B. Three Phase Induction Motor.

Concept of Rotating magnetic field, principle of operation. constructional features of motors. Types - Squirrel cage & wound rotor. Slip & its significance. Simple numericals.

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Introduction

The three phase induction is the most widely used ac motor. It has a stator and rotor. The stator winding is connected to the three phase (3 ϕ) supply. The rotor winding is not connected to the supply. The power is transferred from stator to the rotor only by mutual induction. For this reason, it is called as induction motor. Here stator acts like primary & rotor as secondary. So it is called as rotating transformer. as the power is transferred from stator to rotor by mutual induction.

Advantages of Induction motor.

(1) It has simple and rugged construction
(2) It is relatively cheap.
(3) It requires less maintenance.
(4) ~~Fairly good Power factor~~. Reliable.
(5) It has high efficiency.

Disadvantages

(1) Speed control is difficult
(2) Poor starting torque & high inrush current (about 4 to 8 times rated current)
(3) They operate under lagging power factor.

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Rotating Magnetic Field

The rotating magnetic field is defined as the field or flux having constant amplitude but whose axis is continuously rotating in a plane with a certain speed called synchronous speed.

The threephase induction motor consists of a 3ϕ winding as its stator. The 3ϕ stator windings are connected in star or delta. ~~& displaced from each other by 120°~~. The three phase stator winding are supplied from a 3ϕ balanced supply. 3ϕ currents displaced at 120° flows through the windings. Hence three magnetic flux are produced which are sinusoidal & displaced by 120°. The resultant of these magnetic field is constant in magnitude, but continuously changes its direction. So the field is called rotating magnetic field.

The speed of rotation of stator magnetic field is called synchronous speed (N_s).

The synchronous speed can be calculated as

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

$f \rightarrow$ Frequency

$P \rightarrow$ No. of poles.

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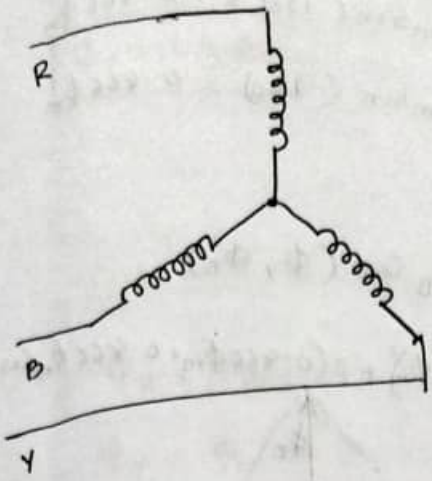
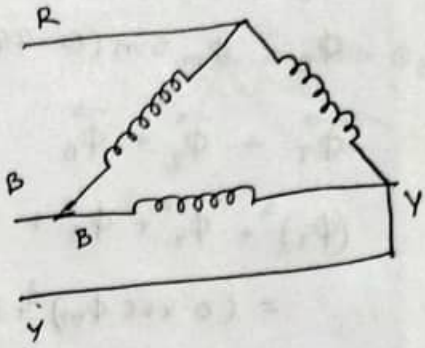
Consider 3ϕ stator winding connected in star or delta with 3ϕ supply.





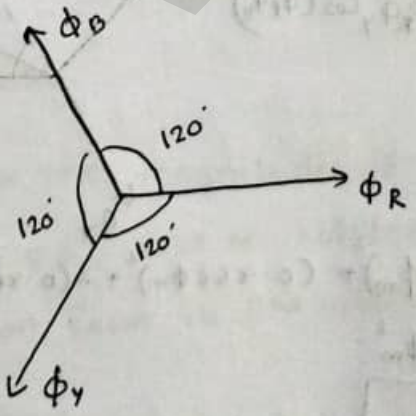
If the phase sequence of the winding is RYB, then the mathematical equation for instantaneous values of the 3 fluxes ϕ_R, ϕ_Y & ϕ_B can be written as

$$\phi_R = \phi_m \sin\theta$$

$$\phi_Y = \phi_m \sin(\theta - 120)$$

$$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(\theta + 120)$$

The vector representation of the three fluxes are shown.



The resultant flux at any instant is given by the vector sum of the individual fluxes

$$\vec{\phi_T} = \vec{\phi_R} + \vec{\phi_Y} + \vec{\phi_B}$$

Consider 4 cases with intervals $\theta = 0°$, $\theta = 60°$, $\theta = 120°$, $\theta = 180°$

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case (1)

When $\theta = 0^\circ$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 0 = 0$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(-120) = -0.866\phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(-240) = 0.866\phi_m$

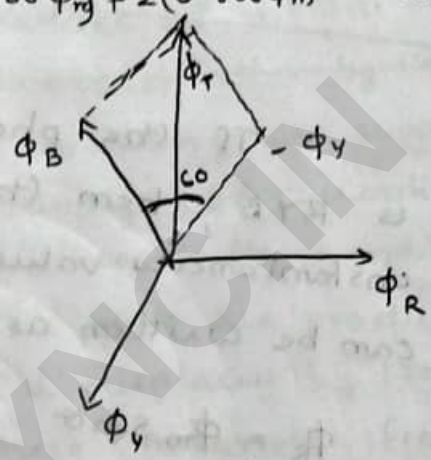
$\vec{\phi}_T = \vec{\phi}_Y + \vec{\phi}_B$

$(\phi_T)^2 = \phi_Y^2 + \phi_B^2 + 2\phi_R\phi_B \cos(\phi_Y \phi_B)$

$= (0.866\phi_m)^2 + (0.866\phi_m)^2 + 2(0.866\phi_m \times 0.866\phi_m \cos 60)$

$\phi_T^2 = 2.25\phi_m^2$

$\boxed{\phi_T = 1.5\phi_m}$



Case (2)

When $\theta = 60^\circ$

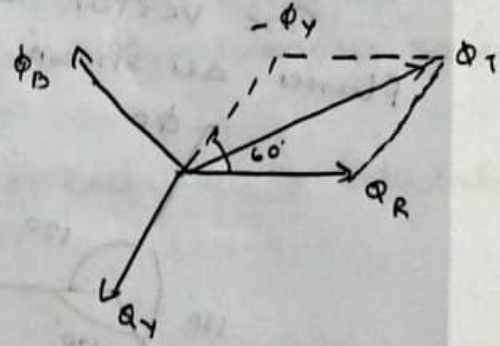
$\phi_R = \phi_m \sin\theta = \phi_m \sin 60 = 0.866\phi_m$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(60 - 120) = -0.866\phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \phi_m \sin(60 - 240) = 0$

$\bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_Y$

$\phi_T^2 = \phi_R^2 + \phi_Y^2 + 2\phi_R\phi_Y \cos(\phi_R\phi_Y)$



$\phi_T^2 = (0.866\phi_m)^2 + (0.866\phi_m)^2 + 2(0.866\phi_m)(0.866\phi_m)\cos 60^\circ$

$\phi_T^2 = 2.25\phi_m^2$

$\boxed{\phi_T = 1.5\phi_m}$

case (iii) $\theta = 120^\circ$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 120 = 0.866\phi_m$

$\phi_Y = \phi_m \sin(\theta - 120) = \phi_m \sin(120 - 120) = 0$

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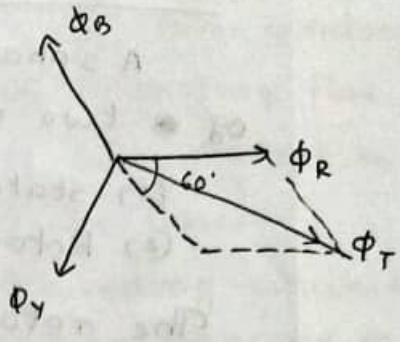
$\phi_B = \phi_m \sin(\theta - 240) = -0.866\phi_m$

$\bar{\phi}_T = \bar{\phi}_R + \bar{\phi}_B$

$\phi_T^2 = \phi_R^2 + \phi_B^2 + 2\phi_R\phi_B \cos 60$

$$\boxed{\phi_T = 1.5\phi_m}$$



<u>case (iv)</u> $\theta = 180°$

$\phi_R = \phi_m \sin\theta = \phi_m \sin 180 = 0$

$\phi_Y = \phi_m \sin(\theta - 120) = \sin 60 = 0.866\phi_m$

$\phi_B = \phi_m \sin(\theta - 240) = \sin(-60) = -0.866\phi_m$

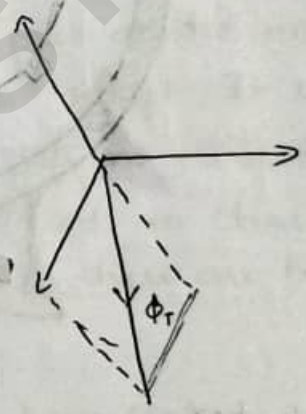
$\vec{\phi}_T = \vec{\phi}_Y + \phi_B$

$\phi_T^2 = \phi_Y^2 + \phi_B^2 + 2\phi_Y\phi_B \cos 60$

$\phi_T^2 = (0.866\phi_m)^2 + (0.866\phi_m)^2 + 2(0.866\phi_m)(0.866\phi_m)\cos 60$

$\phi_T^2 = 2.25\phi_m^2$

$$\boxed{\phi_T = 1.5\phi_m}$$



Hence the magnitude of the resultant flux $\phi_T = 1.5\phi_m$ & it is rotated through in clockwise direction from its previous position.

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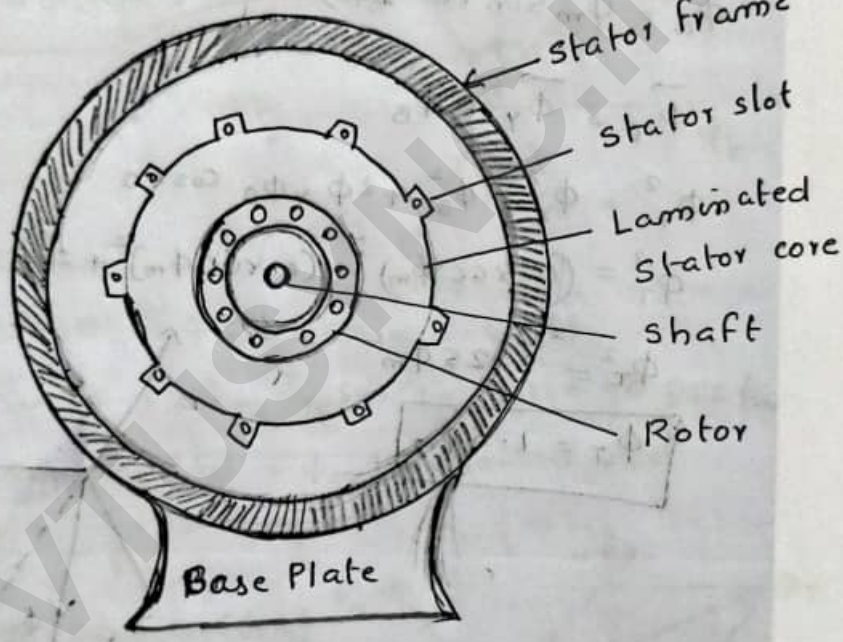
Construction of 3ϕ Induction Motor

A 3 phase induction motor consists of two main parts namely

(1) Stator
(2) Rotor

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



Stator

The main parts of stator are

(i) Stator frame
(ii) Stator core

Stator Frame

It is the outer body of the motor.

The functions of the stator frame are

(i) to support the stator core & winding
(ii) to protect the inner parts of the machine.

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Stator core.

It is a hollow cylindrical core having slots on its inner periphery to carry stator winding since the stator core carries alternating flux it is made of laminations of silicon steel to reduce eddy current & hysteresis losses.

The stator core carries 3ϕ winding which is supplied from 3ϕ supply & can be connected in star / Delta

The stator of the motor is wound for definite number of poles as per the requirement of speed $\left(N_s = \frac{120f}{P}\right)$. Greater the number of poles, lesser the speed.

The airgap between stator & rotor is ~~known~~ kept as small as possible.

Rotor

It is the rotating part of the motor. The rotor is mounted on a shaft. It is a hollow laminated core having slots on its outer periphery. The rotor windings are placed in these slots. Based on the construction, there are two types of rotors.

1. Squirrel Cage Induction Motor
2. Slip Ring Induction Motor (Phase Wound Induction Motor)

1. Squirrel Cage Induction Motor

- Squirrel cage induction motors rotor consists of cylindrical laminated core with parallel slots for carrying rotor conductors.
- The rotor conductors are heavy bars of

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copper or Aluminium. At both ends of the rotor, the rotor conductors are all short-circuited by the continuous end rings of similar material to that of rotor conductors.

- The rotor conductors & their end rings form a complete closed circuit, resembling a squirrel cage. So it is called as squirrel cage induction motor.

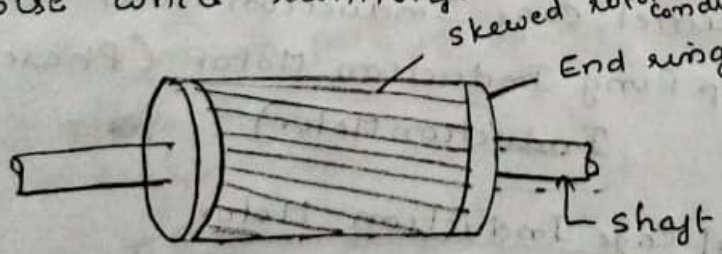
- Since the rotor winding is permanently short circuited, there is no possibility of adding any external resistance in the rotor circuit.

- Almost 90% of the induction motors are produced with squirrel cage rotor because of its simple, robust & almost indestructible construction.

- The slots on the rotor are always not parallel to the motor shaft. But are usually skewed in order to (1) obtain a uniform torque.

(2) To reduce the magnetic locking of stator & rotor

(3) To reduce the magnetic humming noise while running.



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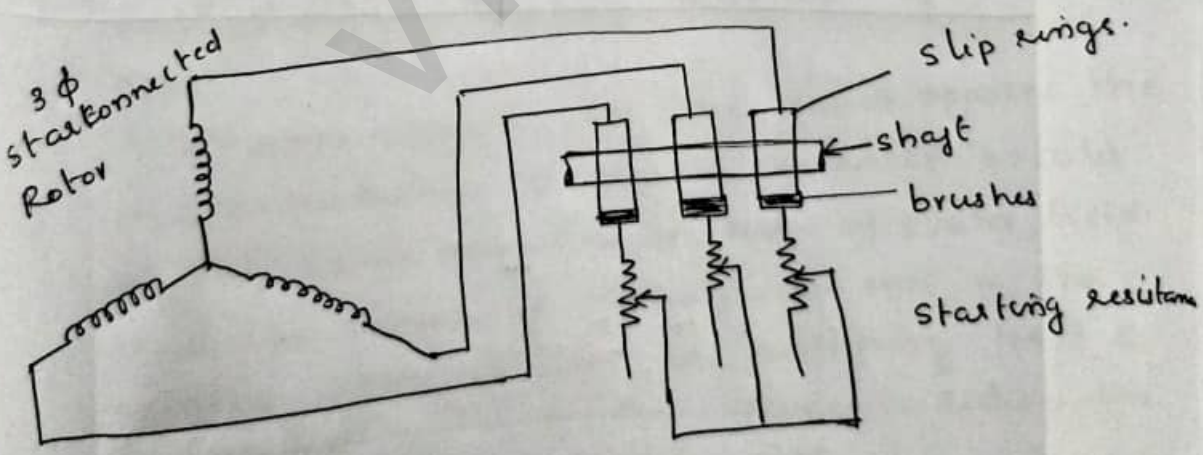
(2) Phase wound or slip ring Rotor.

- It consists of a laminated cylindrical core having uniform slots on its outer periphery.
- The rotor is wound for the same number of poles as that of stator & rotor winding is similar to stator.
- The rotor winding may be star or delta But star connection is preferred.
- The three finishing terminals are connected together to form star point & open ends of the stator windings are brought out and are connected to 3 insulated slip rings mounted on the shaft with brushes resting on them.
- The brushes are further externally connected to 3ϕ star connected rheostat for the purpose of starting & speed control.
- At the time of starting, the external resistance is included in the rotor circuit & the resistance is gradually cut out as the rotor picks up load.



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Comparison of Squirrel Cage & Slip ring Rotor

Squirrel Cage Rotor	Slip Ring Rotor
(1) Rotor consists of heavy bars of copper or Aluminium which are shorted at the ends.	(1) Rotor consists of 3 ϕ winding similar to the stator winding.
(2) Construction is simple.	(2) Construction is complicated.
(3) External Resistance cannot be added.	(3) External Resistance can be added.
(4) Slip Rings & brushes are absent	(4) Slip Rings & brushes are present
(5) Moderate starting torque	(5) High starting torque.
(6) Rotor Copper losses are less & so high efficiency	(6) Rotor Copper losses are more & hence low efficiency
(7) Used for lathes, water pumps, printing machine etc.	(7) Used for lifts, elevators & cranes etc

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Principle of Operation of 3ϕ Induction Motor

When a 3ϕ supply is given to the stator of a 3ϕ induction motor, a rotating magnetic field of constant magnitude & synchronous speed ($N_s = \frac{120f}{P}$) is set up.

~~The stationary rotor conductors at the rotating magnetic field~~

The rotating magnetic passes through the air gap and cuts the rotor conductors which are stationary.

Thus due to electromagnetic induction, an emf is induced in the motor conductors

As the motor conductors are short circuited a current passes through the rotor conductors. Hence a field is set up around Rotor Conductor.

The current carrying rotor conductors are placed in the magnetic field produced by rotor. ~~Hence a field is set up around rotor conductors~~. Both field interact each other. Therefore the rotor conductors experiences a force & a torque is produced.

Due to this torque, the rotor starts rotating in the same direction as that of the stator field.

As per Lenz's Law the result opposes the cause producing it. Hence the rotor rotates in the same direction as that of stator field. Here the cause of the induced emf is the relative speed between the rotating field & the stationary rotor conductors. Hence to reduce the cause the rotor rotates in the same direction of the stator field.

The speed of the rotor gradually increases & tries to catch the speed of the rotating field. But it fails to attain

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to attain the synchronous speed. ~~If it~~
If it reaches the synchronous speed, the relative speed $(N_s - N)$ becomes zero & there would be no induced emf & no current in the rotor conductors. No rotor field & hence no torque. Hence the machine ~~t~~ comes to standstill. Thus the induction motor never runs at synchronous speed.

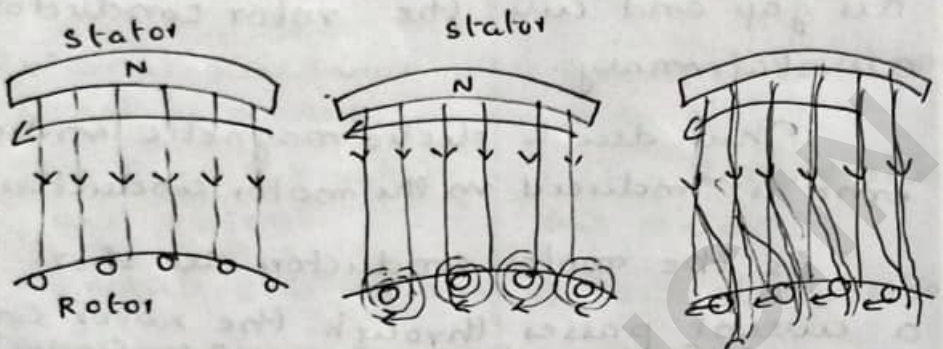

fig (a) fig (b) fig c

Slip of an Induction Motor & its importance

The slip of an induction motor is defined as the ratio of the difference between the synchronous speed N_s of the magnetic field to the actual speed of rotor N to the synchronous speed N_s

$$\text{Slip, } s = \frac{N_s - N}{N_s}$$

$$\% s = \frac{N_s - N}{N_s} \times 100$$

Without slip, (ie the difference in N_s & N, the induction motor will not work. ie If $N_s = N$, then there would be no relative speed between stator field & rotor. Hence no emf & rotor current induced & no torque would be produced.

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to drive the rotor. The friction & windage losses immedeately causes the rotor to slow down. Hence the rotor speed is always less than synchronous speed.

Frequency of the Rotor emf & Current

At start when $N = 0$, $s = \frac{N_s - N}{N_s} = 1$

ie when the rotor is stationary, the rotor conductors are being cut by the rotating flux at synchronous speed. $N_s = \frac{120f}{P}$

Hence maximum emf is induced in the rotor at start & the frequency of the rotor current is same as supply frequency.

$$N_s = \frac{120f}{P} \quad \text{———} \quad (1)$$

But the rotor starts revolving with speed N, the rate at which the rotor conductor is being cut by the rotating flux depends on the relative speed between the rotor & stator rotating flux called slip speed $(N_s - N)$

$$N_s - N = \frac{120 f_r}{P} \quad \text{———} \quad (2)$$

$f_r \rightarrow$ Rotor frequency.

$$(2)/(1) \qquad \frac{N_s - N}{N_s} = \frac{120 f_r}{P} \Big/ \frac{120f}{P}$$

$$\frac{N_s - N}{N_s} = \frac{f_r}{f}$$

$$s = \frac{f_r}{f} \qquad \boxed{f_r = sf}$$

~~Hence~~ where $s \rightarrow$ slip

$f_r \rightarrow$ rotor frequency

$f \rightarrow$ supply frequency

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Application of Induction Motors

Squirrel cage Induction motors having moderate starting torque & constant speed characteristics. Hence used for driving water pumps lathe machines, printing machine, drilling machine

Slip ring induction motors having starting torque, & hence used for elevator, lifts & cranes & compressors.

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Three ϕ Induction Motors

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- Review of concept and generation of RMF, principle construction, classification and types; squirrel cage, slip-ring

Slip of Induction motor

The rotor of an Induction motor is always rotate at a speed less than the synchronous speed. The difference between synchronous speed (Ns) and rotor speed (N) is called slip speed.

Slip of the Induction motor is defined as the difference b/w Ns and N, expressed as a fraction of the synchronous speed (Ns). This is called absolute slip or fractional slip and is denoted as 's'.

$$s = \frac{N_s - N}{N_s} \quad \text{——— (1)}$$

$$\% s = \frac{N_s - N}{N_s} \times 100$$

$$N = N_s(1-s)$$

At start $N = 0 \Rightarrow N_s(1-s) = 0$

(1) becomes $s = \frac{N_s}{N_s} = 1$ [max. value of slip]

when $s = 0$, $N_s = N$ → not possible for an induction motor

Slip ranges — 1% – 5%.

The slip corresponding to full load speed of the motor is called full load slip.

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Effect of slip on rotor parameters

As the motor gathers speed, IM has some slip corresponding to N. Slip affects the frequency of rotor induced emf. Due to this following rotor parameters get affected
1. Rotor frequency 2. Magnitude of rotor induced emf 3. Rotor reactance 4. Rotor PF 5. Rotor current.

Effect on Rotor frequency

Speed of RMF $N_s = \frac{120f}{P}$ — (1) f = Supply frequency

$N_s - N = \frac{120f'}{P}$, — (2) f' = rotor emf frequency

(2) ÷ (1) $\frac{N_s - N}{N_s} = \frac{120f'/P}{120f/P} = \frac{f'}{f}$

$$S = \frac{f'}{f}$$

$$\boxed{f' = Sf} \quad \boxed{f_r = Sf}$$

Effect on magnitude of rotor Induced emf

E_2 = Rotor induced EMF/phase on stand still
E_{2r} = Rotor " " " in running

$E_2 \propto N_s$ $E_{2r} \propto N_s - N$

$$\frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s} = S \qquad \boxed{E_{2r} = SE_2}$$

classmate

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Effect on Rotor resistance and reactance

R_2 = Rotor resistance/phase on standstill
X_2 = Rotor reactance/phase on standstill

$= 2\pi f L_2 \ \Omega/ph$

Now in running

$f_r = sf$

$X_{2r} = 2\pi f_r L_2 = \cancel{2\pi f s}$

$= 2\pi s f L_2 = s \cdot (2\pi f L_2) = s X_2$

$$\boxed{X_{2r} = s X_2}$$

The resistance as independent of frequency remains same at standstill and in running condition.

Z_2 = Rotor impedance on standstill
$= R_2 + jX_2$

Z_{2r} = Rotor impedance in running condition
$= R_2 + jX_{2r}$

$$\boxed{Z_{2r} = R_2 + j(sX_2) \ \Omega/ph}$$

$$\boxed{Z_{2r} = \sqrt{(R_2)^2 + (sX_2)^2} \ \Omega/ph}$$

Effect on rotor power factor

$\cos\phi_2$ = Rotor pf on standstill

$= \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$

$\cos\phi_{2r}$ = Rotor pf in running condition

$$\boxed{\cos\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}}$$

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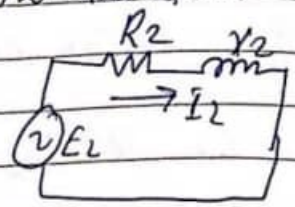
Effect on rotor current

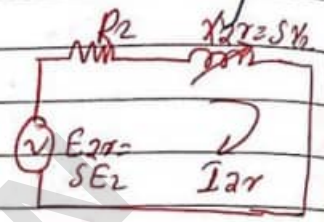
I_2 = Rotor current/phase on standstill

$$= \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$



I_{2r} = Rotor current/phase in running condition

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$



Torque Equation

The torque produced in the induction motor depends on the following factors

1. The RMF which is responsible for inducing emf in the rotor (ϕ)
2. The magnitude of rotor current in running condition (I_{2r})
3. The power factor of the rotor in running condition ($\cos\phi_{2r}$)

Mathematically →

$$T \propto \phi I_{2r} \cos\phi_{2r} \quad \text{——— (1)}$$

The flux ϕ produced by stator is proportional to E_1. (E_1 stator voltage)

$$\phi \propto E_1 \quad \text{——— (2)}$$

E_1 and E_2 are related by turns ratio, k

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

$$E_2 = KE_1 \quad \text{—— (3)}$$

Assume $K = 1$

(3) becomes $E_2 = E_1$

(2) becomes $\phi \propto E_1 \propto E_2$

$$\phi \propto E_2$$

Eq (1) becomes $T \propto E_2 I_2 r \cos\phi_2 r$

$$T \propto E_2 \frac{SE_2}{\sqrt{R_2^2 + (Sx_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (Sx_2)^2}}$$

$$T \propto \frac{SE_2^2 R_2}{R_2^2 + (Sx_2)^2} \quad N\text{-}m$$

$$\boxed{T = \frac{k_1 SE_2^2 R_2}{R_2^2 + (Sx_2)^2}}$$

K_1 = Constant of proportionality

$$\boxed{K_1 = \frac{3}{2\pi n_s}} \qquad n_s = \frac{N_s}{60}$$

$$\boxed{T = \frac{3}{2\pi n_s} \cdot \frac{SE_2^2 R_2}{R_2^2 + (Sx_2)^2}} \text{ — N m.}$$

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Starting Torque

$s = 1, \quad N = 0$

$$\boxed{T_{st} = \frac{3E_2^2 R_2}{2\pi n_s (R_2^2 + X_2^2)} \quad N\text{-}m}$$

Condition for Maximum Torque (T_m) :-

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

To find the condition for max. torque using max, minima theorem

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

$$= \frac{[R_2^2 + (sX_2)^2][K E_2^2 R_2] - K s E_2^2 R_2 [2sX_2^2]}{[R_2^2 + (sX_2)^2]^2} = 0$$

$$R_2^2 + (sX_2)^2 (\cancel{K E_2^2 R_2}) = \cancel{K} s \cancel{E_2^2} \cancel{R_2} (2sX_2^2)$$

$$R_2^2 + (sX_2)^2 = 2s^2 X_2^2$$

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

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

$$\boxed{s = \frac{R_2}{X_2}} \qquad \boxed{s_m = \frac{R_2}{X_2}}$$ slip at max. Torque

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Magnitude of max. Torque

$$T = \frac{K S E_2^2 R_2}{R_2^2 + (S X_2)^2} \quad N\text{-}m$$

Replacing S by S_m in the above equation,

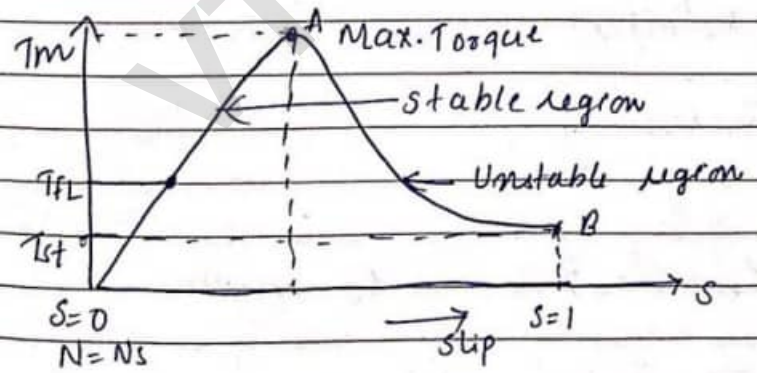
$$T_m = \frac{K S_m E_2^2 R_2}{R_2^2 + (S_m X_2)^2} = \frac{K \times \frac{R_2}{X_2} \cdot E_2^2 R_2}{R_2^2 + \left[\frac{R_2}{X_2}\right]^2 X_2^2}$$

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

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

$$\boxed{T_m = \frac{K E_2^2}{2 X_2} \quad N\text{-}m}$$

Torque slip characteristics



OA = Stable region

C = full load torque

A = Max. Torque

B = starting torque

It consists of 1) low slip region
2) High slip region

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Low slip region:- ($s = 0$ to $s = s_m$)

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \quad \text{--- (1)}$$

for a const supply voltage, E_2 is also constant

Eq: (1)

$$T \propto \frac{s R_2}{R_2^2 + (s X_2)^2} \quad \text{--- (2)}$$

In slow slip region 's' is very very small. Due to this $(sX_2)^2$ is so small compared to R_2^2. so $(sX_2)^2$ can be neglected.

$$(2) \Rightarrow \quad T \propto \frac{s R_2}{R_2^2} \propto \frac{s}{R_2}$$

$\boxed{T \propto s}$ R_2 remains const.

