\frac{T_{FL}}{T_m} = \frac{1}{2} = 0.5$

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

$\frac{T_{FL}}{T_m} = \frac{2 a s_f}{a^2 + s_f^2}$

$S_m = \frac{R_2}{X_2} = 0.2679$.

$\Rightarrow \frac{2 \times 0.2679 \times s_f}{(0.2679)^2 + s_f^2} = 0.5$

$0.5 s_f^2 - 0.5358 s_f + 0.03588 = 0$.

$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

$= \frac{+0.5358 \pm \sqrt{(0.5358)^2 - 4 \times 0.5 \times 0.3588}}{2 \times 0.5}$

$s_f = 0.0717, \ 0.99$.

$\therefore$ full load slip $= 0.0717$ ie 7.17%

(iii) $T \propto \frac{I^2}{s}$. $\because s = 1$, at start

$\frac{T_{st}}{T_{FL}} = \frac{I_{st}^2}{1} \times \frac{s_f}{I_{FL}^2}$ $T_{st} = T_{FL}$

$$1 = \frac{I_{st}^2}{I_{FL}^2} \times 0.0717.$$

i.e $\frac{I_{st}}{I_{FL}} = 3.7345$

$$\boxed{I_{st} = 3.7345\ I_{FL}}$$

So rotor current at start is 3.7345 times full load rotor current.

7. The real power input to a 415 V 50 Hz 6 pole 3φ induction motor running at 970 rpm. is 41 kW. The input power factor is 0.9. The stator losses amount to 1.1 kW and the mechanical losses amount total 1.2 kW. calculate the
(i) line current, (ii) slip, (iii) rotor copper loss, (iv) mechanical power output (V) efficiency.

Solution:
Given :- $V_L = 415V$, $f = 50\ Hz$, $P = 6$, $N = 970$ rpm.
stator losses $= 1.1\ kW$,
$P_{in} = 41\ kW$, $\cos\phi = 0.9$,
Mech. loss $= 1.2\ kW$.

To find:
$I_L = ?$, $s = ?$, $P_{cu} = ?$, $P_{out} = ?$, $\eta = ?$.

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

$$I_L = \frac{P_{in}}{\sqrt{3}\, V_L \cos\phi} = \frac{41 \times 10^3}{\sqrt{3} \times 415 \times 0.9} = 63.377\ A.$$

$$\boxed{I_L = 63.377\ A}$$

(ii)

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm.}$$

$$s = \frac{N_s - N}{N_s} = \frac{1000 - 970}{1000} \Rightarrow 0.03$$

$$\boxed{s = 0.03 \text{ or } 3\%}$$

(iii)

Rotor input = P_{in} − stator losses

$$= (41 \times 10^3) - (1.1 \times 10^3)$$

$$\boxed{P_2 = 39.9 \text{ KW}}$$

$P_{cu} = s \times P_2$ → rotor input.

$$= 0.03 \times 39.9 \times 10^3$$

$$\boxed{P_{cu} = 1.197 \text{ kW}}$$ Rotor copper loss

(iv) Mech. power o/p.

$$\frac{P_{cu}}{P_m} = \frac{s}{1-s} \Rightarrow P_m = \frac{P_{cu}[1-s]}{s}$$

$$= \frac{1.197 \times 10^3 [1 - 0.03]}{0.03} = 38.703 \text{ KW}$$

P_m output = $P_{out} = P_m$ − Mech. loss.

$$\Rightarrow (38.703 \times 10^3) - (1.2 \times 10^3)$$

$$\boxed{P_{out} = 37.503 \text{ KW}}$$

(v) Efficiency

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

$$= \frac{37.503 \times 10^3}{41 \times 10^3} \times 100$$

$$\boxed{\eta = 91.47\%}$$