Unit - 1 Three Phase Induction & Synchronous Motors

## Three Phase Induction Motors

Introduction:- 3 phase induction motor is the most popular type of
A.C motor. It is very commonly used for industrial drives.
Since it a cheap, robust, efficient and reliable. It has
good speed regulation and high static torque. It requires
little maintenance. It has reasonable overload capacity.
A 3 phase induction motor consists of 2 parts stator & rotor
The stator is the stationary part and the rotor is the
rotatory part. Stator (high grade alloy steel lamination
to reduce current loss). Lamination are slotted in the inner
periphery and are insulated from each other. The insulated
stator conductors are placed in the slots. The stator conductors
are connected to form 3-phase windings. The 3-phase
winding can be star & delta connected. The rotor is also
build of thin lamination of same material as stator.
The laminated cylindrical core is mounted directly on shaft.
These laminations are slotted over outer periphery to
~~shaft~~ receive the rotor conductor. There are 2 types of
induction motor rotors. Squirrel cage rotor (It consists of
cylindrical laminated core with slots nearly parallel to the

shaft axis or skewed. At each end of the rotor, the rotor bar conductors are short circuited by heavy end rings of the same material. The conductors skewing of squirrel cage offers the following advantages:-

1 More uniform torque is induced and noise is reduced during operation.

2 Locking tendency of rotor reduced. During locking the rotor and stator teeth attract each other due to magnetic action.

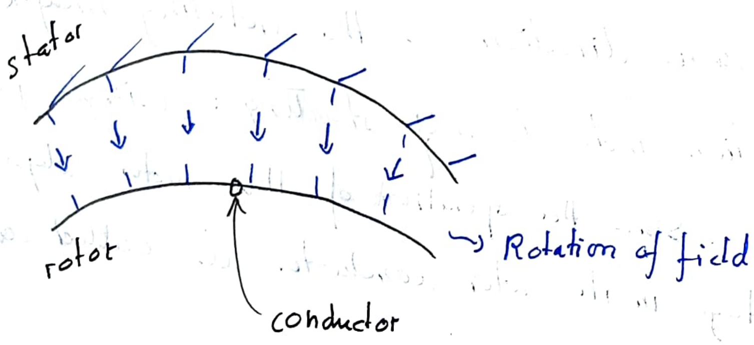
Phase wound rotor:- Motor using it are called slippery motor. The wound rotor consists of slotted armature insulated conductor are put in the slots and connected in 3 phase. The rotor windings are connected in star. The open end of star circuits are bought outside the rotor and connected to 3 slip rings. the slip rings are mounted on the shaft with the brushes resting on them. The brushes to 3 variable resistor connected to star. The purpose of slip rings and brushes is to provided a means of connecting a external resistor in a moving circuit. The resistor enable the variance of each motor phase resist at, it serves two purposes (i) To increase starting torque & decrease the starting current.

(ii) to control the speed of rotor

Comparision of cage/squirrel motor and wound motor :-

| Cage motor | Wound motor |
|---|---|
| * robust construction and cheaper | (i) High starting torque and low starting current. |
| (ii) The absence of brushes reduces the spark risk. | (ii) Additional resistor can be connected in the rotor circuit to control speed. |
| (iii) Higher efficiency and higher power factor | |

Principle of Operation of 3 phase induction motor




Let us consider one conductor on the stationary rotor as shown in figure. Let this conductor be subject to rotating magnetic field produced when a 3 phase supply is connected to the 3 phase winding of the stator. Let the rotation of magnetic field be clockwise. The magnetic field moving clockwise has a same effect as a conductor moving anti clockwise in the stationary field. By faraday's law of electromagnetic induction a voltage will be induced in the conductor. Since the rotor circuit is complete either through the end rings or an external resistance. The induced voltage causes a current to flow in the rotor conductor. Since the magnetic field is rotating clockwise and conductor is stationary we can assume the conductor is in anticlockwise direction w.r.t magnetic field.

We know that when current carrying conductor is put in the magnetic field a force is produced on it. Thus a force is produced on the rotor conductor. This force acts in a tangential direction to the rotor and develop the ~~rt~~. torque on the rotor. Similar torques are produced on all rotor conductors. Since the rotor is force to move it starts rotating in the same direction as the rotating magnetic field. Thus the 3 phase induction motor is self starting. (single phase is not self starting). Since the operation of this motor depends on the induced voltage in its rotor conductor is called as induction motor.

<u>Speed and Slip</u> :- An induction motor cannot run at synchronous speed, the rotor speed is slightly less than the synchronous speed. Induction motor (asynchronous motor) as it does not move at synchronous speed. $N_S - N_R$ is called the slip speed. The slip speed expressed as fraction $N_S$ is called the per unit slip or fractional slip. Per unit slip is usually called slip S.

$N_S$ is synchronous speed in rpm and $N_R$ actual rotor speed in rpm.

## Frequency of Rotor Voltage and Current :-

Frequency of current and voltage in the stator must be same as the supply frequency $f = \frac{N_s P}{120}$ ...(i)

The frequency in the rotor winding is variable and depends on the diff. between synchronous speed and rotor speed. Hence the rotor frequency depends upon slip.