High slip region ($s = s_m$ to $s = 1$)

$$T \propto \frac{s R_2}{R_2^2 + (s X_2)^2}$$

As s is increasing, $s = 1$,

$$T \propto \frac{s R_2}{R_2^2 + s^2 X_2^2}$$ R_2 remains const

$$\cancel{T \propto R_2} \quad T \propto \frac{s}{s^2 X_2^2}$$

$$\boxed{T \propto \frac{1}{s}}$$ X_2 remains const

Hence its nature is like rectangular hyp

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Torque - slip characteristics has 2 parts

→ stable region of operation (straight line)
→ Unstable region of operation (Rectangular hyperbola)

In low slip region load increase N↓ S↑ T↑ linearly, which satisfies the load demand. Linear behaviour continues, till $S = S_m$

If load increases beyond this limit → high slip region. N↓ S↑ T↓ (because $T \propto \frac{1}{S}$)
But Torque must increase to satisfy the load demand. As torque decreases, speed further decreases, and slip further increases. Eventually motor comes to standstill condition. This region is called unstable region.

Max. Torque (breakdown Torque or pull out torque)
Max torque which motor can produce is also called breakdown torque or pull out torque.

Starting torque
At $S = 1$ $N = 0$

Full load Torque
The load which motor can drive safely while operating continuously and due to such load current drawn also within safe limits is called full load condition of motor.

$T_{full\ load} < T_m$

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Motoring, generating, braking Region of modes of operation

(i) Motoring mode Region:-

→ When the slip lies in the region between 0 & 1 the machine runs as motor i.e $0 \le s \le 1$

→ The direction of rotation of the rotor is same as that RMF

→ The rotor speed and corresponding torque are in same direction.

(ii) Braking mode:-

→ When the slip is greater than 1, the machines works in braking mode.

→ The rotor is rotate in opposite direction of that of RMF

→ The motor comes to quick stop under the influence of counter torque, which produces braking action.

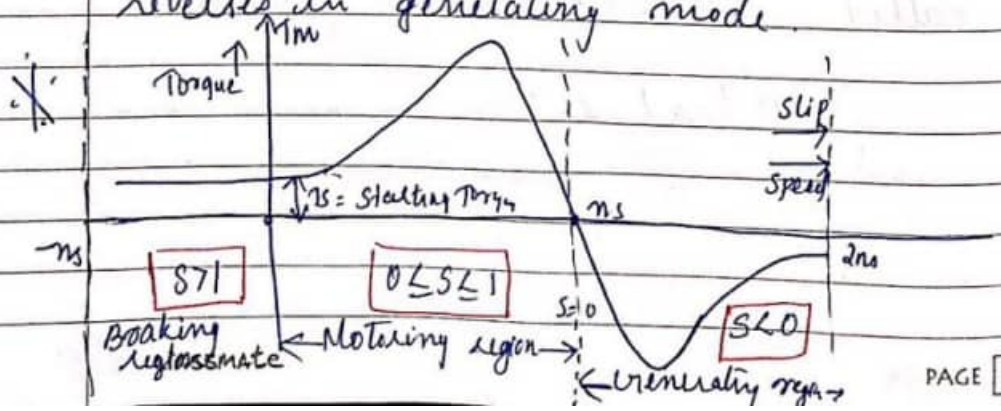
→ The method is also known as plugging

→ ~~[illegible]~~

(iii) Generating mode:-

→ The value of the slip must be less than zero, (negative slip) indicates that the rotor is rotating at a speed above synchronous speed

→ The nature of torque-slip characteristic reverses in generating mode.



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Effect of change in Voltage and frequency

1. Halving the applied voltage, keeping frequency normal

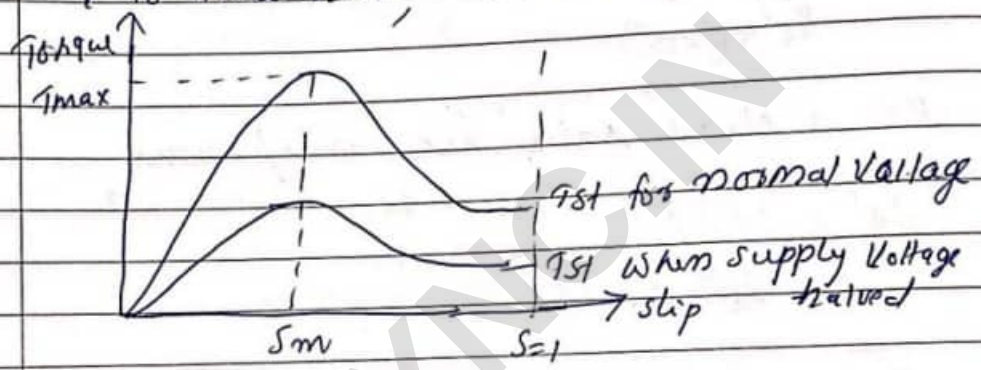
$$T \propto \frac{K S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

$E_2 \propto V$

$$T \propto \frac{K' S V^2 R_2}{R_2^2 + (S X_2)^2} = \frac{K' S V^2}{R_2}$$

$T \propto S V^2$

V is made half, T is reduce by 1/4



Problems

1. A 1000V, 50Hz 3φ IM has star connected stator. The ratio of stator to rotor turns is 3.6. The standstill impedance of rotor/phase is 0.01 + j0.022 Calculate
   i) Rotor current at start
   ii) Rotor pf at start
   iii) Rotor current at slip of 3%.
   iv) External resistance/phase in the rotor ckt to limit starting rotor current to 200A.

$V_L = 1000V$ $\quad V_{ph} = \frac{1000}{\sqrt{3}} = 577.35V$

$f = 50Hz$

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$\frac{\text{stator turns}}{\text{Rotor turns}} = 3.6$

$K = \frac{\text{Rotor turns}}{\text{stator turns}} = \frac{1}{3.6} = 0.277$

$Z_L = R_2 + jX_2 =$
$= 0.01 + j0.2$

i) $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}} =$

$E_2 = K \times E_1 = 0.277 \times 577.35 = 160.37$ V/phase

$I_2 = \frac{160.37}{\sqrt{0.01^2 + 0.2^2}} = 800.85 A \angle -1.52 A$

ii) At start $\phi_2 = \frac{R_2}{Z_2} = \frac{0.01}{\sqrt{0.01^2 + 0.2^2}} = 0.045$

iii) $S = 0.03$

$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{S E_2}{\sqrt{R_2^2 + (S X_2)^2}} = \frac{0.03 \times 160.37}{\sqrt{(0.01)^2 + (0.03 \times 0.2)^2}}$

$= 412.54 A$

iv) Let Rex external resistance

$R_2' = R_2 + Rex$

$I_2 = \frac{E_2}{\sqrt{(R_2')^2 + (X_2)^2}} \Rightarrow 200 = \frac{160.37}{\sqrt{(R_2')^2 + (0.2)^2}}$

$\sqrt{(R_2')^2 + 0.2^2} = 0.8018 \Rightarrow R_2' = 0.7765 \Omega$

$0.7765 = R_2 + Rex = 0.01 + Rex$; $\boxed{Rex = 0.7665 \Omega}$

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2. A 400V, 4 pole 3ϕ, 50Hz star connected induction motor has a rotor resistance and reactance per phase equal to 0.01Ω and 0.1Ω respectively. Determine i) starting torque ii) slip at which max. torque will occur iii) speed at which max. torque will occur iv) Max. torque v) full load torque if full load slip is 4%. Assume ratio of stator to rotor turns as 4

$P = 4 \quad E_{1L} = 400 \quad E_{1ph} = \frac{400}{\sqrt{3}} = 230.94\,V$

$K = \frac{1}{4} \quad E_2 = K \times E_{1ph} = \frac{1}{4} \times 230.94 = 57.735$

$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

i) At start $S = 1$

$T_{st} = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2} \Rightarrow K_1 = \frac{3}{2\pi n_s}$

$n_s = \frac{N_s}{60} = \frac{1500}{60} = 25$

$K_1 = \frac{3}{2\pi \times 25} = 0.01909$

$T_{st} = \frac{0.01909 \times 57.735^2 \times 0.01}{0.01^2 + 0.1^2} = 63.031$ N-m

ii) $S_m = \frac{R_2}{X_2} = \frac{0.01}{0.1} = 0.1 \quad \% S_m = 10\%$

iii) $N = N_s(1 - S_m) = 1500[1 - 0.1] = 1350$ rpm

iv) $T_m = \frac{K E_2^2}{2X_2} = \frac{0.01909 \times 57.735^2}{2 \times 0.1} = 318.16$ N-m

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v) $s_f = 0.04$ $\%s_f = 4\%$

$$T_{fL} = \frac{K s_f E_2^2 R_2}{R_2^2 + (s_f X_2)^2} = \frac{0.01909 \times 0.04 \times 57.735^2 \times 0.01}{0.01^2 + (0.04 \times 0.1)^2}$$

$$= 219.52 \text{ N-m}$$

3. Calculate the torque exerted by an 8 pole 50Hz, 3ϕ IM operating with a 4% slip which develops a max. torque of 150 kg-m at a speed of 660 rpm. The resistance/phase of the rotor is 0.5Ω

$P = 8$, $f = 50Hz$ $S = 4\% = 0.04$ $T_m = 150$ kg-m

$N_m = 660$ rpm, $R_2 = 0.5\Omega$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm}$$

$$s_m = \frac{N_s - N_m}{N_s} = \frac{750 - 660}{750} = 0.12$$

$$s_m = \frac{R_2}{X_2} \Rightarrow 0.12 = \frac{0.5}{X_2} \quad X_2 = 4.16667\Omega$$

$$T_m = \frac{KE_2^2 R_2 s_m}{R_2^2 + (s_m X_2)^2} \qquad T_m = 150 \times 9.81 \text{ N-m at } s_m$$

$$150 \times 9.81 = \frac{KE_2^2 \times 0.5 \times 0.12}{0.5^2 + (0.12 \times 4.16667)^2}$$

$$KE_2^2 = 12262.5098$$

At $s = 0.04$

$$T = \frac{KSE_2^2 R_2 s_m}{R_2^2 + (s_m X_2)^2} = \frac{12262.5098 \times 0.04 \times 0.5}{(0.5)^2 + (0.04 \times 4.1667)^2}$$

$$= 882.9 \text{ N-m}$$

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4. A 440V, 3φ 50Hz 4 pole star connected IM has a full load speed of 1425 rpm. The rotor has an impedance of (0.4+j4) Ω/phase and has an impedance of 0.8. Calculate rotor/stator turns ratio of 0.8. Calculate i) Full load torque ii) Full load copper loss iii) Maximum torque and the speed at which it occurs. iv) Starting current.

$N = 1425$ rpm $\quad f = 50Hz \quad P = 4 \quad R_2 = 0.4\Omega$

$X_2 = 4\Omega$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$$S_{FL} = \frac{N_s - N}{N_s} = 0.05$$

$$E_{1ph} = \frac{E_L}{\sqrt{3}} = \frac{440}{\sqrt{3}}$$

$$K = 0.8 \qquad E_{2ph} = K \times E_{1ph} = 0.8 \times \frac{440}{\sqrt{3}} = 203.227$$

i) $$T_{FL} = \frac{3}{2\pi n_s} \times \frac{S_{FL} E_2^2 R_2}{R_2^2 + (S_{FL} X_2)^2} = 78.88 \text{ N-m}$$

ii) $$I_{2r} = \frac{S_{FL} E_2}{\sqrt{R_2^2 + (S_{FL} X_2)^2}} = \frac{0.05 \times 203.227}{\sqrt{(0.4)^2 + (0.05 \times 4)^2}} = 22.72 \text{ A}$$

$$\text{cu loss} = 3 I_{2r}^2 \times R_2 = 3 \times 22.72^2 \times 0.4 = 619.51 \text{ W}$$

iii) $$T_m = \frac{3}{2\pi n_s} \times \frac{E_2^2}{2X_2} = 98.6 \text{ N-m}$$

$$S_m = \frac{R_2}{X_2} = 0.1 \qquad N_m = N_s(1 - S_m) = 1350 \text{ rpm}$$

$$I_{st} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}} = \frac{203.227}{\sqrt{0.4^2 + 4^2}} = 50.554 \text{ A}$$

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5. A 3ϕ IM having 6 poles, stator wdg is star connected runs on 240V, 50Hz supply. The rotor resistance and stand still reactance are 0.12Ω and 0.85Ω / phase. The ratio of ~~rotor to~~ stator to rotor turns is 1.8 and full load slip is 4%. Calculate the developed torque at full load, maximum torque and the speed at maximum torque.

$R_2 = 0.12\Omega \quad X_2 = 0.85\Omega \quad S = 0.04 \quad K = \frac{1}{1.8}$

$E_{1ph} = \frac{240}{\sqrt{3}} = 138.56\,V \qquad E_{2ph} = K \times E_{1ph} = 76.98\,V$

$N_s = \frac{120 \times f}{P} = 1000$ r.p.m

$n_s = \frac{1000}{60} = 16.67$

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

$= \frac{3}{2\pi \times 16.67} \times \frac{0.04 \times 76.98^2 \times 0.12}{0.12^2 + (0.04 \times 0.85)^2} = 52.372\,Nm$

$T_M = \frac{3}{2\pi n_s} \times \frac{E_2^2}{2X_2} = \frac{3}{2\pi \times 16.67} \times \frac{76.98^2}{2 \times 0.85} = 99.85\,N\text{-}m$

$N_M = N_S(1 - S_M) \qquad S_M = \frac{R_2}{X_2} = \frac{0.12}{0.85} = 0.1411$

$= 1000(1 - 0.1411)$

$N_m = 858.9$ rpm

6. A 6 pole – 3ϕ 50Hz IM runs on full load with a slip of 4%. The rotor stand still impedance/phase is $(0.01 + j0.05)\,\Omega$. Calculate the available max. torque in terms of full load torque. Also determine the speed at which the max. torque occurs.

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5. A 3ϕ IM having 6 poles, stator wdg is star connected runs on 240V, 50Hz supply. The rotor resistance and stand still reactance are 0.12Ω and 0.85Ω / phase. The ratio of ~~rotor to~~ stator to rotor turns is 1.8 and full load slip is 4%. Calculate the developed torque at full load, maximum torque and the speed at maximum torque.

$R_2 = 0.12\Omega \quad X_2 = 0.85\Omega \quad S = 0.04 \quad K = \frac{1}{1.8}$

$E_{1ph} = \frac{240}{\sqrt{3}} = 138.56\,V \qquad E_{2ph} = K \times E_{1ph} = 76.98\,V$

$N_s = \frac{120 \times f}{P} = 1000$ r.p.m

$n_s = \frac{1000}{60} = 16.67$

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

$= \frac{3}{2\pi \times 16.67} \times \frac{0.04 \times 76.98^2 \times 0.12}{0.12^2 + (0.04 \times 0.85)^2} = 52.372\,Nm$

$T_M = \frac{3}{2\pi n_s} \times \frac{E_2^2}{2X_2} = \frac{3}{2\pi \times 16.67} \times \frac{76.98^2}{2 \times 0.85} = 99.85\,N\text{-}m$

$N_M = N_s(1 - S_M) \qquad S_M = \frac{R_2}{X_2} = \frac{0.12}{0.85} = 0.1411$

$= 1000(1 - 0.1411)$

$N_m = 858.9$ rpm

6. A 6 pole – 3ϕ 50Hz IM runs on full load with a slip of 4%. The rotor stand still impedance/phase is $(0.01 + j0.05)\,\Omega$. Calculate the available max. torque in terms of full load torque. Also determine the speed at which the max. torque occurs.

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$P = 6 \quad f = 50Hz \quad S_f = 4\%$

$Z_2 = R_2 + jX_2 = 0.01 + j0.05\,\Omega$

$$\frac{T_{FL}}{T_m} = \frac{S_f R_2}{R_2^2 + (S_f X_2)^2} \times \frac{R_2^2 + (S_m X_2)^2}{S_m R_2}$$

$$= \frac{S_f}{S_m}\left[\frac{R_2^2 + (S_m X_2)^2}{R_2^2 + (S_f X_2)^2}\right] \qquad S_m = \frac{R_2}{X_2} = 0.2$$

$$= \frac{0.04}{0.2}\left[\frac{0.01^2 + (0.2 \times 0.05)^2}{[(0.01)^2 + (0.04 \times 0.05)^2]}\right] = 0.3846$$

$$T_m = \frac{T_{FL}}{0.3846}$$

$$\boxed{T_m = 2.6\, T_{FL}}$$

$N_m = N_s(1 - S_m) \qquad N_s = \frac{120f}{P} = 1000$

$= 1000(1 - 0.2)$

$= 800$ rpm

7. A 6 pole 3ϕ, 50Hz IM develops a max. torque of 30 Nm at 960 rpm. Determine the torque exerted by the motor at 5% slip. The rotor resistance/phase is 0.6 Ω

$P = 6, \quad f = 50Hz \quad T_m = 30\ N\text{-}m \quad N_m = 960$ rpm

$S = 0.05$

$$N_s = \frac{120f}{P} = 1000 \text{ rpm}$$

$$S_m = \frac{N_s - N_m}{N_s} = \frac{1000 - 960}{1000} = 0.04$$

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

$$0.04 = \frac{\cancel{R_2}\ 0.6}{X_2}$$

$$X_2 = 15\Omega$$

$$T_m = 30\ N\text{-}m$$

$$30 = \frac{K E_2^2 R_2 S_m}{R_2^2 + (S_m X_2)^2}$$

$$30 = \frac{K E_2^2 \times 0.6 \times 0.04}{0.6^2 + (0.04 \times 15)^2}$$

$$K E_2^2 = 900$$

T at S = 5%

$$T = \frac{K E_2^2 \times R_2 S}{R_2^2 + (S X_2)^2} = \frac{900 \times 0.6 \times 0.05}{0.6^2 + (0.05 \times 15)^2}$$

$$= 29.268\ N\text{-}m$$

8. A 746 kW, 3φ 50 Hz 16 pole IM has a rotor impedance of $(0.02 + j0.15)\Omega$ at stand still. Full load torque is obtained at 360 rpm. Calculate i) the speed at which max torque occurs (ii) The ratio of max. to full load torque (iii) External resistance/phase to be inserted in the rotor ckt to get max. torque at starting.

$R_2 = 0.02$ $\quad X_2 = 0.15\Omega$ $\quad p = 16,\ f = 50Hz$

$$S_m = \frac{R_2}{X_2} = 0.1333, \quad N_s = \frac{120f}{p} = 375\ rpm$$

i) $N_m = N_s(1 - S_m) = 325\ rpm$

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(i) $\frac{T_m}{T_{FL}} = \frac{s_f^2 + s_m^2}{2 s_f s_m}$ $\quad s_f = \frac{N_s - N}{N_s} = \frac{375 - 360}{375} = 0.04$

$= \frac{0.04^2 + 0.1333^2}{2 \times 0.04 \times 0.1333} = 1.816$

(ii) T_m at start $s_m = 1 = \frac{R_2}{X_2}$ $\quad R_2 = 0.15\Omega$

$R_{ex} = 0.15 - 0.02 = 0.13\Omega$

9. A 4 pole 50Hz, 3ϕ IM develops max torque of 110 Nm at 1360 rpm. The resistance of the star connected rotor is 0.25Ω/phase. Calculate the value of resistance that must be inserted in series with each rotor phase, to produce a starting torque equal to half of the max. torque.

$P = 4 \quad f = 50Hz \quad T_m = 110 Nm \quad N_m = 1360$ rpm

$N_s = \frac{120f}{P} = 1500$ rpm $\quad s_m = \frac{N_s - N_m}{N_s} = 0.09333$

$R_2 = 0.25\Omega/ph \quad s_m = \frac{R_2}{X_2} \Rightarrow X_2 = 2.6786\Omega/ph$

$T_{st} = \frac{1}{2} T_m \quad R_2' = R_2 + R_x$

$\frac{T_m}{T_{st}} = \frac{s_m E_2^2 R_2}{R_2^2 + (s_m X_2)^2} \times \frac{(R_2')^2 + (X_2)^2}{E_2^2 R_2'}$

$= 2$

$(R_2')^2 - 10.7143 R_2' + 7.1748 = 0$

$R_2' = 9.996, \; 0.7177$

Neglecting higher value $R_2' = 0.7177 = R_2 + R_x$

$R_x = 0.4677\Omega$/phase

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Losses in an IM

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i) Constant losses
ii) Variable losses

i) Constant losses

→ Core losses + Mechanical losses

→ Core losses → Stator core losses + Rotor core losses

Core losses →

→ This include eddy current losses and hysteresis losses

→ Iron losses depend on frequency.

→ Stator iron losses are dominant (because stator supply frequency is always supply frequency)

→ Rotor iron losses are very small (because rotor frequency is very very small) hence can be neglected.

Mechanical losses = frictional losses + windage losses

Variable losses

→ Cu losses in stator and rotor wdg due to current flowing in the wdg.

Rotor cu losses $= 3I_{2r}^2 R_2$

Power flow diagram

$P_{in} = \sqrt{3} V_L I_L \cos\phi$ = Net i/p electrical power
= Stator i/p

$P_2 = P_{in}$ − Stator losses (core + copper)
= Rotor i/p

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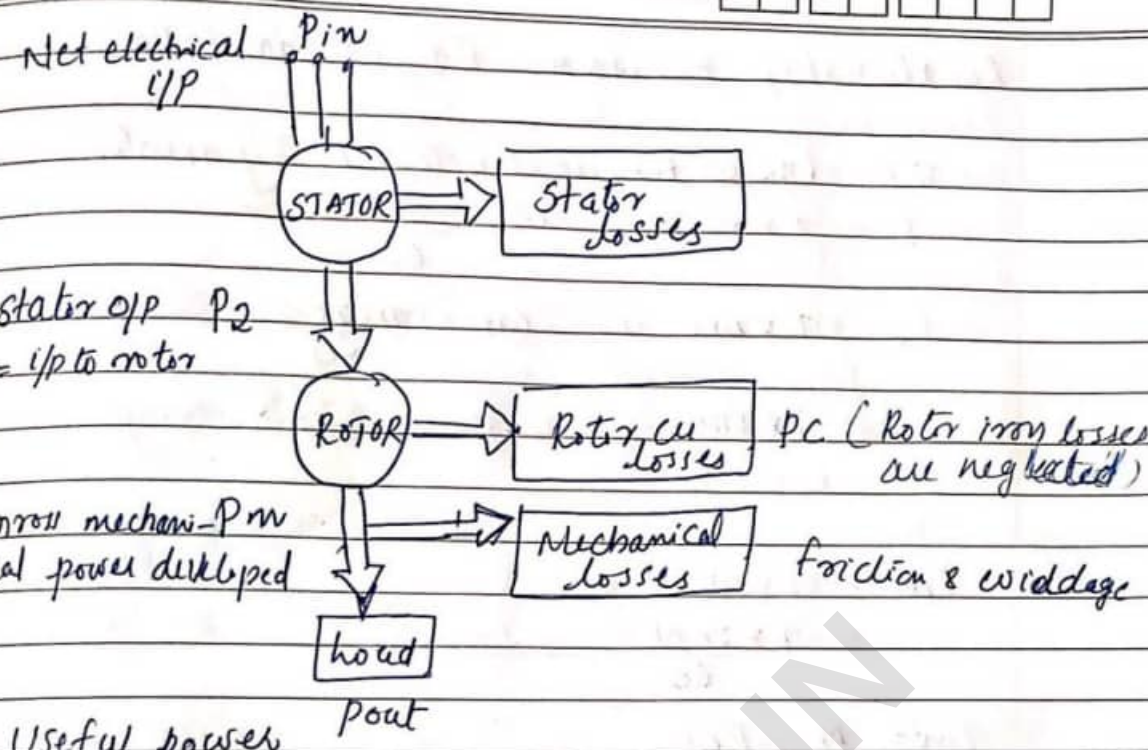

$P_m = P_2 - P_C$ $\qquad$ $P_C = 3I_{2r}^2 \times R_2$

$P_{out} = P_m -$ mechanical losses

$$\text{Rotor efficiency} = \frac{\text{Rotor o/p}}{\text{Rotor i/p}} = \frac{\text{Gross mechanical power}}{\text{Rotor i/p}}$$

$$= \frac{P_m}{P_2}$$

$$\text{Net motor } \eta = \frac{\text{Net o/p at shaft}}{\text{Net electrical i/p to motor}} = \frac{P_{out}}{P_{in}}$$

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Relationship between P_2, P_C and P_m:-

T = Gross torque developed by motor in N-m

$P = T \times \omega$ $\qquad \omega = \frac{2\pi N}{60}$

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

$= T \times \frac{2\pi N_s}{60}$ —— (1)

$P_m = T \times \omega$

$= T \times \frac{2\pi N}{60}$ —— (2)

$P_m = P_2 - P_C$

$P_C = P_2 - P_m$

$= T \times \frac{2\pi N_s}{60} - T \times \frac{2\pi N}{60}$

$P_C = T \times \frac{2\pi}{60}[N_s - N]$ —— (3)

(3) ÷ (1) $\frac{P_C}{P_2} = \frac{T \times \frac{2\pi}{60}[N_s - N]}{T \times \frac{2\pi}{60}[N_s]} = \frac{N_s - N}{N_s} = S$

$\therefore \frac{P_C}{P_2} = S \Rightarrow \boxed{P_C = SP_2}$

$P_m = P_2 - P_C = P_2 - SP_2 = P_2(1-S)$

$\boxed{P_m = P_2(1-S)}$

$\therefore P_2 : P_C : P_m = 1 : S : (1-S)$

Load torque $= \frac{P_{out}}{\omega}$ N-m

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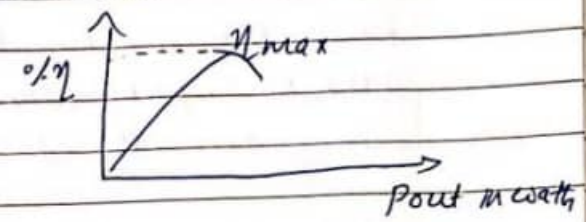
Efficiency of an Induction motor

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



Equivalent Ckt of 3ϕ IM :-

3ϕ IM can be treated as a generalised transformer

E_1 = EMF induced in rotor/phase

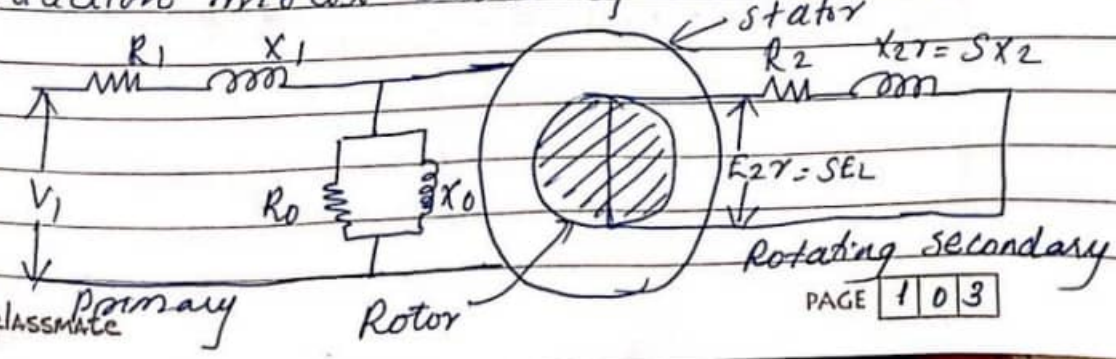
E_2 = Rotor induced emf/phase on standstill

$K = \frac{\text{Rotor turns}}{\text{stator turns}}$ $\quad K = \frac{E_2}{E_1}$

V_1 = supply voltage/phase to stator
it produces RMF

In running condition E_2 becomes $E_{2r} = SE_2$
E_{2r} = Rotor induced emf in ~~stator~~ running condition/phase
R_2 = Rotor resistance/phase
X_{2r} = Rotor reactance/phase running
R_1 = Stator reactance/phase
X_1 = stator reactance/phase

Induction motor can be represented as a transformer



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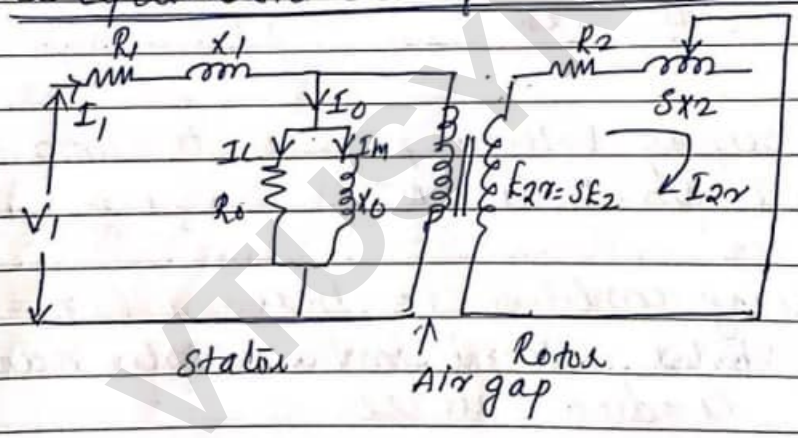
When IM is on no load, it draws current from the supply to produce the flux in airgap and to supply iron losses.
This current I_0 has 2 components I_m & I_c

I_m = magnetising component which sets up flux in core and airgap
I_c = Active component which supplies no load losses.

$$R_0 = \frac{V_1}{I_C} \quad ; \quad X_0 = \frac{V_1}{I_m}$$

$$I_0 = I_C + I_m$$

The equivalent ckt of induction motor is



$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Note :- As load on the motor changes, the motor speed changes. Thus slip changes. Thus reactance X_{2r} changes [$X_{2r} = SX_2$]

Representation of rotor impedance

$$I_{2r} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} = \frac{E_2}{\sqrt{\left[\frac{R_2}{S}\right]^2 + X_2^2}}$$

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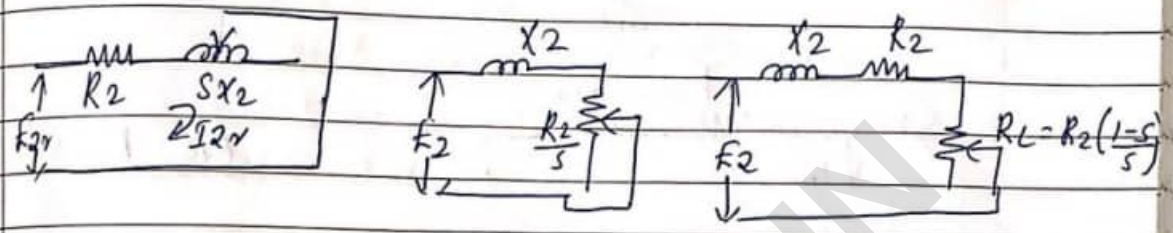
$$\frac{R_2}{s} = R_2 + \frac{R_2}{s} - R_2$$

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

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

Rotor equivalent ckt

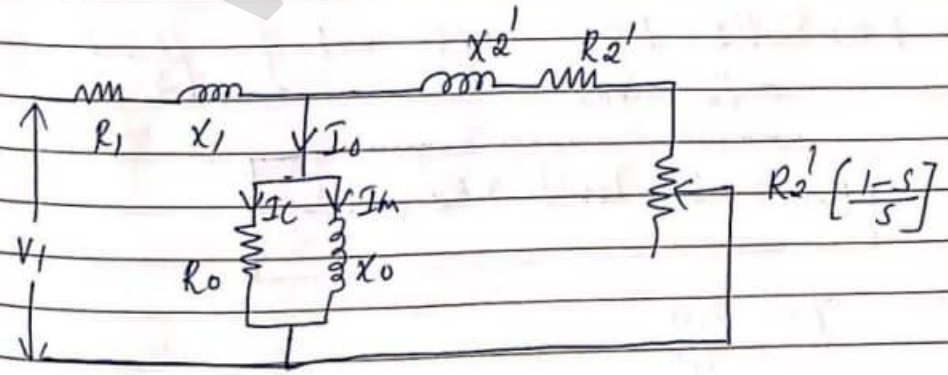


Equivalent ckt referred to stator

$$K = \frac{E_2}{E_1} \qquad E_2' = \frac{E_2}{K} \qquad I_{2r}' = K I_{2r} = \frac{KsE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$X_2' = \frac{X_2}{K^2} \qquad R_2' = \frac{R_2}{K^2} \quad \rightarrow \text{referred to stator}$$

$$R_L' = \frac{R_L}{K^2} = \frac{R_2}{K^2}\left(\frac{1-s}{s}\right) = R_2'\left(\frac{1-s}{s}\right)$$



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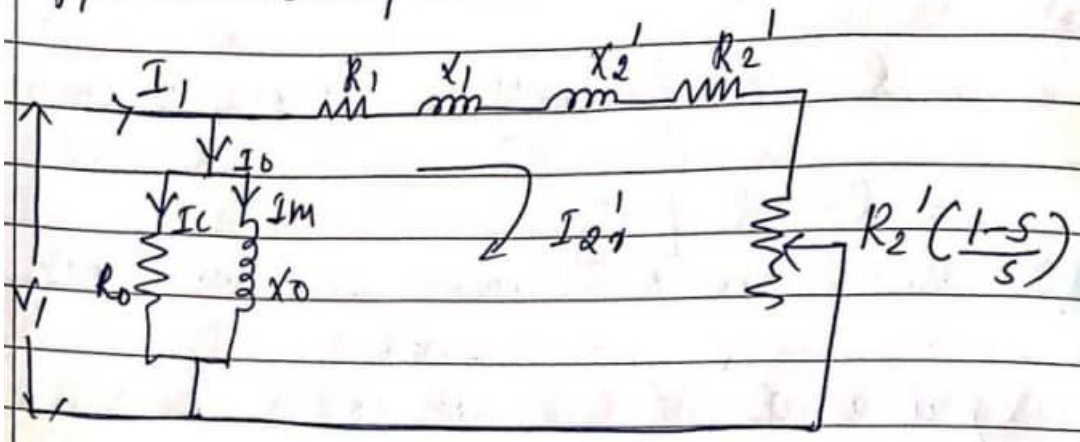
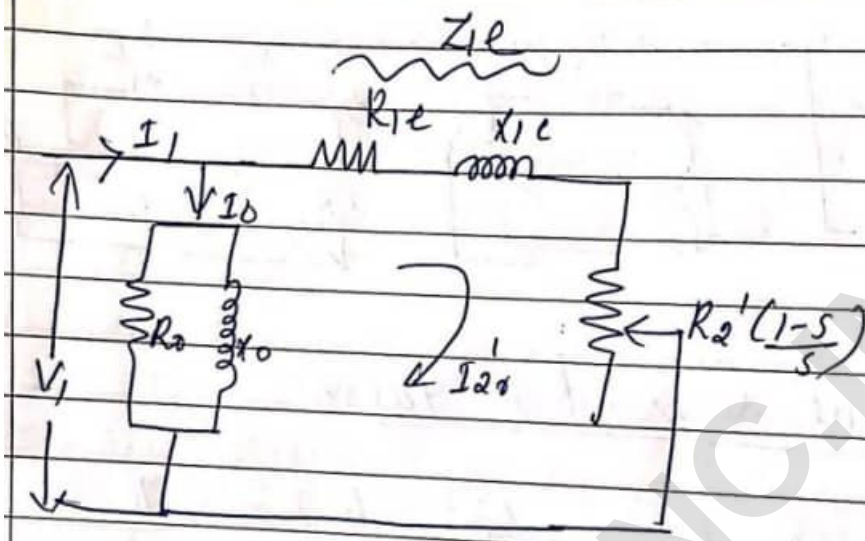
Approximate Equivalent Ckt





$$R_{1e} = R_1 + \frac{R_2}{k^2}$$

$$X_{1e} = X_1 + \frac{X_2}{k^2}$$

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

$$I_0 = I_c + I_m$$

R_{1e} = Equivalent resistance referred to stator
X_{1e} = Equivalent reactance referred to stator
$Z_{1e} = R_{1e} + jX_{1e}$

Power Equations from Equivalent ckt

$$P_m = P_2 - P_c = \left[\frac{P_c}{s} - P_c\right] = \left[\frac{1}{s} - 1\right]P_c$$

$$= \cancel{P_2 - sP_2} =$$

$$\boxed{P_m = 3 \times (I_{2r}')^2 \times R_2' \left[\frac{1-s}{s}\right]}$$

$$T = \frac{P_m}{\omega}$$

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Phasor diagram of IM

Phasor diagram of loaded IM is similar to loaded transformer.

Let ϕ = magnetic flux linkes with both 1° & 2°
E_1 = Induced emf in stator
E_{2r} = " " rotor
R_1 = ~~Rotor~~ stator resistance/phase
X_1 = stator reactance/phase
V_1 = stator voltage/phase has to overcome E_1 and also supply voltage drops I_1R_1 and I_1X_1

$$\vec{V_1} = -E_1 + \vec{I_1}R_1 + j\vec{I_1}X_1$$

$$= -E_1 + \vec{I_1}[R_1 + jX_1]$$

$$\vec{V_1} = -\vec{E_1} + \vec{I_1}Z_1$$

The rotor induced emf in running condition has to supply the drop across impedance as rotor is short circuited.

$$\vec{E_{2r}} = \vec{I_{2r}}R_2 + j\vec{I_{2r}}X_2 = \vec{I_{2r}}(R_2 + jX_2) = \vec{I_{2r}}(Z_{2r})$$

$$I_{2r}' = kI_{2r}$$

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

Steps to draw phasor diagram

1. Take ϕ as reference phasor
2. The induced voltage E_1 lags ϕ by 90°
3. Show $-E_1$ by reversing voltage phasor E_1
4. The phasor E_{2r} is in phase with E_1
   I_{2r} lagging E_{2r} by ϕ_{2r}
5. Show $I_{2r}R_2$ in phase with I_{2r} and $I_{2r}X_{2r}$ leading resistive drop by 90° to get E_{2r}

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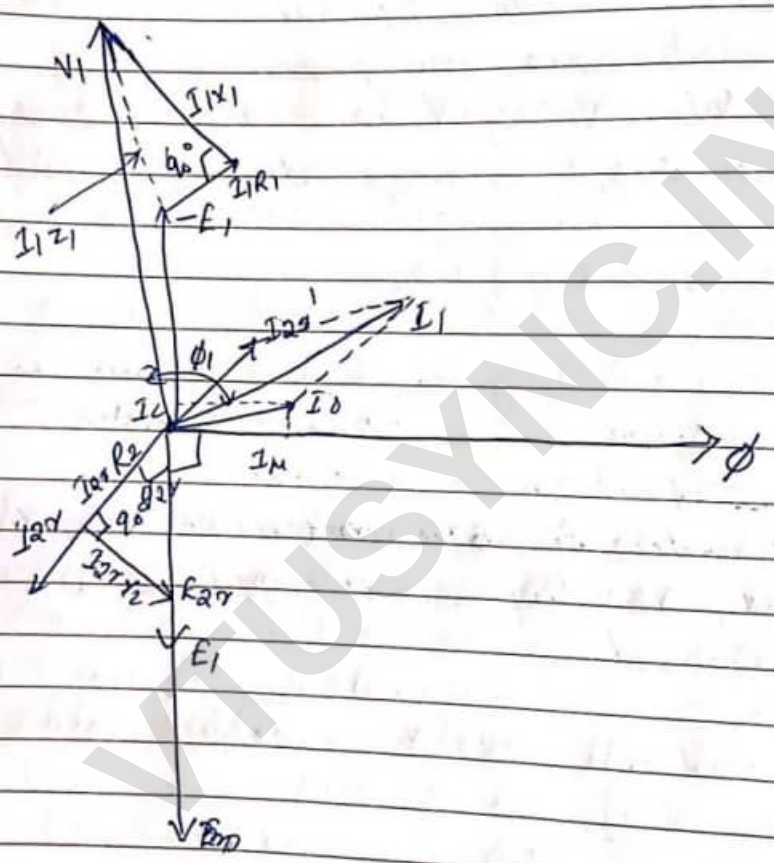
6. Reverse I_{2r} to get I_{2r}'
7. I_m is in phase with ϕ, I_c is $90°$ leading with ϕ. Add I_m & I_c to get I_0.
8. Add I_0 and I_{2r}' to get I_1
9. from the tip of $-E_1$ phasor add I_1R_1 in phase with I_1 and I_1X_1 at $90°$ leading to to get V_1 phasor
10. Angle between V_1 and I_1 is ϕ_1



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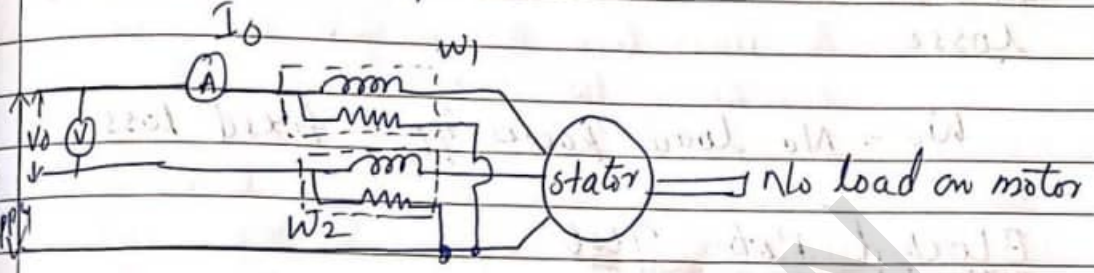
Circle diagram

The data required to draw the circle diagram is obtained by conducting 2 tests, which are
1. No load test or open ckt test
2. Blocked rotor test or short ckt test

No load test on 3ϕ IM



The motor is made to run without any load. The rated voltage is applied to the stator. The input line current and total i/p power is measured. (two wattmeter method is used to measure the total input power.

As the motor is on no load the pf is low which is less than 0.5 and one of the 2 wattmeters reads negative. It is necessary to reverse the current coil or pressure coil connections of such a wattmeter to get the positive reading.

V_0	I_0	$W_0 = W_1 + W_2$
Rated line voltage	No load current	

$W_0 = \sqrt{3}\, V_0 I_0 \cos\phi_0 \qquad \cos\phi_0 = \dfrac{W_0}{\sqrt{3}\, V_0 I_0}$

This is no load pf.

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$I_c = I_0 \cos\phi_0$

$I_m = I_0 \sin\phi_0$

$R_0 = \frac{V_0}{I_c}$

$X_0 = \frac{V_0}{I_m}$

W_0 consists of 1. stator copper loss $3 I_0^2 R_1$
2. stator core loss 3. friction and windage losses

W_0 = No load power i/p = fixed loss

Blocked Rotor Test

1. In this test, the rotor is locked and it is not allowed to rotate.
2. Slip $s=1$ $R_L' = R_2'\left(\frac{1-s}{s}\right)$ is zero

In this test primary excited with rated voltage a large short ckt ~~can~~ current can flow which is dangerous.
In this test, Rated current is applied to the ~~rotor~~ stator. Now the applied voltage V_{sc}, the input power W_{sc} and a short ckt current I_{sc} are measured.

V_{sc} = Short ckt reduced voltage
I_{sc} = short ckt current
W_{sc} = short ckt i/p power
$= \sqrt{3}\, V_{sc} I_{sc} \cos\phi_{sc}$

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

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$W_{SC} = 3(I_{SC})^2 \cdot R_{1e}$

I_{SC} = per phase value

$$R_{1e} = \frac{W_{SC}}{3(I_{SC})^2}$$

$$Z_{1e} = \frac{V_{SC}}{I_{SC}}$$

$$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}$$

W_{SC} = stator cu loss + Rotor cu loss

$$I_{SN} = \left[\frac{V_L}{V_{SC}}\right] \times I_{SC}$$

$$\boxed{W_{SN} = \left[\frac{I_{SN}}{I_{SC}}\right]^2 \times W_{SC}}$$

W_{SN} = Core loss + Stator and rotor cu loss.

Construction of the Circle Diagram

1. Step 1 : Take reference phasor V as vertical (Y-axis)

Step 2 : Select suitable current scale such that diameter of circle is about 20-30 cm

Step 3 : from no load Test I_0 and ϕ_0 are obtained. Draw Vector I_0 lagging V by angle ϕ_0

Step 4 : Draw horizontal line through extremity of I_0. O' parallel to horizontal axis

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Step 5: Draw the current I_{SN} calculated from I_{SC} with the same scale, lagging V by angle ϕ_{SC} from the origin O. This phasor OA as shown

Step 6: Join O'A, the line O'A is called o/p line

Step 7: Draw ⊥r bisector of O'A. Extend it to meet line O'B at pt C. This is the centre of the circle

Step 8: Draw the circle, with C as a centre and radius equal to O'C. This meets the horizontal line drawn from O' at B as shown in fig

Step 9: Draw the ⊥r from point A on the horizontal axis, to meet O'B line at F and meet horizontal axis at D

Step 10: Torque line

→ length AD represents the power i/p at short ckt i.e W_{SN}

→ FD = fixed losses

length (AF) & Stator cu loss + rotor copper loss

The point E can be located as

I_1 = stator current

I_2 = rotor current

$K = \frac{I_1}{I_2}$

Assume O'E represents the torque line

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$$\frac{AE}{Ef} = \frac{\text{Rotor cu loss}}{\text{stator cu loss}} = \frac{I_2^2 R_2}{I_1^2 R_1} = \frac{R_2}{R_1} \times \frac{1}{K^2}$$

$$R_2' = \frac{R_2}{K^2}$$

The point E can be obtained by dividing the line in the ratio $\frac{R_2'}{R_1}$

<u>Squirrel cage rotor</u>

stator cu losses $= 3 I_{SN}^2 R_1$

Neglecting core loss -

$$WSN = \text{Stator cu loss} + \text{Rotor cu loss}$$

$$\text{Rotor cu loss} = WSN - 3 I_{SN}^2 R_1$$

$$\frac{AE}{Ef} = \frac{WSN - 3 I_{SN}^2 R_1}{3 I_{SN}^2 R_1}$$

$$\text{power scale} = \frac{WSN}{l(AD)}$$

Predicting performance parameters using circle diagram.

Let the motor takes a current of OP

1. Total motor input = PT x power scale
2. Fixed loss = ST x power scale
3. Stator copper loss = SR x power scale
4. Rotor copper loss = QR x power scale
5. Total loss = QT x power scale
6. Rotor output = PQ x power scale

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7. Rotor i/p = PQ + QR = PR × Power Scale

8. Slip $s = \frac{QR}{PR}$

9. $\cos\phi = \frac{PT}{OP}$

10. Motor $\eta = \frac{O/P}{I/P} = \frac{PQ}{PT}$

11. Rotor efficiency $= \frac{PQ}{PR}$

12. $\frac{\text{Rotor o/p}}{\text{Rotor i/p}} = 1 - s = \frac{PQ}{PR}$

1. Maximum o/p

Draw ~~OA~~ a line parallel to O'A and is also tangent to the circle at point M. Then the max. o/p is given by l(MN) at the power scale

2. Max. i/p

It occurs on the highest point on the circle at point L. At this point, tangent to the circle is horizontal. The max. i/p is given by (LL') at the power scale

3. Max. torque

Draw a line ∥el to the torque line and tangent to the circle at point J. The l(JK) represents max. torque in synchronous watts.

4. Max. Pf

Draw a line ~~AC~~ tangent to the circle from meeting circle at point H. Draw a ⊥r from H on horizontal axis till it meets it at I

Max Pf = cos ∠OHI

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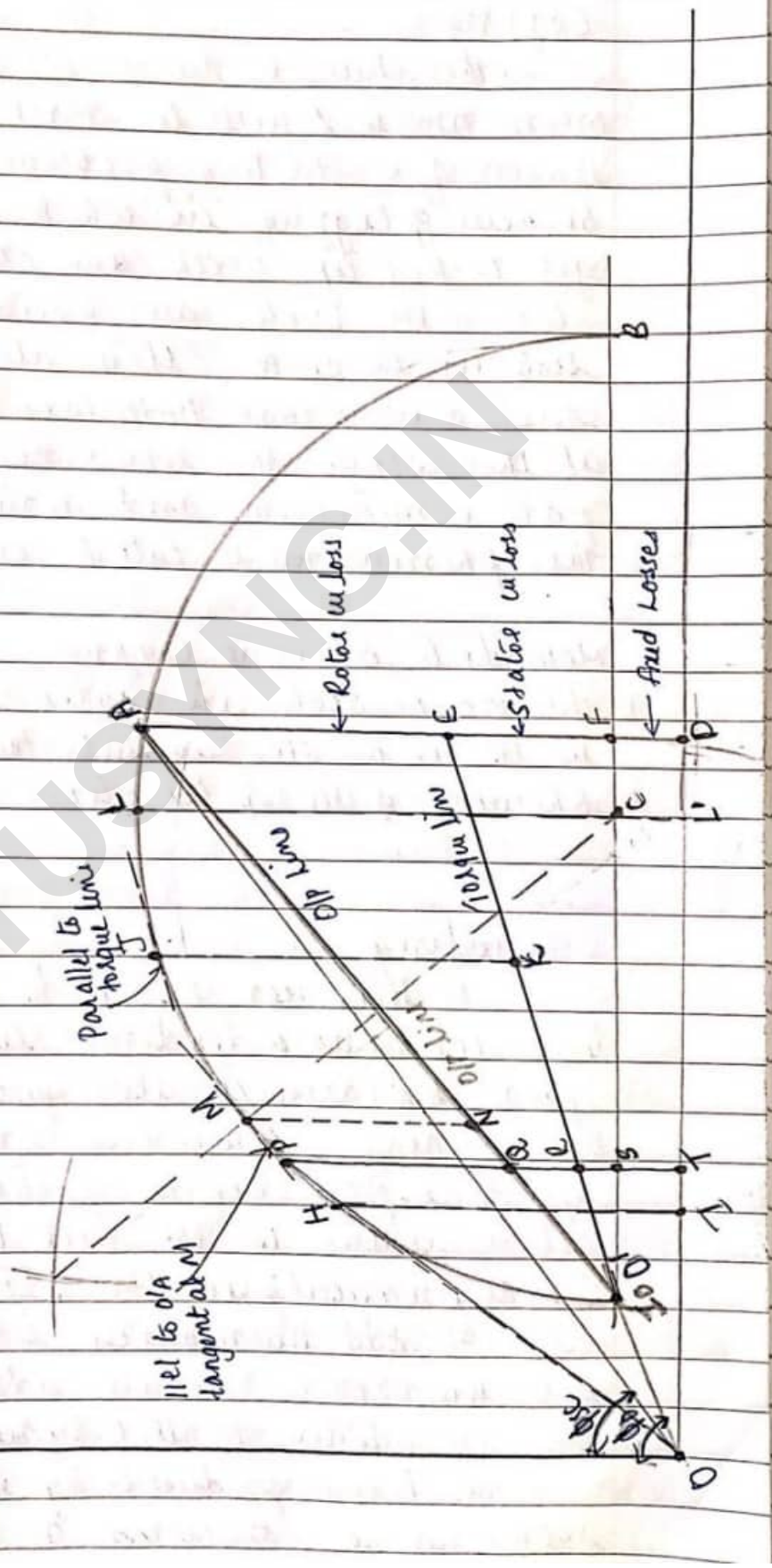
Starting torque:-

T_{start} = l(AE) x power scale



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Cogging and crawling [Effects of Harmonics]

Cogging

This characteristic of IM comes into picture when motor refuses to start at all. The main reason for starting problem in the motor is because of cogging, in which slots of the stator get locked up with the rotor slots. When the slots of the rotor are equal in number with slots in the stator, they align themselves in such a way that both face each other and at this stage the reluctance of the magnetic path is minimum and motor start to refuse. This phenomenon is called cogging

Methods to overcome cogging

1. The no. of slots in rotor should not be equal to the no. of slots in the stator
2. Skewing of the rotor slots.

Crawling

It has been observed that the squirrel cage type IM has a tendency to run at very low speed, compared to its synchronous speed. This phenomenon is known as crawling. The resultant speed is 1/7th of its synchronous speed. This action is due to the fact that harmonics fluxes produced in the gap of the stator wdg of odd harmonics like 3rd, 5th, 7th etc. These harmonics create additional torque fields in addition to the synchronous torque.

The torque produced by the harmonics rotates in the forward or backward direction

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at $N_s/3$, $N_s/5$, $N_s/7$ speed respectively.
Here we consider 5th & 7th harmonics and rest are neglected. The torque produced by the 5th harmonics rotates in backward direction. But this in small quantity and can be neglected. Now the 7th harmonic produces a forward rotating torque at synchronous speed $N_s/7$.

Hence Net forward torque = The torque produced by 7th harmonic + fundamental torque

The torque produced by 7th harmonic reaches its max. +ve value just below 1/7 of N_s. and at this pt slip is high. At this stage motor does not reach up to its normal speed and continues to rotate at a speed lower than its normal speed.
This causes cracking of the motor at just below 1/7 synchronous speed.

High torque rotors

In case of squirrel cage IM, there is no provision made for adding external resistance. High starting torque can be obtained by the use of deep bar or double cage rotors.

Deep Bar rotor Construction

There is no constructional difference b/w stator of deep bar motor and that of ordinary IM. It is used to obtain high rotor resistance at starting and low rotor resistance at running condition.

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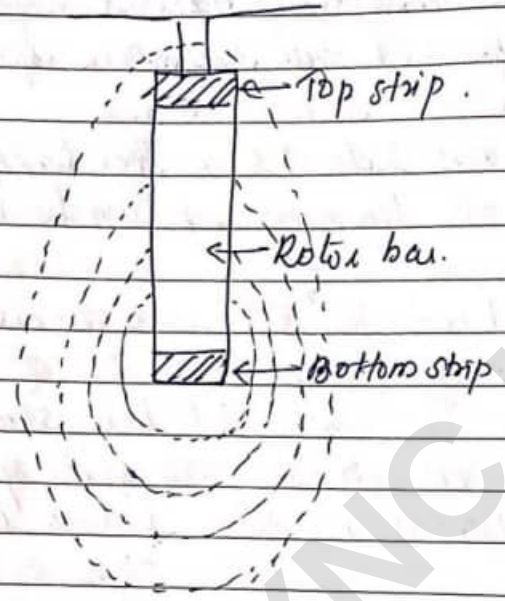
A bar may be assumed to be made up of a number of narrow layers connected in parallel. The magnetic leakage pattern set up by the bar ~~is~~ current is indicated in dotted lines in the figure.



The leakage flux links the bottom ~~elem~~ strip is more than the top strip. As a consequence, the starting reactance (50Hz reactance for the bottom strip is much larger than that of the top strip. Thus current in the top strip is much more than the current in the bottom strip, and further the top strip current leads bottom strip current bcz of its lower reactance. Thus there is non-uniform distribution of current; and due to skin effect effective area of cross section decreases, hence rotor resistance increases resulting in high starting torque.

As leakage reactance is ∝ frequency, the current depends upon the frequency. With the increase in rotor speed, the rotor frequency decreases and skin effect also dec

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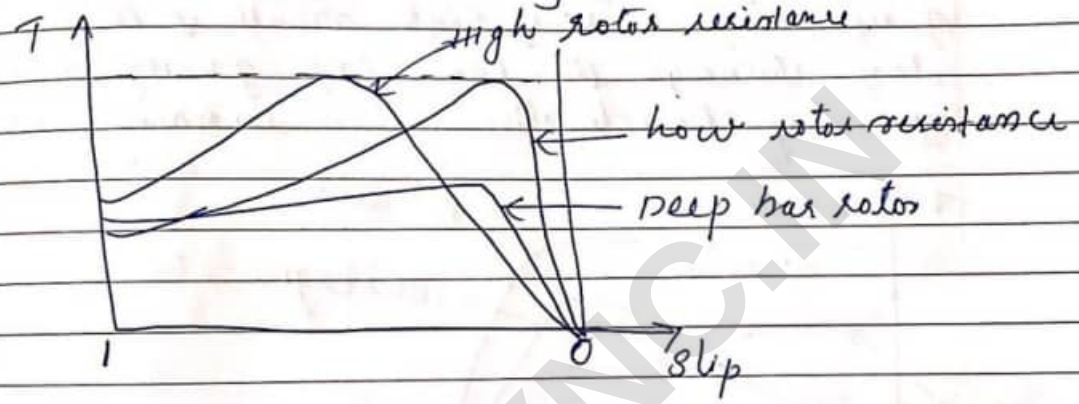
The reactances of various elementary strips at this low frequency become almost equal and the current density becomes nearly uniform so its offered a resistance almost equal to dc value.

A deep bar rotor therefore has a low starting current and high starting ~~current~~ torque and a low running resistance so that it can meet desired starting and running performances.



Double Cage Rotor

Though it is more expensive it gives better performance than deep bar rotor construction. The squirrel cage wdg in this design consists of 2 layers of bars short ckted by end rings. The upper bars have a small cross sectional area than the lower bars and consequently a higher resistance.

The slots accomoding the 2 sets of bars are joined by a constriction. The upper bars have a much lower leakage flux linkage and a lower reactance.

The outer cage has high resistance and low reactance while the inner cage has low resistance and high reactance.

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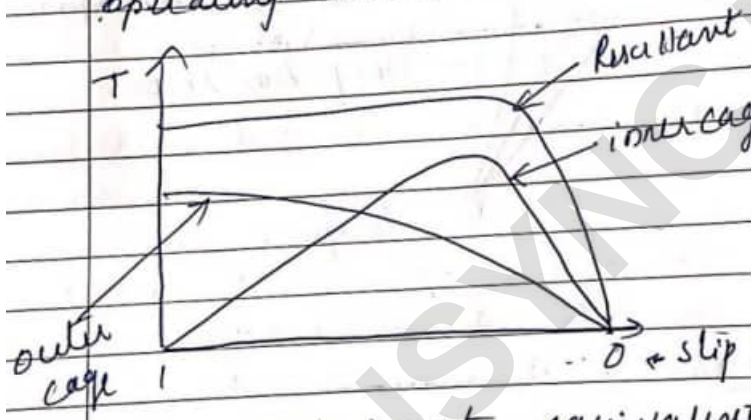
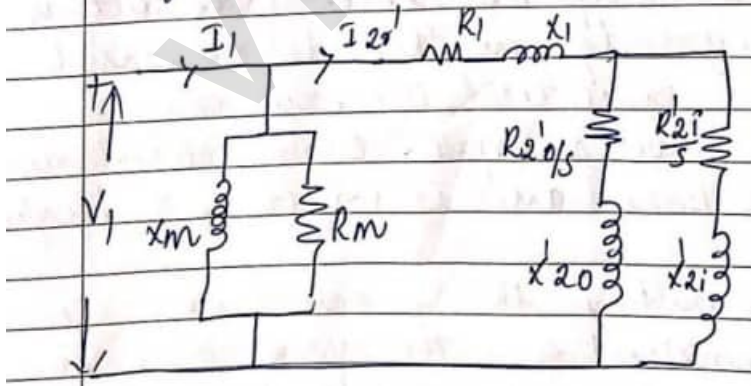
Then in starting the current is mainly confined to the outer cage with a consequent decrease in starting current and an increase in starting torque.
At normal operating speed the reactance difference b/w the 2 cages events out bcz of low frequency of rotor currents. Hence the division of rotor current is mainly decided by the resistances of the two cages. As resistance of upper cage is very high most of the current flows through the lower cage giving excellent operating characteristics under running condition.



The approximate equivalent ckt of double cage rotor IM is shown in figure.