$f_r = \frac{P(N_s - N_r)}{120}$ ...(ii). With the help of (i) and (ii)

$$\boxed{f_r = sf}$$

($f$ → stator)

Q The frequency of emf in the stator of 4 pole induction motor is 50 Hz and that in rotor is ~~1~~.5 Hz. What is the slip and at what speed is the motor running? ($N_r = (1-s) N_s$)

→ Given :- $p = 4$ $\quad f_1 = 50 Hz = f_s$

$f_2 = f_r = 1.5 Hz$

$\frac{1.5}{50} = s$ $\qquad$ ~~$\frac{50}{1.5} = s$~~

$s = 0.03$ rpm (~~33.33 rts~~)

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

$50 = \frac{N_s \times 4}{120}$ $\qquad 1500 = N_s$

$N_r = (1 - 0.03)\, 1500$ (~~33.33~~)

=>

Ex A 3 phase 6 pole 30Hz induction motor has a slip of 1% at no load and 3% at full load.

Determine (a) synchronous speed (b) No load speed (c) Full load speed (d) Frequency of rotor current at stand still. (e) Frequency of rotor current at full load.

→ Given:- $p = 6$ $f_1 = 30Hz$ $s_0 = 0.01$ $s_L = 0.03$

(a) $f = \frac{N_s p}{120}$ $30 = \frac{N_s \times 6}{120}$ $N_s = 600\ rpm$

(b) $\frac{N_s - N_r}{N_s} = s_0$

$\frac{600 - N_r}{600} = 0.01$

$594\ rpm = N_r$

No load speed

(c) $\frac{600 - N_r}{600} \Rightarrow 0.03$

$N_r = 600 - 18$

$N_r \Rightarrow 582\ rpm$

full load speed.

(d) $f_r = s_0 f$

$f_r = 0.01 \times 30$

$f_r \Rightarrow 0.3$

still

(e) $f_r = s_L f$

$f_r = 0.03 \times 30$

$f_r = 0.9$

full load

## Rotor current:-

(a) Stand still condition:- $I_{20} = \frac{E_{20}}{Z_{20}}$ where $E_{20}$ is emf induced per phase of the rotor at stand still.

$Z_{20}$ is rotor impedence per phase at stand still.

$$Z_{20} = R_2 + jX_{20}$$

(b) Rotor current at slip s :- Induced emf

$$[E_{2s} = S.E_{20}]$$

$$I_{2s} = \frac{E_{2s}}{Z_{2s}}$$

$$I_{2s} \Rightarrow \frac{s E_{20}}{R_2 + sjX_{20}}$$

Ex:- A 3 phase 50Hz 4 pole induction motor has a slip of 4%. Calculate (a) speed of motor (b) frequency of the rotor emf

If a rotor has a resistance of 1Ω and stand still reactance of 4Ω. Calculate the power factor at stand still.

At the speed of 1400 rpm.

Given:- $f = 50Hz$ $p = 4$ $slip = 4\%$

$f_r = sf$

$f_r = 0.04 \times 50$

$f_r \Rightarrow 2Hz$

$N_r = (1-s) N_s$

$N_r \Rightarrow (1-0.04) 1500$

$N_r \Rightarrow 1440$ rpm

$N_s = \frac{120 \times f}{p}$

$\Rightarrow \frac{120 \times 50}{4}$

$\Rightarrow 1500$

$\cos\phi_0 = \frac{R_2}{Z_{20}} = \frac{R_{20}}{\sqrt{R_2^2 + X_{20}^2}}$

$\cos\phi_{2s} = \frac{R_2}{Z_{2s}}$

$Z_{20} \Rightarrow$

$\cos\phi_0 \Rightarrow \frac{R_2}{Z_{20}} \Rightarrow \frac{1}{\sqrt{1^2+4^2}} \Rightarrow \frac{1}{\sqrt{17}} \Rightarrow \frac{1}{4.123} \Rightarrow 0.242$

$\cos\phi_{2s} \Rightarrow \frac{R_2}{Z_{2s}} \Rightarrow \frac{1}{\sqrt{1^2+(0.04)\times 4^2}} \Rightarrow \frac{1}{\sqrt{1+}}$

$\Rightarrow \frac{1}{1.28} \Rightarrow 0.78125$

Relationship b/w Rotor copper loss & rotor input :-

input power to rotor = $P_g$ = $\omega_s T_d$ (developed torque)

(air gap power)

Total mechanical power developed by rotor =

~~$P_{mech}$~~ = $P_{md} = \omega_r . T_d$

↙ rotor angular speed

$\omega_s = 2\pi N_s$

$\omega_r = 2\pi N_r$

Total $i^2R$ loss in rotor = Power transfer from stator to rotor

− ~~Power~~ Total mechanical power developed by rotor.

$\Rightarrow P_g - P_{md}$

$\Rightarrow 2\pi (N_s - N_r) T_d$

Divide the above equation by $P_g$

$$\frac{P_{rc}}{P_g} \Rightarrow \frac{2\pi (N_s - N_r) T_d}{2\pi N_s T_d}$$

$$\frac{P_{rc}}{P_g} \Rightarrow S$$

$$\boxed{P_{rc} = S.P_g} = S.P_{air}$$

Thus the rotor Cu loss is equal to the slip times the rotor input (air gap power). The term $S \times P_g$ is known as slip power.

Also,
rotor input = mechanical Power output + Rotor Cu loss

$$P_{ai} = P_{md} + P_{rc}$$

$$\frac{P_{rc}}{s} \Rightarrow P_{md} + P_{rc}$$

$$- P_{md} \Rightarrow P_{rc}\left[1 - \frac{1}{s}\right]$$

$$P_{md} \Rightarrow P_{rc}\left[\frac{1}{s} - 1\right]$$

$$P_{md} \Rightarrow P_{rc}\left[\frac{1-s}{s}\right]$$

$$\left(\frac{s}{1-s}\right) P_{md} = P_{rc}$$

$$P_g : P_{rc} : P_{md} = 1 : s : 1-s$$

**Developed Torque :- ($T_d$)**

The induced torque in a machine is defined as the torque is generated by the internal electrical to mechanical power conversion. The torque is also called the electromagnetic torque. This torque is differ from the torque actually available at the terminal of the motor by the amount equal to the friction and ~~vintage~~ windage torque in the machine.

$$T_d = \frac{P_{md}}{\omega_r}$$

S.M.

Ex Power input ~~in~~ to a 3 phase induction motor is 60 kW. The Stator losses are 1 kWatt. Find the total mechanical power developed and the rotor copper loss per phase. If the motor is running with a slip s = 3%.

→ ~~$P_g = 60kW$ $P_{r.c} = 1kW$~~

~~$P_{md} \Rightarrow 1 \left[ \frac{1-0.03}{0.03} \right]$~~

$s = 0.03$

~~$P_{md} \Rightarrow 32.33$~~

$P_{input} - P_{stator\ loss} = P_g$

$60 - 1 = P_g$

$59 = P_g$

~~$P_g \Rightarrow 60\ kW$ $L_s \Rightarrow 1kW$~~

~~$P_{rc} \Rightarrow s \times P_g \Rightarrow 0.03 \times 60$~~

~~$\Rightarrow 1.8\ kW$~~

$P_{rc} = s \times P_g$

$P_{rc} = 0.03 \times 59$

$\boxed{P_{rc} = 1.77\ kW}$

~~$P_{md} \Rightarrow 1.8 \times \left[ \frac{1-0.03}{0.03} \right]$~~

~~$\Rightarrow 58.2$~~

$P_g - P_{rc} = P_{md}$

$59 - 1.77 = P_{md}$

$\boxed{57.23 = P_{md}}$

Power input to rotor 440 ~~kW~~ V, 50 Hz, 6 pole in a 3 phase induction motor is 80 kW. The rotor emf is observed to make 100 complete alternation per minute. Calculate (a) slip (b) rotor speed (c) mechanical power developed (d) rotor Cu loss/phase (e) rotor resistance/phase if the rotor current is 65 A.

$50 \Rightarrow s f$

→ $P_g \Rightarrow 80\,kW$ $N_r = 100\,rpm$

(a) slip $P_{rc} \Rightarrow P_g \times s$

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

⇒ $N_s - N_r \Rightarrow 100$ ← observed rotor speed

$50 = \frac{N_s \times 6}{120}$

$1000\,rpm = N_s$

$S = \frac{N_s - N_r}{N_s} \Rightarrow$ ~~$\frac{1000-100}{1000}$~~

$\Rightarrow \frac{100}{1000} \Rightarrow 0.1$ ~~$\Rightarrow \frac{900}{1000} \Rightarrow 0.9$~~

(b)

$N_s - N_r = 100$

$1000 - N_r = 100$ $N_r = 900\,rpm$

(c) $P_g \Rightarrow 80\,kW$ $P_{md} = ?$ $s = 0.1$

$P_g : P_{md} \Rightarrow 1 :$ ~~$s$~~ $1-s$

$\frac{P_g}{1} = \frac{P_{md}}{\cancel{s}\; 1-s}$

$80 = \frac{P_{md}}{1-0.1}$

$0.9 \times 80 \Rightarrow P_{md}$

$72\,kW$

(d) $P_{cu} = P_g - P_{md}$

$\Rightarrow 80 - 72$

$\Rightarrow 8\,kW$

(c) $i_n \Rightarrow 65A$

Rotor Cu loss = 8 kW

Let, rotor resistance / phase = $r$

$$\text{Cu loss} = 3 \times I^2 \times r$$

$$8000 = 3 \times I^2 \times r$$

$$r = 0.74\Omega$$

Torque of induction motor :-

$$T_d = \frac{K_s \times s\, E_{20}^2 R_2}{R_2^2 + s^2 X_{20}^2} \quad \text{where } K_s = \frac{3}{2\pi N_s} = \frac{3}{\omega_s} \Rightarrow \text{constant}$$