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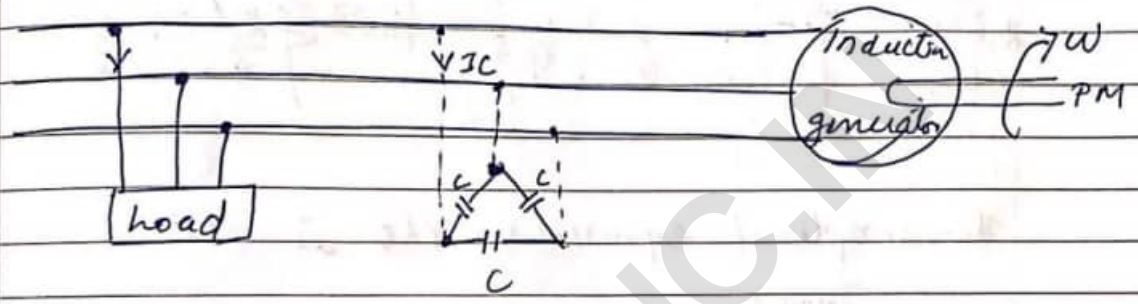
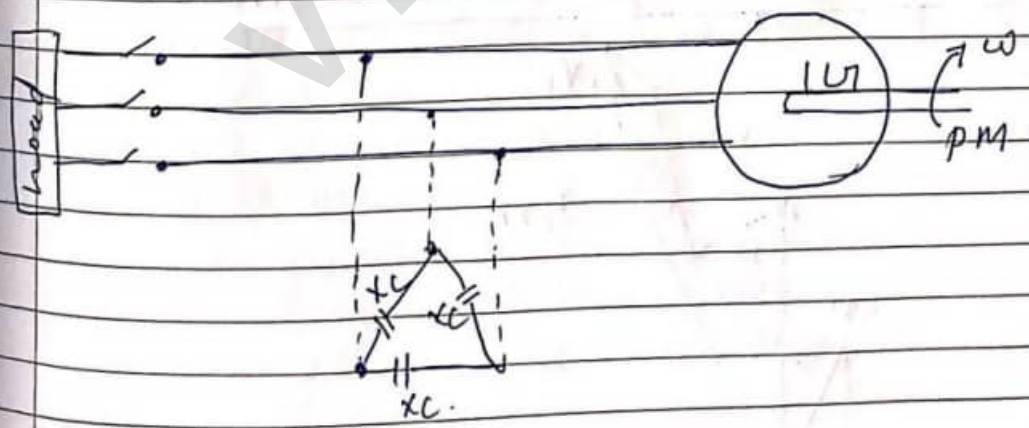
Induction Generators

To run the induction machine as a generator its slip must be less than zero ($S < 0$), $-ve$.
An Induction generator is asynchronous in nature bcz of which it is commonly used as windmill generator.
A transmission line connected to an IG feeding a local load is shown in figure



The primemover must be provided with automatic control to increase the generator speed when it is required to meet increased load.

Isolated IG



The isolated IG feeding a load is shown in figure. The delta connected capacitors across the generator terminals provide the magnetising current

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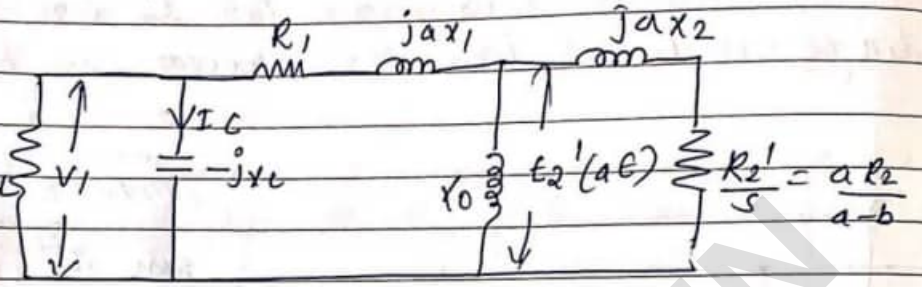
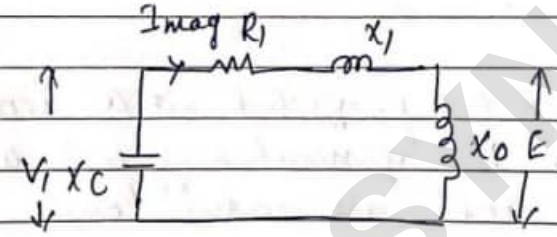
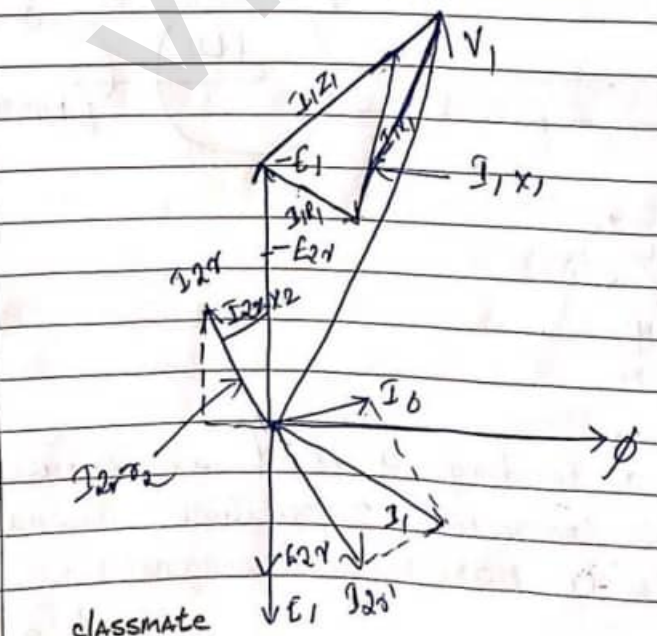
necessary to excite the isolated generator. As the generator is loaded, the operating freq. depends primarily upon the rotor speed but depends primarily upon the load, while the voltage is affected by the load, while the voltage is mainly decided by capacitor reactance at the operating frequency. The equivalent ckt on per phase basis is shown in fig.



The simplified equivalent ckt is shown.



Phasor diagram of Induction generator



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Problems

losses and Efficiency.

1. A 25kW, 4 pole, 3ϕ, 50Hz induction motor is running at 1410 rpm, supplying full load. The mechanical losses are 850W and stator losses are 1.7 times rotor cu losses on full load. Calculate
i) Gross mechanical power developed
ii) Rotor cu losses
iii) The value of rotor resistance/phase if rotor current on full load/phase is 65A
iv) The full load efficiency.

P_{out} 25kW

$N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ r.pm $N = 1410$ rpm

$S = \frac{N_s - N}{N_s} = \frac{1500 - 1410}{1500} = 0.06$

i) P_m – mechanical losses = P_{out}

$P_m - 850 = 25 \times 10^3$ $P_m = 25 \times 10^3 + 850 = 25850W$

ii) $P_2 : P_c : P_m = 1 : S : 1-S$ $\frac{P_c}{P_m} = \frac{S}{1-S}$

$P_c = 25850 \times \frac{0.06}{1-0.06} = 1650W$

iii) $I_{2r} = 65A$ $P_c = 3 I_{2r}^2 R_2$

$R_2 = \frac{P_c}{3 \times (I_{2r})^2} = \frac{1650}{3 \times 65^2} = 0.13\Omega$/phase

iv) stator losses $= 1.7 \times P_c = 1.7 \times 1650 = 2805W$

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$P_c = S \times P_2$ $\quad P_2 = \frac{P_c}{S} = \frac{1650}{0.06} = 27500\ W$

P_{in} − stator losses $= P_2$ $\quad P_{in} = 27500 + 2805 = 30305\ W$

$\% \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{25000}{30305} \times 100 = 82.49\%$

1. A 6 pole 50Hz, 3ϕ IM running on full load with 4% slip develops a torque of 149.3 N-m and its pully rim. The friction and windage losses are 200W and the stator copper and iron losses are equal to 1620W. Calculate: i) output power ii) The rotor copper losses iii) The efficiency at full load.

$T_{sh} = 149.3\ N\text{-}m \quad P = 6, \quad f = 50Hz \quad S = 4\% = 0.04$

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

$N = N_s(1-S) = 960\ rpm$

i) $P_{out} = T_{sh} \times \omega = T_{sh} \times \frac{2\pi N}{60} = 15.0092\ kW$

ii) $P_m = P_{out} + \text{frictional losses} = 15009.2 + 200$
$= 1509.2\ W$

$P_2 : P_c : P_m = 1 : S : 1-S$

$\frac{P_c}{P_m} = \frac{S}{1-S} \quad P_c = P_m \times \frac{S}{1-S} = 633.7166\ W$

iii) $P_2 = \frac{P_c}{S} = 15842.9167\ W$

$\therefore P_{in} = P_2 + \text{Stator losses} = 15842.9167 + 1620 =$
$= 17462.916$

$\% \eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{15009.2}{17462.916} \times 100 = 85.94\%$

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3. A 6 pole IM develops 30HP including mechanical losses total 2HP at a speed of 950 rpm on 550V, 50Hz mains. The pf is 0.88. Calculate for this load i) slip ii) rotor cu loss iii) the total i/p if the stator cu losses are 2000W iv) the efficiency v) the line current vi) the no. of complete cycles of the rotor emf per minute

$p_{out} = 30HP = 30 \times 735.5 = 22065\ W$

Mechanical losses $= 2HP = 2 \times 735.5 = 1471\ W$

$P = 6,\ f = 50Hz,\ N = 950\ rpm \quad N_s = \frac{120f}{P} = 1000\ rpm$

i) Slip $S = \frac{N_s - N_s}{N_s} = \frac{1000 - 950}{1000} \times 100 = 5\%$

ii) $P_m = P_{out} + \text{Mechanical losses} = 23536\ W$

$P_2 : P_c : P_m = 1 : S : 1-S$

$\frac{P_c}{P_m} = \frac{S}{1-S} \quad P_c = \frac{P_m \times S}{1-S} = 1238.736\ W$

iii) $P_2 = \frac{P_c}{S} = \frac{1238.736}{0.05} = 24774.736\ W$

$p_{in} = P_2 + \text{Stator losses} = 24774.73 + 2000 = 26774.7$

iv) $\% \eta = \frac{P_{out}}{p_{in}} \times 100 = \frac{22065}{26774.7} \times 100 = 82.409\%$

v) $p_{in} = \sqrt{3}\, V_L I_L \cos\phi \quad I_L = \frac{26774.7}{\sqrt{3} \times 550 \times 0.88} = 31.938A$

vi) $f_r = Sf = 0.05 \times 50 = 2.5Hz$ cycles/sec

$f_r = 2.5 \times 60 = 150$ cycles/min

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4. The power i/p to the rotor of a 440V, 50Hz, 3ϕ 6 pole IM is 60kW. It is observed that rotor EMF makes 90 complete cycle/minute. Calculate i) slip ii) Rotor cu loss iii) mechanical power developed.

$P_2 = 60kW$ $\quad f_r = 90$ cycles/min $\quad f = 50Hz$

$f_r = \frac{90}{60} = 1.5$ cycles/sec.

i) $S = \frac{f_r}{f} = \frac{1.5}{50} = 3$ $\quad$ 3%

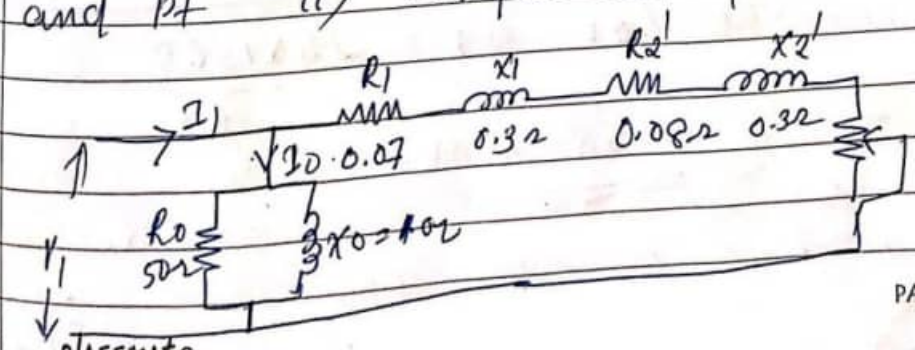
(i) $P_2 : P_C : P_M = 1 : S : 1-S$ $\quad \frac{P_2}{P_C} = \frac{1}{S}$

$P_C = SP_2 = 0.03 \times 60 \times 10^3 = 1800W$

(ii) $\frac{P_2}{P_m} = \frac{1}{1-S}$ $\quad P_m = (1-0.03) \times 60 = 58.2kW$

5. Equivalent Ckt

1. A 3ϕ 400V, 50Hz, 4 pole star connected IM has stator impedance of $Z_1 = (0.07 + j0.3)\Omega$/phase and rotor impedance of $Z_2' = (0.08 + j0.3)\Omega$/phase referred to stator side. The magnetising reactance is 10Ω/phase and core loss resistance is 50Ω/phase. Under these condition slip is found to be 4%. Using approximate equivalent ckt i) calculate i) stator current and pf ii) Torque developed.



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$S = 0.04$

$N_S = \frac{120f}{P} = 1500 \text{ rpm}$

$R_L' = R_2'\frac{(1-S)}{S} = 1.92\Omega$

$R_{1e} = R_1 + R_2' = 0.15\Omega \quad X_{1e} = X_1 + X_2' = 0.6\Omega$

$V_1 = \frac{400}{\sqrt{3}} = 230.94 \text{ V (ph)}$

$I_{2r}' = \frac{V_1}{(R_{1e}+R_L') + jX_{1e}} = \frac{230.94}{(0.15+1.92)+j0.6}$

$= 107.1547\angle -16.64^\circ \text{ A} = 102.93 - j29.83\text{A}$

$I_0 = \frac{V_1}{R_0 \| jX_0} = \frac{230.94}{\frac{50\times 10\angle 90}{50+j10}} = 23.551\angle -78.69^\circ\text{A}$

$= 4.6188 - j23.0938\text{A}$

i) $I_1 = I_0 + I_{2r}'$

$= 4.6188 - j23.093 + 102.93 - j29.83\text{A}$

$= 119.8544\angle -26.204^\circ \text{A}, = 107.5 - j52.9\text{A}$

$pf = \cos(26.204) = 0.8972$ lagging

ii) $T = \frac{3(I_{2r}')^2 R_2/S}{2\pi N_S/60} = \frac{3\times(107.154)^2\times 0.08/0.04}{\frac{2\pi\times 1500}{60}}$

$= 438.585 \text{ N-m}$

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Circle diagrams

1. A 50kW, 6 pole 50Hz, 450V, 3ϕ IM motor furnished the following test figures.
No load test : 450V, 20A, pf = 0.15
Blocked rotor test : 200V, 150A, pf = 0.3
The ratio of stator to copper losses on short ckt was 5 : 4. Draw the circle diagram and determine from it.
i) full load current and pf ii) Max. torque & max power i/p iii) slip at full load ~~iv)~~
iv) Efficiency at full load

$\cos\phi_0 = 0.15 \quad \phi_0 = 81.37^\circ \quad \cos\phi_{SC} = 0.3 \quad \phi_{SC} = 72.54^\circ$

$$I_{SN} = I_{SC} \times \left[\frac{V_L}{V_{SC}}\right] = 150 \times \frac{450}{200} = 337.5\,A$$

$$W_{SC} = \sqrt{3}\, V_{SC} I_{SC} \cos\phi_{SC} = 15588.457\,W$$

$$W_{SN} = W_{SC} \times \left[\frac{I_{SN}}{I_{SC}}\right]^2 = 15588.457 \times \left[\frac{337.5}{150}\right]^2$$

$$= 78916.56\,W$$

current scale 1 cm = 25A

1) $I_0 = 20A \Rightarrow$ ~~0.8 cm~~ $1.33 \angle 81.37$ (OO')

2) $I_{SC} = \frac{150}{25} = 16$ cm (OA)

~~3)~~ join O'A.

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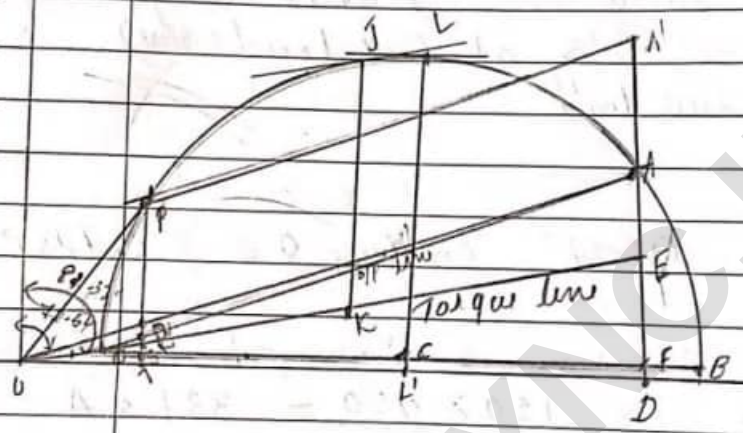
4. Draw ⊥r bisector for O'A find C on the O'B
5. Draw circle with C as centre and CO' as radius.
6. Draw ⊥r from A on x axis to meet it At
7. l(AD) = 3.3cm = WSN
8. power scale $\frac{WSN}{l(AD)} = \frac{78916.56}{3.3} = 23914.1$



9. $\frac{\text{Stator cu loss}}{\text{Rotor cu loss}} = \frac{5}{4} = \frac{AE}{EF}$ and $AF = AE + EF$

$AF = AE + \frac{5}{4}AE = 2.25AE$

$AE = 0.45AF$

$l(AF) = 3cm$, $AE = 0.45 \times 3 = 1.35cm$

O'E = Torque line

10. full load o/p = 50kW, Draw a line AA' = full load op in scale $l(AA') = \frac{50 \times 10^3}{}$

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11. Draw $\parallel^{el}$ to the o/p line from A' to meet the circle at pt P. this is full load pt.

12. $l(OP) = 3.3$ cm = full load current
$= 3.3 \times 15 =$
$\cos\phi =$
$\cos 39°$

13. for max. torque draw $\parallel^{el}$ to torque line such that it is tangent to circle at J

length (JK) = max. torque in syn. watts
= 4 cm = 4×23914.1
=

14. for max i/p draw horizontal line tangent to circle at point L. The $l(LL')$ max. i/p

$l(LL') = 5$ cm $= 5 \times 23914.1$

15) Slip at full load $= \frac{QR}{PR} =$

16. $\cdot\cdot\eta = \frac{PQ}{PT} =$

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2. Draw the circle diagram for a 20 HP, 50 Hz, 3ϕ star connected IM with the following d

No load test = 400V, 9A, 0.2 pf lagging
Blocked rotor test : 200V, 50A, 0.4 pf lagg
Determine the line current η and slip for full load condition from the circle diagram.

$\cos\phi_0 = 0.2 \quad \phi_0 = 78.46^\circ$
$\cos\phi_{SC} = 0.4 \quad \phi_{SC} = 66.42^\circ$

$I_0 = 9A$

$I_{SC} = 50A$

$I_{SN} = I_{SC}\left[\frac{V_L}{V_{SC}}\right]$

$= 50 \times \left[\frac{400}{200}\right] = 100A$

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

$= 6928.20\ W$

$W_{SN} = W_{SC} \times \left[\frac{I_{SN}}{I_{SC}}\right]^2 = 6928.20 \times \left[\frac{100}{50}\right]^2$

$= 27712.8\ W$

choose current scale 1cm = 5A

1. Draw $OO' = I_0 = 9A = \frac{9}{5} = 1.8$ cm at an angle 78.46
2. Draw horizontal line ||el to x axis
3. Draw vector $I_{SN} = 100A \quad \frac{100}{5} = 20$ cm at an angle 66.42°
4. Join O'A (O/P line)
5. Draw ⊥r bisector of O'A to meet horizontal line drawn from O' at pt C. C centre of the circle
6. With C as centre and CO' as radius draw semicircle to meet horizontal line from O' at pt B

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7. Draw ⊥r from A on the x axis to meet it at D.

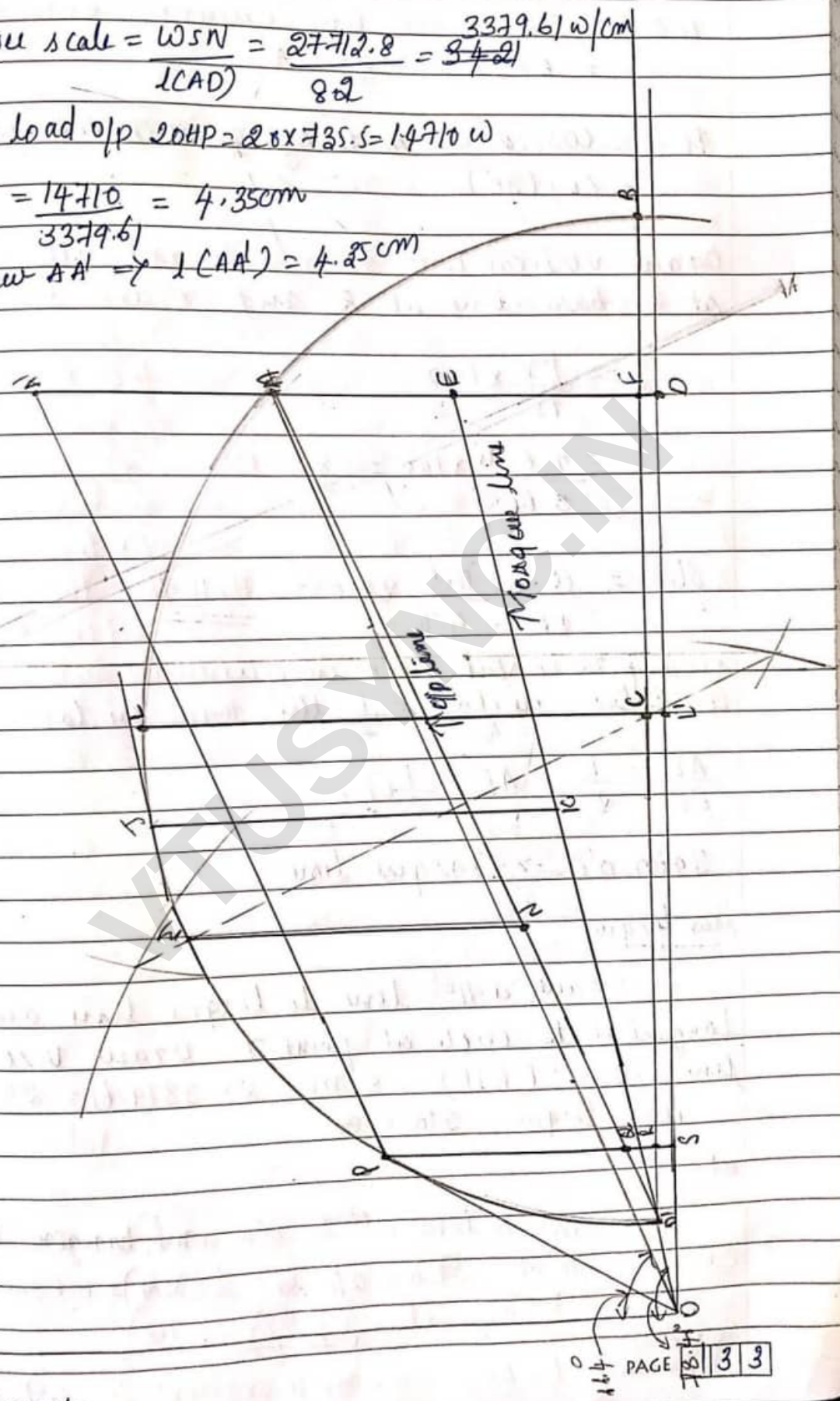
8. $l(AD) = 8.1\ cm = WSN$

Power scale $= \frac{WSN}{l(AD)} = \frac{27712.8}{8.2} = \cancel{3421}$ 3379.61 w/cm

9. Full load o/p 20HP $= 20 \times 735.5 = 14710\ w$

$= \frac{14710}{3379.61} = 4.35\ cm$

10. Draw AA' ⇒ $l(AA') = 4.25\ cm$



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Draw ||el to the o/p line from A' to meet circle at pt P. This is full load pt.

$l(OP)$ = full load line current = ~~6cm~~ 6.5cm

$= 6.5 \times 5 = \underline{32.5\ A}$

$pf = \cos(\text{angle made by op with Voltage axis})$

$= \cos(30°)$

Draw vertical line from P to intersect o/p line at O base line at R and x axis S,

$$\eta = \frac{PQ}{PS} \times 100$$

$$= \frac{4.6cm}{5.6cm} \times 100 = \underline{82.1\%}$$

$$Slip = \frac{QR}{PR} = \frac{0.6}{5.4} \times 100 = \underline{11.11\%}$$

Assumption (Not given in question)

If Rotor cu loss $= \frac{1}{2}$ the total cu loss

$$\frac{AE}{EF} = \frac{1}{2} \quad AE = \frac{1}{2}EF$$

Join O'E → Torque line

Max torque

Draw a ||el line to torque line and tangential to circle at point J. Draw vertical line JK $l(JK) = 8cm = 8 \times 3379.61 = 27036.88$ Nm

Max. Torque = 27036.88

Max o/p

Draw a line ||el to O'A and tangent to the circle at pt M. Max. o/p is $l(MN) = 6.6cm$

$= 6.6 \times 3379.61 = \underline{22305.42\ W}$

Max i/p

$l(LL') = 10.4cm = 10.4 \times 3379.61 = 35147.9$

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Module - 4

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Starting & Speed control

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Necessity of starter

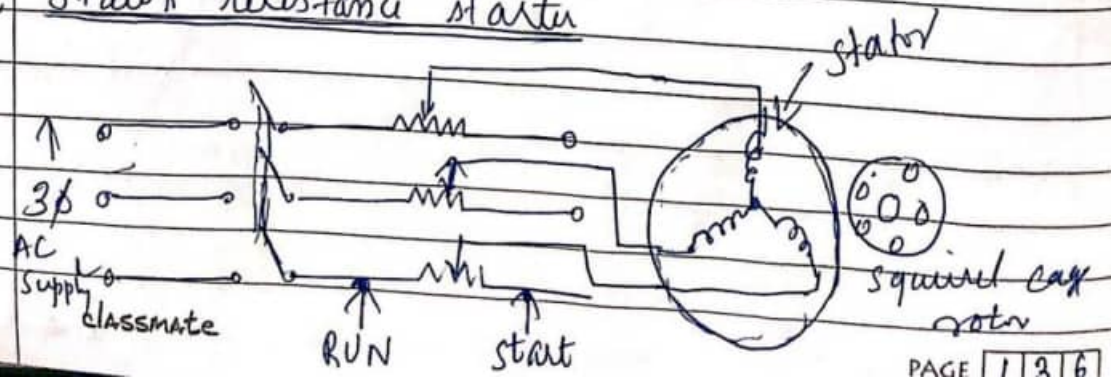
In a 3ϕ IM, $I_{2r} = \dfrac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

But at start $s = 1$ [$N = 0$]. So magnitude of rotor induced emf is very large at start. As rotor conductors are short circuited, a large induced emf circulates very high current through ~~short circuited~~ rotor at start, consequently the stator draws a very high current from the supply in the order of 5 to 8 times the full load current.

Due to such heavy inrush of current at start there is possibility of damage of the motor wdg. The starter is a device which is basically used to limit high starting current by supplying reduced voltage to the motor at the time of starting. Such reduced voltage is applied only for short period and once rotor gets accelerated, full normal rated voltage is applied.

The various types of starters are
1. Stator resistance starter
2. Auto transformer starter
3. Star-delta starter
4. Rotor resistance starter
5. Direct online starter

1. Stator resistance starter



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3 resistances are added in series with each phase of the stator wdg. Initially resistances are kept maximum. Due to this large voltage gets dropped across the resistances. Hence reduced voltage gets applied to the stator which reduces the starting current.

When the motor starts running, the resistances are gradually cut-off from the stator ckt. and rheostat will be in RUN position, then rated voltage gets applied to the ~~ckt~~ stator. Motor runs with normal speed.

Relationship between T_{st} & T_{FL}

$P_2 = T \times \omega_s$

$T \propto P_2$

$P_2 = \frac{P_c}{s} = \frac{3 I_{2r}^2 R_2}{s}$ $\therefore T \propto \frac{I_{2r}^2}{s}$

$T \propto \frac{I_1^2}{s}$ I_1 = stator current

At start $s = 1$ $T = T_{st}$ $I_1 = I_{st}$

At start $T_{st} \propto I_{st}^2$

when starter is used, stator voltage is reduced by 'x'

so $I_{st} = x I_{sc}$

$T_{st} \propto (x I_{sc})^2$

$T_{FL} \propto \frac{(I_{FL})^2}{s_f}$ s_f = full load slip

$$\frac{T_{st}}{T_{FL}} = x^2 \left[\frac{I_{sc}}{I_{FL}}\right]^2 s_f$$

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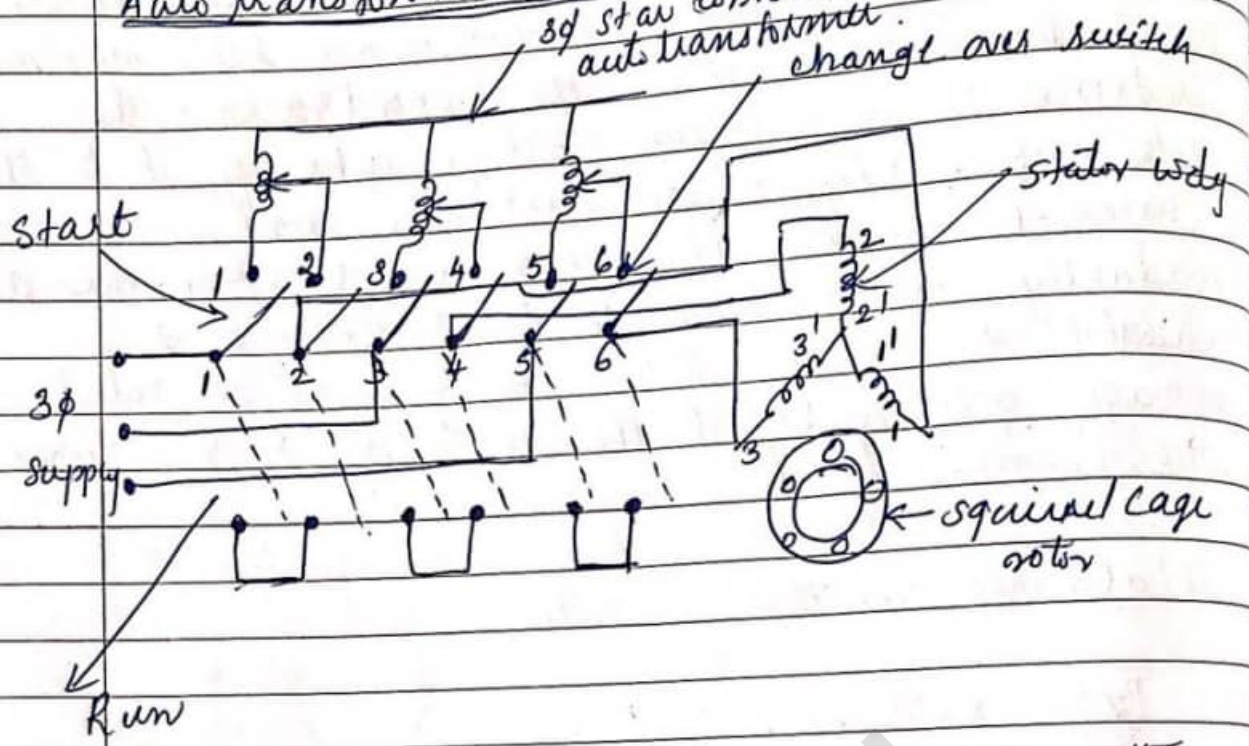
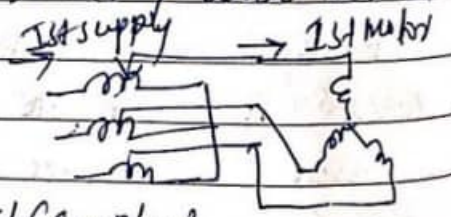
Auto transformer starter



When the switch is in the start position, the stator wdg is supplied with reduced voltage. This can be controlled by tappings provided with auto transformer.