# Starting torque (At starting $N_r = 0$ $N_s = 1$)

$$T_d \Rightarrow \frac{K_s E_{20}^2 R_2}{R_2^2 + X_{20}^2}$$

Torque at synchronous speed :-

$$T_d \Rightarrow \frac{K_s \times s\, E_{20}^2}{R_2}$$

$$T_d \Rightarrow 0$$

Condition for max torque :-

$$T_d \Rightarrow \frac{K \times s \times E_{20}^2 R_2}{R_2^2 + s^2 \times X_{20}^2}$$

if impedance of stator winding assumed to be negligible for the given supply voltage $V_1$. $E_{20}$ remains constant

Let $kE_{20} = K_1$

$$T_d = \frac{K_1 \times s \times R_2}{R_2^2 + s^2 X_{20}^2}$$

$$T_d \Rightarrow \frac{K_1 . R_2}{\left[\frac{R_2}{\sqrt{s}} - X_{20}\sqrt{s}\right]^2 + 2R_2 X_{20}}$$

The developed Torque will be max. when the R.H.S of the above eqn is maximum which is possible when denominator be minimum.

$$\frac{R_2}{\sqrt{s}} - X_{20}\sqrt{s} = 0$$

$$\frac{R_2}{\sqrt{s}} = X_{20}\sqrt{s}$$

$$R_2 = s \times X_{20}$$

$$\boxed{R_2 = X_{2s}}$$

Hence the developed torque is max. when the rotor resistance per phase is equal to rotor reactance / phase under running condition.

The max. torque is obtained by $R_2 = X_{2s}$ in the above expression of torque

$$T_d \Rightarrow \frac{K_1 \times s \times X_{2s}}{(X_{2s})^2 + s^2 X_{20}^2}$$

$$\Rightarrow \frac{K_1 \times s \times X_{2s}}{(X_{2s})^2 + (X_{2s})^2}$$

$$\Rightarrow \frac{K_1 \times s \times X_{2s}}{2 (X_{2s})^2}$$

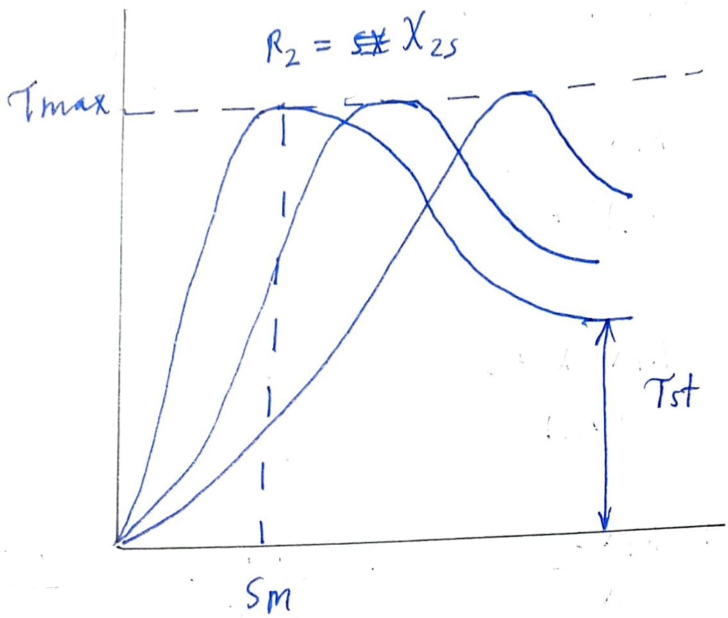
$$\Rightarrow \frac{K_1 \times s}{2 X_s} \Rightarrow \frac{K_1}{2 X_0} \Rightarrow \frac{K E_{20}^2}{2 X_0}$$

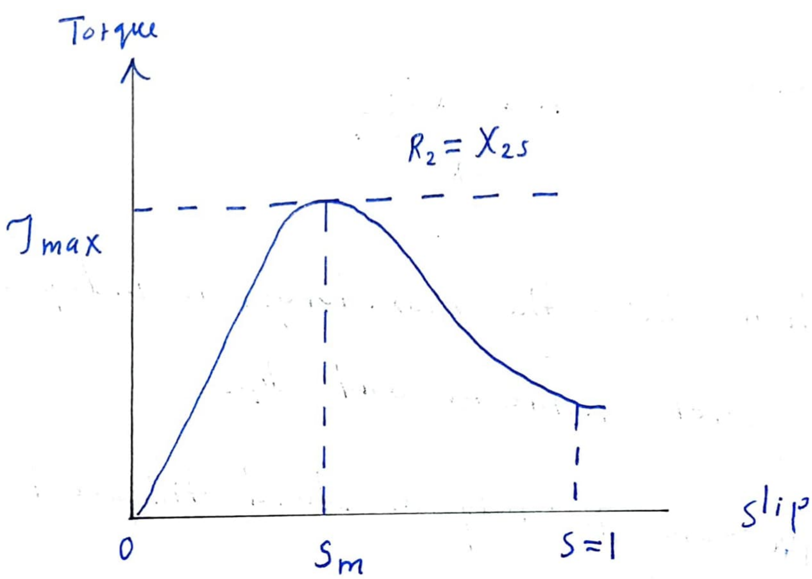
Similary $T_d = \frac{K \times s \times E_{20}^2}{2 R_2}$

This relation shows the max. torque is independent of rotor resistance ~~and slip~~.