When motor gathers 80% of normal speed, the change over switch is thrown into run position. The motor starts rotating with normal speed.

$I_{st} = x I_{SC}$ (motor)



Relation b/w Ist & TFL

Auto transformer ratio $x = \frac{I_{st}(\text{supply})}{I_{st}(\text{motor})}$

$$I_{st}(\text{supply}) = x\, I_{st}(\text{motor}) = x \times x\, I_{SC}$$

At start $s = 1$, $T = T_{st}$ $\quad T_{st} \propto I_{st}^2 \propto x^2 I_{SC}^2$

$$T_{FL} \propto \frac{(I_{FL})^2}{s_f}$$

$$\frac{T_{st}}{T_{FL}} = \frac{x^2 I_{SC}^2}{(I_{FL})^2 s_f} = x^2 \left(\frac{I_{SC}}{I_{FL}}\right)^2 \times s_f$$

Starting torque is reduced by x^2

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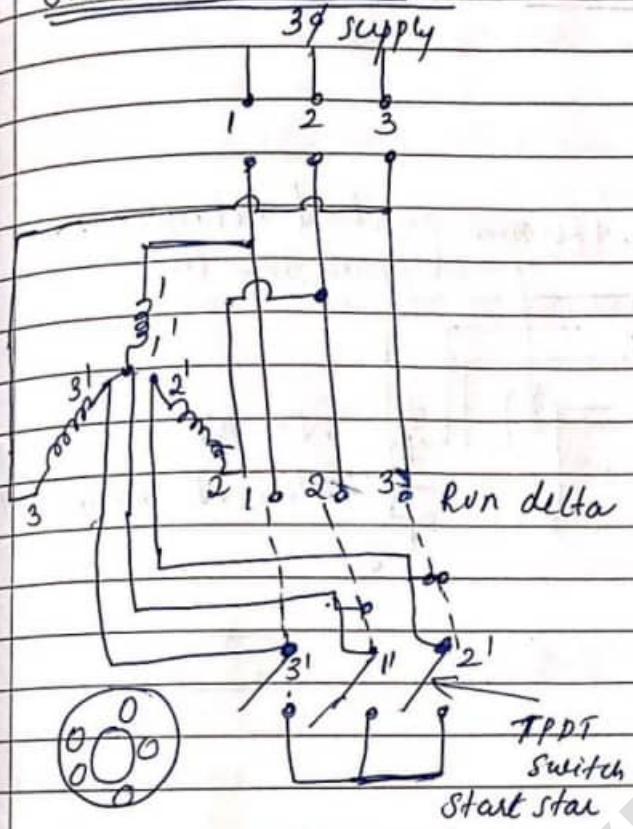
Star - delta starter



Triple pole Double Throw (TPDT) switch is used in this. It connects the stator wdg in star at start. Hence per phase voltage gets reduced by the factor $1/\sqrt{3}$. Due to this reduced voltage, starting current is reduced. When the switch is thrown ~~for~~ on other side, the wdg gets connected in delta, across the supply. So its gets normal voltage.

Relation between Ist and IfL

$$\frac{I_{st}}{I_{fL}} = x^2 \left[\frac{I_{sc}}{I_{fL}}\right]^2 \times s_f$$

$$x = \frac{1}{\sqrt{3}}$$

$$\boxed{\frac{I_{st}}{I_{fL}} = \frac{1}{3}\left[\frac{I_{sc}}{I_{fL}}\right]^2 \times s_f}$$

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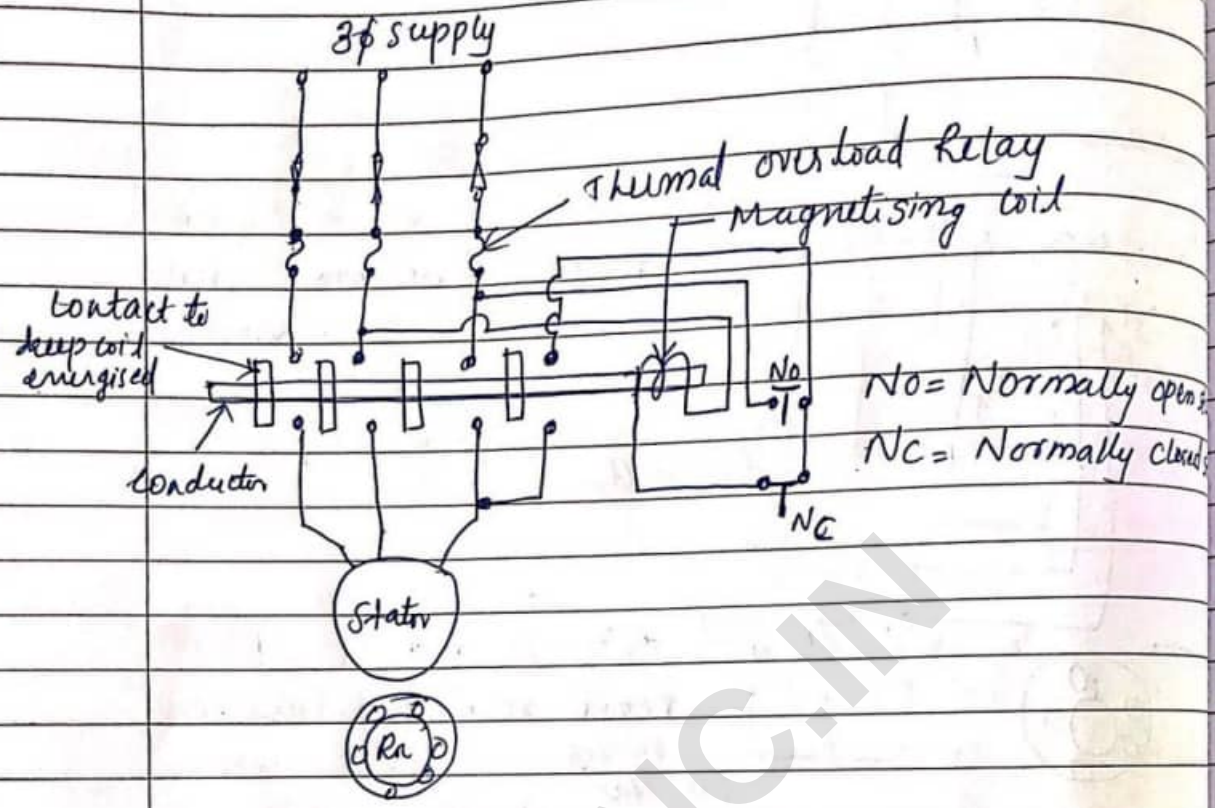
Direct on Line Starter (D.O.L)



In case of small capacity motors having rating less than 5 hp, the starting current is not very high and such motors can withstand such starting current without any starter. Such type motors use a starter which is used to connect stator directly to the supply line without any reduction in voltage. Hence the starter is known as direct online starter.

It protects the motor from various severe abnormal conditions like over loading, low voltage, single phasing etc.

The NO contact is normally open and NC is normally closed. At start NO is pushed for fraction of second due to which coil gets energised and attracts the contactor. So stator directly gets supply. When NC is pressed, the coil ckt gets opened due to which coil gets deenergised and motor gets switched off from the supply. Thermal relays

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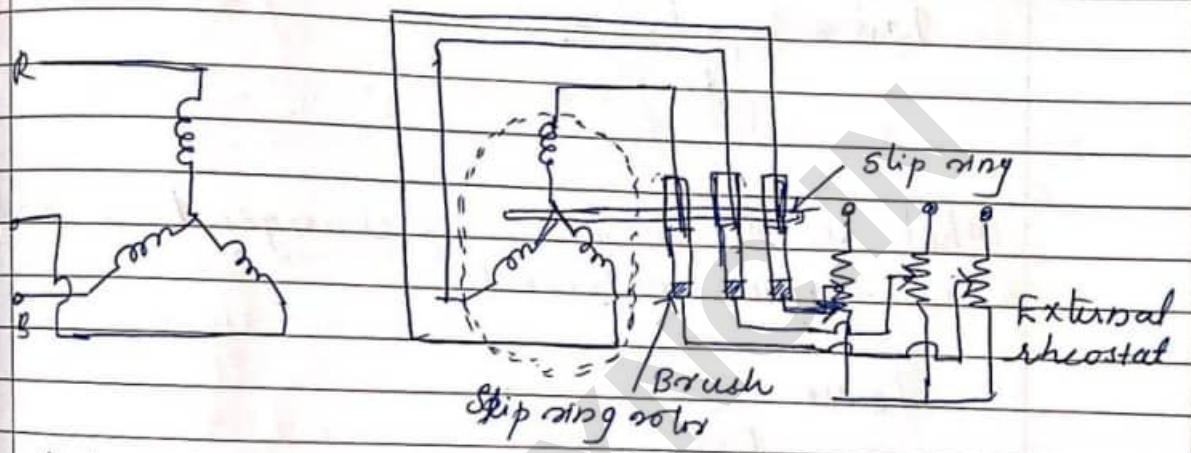
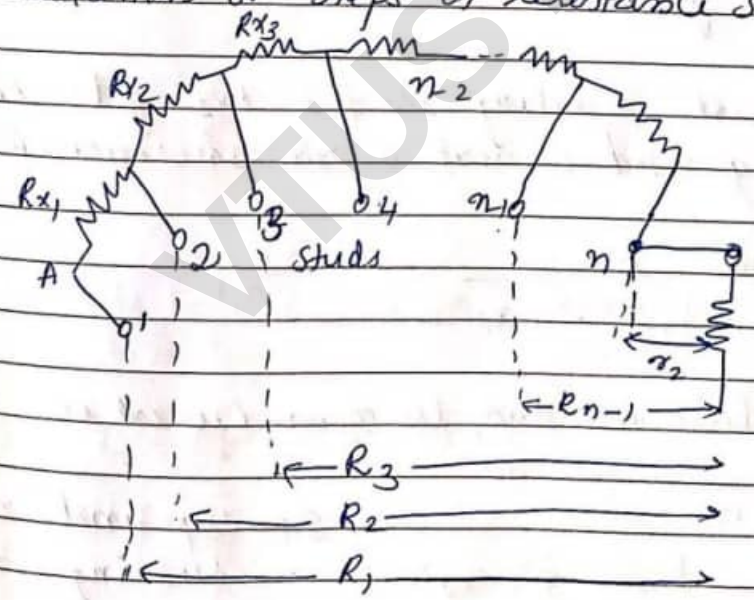
get opened due to high temperature, protecting the motor from overload condition.

Rotor Resistance Starter

To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor ckt at start.



Calculation of steps of resistance starter



E_2 = Standstill rotor emf per phase

When handle is moved to stud 1, the current is maximum given by,

$$I_{2max} = \frac{S_1 E_1}{\sqrt{R_1^2 + (S_1 X_2)^2}}$$

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$$= \frac{E_2}{\sqrt{\left(\frac{R_1}{S_1}\right)^2 + X_2^2}}$$

S_1 = slip at start = 1

while moving to stud 2, the current reduces I_{2min}

$$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_1}{S_2}\right)^2 + X_2^2}}$$

while leaving stud 2, slip changes to S_3 and current again reduces to

$$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_2}{S_3}\right)^2 + X_2^2}}$$

While just reaching stud 3, R_{V_2} gets cut off completely and current again increases to

$$I_{2max} = \frac{E_2}{\sqrt{\left(\frac{R_3}{S_3}\right)^2 + X_2^2}}$$

Hence at last n^{th} stud, the max. current is

$$I_{2max} = \frac{E_2}{\sqrt{\left(\frac{r_2}{S_n}\right)^2 + X_2^2}}$$

S_n = slip under normal running condition

$$I_{2max} = \frac{E_2}{\sqrt{\left(\frac{R_1}{S_1}\right)^2 + X_2^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{S_2}\right)^2 + X_2^2}} = \dots \frac{E_2}{\sqrt{\left(\frac{r_2}{S_n}\right)^2 + X_2^2}}$$

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$$\frac{R_1}{S_1} = \frac{R_2}{S_2} = \cdots \frac{r_2}{S_n}$$

$$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_1}{S_2}\right)^2 + X_2^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{S_3}\right)^2 + X_2^2}} = \cdots \frac{E_2}{\sqrt{\left(\frac{R_{n-1}}{S_n}\right)^2 + X_2^2}}$$

$$\frac{R_1}{S_1} = \frac{R_2}{S_2} \cdots \frac{R_{n-1}}{S_n}$$

$$\frac{S_2}{S_1} = \frac{S_3}{S_2} = \frac{S_4}{S_3} = \cdots \frac{R_2}{R_1} = \frac{R_3}{R_2} = \frac{R_4}{R_3} = \cdots \frac{r_2}{R_{n-1}} = k$$

k = constant

$$R_1 = \frac{S_1 r_2}{S_n} \qquad S_1 = 1$$

$$R_1 = \frac{r_2}{S_n}$$

$$R_2 = kR_1, \quad R_3 = kR_2 = kkR_1 = k^2R_1 \quad R_4 = k^3R_1$$

$$r_2 = k^{n-1}R_1$$

$$r_2 = \left[\frac{r_2}{R_1}\right]^{\frac{1}{n-1}} = [S_n]^{1/n-1}$$

$$R_{x1} = R_1 - R_2 = (1-k)R_1$$

$$R_{x2} = R_2 - R_3 = kR_1 - k^2R_1 = k(1-k)R_1 = kR_{x1}$$

$$R_{x3} = k^2R_{x1} \cdots$$

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Speed control of Induction Motor

IM is practically constant speed motor like d.c shunt motor. ~~but the speed control is achieved by~~

For IM $N = N_s(1-s)$

From the above expression, it is seen that speed of the IM can be changed either by changing the synchronous speed N_s or by changing the slip 's'.

Similarly Torque produced is given by

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

If parameters E_2 and R_2 are changed to keep the torque constant for constant load condition, motor reacts by change in its slip. Effectively speed changes.

Types of speed control method

1. From stator side
2. From rotor side

From stator side

1. Supply frequency control to control N_s, called V/f control
2. Supply Voltage control
3. Controlling no. of stator poles to control N_s
4. Adding rheostats in stator ckt

From Rotor side

1. Adding external resistance in the rotor ckt
2. Cascade Control

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3 Injecting slip frequency voltage in to the rotor ckt

Supply frequency Control Or V/f control.

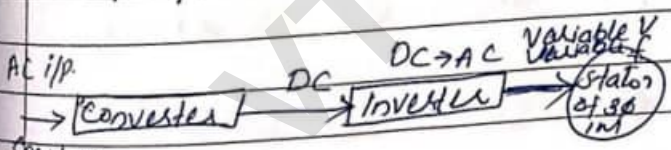
$$N_s = \frac{120f}{P}$$

Expression for air gap flux is given by

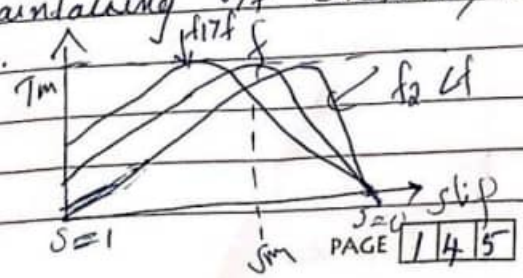
$$\phi_g = \frac{1}{4.44 K T_{ph}} \left(\frac{V}{f}\right)$$

K = Stator wdg const
T_{ph} = Stator turns/phase
V = Supply Voltage
f = Supply frequency

If f is changed ϕ_g is changed. This may results into saturation of ~~saturat~~ stator core and rotor core, and hence it is necessary to maintain air gap flux constant.
To achieve this along with frequency f, supply voltage V also must be changed and ratio of (V/f) should be maintained constant. Hence this method is called V/f control.



The converter converts constant voltage constant frequency supply into a d.c supply. This dc supply is then given to inverter which converts dc supply to variable voltage, variable frequency ac supply which is required to keep V/f ratio constant. By selecting proper frequency and maintaining V/f constant, smooth speed control is possible.



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Supply voltage control

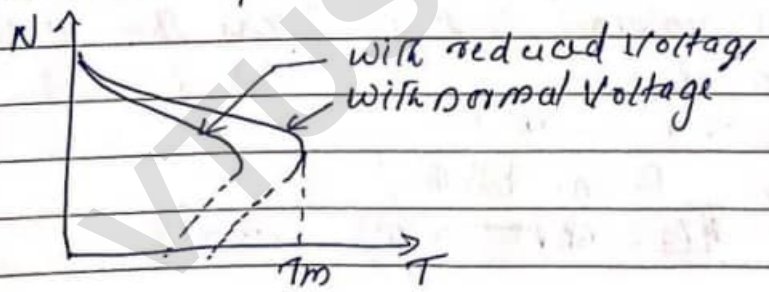
$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (Sx_2)^2}$$

$E_2 \propto V$, $(Sx_2)^2 << R_2$ can be neglected (in low slip)

$$T \propto \frac{S V^2 R_2}{R_2^2} \propto S V^2 \text{ for const } R_2$$

$$\boxed{T \propto S V^2}$$

if supply voltage is reduced below rated voltage torque also reduces, But to supply the same load, it is necessary to develop same torque hence value of slip increases, so that torque produced remains same. [V↓ T↓ S↑ N↓]
If slip increases motor runs at lower speed so motor produces the required load torque at a lower speed.



Disadvantages

1. Large change in voltage is necessary for small change in speed
2. Additional voltage changing equipment is necessary

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Controlling no. of Poles in the Stator [Pole changing Method]

1. Consequent Poles Method
2. Multiple stator wdg Method

Consequent Poles Method

In this method connections of stator wdg are changed with the help of simple switching technique Due to this no. of stator poles are changed in the ratio 2:1. Hence either of the 2 synchronous speeds can be selected.

Multiple Stator Winding Method

In this method ~~method~~ instead of one wdg two separates stator wdgs are placed in the stator core. The wdgs are placed in the same stator slots, but are electrically isolated from each other. Each wdg is divided into coils, to which pole changing with consequent poles, facility is provided.

Limitations

Consequent Poles Method

1. Smooth speed control is not possible

2. Multiple stator wdg Method

1 can be applied only to squirrel cage motors
2 Smooth speed control is not possible
3 Complicated from the design pt of view
4 Two different stator wdgs are required, which increases the cost of the motor

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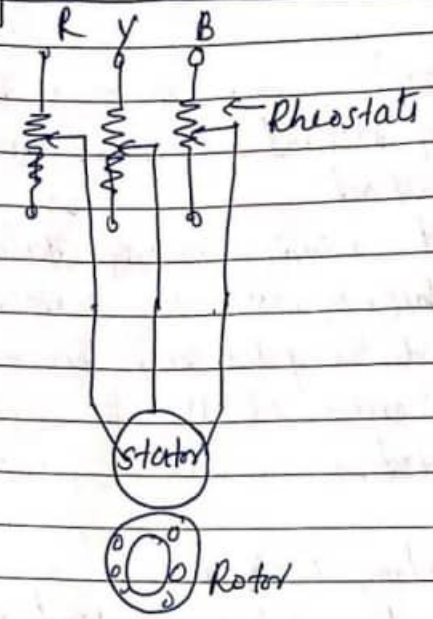
Adding rheostats in the stator circuit.



Reduced voltage can be applied to the stator wdg by adding rheostat in the stator circuit. A part of the supply voltage gets dropped across the rheostats and in turn reduces the voltage applied to the stator. This causes reduction in the speed. The rheostats can be varied as per the required change in speed.

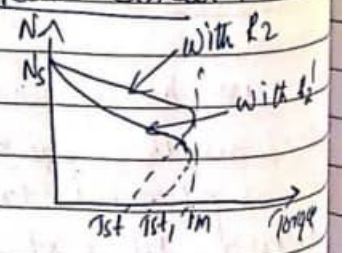
Disadvantages:

There are large power loss due to the rheostat.

Speed control from Rotor side

Adding external Resistance in Rotor circuit.

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$



for low slip region $(sX_2)^2 << R_2$

$$T \propto \frac{s E_2^2 R_2}{R_2^2}, \quad \text{if } E_2 \text{ is const}$$

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

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If R_2 is increased, the torque produced decreases. But for same load on the motor, the motor has to supply same torque. So slip increases and maintains the load torque constant. So due to additional rotor resistance R_2, motor slip increases. ie the speed of the motor decreases. $R_2 \uparrow$ $T \downarrow$ but $S \uparrow$ $N \downarrow$

As $R_2 \downarrow$ $T \uparrow$ $S \downarrow$ speed $(N) \uparrow$

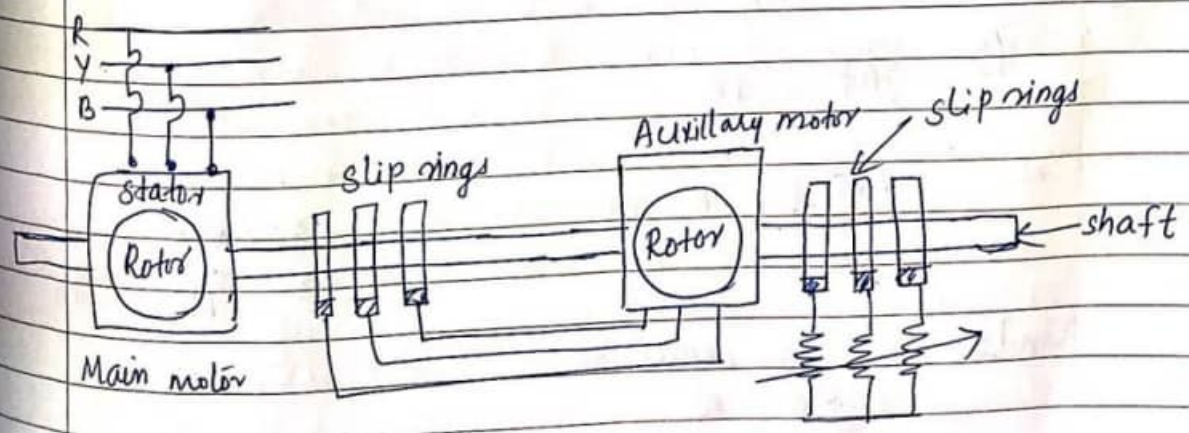
Advantages

1. By increasing R_2, speed below normal speed can be achieved
2. The starting torque of the motor increases proportional to rotor resistance

Disadvantages

1. Large speed changes are not possible
2. Cannot be used for squirrel cage IM
3. Speed above normal speed cannot be obtained
4. Large power loss due to I^2R losses
5. Efficiency is low.

Cascade Control



In this method, 2 induction motors are mounted on

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the same shaft, first motor called main motor is a slip ring IM. second motor is called Auxillary motor can be slip ring or squirrel cage. The supply to the main motor is from 3ϕ supply. The supply to the auxillary motor is derived at a slip frequency from the slip rings of main motors. This is called cascading of motors. If the torque produced by both act in the same direction, cascading is called cumulative cascading. If torque produced are in opposite direction, cascading is called differential cascading.

Let P_A = No. of poles of main motor
P_B = No. of poles of auxillary motor
f = supply frequency
N = speed of the set.
f_A = frequency of rotor induced emf of motor A
f_B = frequency of rotor induced emf of auxillary motor

$$f_A = f_B$$

$$N_{SA} = \frac{120f}{P_A}$$

$$\%S_A = \frac{N_{SA} - N}{N_{SA}} \times 100 \quad \text{--- (1)}$$

$$f_A = S_A f = f_B$$

$$N_{SB} = \frac{120 f_B}{P_B} = \frac{120 f_A}{P_B} = \frac{120 S_A f}{P_B} = 120 \frac{(N_{SA} - N)}{N_{SA}} \times \frac{f}{P_B}$$

Under no load condition
$N_{SB} \approx N$

$$N = \frac{120f}{P_B}\left[\frac{N_{SA} - N}{N_{SA}}\right]$$

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$$N = \frac{120f}{P_B}\left[1 - \frac{N}{N_{SA}}\right] = \frac{120f}{P_B} \times \left[1 - \frac{N}{\left(\frac{120f}{P_A}\right)}\right]$$

$$N = \frac{120f}{P_B} \times \left[1 - \frac{NP_A}{120f}\right]$$

$$\therefore N\left[1 + \frac{P_A}{P_B}\right] = \frac{120f}{P_B}$$

$$\boxed{N = \frac{120f}{P_A + P_B}} \rightarrow \text{for cumulative cascading}$$

$$\boxed{N = \frac{12f}{P_A - P_B}} \rightarrow \text{for differential cascading}$$

4 speed control can be possible

1. $N_S = \frac{120f}{P_A}$ 2. $N_S = \frac{120f}{P_B}$ 3. $N = \frac{120f}{P_A + P_B}$ 4. $N = \frac{120f}{P_A - P_B}$

Injecting Slip frequency Voltage in the rotor ckt

In this method voltage/emf having the slip frequency is injected into the rotor ckt.

It is possible that the injected slip frequency voltage may oppose the rotor induced emf, thus the effective rotor resistance increases.

If the injected slip frequency voltage assists or helps the rotor induced emf, then effective rotor resistances decreases

Two methods are available

1. Kramer system 2. Sherbius system

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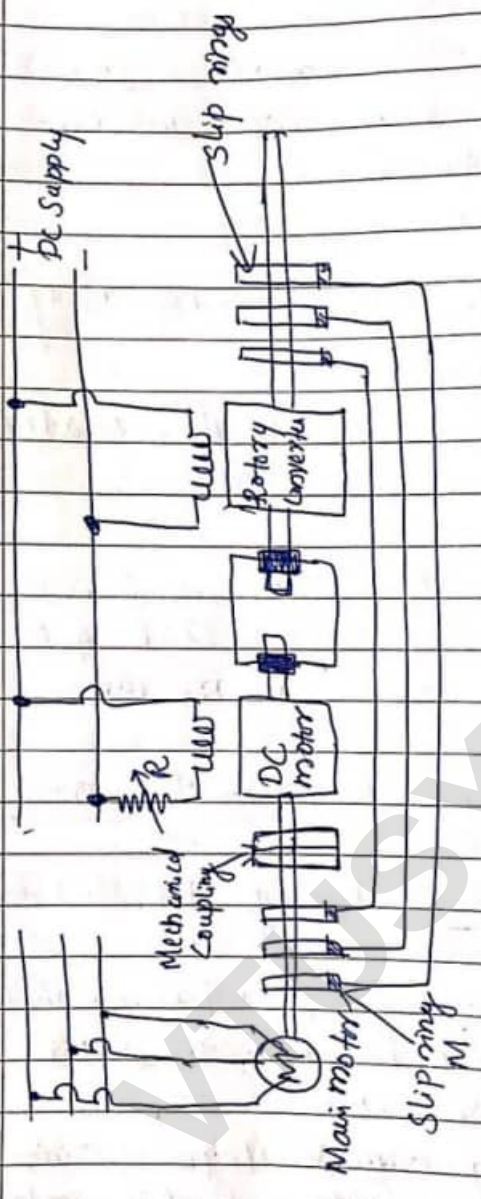
Kramer system



It consists of main IM whose speed of which is to be controlled. The 2 additional equipments are dc motor and a rotary converter. The slip rings of the main motor are connected to the ac side of the rotary converter. The dc side of rotary converter feeds a dc shunt motor connected which is directly connected to the shaft of the main motor. A separate dc supply is required to excite field wdg of dc motor and exciting wdg of a rotary converter.

The speed of the set is controlled by varying the field of the dc motor with Rheostat R. When R changes back emf of motor changes. Thus dc voltage at the commutator changes. The voltage on ac side of ~~moto~~ changes. This ac voltage is given to the slip ring of main motor. So the voltage injected in the rotor of main motor changes which produces the required speed control.