Max. torque varies inversely as stand still reactance of the rotor.

# Torque slip Characteristics :-




We know that $T = \dfrac{K s R_2 E_{20}^2}{R_2^2 + (s X_{20})^2}$ ~ (1) It is seen that if $R_2$ and $X_{20}$ are kept constant the torque depends upon the slip.

At synchronous speed $(s = 0)$. Therefore $T = 0$

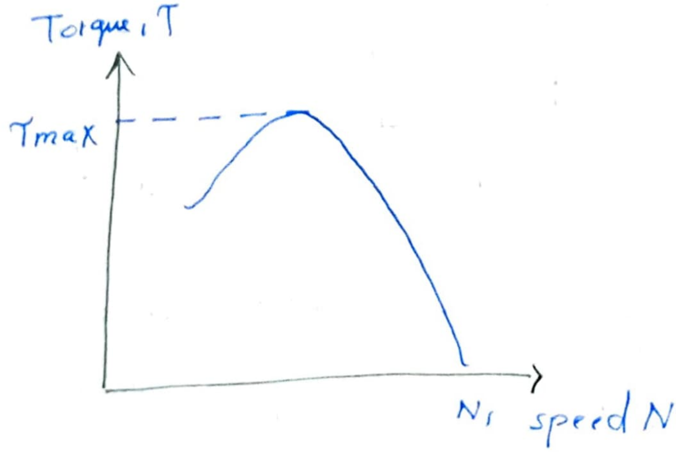
When the speed is very near to synchronous speed, the slip is very low and $(sX_{20})^2$ is negligible in comparision with $R_2$. Therefore $T = \frac{K_1 S}{R_2}$ or $\boxed{T \propto S}$ → (2)

As slip increases (as speed decreases with increase in load) the term $(sX_{20})^2$ becomes large so that $R_2^2$ may be neglected in comparision with $(sX_{20})^2$ and $T = \frac{K_s R_2 \times S}{S^2 X_{20}^2}$

$$\boxed{T \propto \frac{1}{S}} \rightarrow (3)$$

The characteristics also passes through the point of max. torque $T_{max}$ $(R_2 = X_{2S})$. The max. torque developed in induction motor is called pull out torque / breakdown torque.

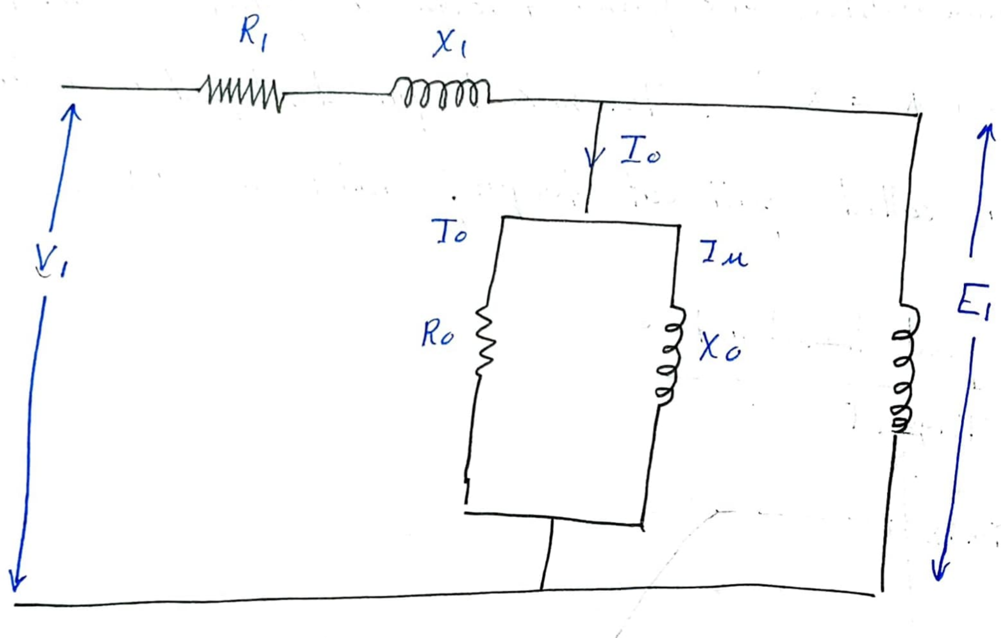
## Torque speed charactaristic :-



# Equivalent circuit of an induction motor :-

An induction motor is based for its operation on the induction of voltage and current in it's rotor circuit from stator circuit bcz the induction of voltages and current in the rotor circuit of an induction is essentially a transformer operation, the equivalent circuit of an induction motor ≈ equivalent circuit of transformer.