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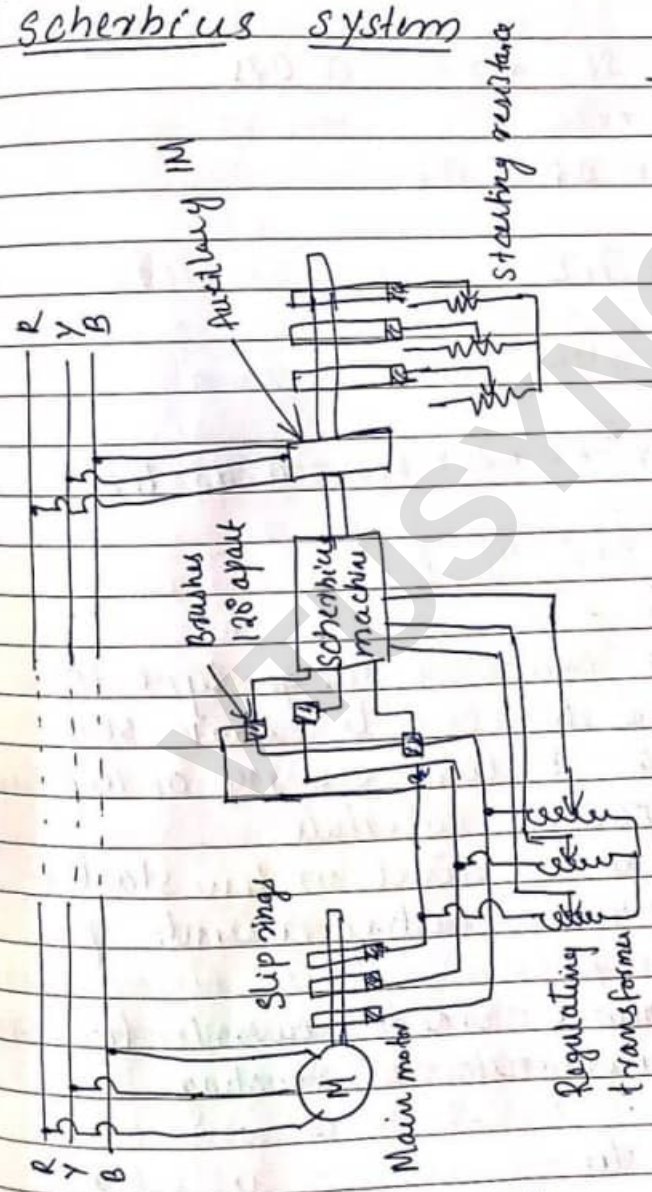
Advantages:

1. Smooth speed control is possible
2. Wide range of speed control is possible

Disadvantages

1. It can be used only for speed control of slip ring IM.
2. Two additional equipments like, DC shunt motor and a rotary converter is required which increases the overall cost.

Scherbius system



→ This method requires an auxillary 3ϕ AC commutator machine, which is called Scherbius machine.

→ The scherbius m/c is excited at a slip frequency from the rotor of a main motor through a regulating transformer.

→ The taps on the regulating transformer can be varied, this changes the voltage developed in the rotor of Scherbius machine, which is injected to the rotor of the main motor. This control the speed of the main motor.

Advantage → for large motors

Disadvantages → only for slip ring IM.

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Problems
Starters

1. A 3 ϕ IM in a short ckt current equal to 4 times the full load current. Determine the starting torque as a % of full load torque if full load slip is 2.5%.

$$\frac{T_{st}}{T_{FL}} = x^2 \left[\frac{I_{SC}}{I_{FL}}\right] S_f$$

$I_{SC} = 4 I_{FL}$ $\quad S_f = 2.5\% = 0.025$

$$\frac{T_{st}}{T_{FL}} = 4^2 \times 0.025 = 0.4$$

$T_{st} = 40\%$ of T_{FL}

If star-delta starter

$$T_{st} = \frac{1}{3} \times 4^2 \times 0.025 \times I_{FL} = 0.1333 T_{FL}$$

$$\boxed{T_{st} = 13.33\% \text{ of } T_{FL}}$$

2. A 3ϕ - delta connected cage type IM when connected directly to 400V, 50Hz supply takes a starting current of 100A in each stator phase. Calculate:
i) The line current for direct on-line starting
ii) line and phase starting currents for star-delta starting
iii) line and phase starting currents for a 70% tapping on autotransformer starting.

i) In D.O.L starter

$I_L = \sqrt{3} I_{ph} = \sqrt{3} \times 100 = 173.205 A$

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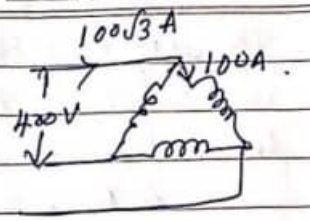
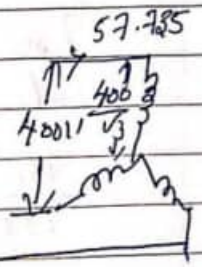
(i) In star-delta starter



$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94\ V$

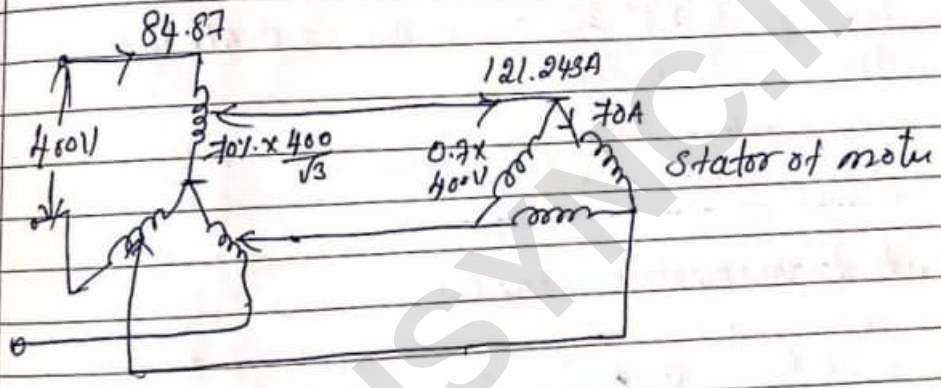
$I_{ph} = \frac{100}{\sqrt{3}} = 57.785A$



starting phase current = 57.735A
In star connection $I_L = I_{ph}$
starting line current = 57.735 A

(ii) 70% tapping on autotransformer starting

$V_{ph} = \frac{400}{\sqrt{3}}$



line voltage for delta connected stator = 0.7×400 = 280V
Phase " " " " = 280V
400V circulates 100A phase current hence 280V circulates a phase current of $\frac{280}{400} \times 100 = 70A$

∴ starting phase current of motor = 70A
starting line current of motor = √3 × 70 = 121.2A
Supply line current = 0.7 × 121.243 = 84.87A

8. Determine the starting torque of 3ϕ IM inline of full load ~~load~~ torque when started by i) Star-delta starter ii) Autotransformer with 50% tapping.

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The ~~starting~~ short ckt current of the motor is 5 times the full load current and full load slip is 5%

$\% x = 50\%$ $x = 0.5$

$I_{sc} = 5 I_{fl}$

$S_f = 5\% = 0.05$

$$\frac{T_{st}}{T_{FL}} = x^2 \times \left[\frac{I_{SC}}{I_{fL}}\right]^2 \times S_f$$

i) Star-delta starter :

$x = \frac{1}{\sqrt{3}}$ $x^2 = \frac{1}{3}$

$$\frac{T_{st}}{T_{FL}} = \frac{1}{3} \times \left[\frac{5 I_{fL}}{I_{fL}}\right]^2 \times 0.05 = 0.416 T_{fl}$$

$$\boxed{T_{st} = 41.66\% \text{ of } T_{FL}}$$

(ii) Auto transformer starter

$$\frac{T_{st}}{T_{FL}} = 0.5^2 \times \left[\frac{5 I_{fL}}{I_{fL}}\right]^2 \times 0.05$$

$$\boxed{T_{st} = 0.3125 T_{FL}}$$

$$\boxed{T_{st} = 31.25\% \text{ of } T_{FL}}$$

4. A 3ϕ 6 pole, 50Hz induction Motor takes 60A at full load speed of 940 rpm and develops a torque of 150 Nm. The starting current at rated voltage is 300A. What is the starting torque, if a star-delta starter is used, determine the starting torque & starting current.

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$P = 6$ $f = 50Hz$, $I_{fL} = 60A$ $N = 940 rpm$

$T_{fL} = 150$ N-m, $I_{sc} = 300A$

i) without starter

$N_s = \frac{120 \times f}{P} = 1000 rpm$

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

$s_f = \frac{N_s - N}{N_s} = 0.06$

$$\frac{T_{st}}{150} = \left[\frac{300}{60}\right]^2 \times 0.06$$

$$\boxed{T_{st} = 225 \text{ N-m}}$$

ii) With star-delta starter

$$\frac{T_{st}}{T_{fL}} = x^2 \left[\frac{I_{sc}}{I_{fL}}\right]^2 s_f = \frac{T_{st}}{150} = \frac{1}{3} \times \left[\frac{300}{60}\right]^2 \times 0.06$$

$$I_{sc} = \sqrt{\frac{T_{st}}{T_{fL}}} \times \frac{I_{fL}}{x\sqrt{s_f}}$$

$$\boxed{T_{st} = 75 \text{ N-m}}$$

$$= \sqrt{\frac{75}{150}}$$

(iii) starting current with starter

$$\frac{T_{st}}{T_{fL}} = x^2 \left[\frac{I_{sc}}{I_{fL}}\right] \times s_f$$

$$I_{sc} = \sqrt{\frac{T_{st}}{T_{fL}}} \times \frac{I_{fL}}{x\sqrt{s_f}}$$

$$= \sqrt{\frac{75}{150}} \times \frac{60}{1/\sqrt{3} \times \sqrt{0.06}}$$

$$\boxed{I_{sc} = 300A}$$

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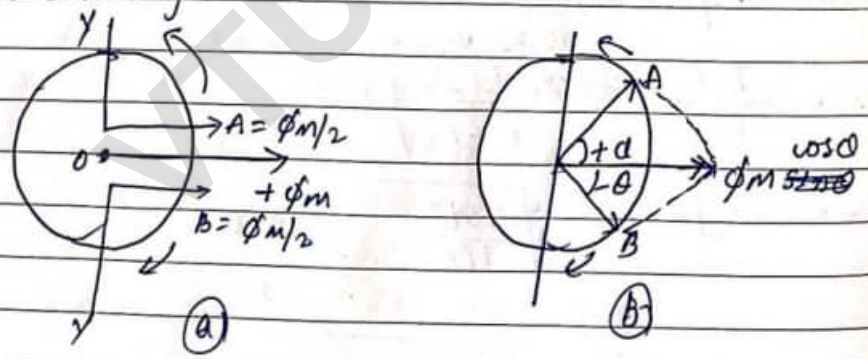
Single phase Induction Motor

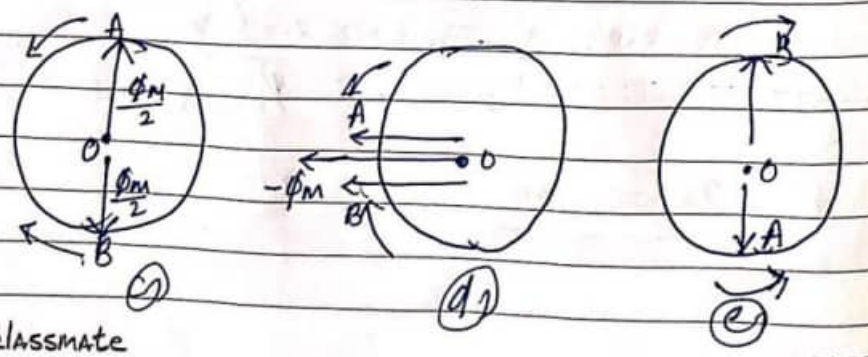
Construction :-
1) Stator
2) Rotor → squirrel cage rotor

	3ϕ IM	1ϕ IM
1.	self starting	Not self starting
2.	flux produced is rotating flux	flux produced is alternating

Double field revolving Theory

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite direction and each having magnitude as half of the maximum magnitude of the alternating quantity.





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As shown in figure (a), let the alternating flux have a max. value of ϕ_m. Its component fluxes A & B will each be equal to $\frac{\phi_m}{2}$, revolving in anti-clockwise and clockwise direction respectively.

After some time, when A & B would have rotated through angle $+\theta$ and $-\theta$ as in fig (b). The resultant flux will be

$$2 \times \frac{\phi_m}{2} \cos\frac{2\theta}{2} = \phi_m \cos\theta$$

After a quarter cycle of rotation, fluxes A & B will be oppositely directed as shown in fig (c) so that resultant flux will be zero.

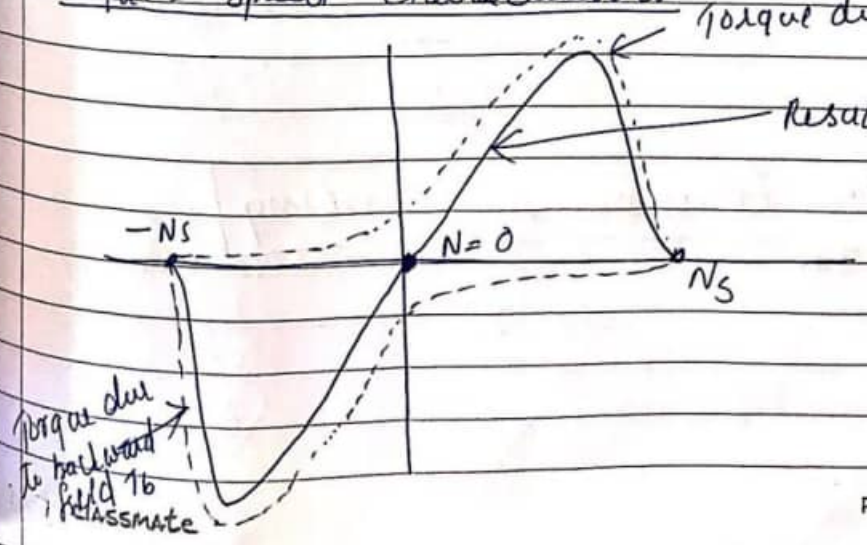
After half cycle, fluxes A and B will have a resultant of $-2 \times \frac{\phi_m}{2} = -\phi_m$

After 3 quarters of cycle again the resultant is zero, as shown in fig (e).

This continuous rotation of the 2 components gives the original alternating stator flux.

Both the components are rotating and hence get cut by rotor conductors. Dual to emf gets induced in the rotor

Torque - speed characteristics



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The slip of the rotor with respect to the forward rotating field

$$S_f = \frac{N_s - N}{N_s} = s$$

The slip of the rotor with respect to the backward rotating field

$$S_b = \frac{N_s - (-N)}{N_s} = \frac{2N_s - (N_s - N)}{N_s}$$

$$\boxed{S_b = 2 - s}$$

Power developed $P_g = \left[\frac{1-s}{s}\right] I_2^2 R_2$ $\quad I_2^2 R_2 = k$

$$T_f = \frac{P_g}{\omega} = \frac{1}{2\pi N}\left(\frac{1-s}{s}\right] I_2^2 R_2$$

$$= \frac{1}{2\pi (1-s) N_s}\left[\frac{1-s}{s}\right] I_2^2 R_2$$

$$= \frac{1}{2\pi N_s} \times \frac{I_2^2 R_2}{s}$$

$$= k \frac{I_2^2 R_2}{s}$$

$$T_b = -k \frac{I_2^2 R_2}{2-s}$$

At $s = 1$ (Stand)

$$T_R = T_f + T_b = \frac{k' I_2^2 R_2}{1} + -\frac{k I_2^2 R_2}{1}$$

$$\boxed{T_R = 0}$$

$\boxed{\text{So it is not self starting}}$

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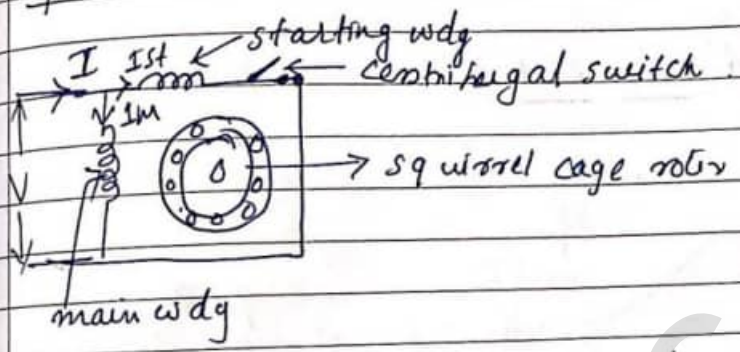
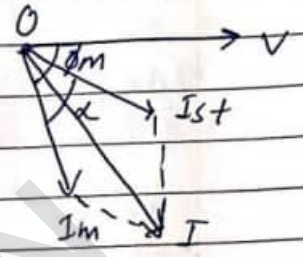
Types of Single Phase IM

1. Split phase IM
2. Capacitor Start IM
3. Capacitor start capacitor Run IM
4. shaded pole IM

Split phase Induction Motor





This type of motor has single phase stator wdg called main winding. In addition to this, stator carries one more wdg called auxillary wdg or starting current. The auxillary wdg carries a series resistance such that its impedance is highly resistive nature. The main wdg is inductive in nature.

Im = Current through the main wdg
Ist = C " " " starting wdg
V = supply Voltage

Phasor diagram

Im lags V by an angle φm while Ist is in almost in phase with V. (Aux wdg is resistive in nature.) Thus there exists a phase difference of α b/w the 2 currents and hence b/w 2 fluxes produced by 2 currents. the resultant of these fluxes is a RMF.

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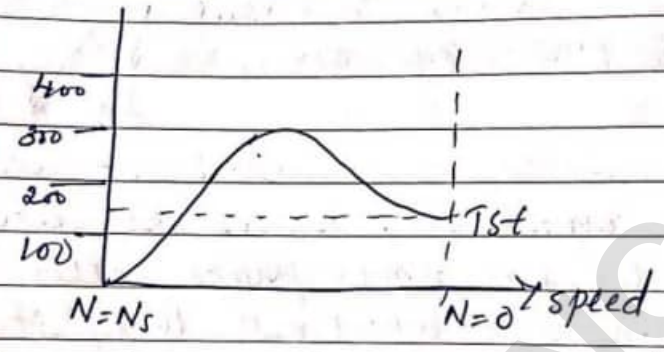
when motor gathers a speed upto 75–80% of N_s, centrifugal switch opened mechanically and in running condition aux. wdg remains out of the circuit.

As current I_m & I_{st} are splitted from each other by an angle α at start, the motor is called split phase IM.

Torque-speed characteristics



starting torque is equal to around 150% of full load torque. (poor starting torque)

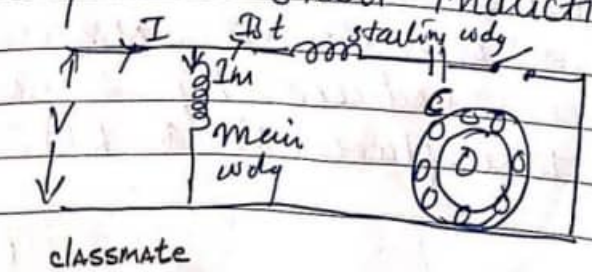
Applications

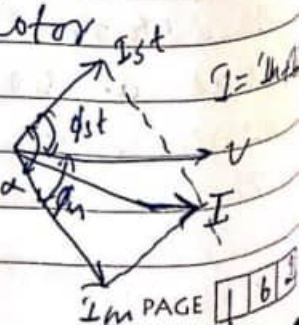
These motors have low starting current and moderate starting torque

→ used for fans, blowers, grinders, centrifugal pumps, washing machines, oil burners etc.

→ They are available in the range of $\frac{1}{20}$ to $\frac{1}{2}$ kW.

Capacitor start Induction Motor





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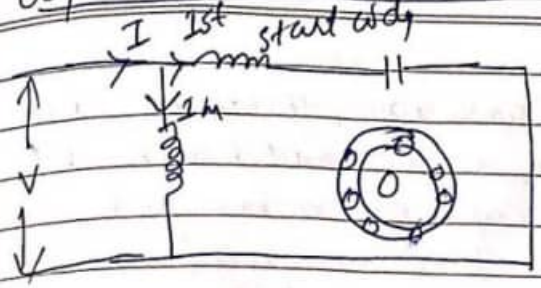
Capacitor start - capacitor Run



Depending whether the capacitor remains in the ckt permanently or is disconnected from the ckt using a centrifugal switch, these motors are classified as

1. Capacitor start Motors 2. Capacitor start capacitor run Motors.

Due to the capacitor, the current Ist leads the voltage by an angle ϕ_{st}. Hence there exists a large phase difference b/w Im & Ist.

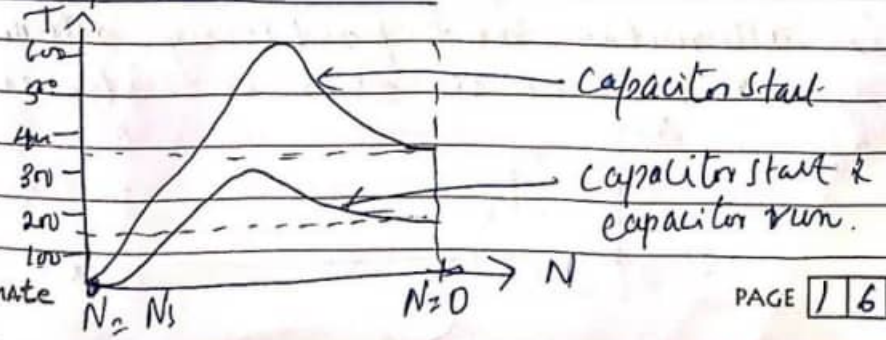
$I_{st} \propto (\alpha)$

Hence such motors produce a very high starting ~~tor~~ torque. ie Ist lies b/w 350-400% of full load torque and for capacitor start capacitor run IM Ist lies b/w 50-100% of full load torque.

In case of capacitor start capacitor run IM there is no centrifugal switch and the capacitor remains permanently in the ckt.

These motors are costly compared to split phase IM.

Torque speed characteristics



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Applications

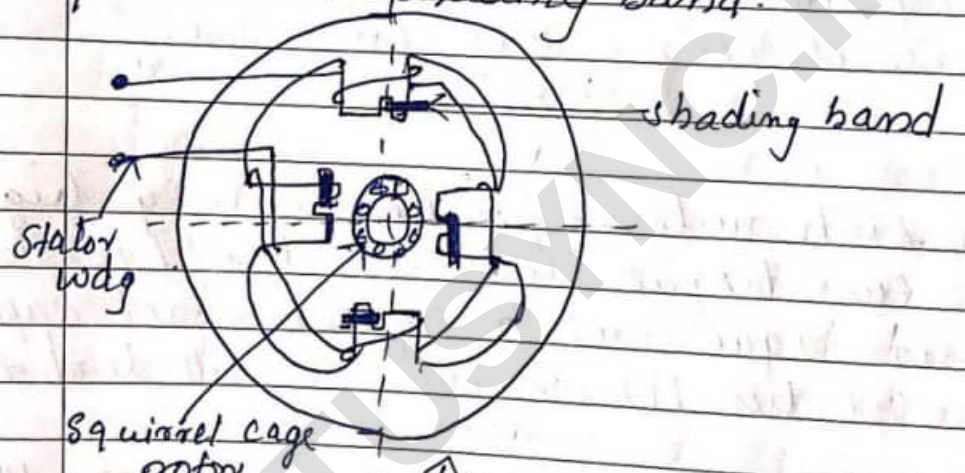
→ compressors, conveyors, grinders, fans, blowers, refrigerators, air conditioners etc.

→ capacitor start capacitor run motors are used in ceiling fans, blowers and air circulators

→ Motors are available upto 6kW.

Shaded pole Induction Motor

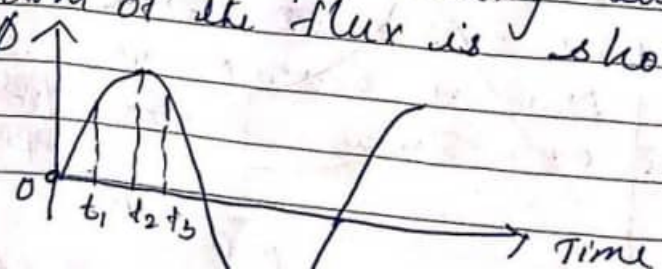
This motor consists of a squirrel cage rotor and stator consisting of salient poles. The poles are shaded. Each pole carries a copper band on one of its unequally divided part called shading band.



↑ 4 pole shaded pole construction

When single phase a.c supply is given to stator wdg due to shading provided to the poles, RMF is generated.

The current carried by the stator wdg is alternating and producing alternating flux. The waveform of the flux is shown in the fig.



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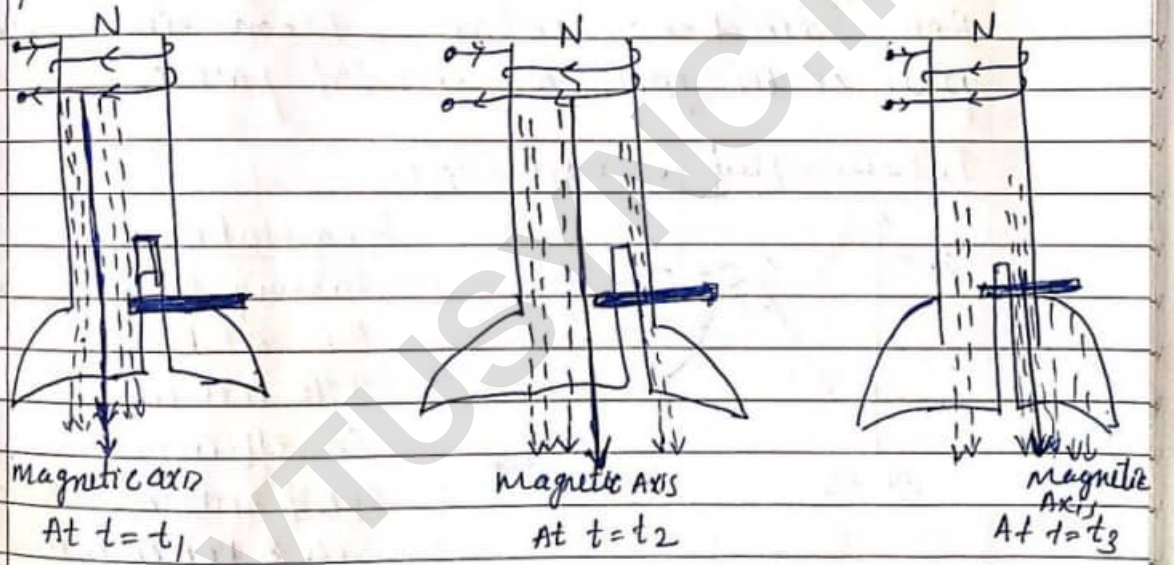
Consider 3 instants say t_1, t_2, and t_3.

At $t = t_1$ rate of rise of current and hence the flux is very high. Due this large emf gets induced emf in the copper shading band, and circulates current through the copper shading bands producing its own flux.
By Lenz's law the shading band flux is opposing to the main flux. Hence there is crowding of flux under the non shaded part while there is a weaking of flux under the shaded part.
overall magnetic axis shifts to the non shaded part shown.



At $t = t_2$, rate of rate of current (flux) is almost ~~constant~~ zero as flux almost reaches to its max. value
$\frac{d\phi}{dt} = 0$

Hence very little emf gets induced in the copper shading bands. Hence shading band flux is almost negligible. Thus it doesnot affect the main flux. Hence main flux gets equally under both shaded and non shaded part of pole.

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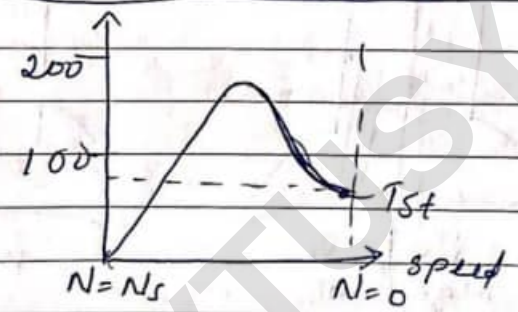
At $t = t_3$ the current or flux is reducing, the rate of decrease is high and thus a large emf gets induced in copper shading band. Direction of the flux produced by the shaded band opposes the decrease in flux. Stream direction is same as that of main flux, strengthening it. Thus there is more flux under the shaded part when compared to non-shaded part. Thus magnetic axis lies under the shaded part of the pole.

During negative half cycle

This sequence keeps on repeating for -ve half cycle also and produces the effect of RMF, direction of which is from non shaded part of the pole to shaded part of the pole.

Torque speed characteristics



Limitations

1. Starting torque is low
2. Pf is low
3. I^2R loss in shading band so efficiency is low
4. Speed reversal is difficult
5. Size & power rating is very small ($\frac{1}{300}$ to $\frac{1}{20}$ hp)

Applications

Used for small fans, toy motors, advertising displays, film projectors, record players, hair dryers, photo copying machines etc.

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Synchronous Motors

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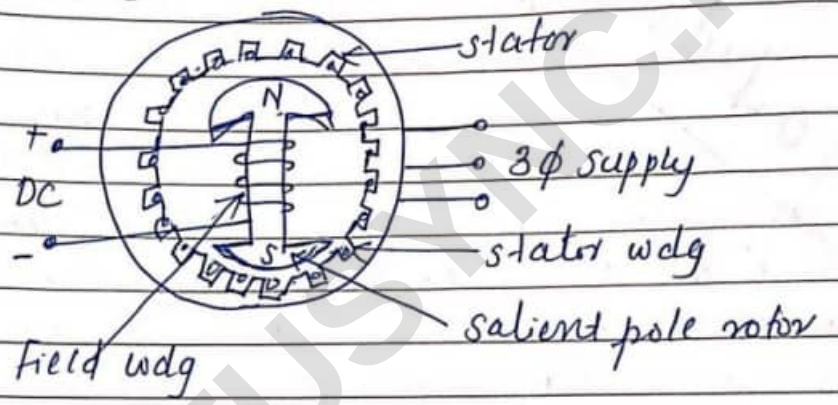
Synchronous motor works only at synchronous speed and cannot work at speed other than the synchronous speed.

Construction

i) Stator – consists of 3ϕ star or delta connected wdg, which is excited by a 3ϕ AC supply.
ii) Rotor – is a field wdg, construction of which can be salient or nonsalient type. The field wdg is excited by seperate d.c supply through slip rings.



The speed at which RMF rotates is given by
$N_s = \frac{120f}{P}$ rpm.

90% of rotor are salient pole rotor

Principle of working

→ works on the principle of magnetic locking
→ To have magnetic locking there must exist 2 unlike poles and magnetic axis of the 2 poles must be brought very close to each other
→ Assume the stator is wound for 2 poles with 50Hz supply.

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Let this 2 poles be N_1 and S_1 which are rotating at a speed of N_s (rpm). Assume direction of rotation of RMF as clockwise. When the field wdg on rotor is excited by a dc supply. It also produces 2 poles. Let these 2 rotor poles be N_2 and S_2.

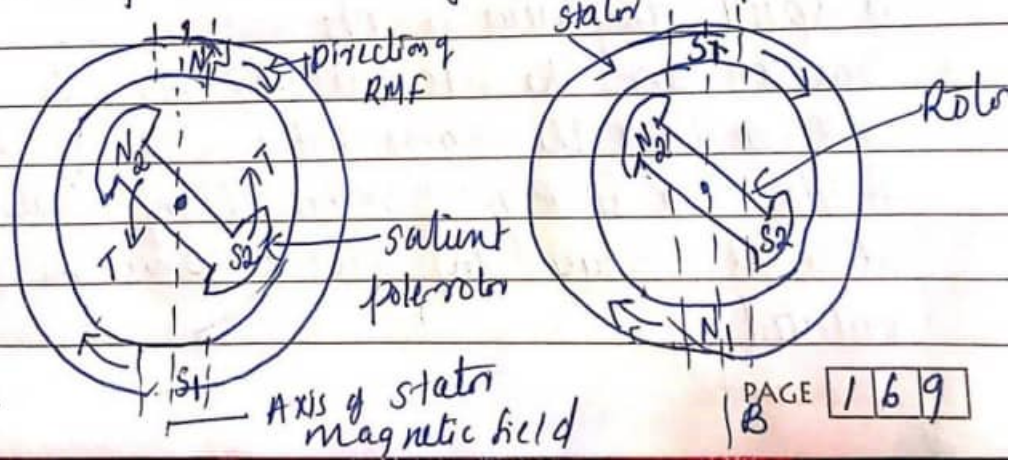
At starting $N_1 S_1$ are rotating at N_s rpm. Second magnet is stationary having poles N_2 & S_2. If somehow the unlike poles N_1 and S_2 or S_1 & N_2 are brought near each other, magnetic locking may get established b/w stator and rotor poles. As stator poles are rotating, due to magnetic locking rotor will also rotate in the same direction as that of stator poles. (N_s speed)

Synchronous Motor is not self starting

Practically it is not possible for stator poles to pulls the rotor poles from their stationary position into magnetic locking condition. Hence it is not self starting.

Consider the RMF as equivalent to physical rotation of 2 stator poles N_1 and S_1, and are at a position where stator ~~magn~~ magnetic axis is vertical along AB.

At this instant rotor poles are arbitrarily positioned. At this instant rotor is stationary and unlike poles will try to attract each other



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Due to this rotor will be subjected to an instaneous torque in anti clockwise direction. Now stator poles are rotating very fast at a speed Ns rpm. Due to inertia, before rotor hardly rotates in the direction of anticlockwise torque to which it is subjected, the stator poles change their positions. Consider an instant half a period later where stator poles are exactly reversed, but due to inertia rotor is unable to rotate from its initial position.

At this instant, due to unlike poles trying to attract each other, the rotor will be subjected to a torque in clockwise direction. This will tend to rotate rotor in the direction of RMF.

But before this happens, stator poles again change their positions reversing the direction of the torque exerted ~~by~~ on the rotor.

As a result, the average torque exerted on the rotor is zero. and hence the synchronous motor is not self starting.

Procedure to start synchronous motor:-

1. Give a 3ϕ AC supply to a 3ϕ wdg. This will produce RMF rotating at a speed Ns.
2. Then drive the rotor by some external means like diesel engine in the direction of RMF, at a speed very near to Ns
3. Switch on the dc supply given to the rotor, which will produce the rotor poles. Now there are 2 fields, one is RMF produced by stator while the other is produced by rotor which is physically rotated

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4. At a particular instant both fields gets magnetically locked. The stator field pulls rotor field into synchronism. Then the external device used to rotate rotor can be removed.

Methods of starting Synchronous Motor

1. Using pony motors
2. Using damper winding
3. As a slip ring IM
4. Using small dc m/c coupled to it.

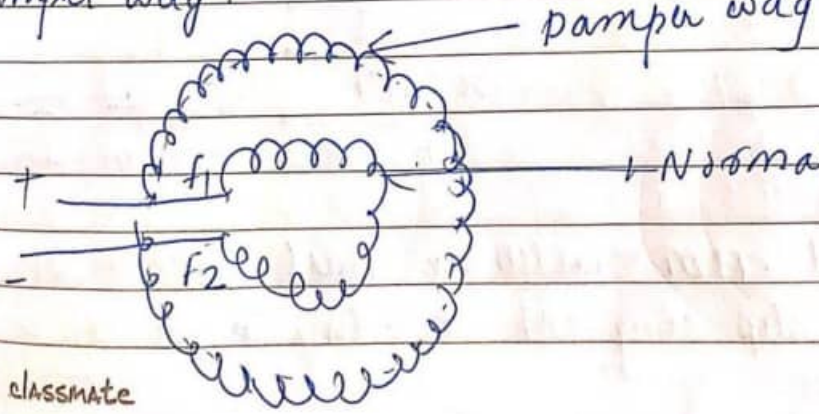
Using pony Motors

The motor rotor is brought to the synchronous speed with the help of some external devices like small induction motor, such external device is called pony motors.

once synchronisation is established, the pony motor is decoupled.

Using damper wdg

In this method, in additional to the normal field wdg, an additional wdg consistings of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional wdg is called damper wdg.



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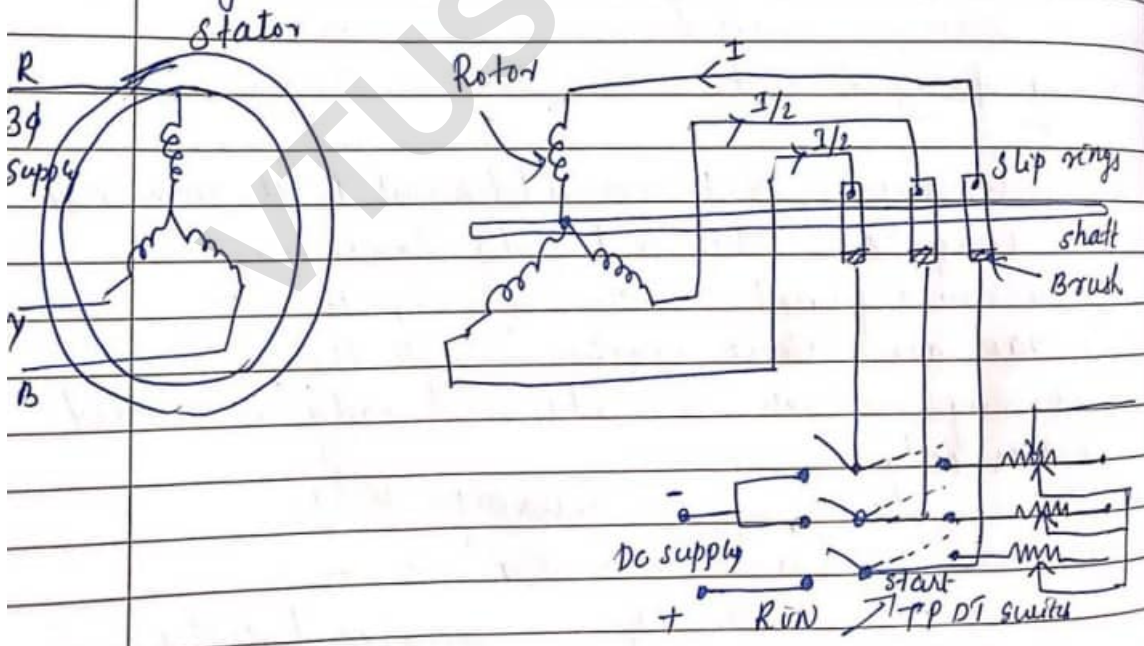
Once the stator is excited by a 3ϕ supply the motor starts rotating as an induction motor at subsynchronous speed.

Then dc supply is given to the field wdg. At particular instant motor gets pulled into synchronism and starts rotating, at a synchronous speed. As rotor rotates at N_s the relative motion b/w damper wdg and RMF is zero. In Damper wdg there cannot be any induced emf. So damper wdg is active only at start, to run the motor as an IM. After wards it is out of the circuit.

As a slip ring IM

In the damper wdg method it is difficult to achieve high starting torque. To achieve high torque instead of shorting the damper wdg, it is designed to form a 3ϕ star or delta connected wdg.



At start TPDT switch in start position. It acts as a slip ring IM. Starting torque can be varied

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by varying starting resistance. The resistance is then gradually cut off as motor gathers speed. When motor attains speed near synchronous, dc excitation is provided to the rotor, then motor gets pulled into synchronism and start rotating at Ns.

Using small DC machines

A large synchronous motors are provided with a coupled dc machine. This machine is used as a dc motor to rotate the rotor of synchronous motor at Ns. once motor starts running as a synchronous motor, same DC m/c act as a DC generator called exciter. The field of synchronous motor is then excited by this exciter itself.

Behaviour of Synchronous motor on loading

In case of synchronous motor once rotor starts rotating at Ns, stator conductor cuts the flux produced by rotor. Because of this there is an induced emf in the stator which opposes the supply voltage. This induced emf called back emf

E_{bph} - back emf/phase

$E_{bph} = 4.44 K_c K_d \phi f T_{ph}$

$E_{bph} \propto \phi$

Let R_a = Stator wdg resistance

X_s = Synchronous reactance of the stator

$Z_s = R_a + jX_s$ Ω/ph → synchronous impedance

$\vec{V_{ph}} = \vec{E_{bph}} + \vec{I_{aph}} Z_s$

$$\boxed{\vec{I_{aph}} = \frac{V_{ph} - E_{bph}}{Z_s}}$$ Amp

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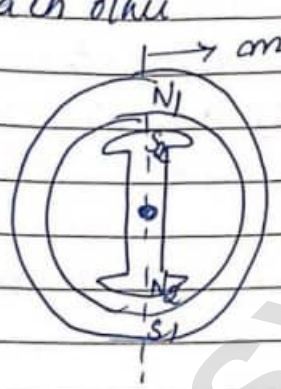
Ideal condition on no load

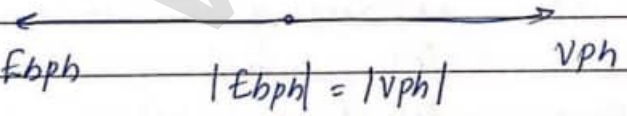
The ideal condition on no load can be assumed by neglecting various losses in the motor.

$$V_{ph} = E_{bph}$$

Under this condition, the magnetic locking b/w stator and rotor is in such a way that the magnetic axes of both coincide with each other



The magnitude of E_{bph} and V_{ph} are equal but they are in opposite direction (Lenz's law)



$|E_{bph}| = |V_{ph}|$

$$\vec{I}_{ph} = \frac{V_{ph} - E_{bph}}{Z_s} = \frac{0}{Z_s} = \underline{\underline{0}}$$

In practice current cannot be zero and motor has to supply mechanical losses and iron losses under no load condition

To produce torque to overcome these losses motor draws current from the supply

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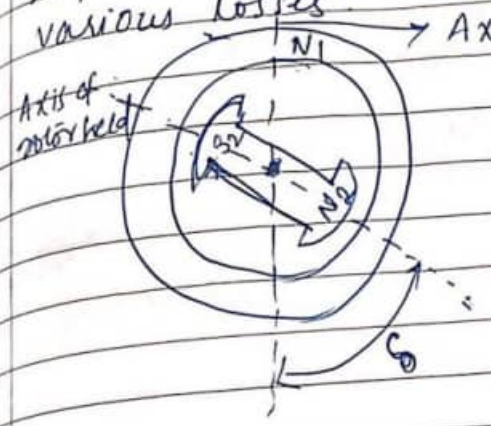
Synchronous Motor on No load (with losses)

Due to various losses present on no load, the magnetic locking exists b/w stator and rotor but in such a way that there exists a small angle difference b/w the axis of 2 magnetic field.

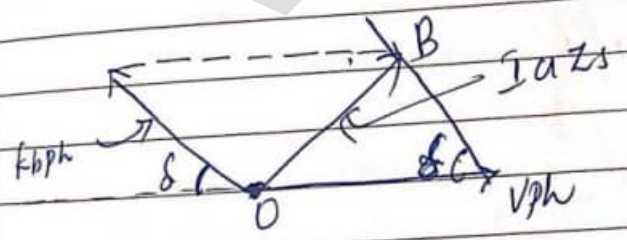
The rotor magnetic axis falls back wrt to stator axis by angle 'δ' as shown in figure. This angle decides the amount of current required to produce the torque to supply various losses.



This angle δ is called load angle, power angle, coupling angle, torque angle or angle of retardation. Magnetic locking still exists.

phasor diagram

$\vec{V_{ph}} - \vec{E_{bph}} = \vec{I_a Z_s}$
$= E_{Rph}$
$= OB$



Though $|E_{bph}| = |V_{ph}|$, E_{bph} will not be located in exact opposition with V_{ph} but will get displaced from its initial position by angle 'δ'.

The resultant E_{Rph} decides the amount of current I_{aph} to be drawn to produce the torque to meet various losses.

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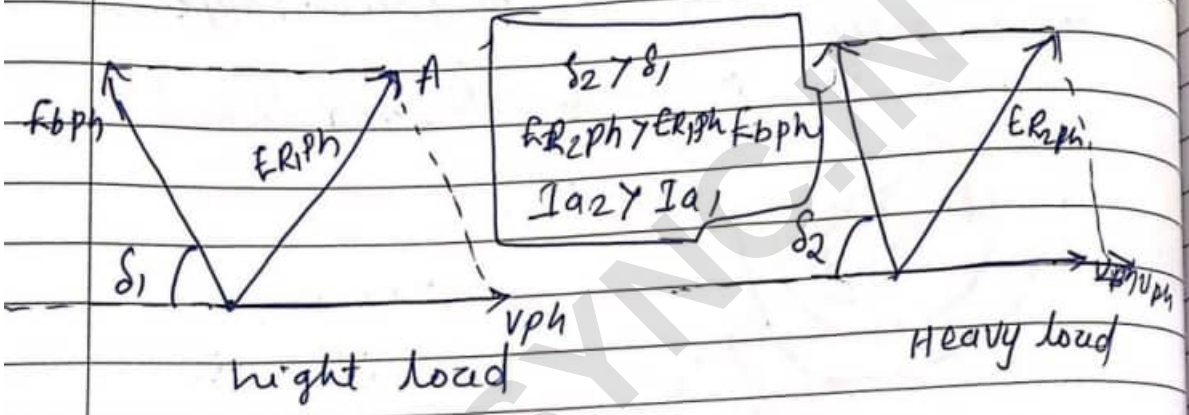
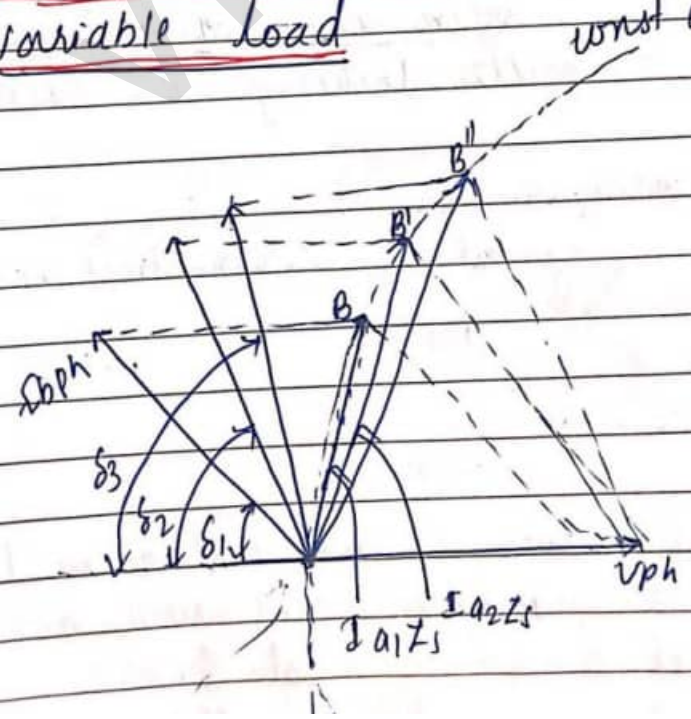
Synchronous Motor on load

As the load on the synchronous motor increases, the load angle δ gets affected. Hence if the load increases, δ increases but speed remains synchronous.

As δ increases displacement of E_{bph} from it ideal position increases. Hence $V_{ph} - E_{bph}$ increases. I_{aph} increases as load increases. This current produces the necessary torque which satisfies the increased load.



Operation of SM at constant excitation, variable load



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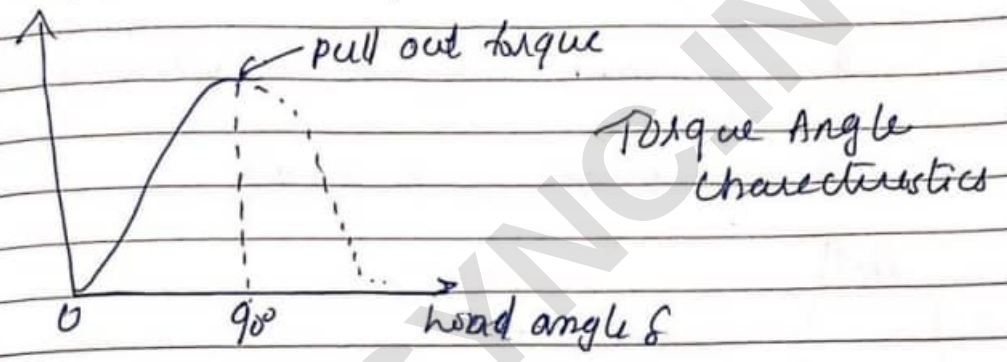
for const excitation, if Load is varied, then δ keeps on changing, due to which $E_{Rph} = I_{aph} Z_s$ keeps on changing. The locus of extremities of $E_{Rph} = I_{aph} Z_s$ is a circle and as Z_s const., represents current locus for the SM under const. excitation, and variable load condition.

As δ increases, torque produced by the motor increases. As δ reaches upto 90° electrical, the stretched flux lines get broken and hence magnetic locking b/w stator and rotor no longer exists. The motor comes out of synchronism so at $\delta = 90°$, is maximum torque. Such a torque is called pull out torque



Types of Torque in Synchronous Motor :-

1) Starting Torque :-
Torque developed by SM at start when rated voltage is applied to the stator, it is also called breakaway torque.

2) Running Torque :-
Torque developed by SM under running condition. It is decided by the o/p rating of the motor and speed

3) Pull in Torque :-
The amount of torque developed by

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the motor at the time of pulling into synchronism is called pull in Torque

4) Pull out torque

The max. torque developed by the synchronous motor without pulling out of synchronism is called pull out Torque

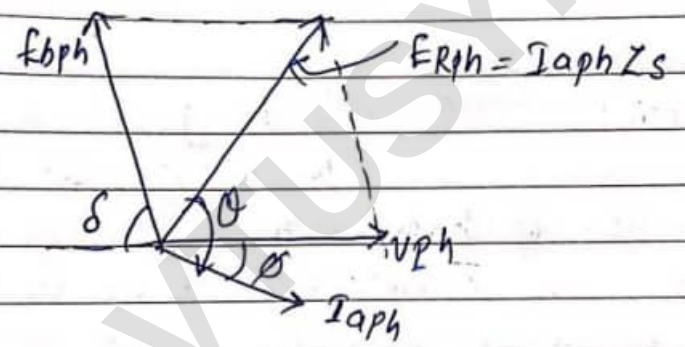
Analysis of phasor diagram

Consider a phasor diagram with normal excitation $|E_{bph}| = |V_{ph}|$

$Z_s = \sqrt{R_a^2 + X_s^2}\ \Omega$ $\qquad \theta = \tan^{-1}\left[\frac{X_s}{R_a}\right]$

$\theta \rightarrow$ internal machine angle or impedance angle

$\phi = V_{ph} \wedge I_{aph}$ = pf angle



Practically R_a is very small compared to X_s and θ tends to 90°.

Operation of synchronous Motor at Constant load Variable Excitation

If excitation is changed (field current I_f is changed), keeping the load constant, SM reacts by changing its pf of operation.

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Entire operation of variable excitation it is necessary to remember that the cosine component of armature current, $I_a\cos\phi$ remains constant.

[$P_{in} = \sqrt{3}V_L I_L \cos\phi = 3V_{ph}I_{ph}\cos\phi$]

[Most of the times, the V_{ph} is constant. Hence for const power i/p, $I_{aph}\cos\phi$ is const]

Under excitation

When the excitation is adjusted in such a way that the magnitude of induced emf is less than the applied voltage ($E_b < V$) the excitation is called under excitation.

Due to this E_R increases in magnitude for constant Z_s, current drawn by the motor increases. E_R phase shifts in such a way that phasor I_a also shifts. ($E_R \wedge I_R = \theta$) to keep $I_a\cos\phi$ constant pf $\cos\phi$ decreases bcz current increases.

Over Excitation

The excitation to the field wdg for which induced emf becomes greater than applied voltage ($E_b > V$) is called over excitation.

Due to increased magnitude of E_b, E_R also increases in magnitude. But phase of E_R also changes. Now $E_R \wedge I_R = \theta$ is constant, hence I_a also changes its phase. So ϕ changes. The I_a increases to keep $I_a\cos\phi$ constant. The phase of E_R changes so that I_a becomes leading wrt V_{ph}. So pf become leading in nature. So over excited synchronous motor works on leading pf.

Critical Excitation

The ~~pf~~ excitation for which the pf of the motor is unity ($\cos\phi = 1$) is called critical excitation. Then I_{aph} is in phase with V_{ph}. $I_a\cos\phi$ must be

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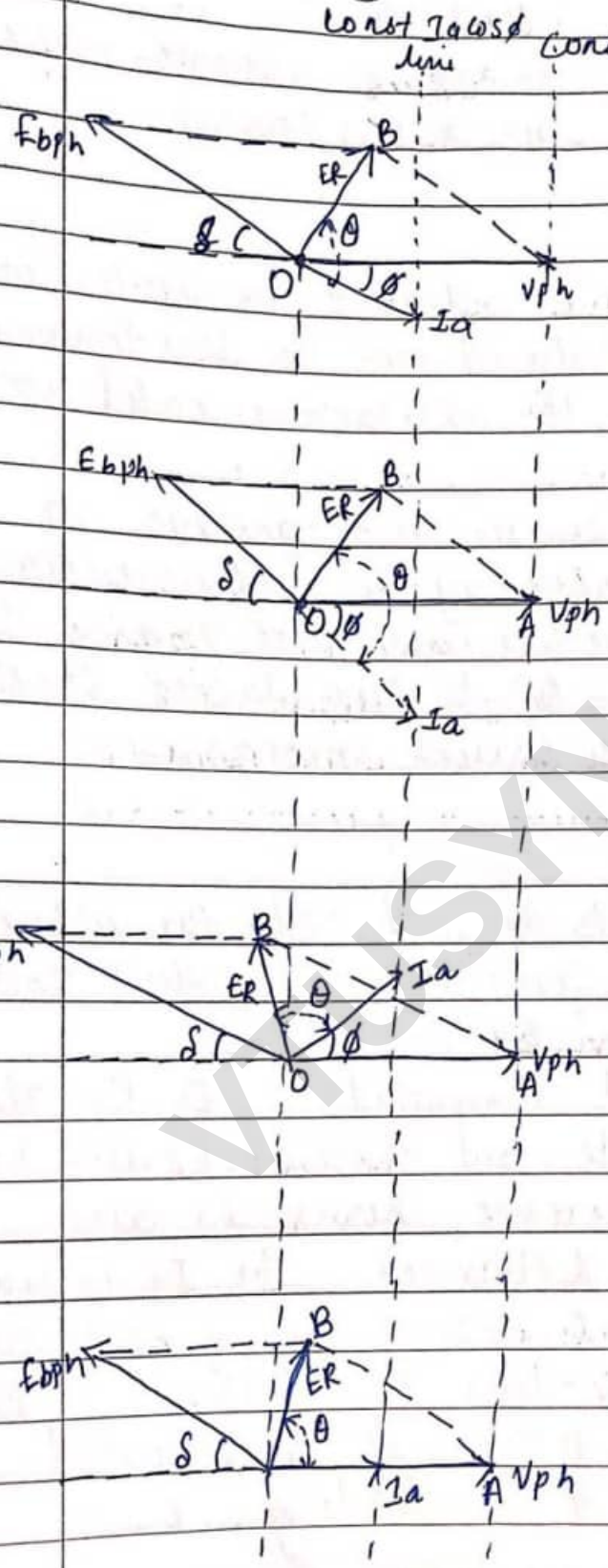
constant. $\cos\phi = 1$ is at its maximum, motor has to draw minimum current from supply for upf condition.



(a) Normal Excitation
$E_{bph} = V_{ph}$ lagging

(b) Under Excitation
$E_{bph} < V_{ph}$
More lagging pf
I_a increases

(c) Over Excitation
$E_{bph} > V_{ph}$
Leading pf
I_a increases

(d) Critical Excitation
$E_{bph} = V_{ph}$
Upf
I_a is minimum

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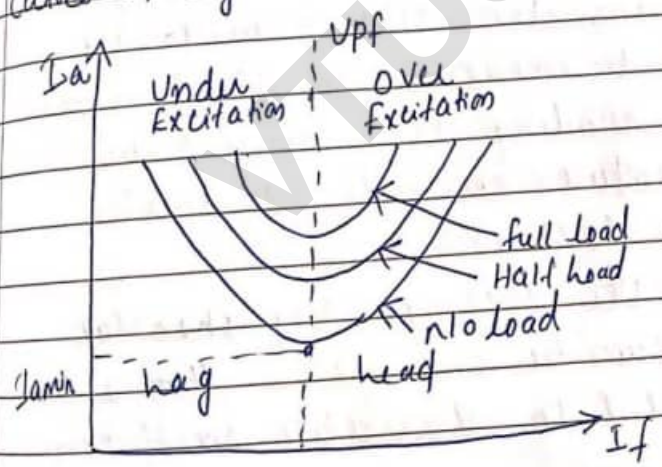
undu Excitation	Lagging pf	$E_b < V$
over Excitation	Leading pf	$E_b > V$
Critical Excitation	upf	$E_b = V$
Normal Excitation	Lagging	$E_b = V$

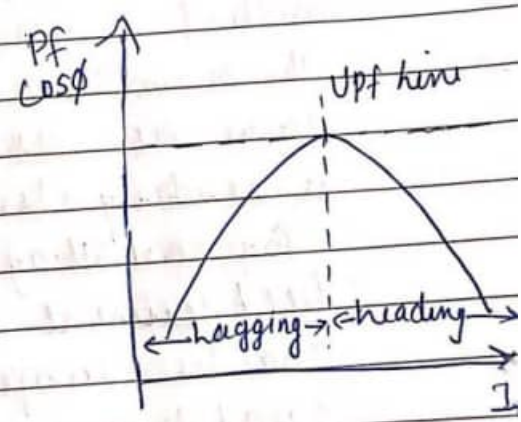
V- curves and Inverted V- curves

Excitation can be increased by increasing the field current passing through the field wdg of synchronous motor.

If the graph of armature current drawn by the motor (I_a) against field current (I_f) is plotted, then its shape looks like an english alphabet 'V'. If such graphs are obtained at various load conditions, we get family of curves called 'V' curves of synchronous motor.

If the pf is plotted against field current (I_f) then the shape of the graph looks like a inverted 'V' curves of synchronous motor.





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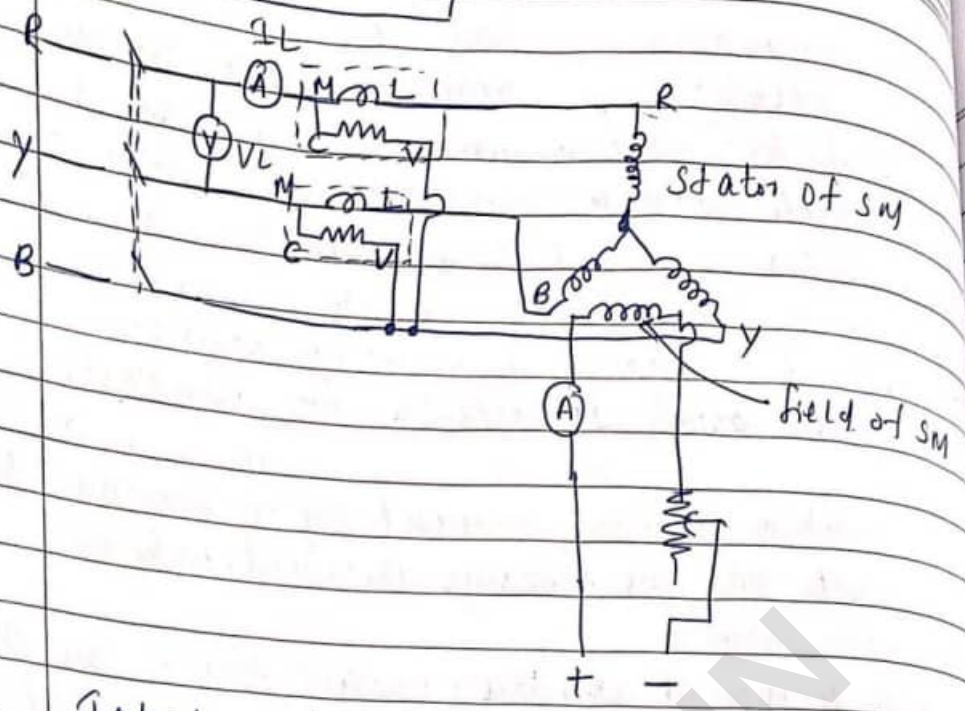
Experimental set up



Tabular column

SL No	VL (V)	IL (A)	W_1 (W)	W_2 (W)	If (A)	cosφ

Stator is connected to 3φ supply through wattmeters and ammeter. The 2 wattmeter method is used to measure i/p pf of motor. The ammeter is reading line current which is same as armature current. Voltmeter is reading line voltage.

By controlling the voltage by rheostat, the field current can be changed. Hence motor can be subjected to variable excitation condition.

$$\cos\phi = \cos\left\{\tan^{-1}\left[\sqrt{3}\,\frac{(W_1 - W_2)}{W_1 + W_2}\right]\right\}$$

The entire procedure can be repeated for various load condition to obtain family of VC and inverted V curves.