## Stator circuit model :-




The equivalent ckt of stator is shown above. It consist of stator phase winding resistance $R_1$ and stator phase winding leakage reactance $(X_1)$. The no load current $(I_0)$ is simulated by a pure inductive reactor $(X_0)$ having the magnetising current $I_\mu$ and a non inductive resistor $(R_0)$ having the current $I_w$ (core loss current)

II - ~~Total magnetising~~

No load current $I_0$ is considerably larger in case of induction motor as compared to the transformer.

In transformer $I_0$ is about 2-5% of rated current while in an induction motor it is approx. 25-40% of rated current depending upon the size of motor.

In an induction motor when a 3phase supply is applied to the stator winding a voltage is induced in the rotor winding in machine. In general the greater the relative motion of the motor and the stator magnetic field. Greater the resulting rotor voltage. We know that

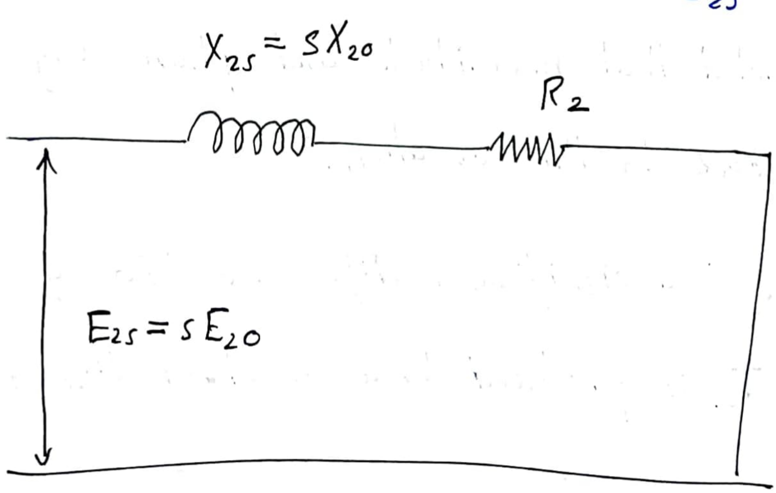
$E_{2s} = s.E_{20}$ and $X_{2s} = sX_{20}$

$Z_{2s} \Rightarrow R_2 + j\,X_{2s}$

$Z_{2s} \Rightarrow R_2 + j.sX_{2s}$

Rotor current =

$$I_{2s} = \frac{E_{2s}}{Z_{2s}}$$

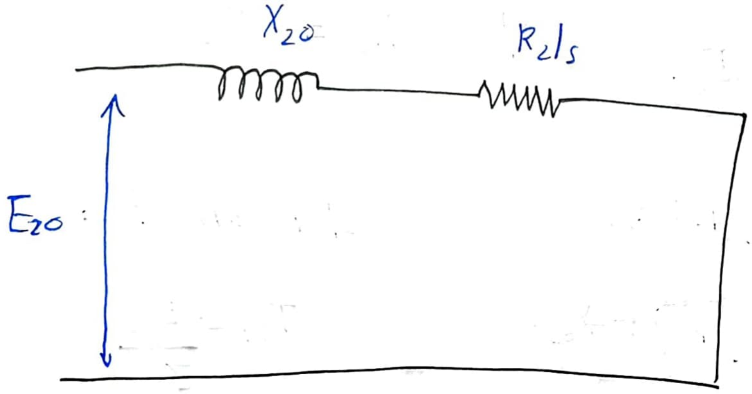


$$I_2 \Rightarrow \frac{s E_{20}}{R_2 + js X_{20}} \quad \text{— (iv)}$$

circuit interpr. It shows the $I_2$ is slip frequency current produced by a slip frequency induced voltage $s \times E_{20}$ having an impedance $R_2 + jsX_{20}$. By dividing both numerator and denominator by s

$$I_{2s} = \frac{s E_{20}}{s\left[\frac{R_2}{s} + j X_{20}\right]} \quad \text{— (v)}$$

The circuit interpretation of eq (v) is shown in fig (iii)

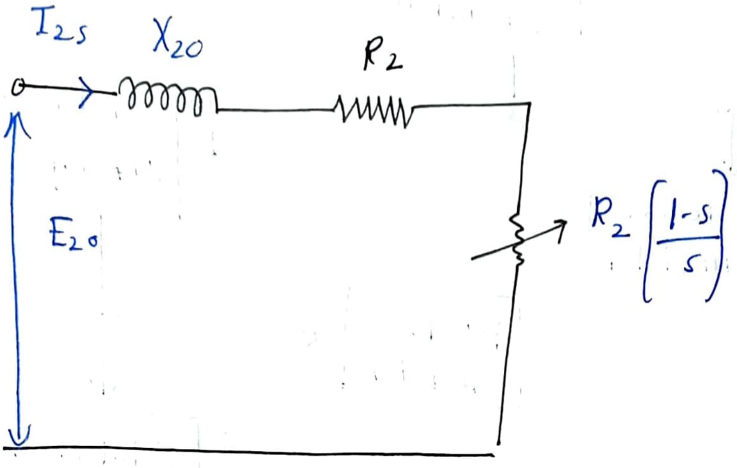



It is to be noted that magnitude and phase angle of $I_{2s}$ remain the same by this operation.