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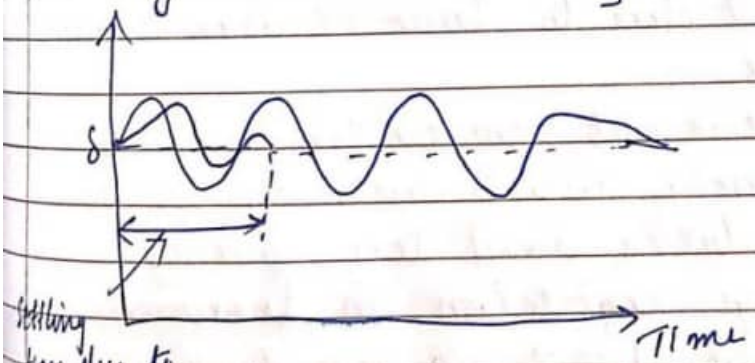
Hunting in Synchronous Machine

Due to inertia of the rotor it cannot achieve its final position instantaneously when the motor is loaded. There is a periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load. Such oscillations of the rotor about its new equilibrium position due to sudden application or removal of load is called swinging or hunting in synchronous motor.

If such oscillations continue for longer period, there are large fluctuations in the current. At this instant mechanical stress on the rotor are severe and current drawn by the motor is so large. So motor gets subjected to large mechanical and eletrical stresses.

Use of damper wdg to prevent hunting

When the rotor starts oscillating, ie when hunting starts a relative motion b/w damper wdg and RMF gets created, due to this relative motion, e.m.f gets induced in the damper winding. According to Lenz's law the direction of induced emf is always so as to oppose the cause producing it. The cause is the hunting. So such emf oppose the hunting. Thus hunting is minimised by damper wdg.



Settling time due to damper wdg

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Synchronous condensers

A synchronous motor running on no load when over excited ($E_{bph} > V_{ph}$) is called a synchronous condenser or synchronous capacitor.

Under such condition, the current I_A will lead the voltage (V_{ph}) by an angle almost equal to 90°. This is the property due to which synchronous motor is used as a phase advancer or as powerfactor improvement device.

Disadvantages of low pf

$P = VI\cos\phi \qquad I = \frac{P}{V\cos\phi}$

Let $P = 5kW$ and $V = 230V$

Case i) $pf = 0.8$

$$I = \frac{5\times10^3}{230\times0.8} = 27.17A$$

Case ii) $pf = 0.6$

$$I = \frac{5\times10^3}{230\times0.6} = 36.23A$$

Thus as pf decreases the current drawn from the supply increases to supply same power to the load.

High current due to low pf has following disadvantages

1. For higher current, conductor size required is more which increases the cost.
2. More copper losses and less efficiency
3. Poor voltage regulation in transmission lines bcz of large voltage drop.

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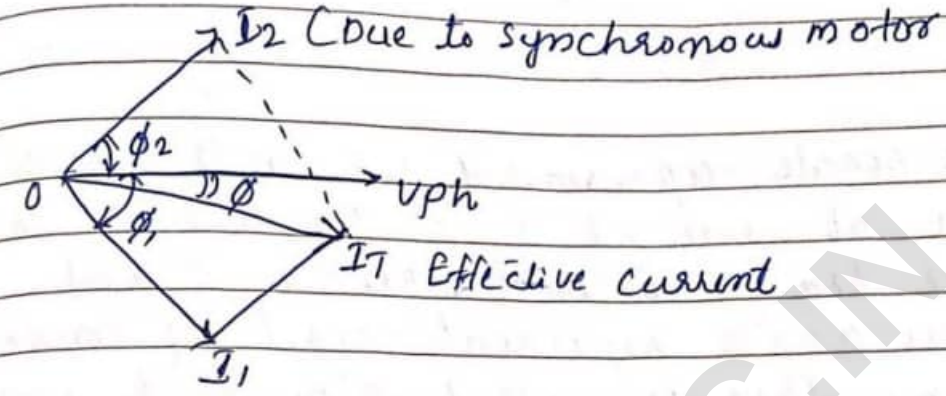
4. $\cos\phi = \frac{P}{S}$

If pf is low then KVA rating of the equipment is high which increases the cost.

Use of Synchronous Condenser in Pf Improvement

Pf correction is possible by connecting synchronous motor across the supply and operating it on no load with over excitation



As ϕ decreases, $\cos\phi$ increases and power factor increases.

Blondel Diagram

Blondel diagram of a synchronous motor is an extension of a simple phasor diagram of a synchronous motor.

$P = V_{ph} I_{ph} \cos\phi$

The gross mechanical power developed/phase

$P_m = V_{ph} I_{ph} \cos\phi - (I_{aph})^2 R_a$

$= VI\cos\phi - I^2 R_a$

$I^2 R_a - VI\cos\phi + P_m = 0$

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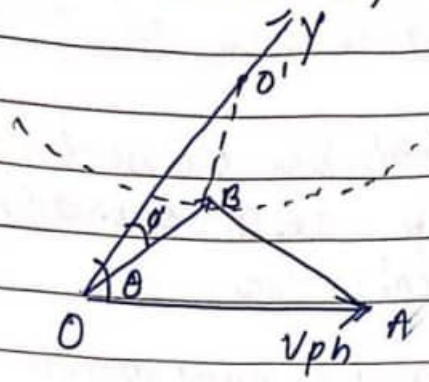
$$I^2 - \frac{VI\cos\phi}{R_a} + \frac{P_m}{R_a} = 0 \quad \text{--- (1)}$$

Eq ① represents polar equation to a circle. Draw a line OY an angle θ wrt OA.



circle of const. power

$\angle YOA = \theta$

$\angle YOB = \phi$

The circle represented by eq: ① has a centre at some pt O' on the line OY. The circle drawn with centre as O' and radius as O'B represents circle of constant power. This is called Blondel diagram. Thus if excitation is varied power is kept constant, then working pt B move along the circle of constant power.

O'B = Radius of circle = r

OO' = Distance d

$$r = \frac{V}{2R_a}\sqrt{1 - \frac{4P_mR_a}{V^2}}$$

$$P_{max} = \frac{V^2}{4R_a}$$

$$m = \frac{P_m}{P_m(max)}$$

$$r = d\sqrt{1-m}$$

$$d = \frac{V}{2R_a}$$

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Other Motors

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Universal Motors

There are small capacity series motors which can be operated on dc supply or ac supply of same voltage with similar characteristics called Universal Motors.

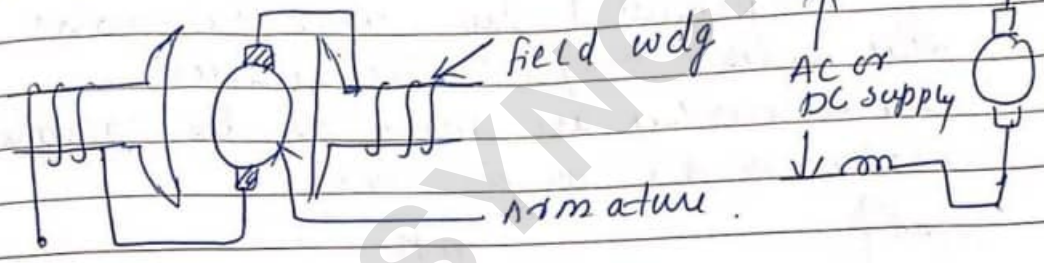
Construction

It is manufacture in 2 types.

1. Non compensated type, low h.p
2. Compensated type, high h.p.

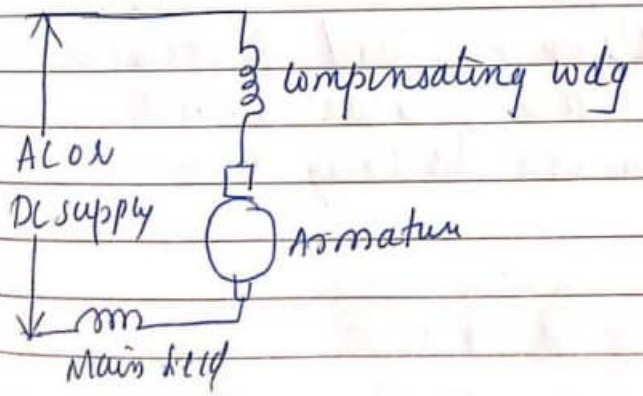
Non compensated type (Concentrated field type)

→ has 2 poles having entire magnetic path as laminated. Armature is wound type similar to the normal dc motor



2. Compensated type (distributed field type)

→ The motor has distributed field wdg consisting of main field and compensating type winding. This has wound armature similar to normal dc motor



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The frames of universal motors are usually made of aluminium, cast iron and rolled steel.

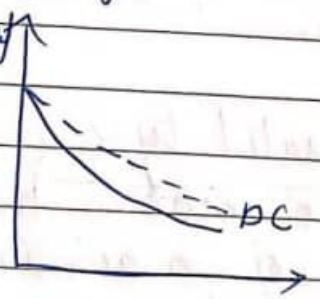
Operation:-

In a series wound motor, the same current flow through field wdgs and armature being connected in series with each other, when motor is connected to either dc or a.c supply. The magnetic fields developed by the series field wdg and armature currents react with each other and hence develop uni-directional torque.

Speed - Torque characteristics

Compensated type universal motor has better speed - torque characteristics. Characteristics are same for the operation of motor on a.c or dc supply.

Non compensated type



Compensated type.

Applications:-

Vacuum cleaners, food processors and mixers, hair driers, coffee grinders, electric shavers, blowers, drilling machines and small drives.

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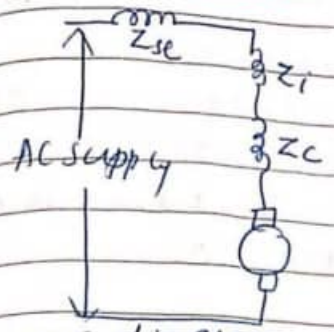
AC Series Motor



phasor diagram

$V = E_b + I_a Z_{se} + I_a Z_i + I_a Z_c + I_a Z_a$

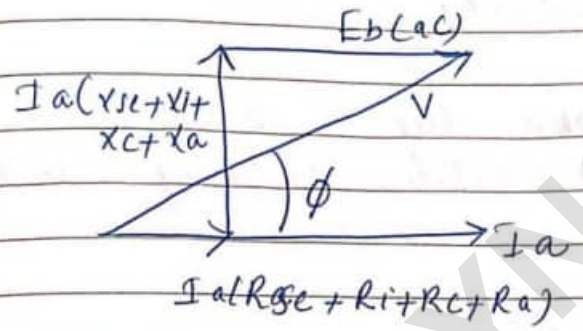
$Z_{se} = R_a + jX_{se}$

$Z_i = R_i + jX_i$

$Z_c = R_c + jX_c$

$Z_a = R_a + jX_a$

$V = E_b + I_a R_{se} + I_a R_i + I_a R_c + I_a R_a + j[I_a X_{se} + I_a X_i + I_a X_c + I_a X_a]$



AC ServoMotor

Most of the servomotors used in low power servomechanisms are ac servomotors.

→ It is basically 2 phase Induction Motor.

Construction

The a.c servomotor is basically consists of a stator and a rotor

the stator carries 2 wdg one wdg is called main wdg or fixed wdg or reference wdg. The reference wdg is excited by a constant voltage ac supply.

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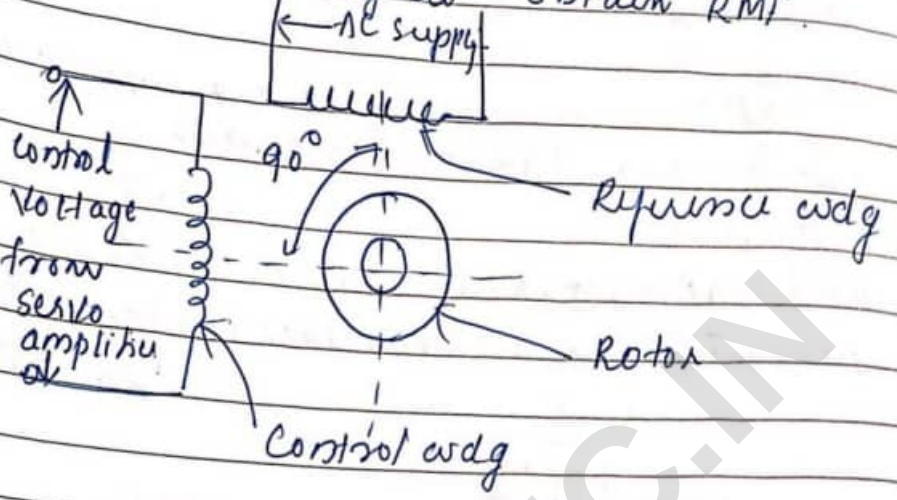
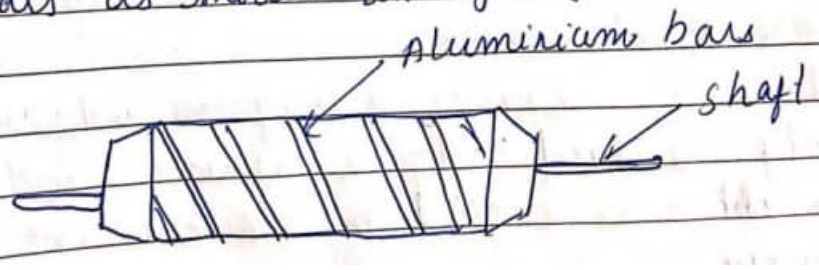
The other wdg is called control wdg, it is excited by variable control voltage, which is obtained from a servo amplifier.
The wdgs are 90° away from each other and control voltage is 90° out of phase wrt voltage applied to the reference wdg this is necessary to obtain RMF.



The rotor is generally of 2 types,
1. Squirrel cage rotor 2. Drag cup type rotor

1. Squirrel cage rotor

→ It has aluminium bars which are shorted at the ends with the help of the end rings. Construction is look like a cage. similar to the squirrel cage rotor used for the 3ϕ IM. this has small diameter and large length. Aluminium conductors are used to keep weight small. It uses skewed bars as shown in figure.



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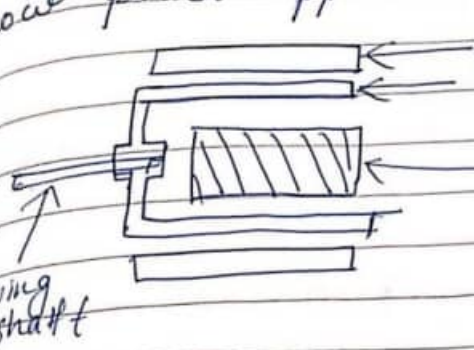
2. Drag cup type Bar

To reduce the inertia further, a drag cup type of rotor construction is used. There are 2 air gaps. The drag cup is made up of non magnetic material like copper, aluminium or an alloy. It is used in very low power applications



Operating principle

→ is same as that of normal 3ø IM. The control voltage applied to the control wdg and the voltage applied to the reference wdg are 90° out of phase. Hence flux produced by current through the control wdg is 90° out of phase wrt to the flux produced by the current through the reference wdg.

The resultant flux in the air gap is rotating in nature called RMF

The rotor is stationary at start. RMF sweeps over the rotor, the emf gets induced in the rotor. This emf circulates the current through the rotor. The rotor ~~flux~~ current creates its own flux called rotor flux, which interacts with RMF producing a torque on the rotor and rotor starts rotating.

A change in the sign of the control voltage reverses the direction of the motor.

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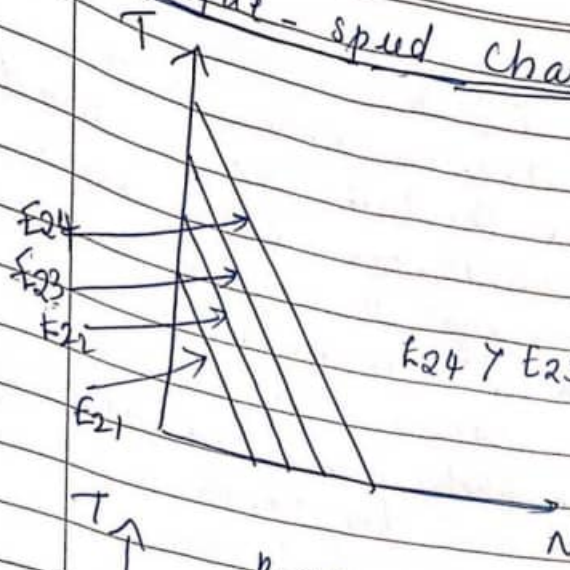
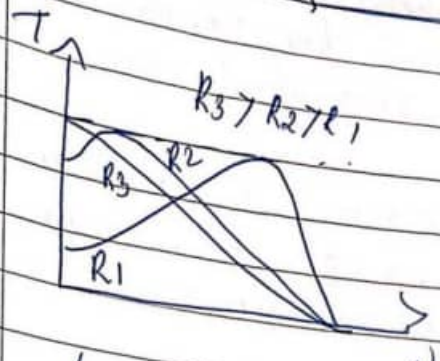
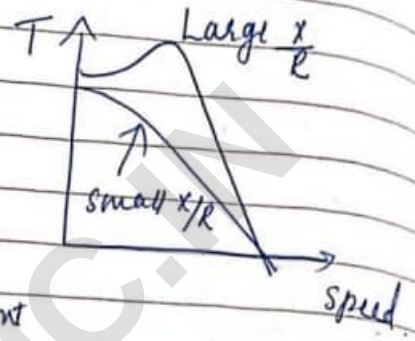
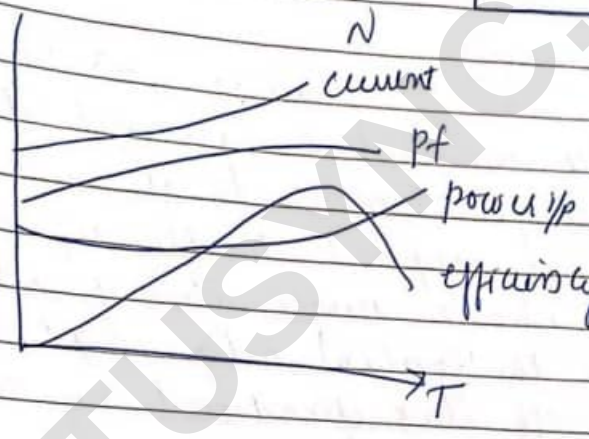
Torque - speed characteristics









Features

1. Robust in construction
2. No brushes or slip rings are required Hence maintenance free
3. Light in wt for quick response
4. It is reliable and its operation is stable
5. Smooth and noise free operation

Applications

1. Instrument servos 2. Process controllers
3. Robotics 4. Self balancing recorders
5. Machine tools.

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Linear Induction Motors

→ Works on the same principle as that of normal induction motor, with the difference that instead of rotational movement, the rotor moves linearly. If the stator and rotor of the IM are made flat then it's forms linear Induction Motor. The flux produced by the flat stator moves linearly with the synchronous speed from one end to the other. The synchronous speed is given by,

$V_s = 2wf$

V_s = Linear synchronous speed (m/s)

w = width of one pole pitch (m)

f = frequency of supply (Hz)

Synchronous speed is independent of no. of poles but depends only on width of pole pitch and supply frequency.

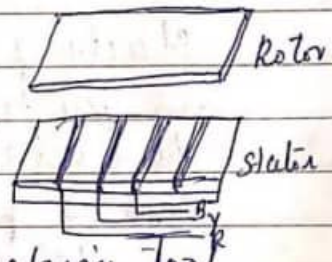
The flux moves linearly and forces the rotor to move in straight line in the same directions.

Slip $S = \frac{V_s - V}{V_s}$ $V \rightarrow$ Actual speed

Force, $F = \frac{P_2}{V_s}$ P_2 is the active power

Rotor cu loss $P_{cu} = S P_2$

Mechanical power $P_m = (1-S) P_2$



Applications :-

Electric trains, Robotics, machine tool Industry, reciprocating Compressors.

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Stepper Motors

Stepper Motor convert a train of i/p pulses (square wave) into a precisely defined increment in the shaft position. Stepper motor rotates a precise angular distance, one step for each pulse. There is one-one relationship b/w an input pulse and step movement of the shaft. The angle through which the motor turns or shaft moves for each pulse is known as the step angle, expressed in degrees.

The motor is ~~too~~ suitable for controlling position by controlling the no. of i/p pulses by position control system. Stepper motor is compatible with modern digital equipment. The stepper motors are widely used in x-y plotters, floppy disk drives, machine tools, robotics, printers, tape drives.

Types of Stepper Motors

1. Variable reluctance stepper motors
2. Permanent magnet stepper motors.
3. Hybrid stepper Motors

Variable reluctance Stepper Motor

→ consists of a single or several stacks of stator and rotors. The stator is pulse excited, rotors are unexcited. The operation is based on the various reluctance positions of rotor wrt stator.

When any one phase of stator is excited, it produces its magnetic field whose axis [illegible] the phase around which

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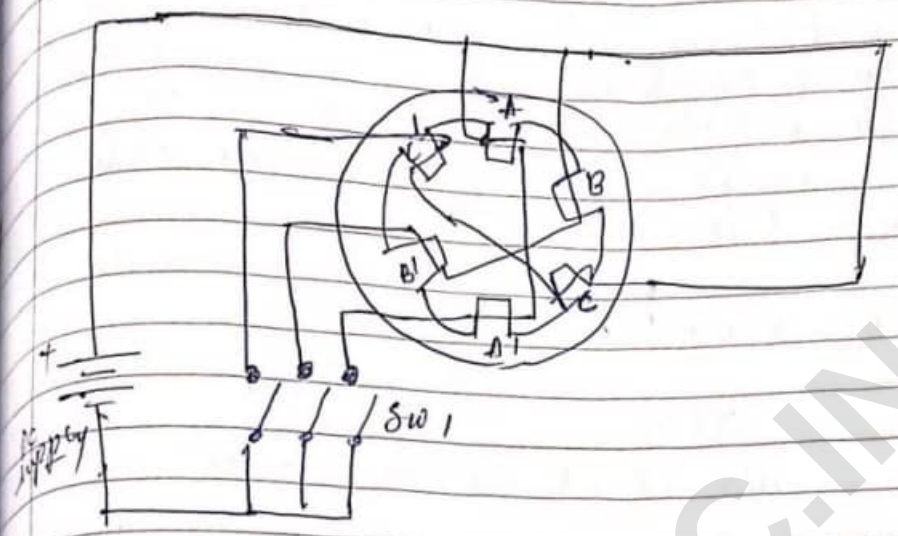
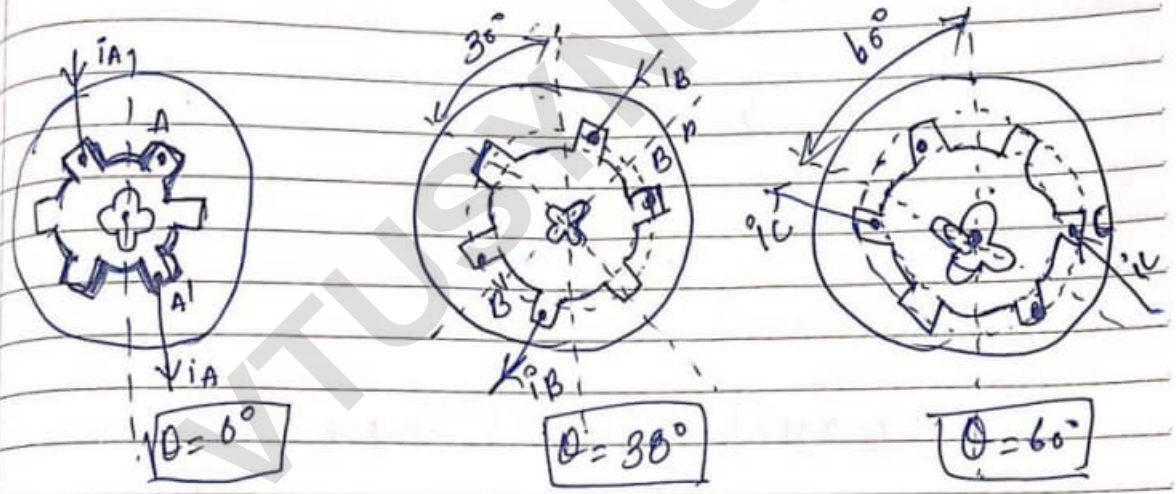
is excited. The rotor moves in such a direction so as to achieve minimum reluctance position. i.e axis of magnetic field of stator matches with the axis passing through the 2 poles of the rotor.





When AA' is excited with SW1 closed stator magnetic axis exists along the poles formed due to AA'. i.e Vertical. Rotor adjust itself in minimum reluctance position

When BB' is excited with the switch SW2 closed and phase AA' de-energised with SW1 open stator magnetic axis shifts along the poles formed due to BB'. Then rotor tries to align in the minimum reluctance position and turns

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anti clockwise direction.

3. When the phase CC' is excited with the switch S_{W3} closed and the phase AA' and BB' are deenergised, then stator magnetic axis shifts along the poles formed due to CC'. Then to achieve minimum reluctance position, rotor gets subjected further anticlockwise torque. So it turns through further 30° in anti clockwise direction.

Stepping angle is given by

$$\alpha = \frac{360^\circ}{\text{No. of phases} \times \text{no. of poles}}$$

$$= \frac{360^\circ}{nP}$$

For 3ϕ 4 rotor poles

$$\alpha = \frac{360^\circ}{3 \times 4} = 30^\circ$$

2. Permanent Magnet Stepper Motor

Stator is multipolar. Around the poles the exciting coils are wound. Rotor is salient pole or smooth cylindrical pole. It is made out of ferrite material which permanently magnetised.

The voltage pulses to the stator wdg can be obtained by using a driving ckt.

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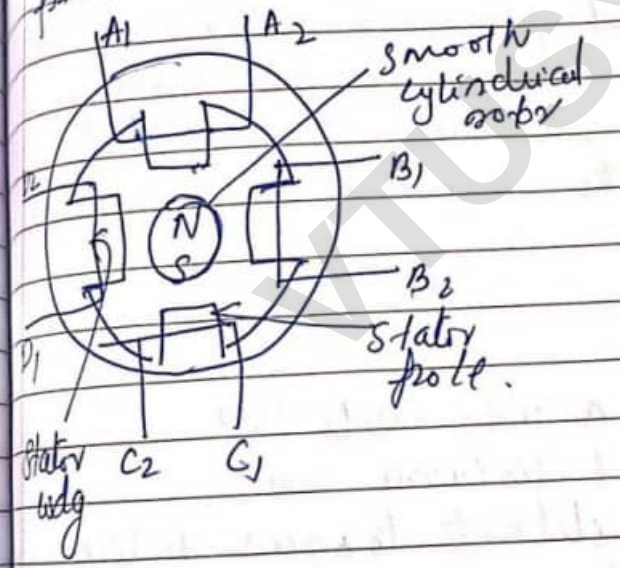
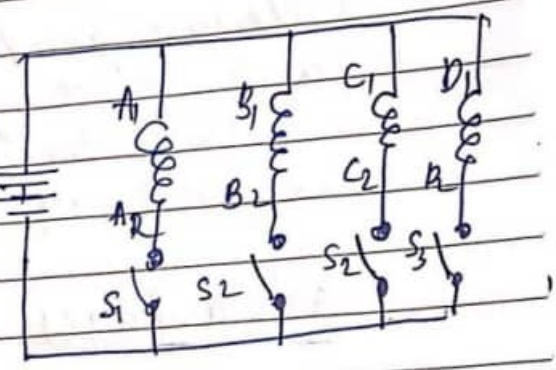
As soon the voltage pulses are applied to various phases with the help of driving ckt rotor starts rotating through a step for each i/p voltage.

At first switch SW_1 is closed exciting the phase A. Due to the electromagnetical torque developed, rotor rotates such that magnetic axis of permanent magnet rotor adjusts with the magnetic axis of stator.

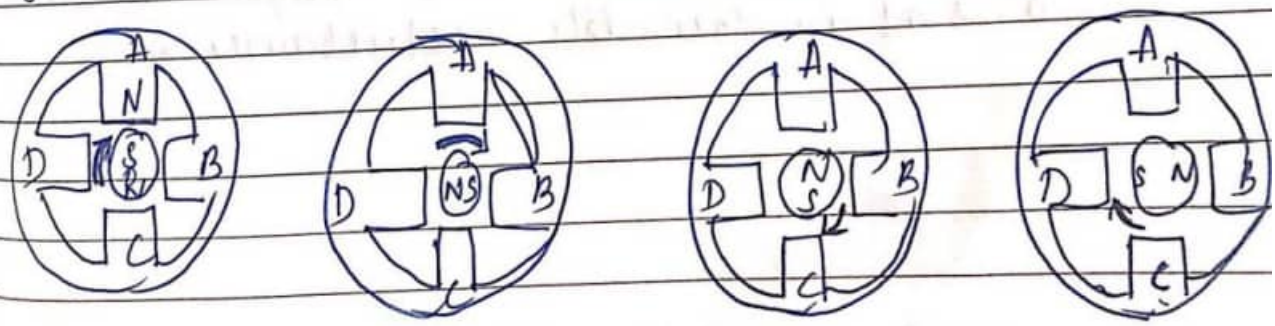
Next phase B is excited with switch SW_2, disconnecting phase A. Due to this rotor further adjusts. Hence its rotate through 90° in clockwise direction.

Similarly when phase C and D are sequentially excited, the rotor tends to rotate 90° clockwise direction, every time when phase is excited.





Drive ckt.



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DATE

Hybrid stepper Motor

⇒ It uses the principles of permanent magnet and variable reluctance stepper motors. The permanent magnet is placed in the middle of the rotor. It is magnetised in the axial direction. Each pole of the magnet is surrounded with the soft-toothed laminations.

There are usually 8 poles on the stator. The coils on 1, 3, 5 & 7 are connected in series to form Phase A while the coils on poles 2, 4, 6 and 8 are connected in series to form phase B. The wdgs of A and B are energised alternately

When phase A carries +ve current, stator poles 1 and 5 become south and 3 become north. When phase A is deenergised and phase B is excited, rotor will move by one quarter of tooth pitch. The rotor field remains constant as it is produced by the permanent magnet.

Advantages

1. very small step angles upto 18°
2. Higher torque / unit volume
3. Motor has some detent torque which is absent in variable reluctance motor.

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