However there is a significance difference b/w eq (iv) & (v).

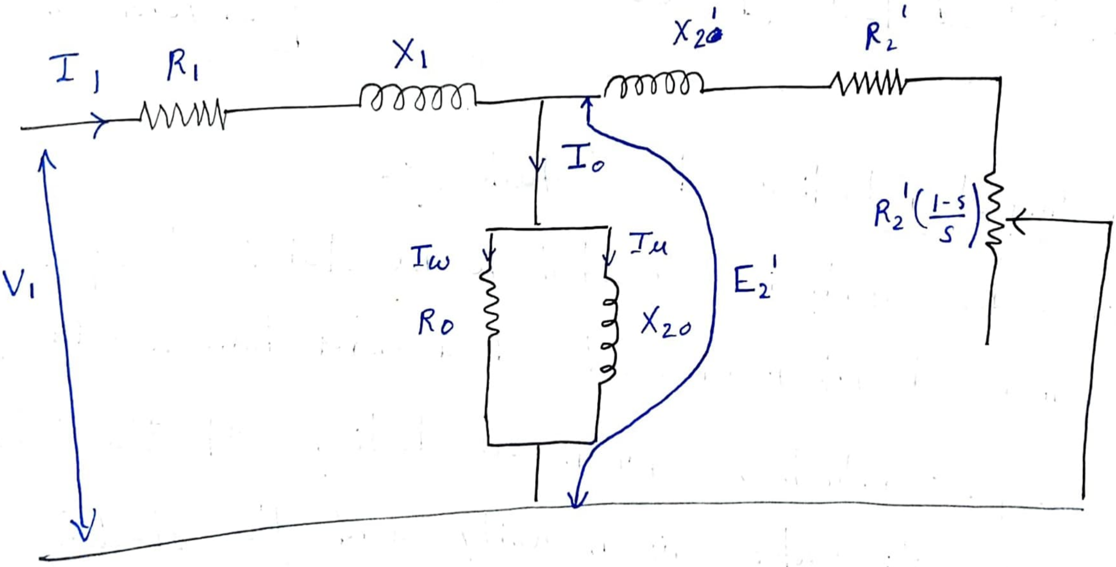
In eq (v) $I_{2s}$ is produced by a constant line frequency voltage $E_{20}$

and this current current is a line frequency current while $I_{2s}$ of eq ckt is a slip frequency current.




per phase eq. circuit with rotor Cu losses and mechanical developed power.

## Complete Circuit model Referred to Stator :-

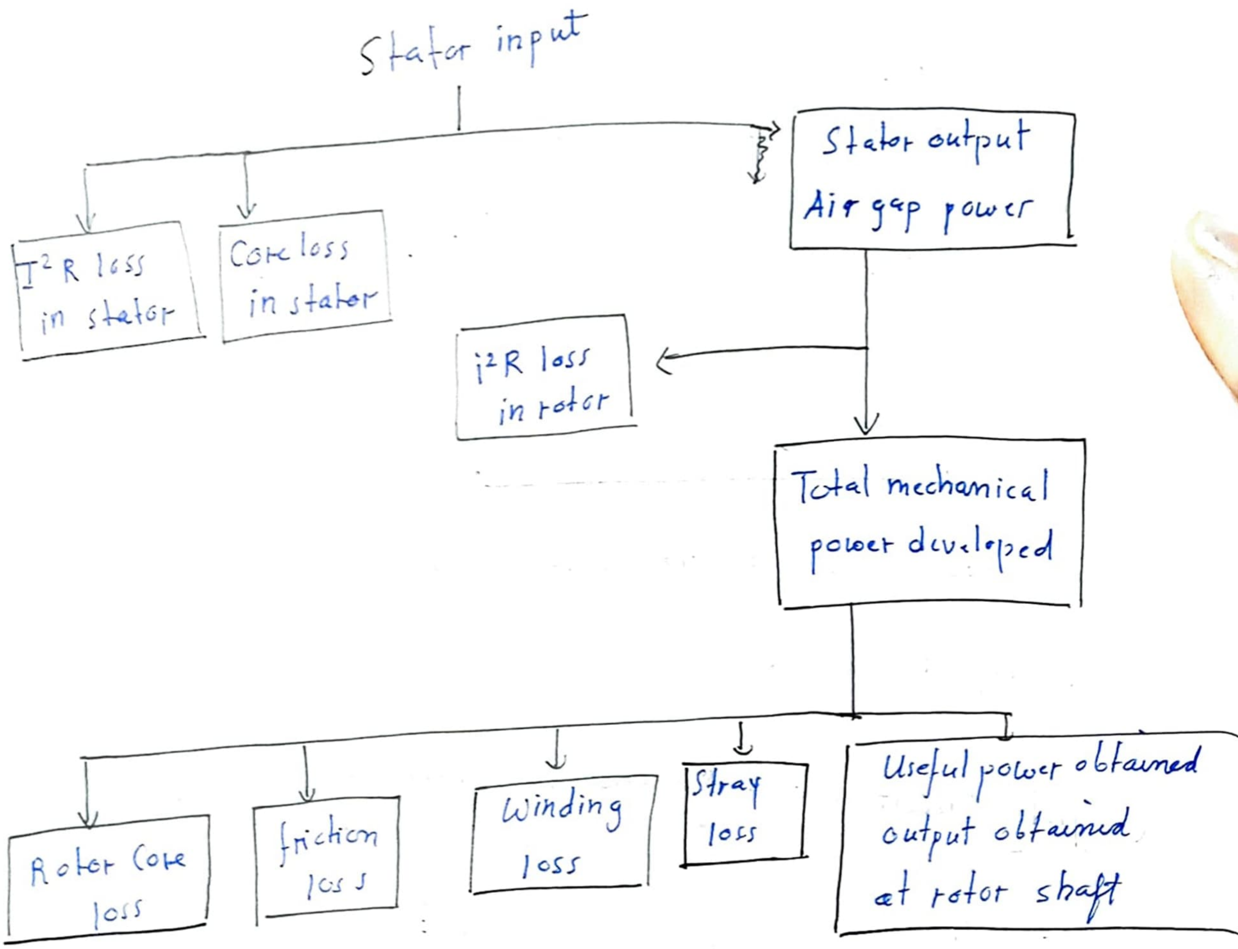



$$E_2' = a.E_2$$

$$X_2' = a^2 X_2$$

$$R_2 = a^2 R_2$$

## Power flow Diagram of an induction motor :-




## Starting of induction motor (Starters) :-

When the supply is connected to the stator of 3 phase induction and emf is produced and a rotor starts rotating. Thus 3 phase induction motor is self starting At the time of starting the motor slip is unity and the starting current is very large. Purpose of ~~stator~~ starter is not to start the motor as the name implies. The starter of motor perform 2 functions

(i) To reduce the heavy starting current

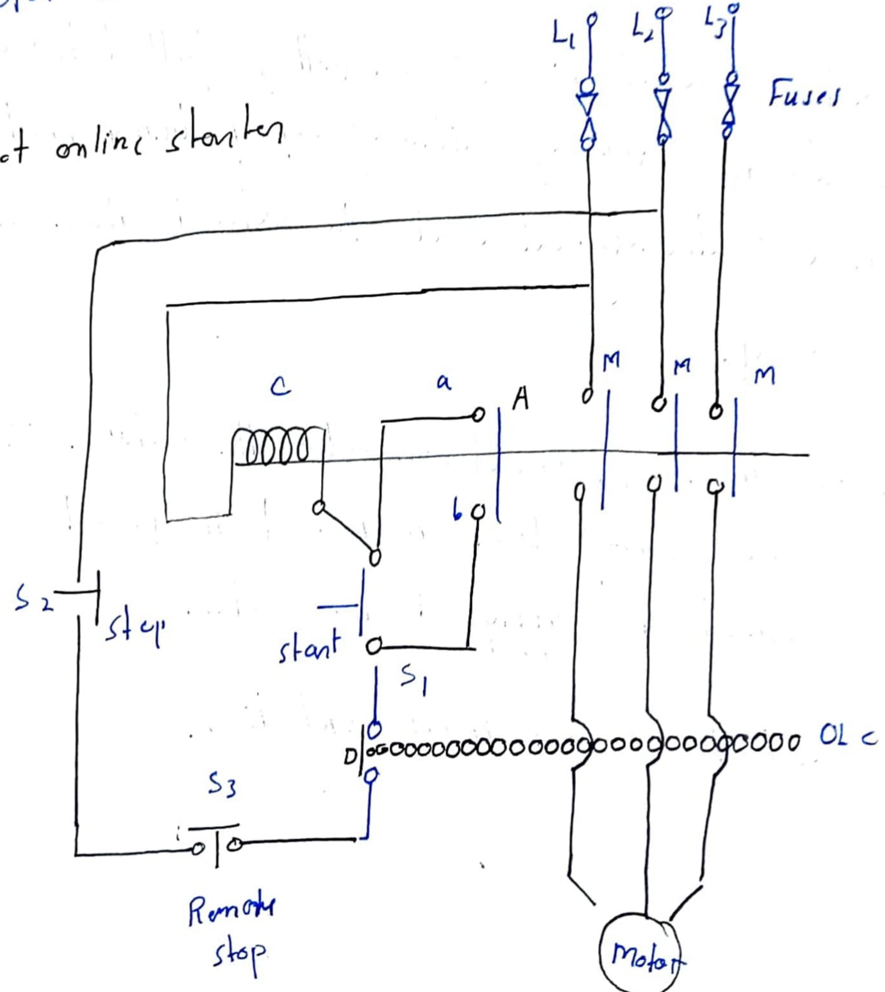
(ii) To provide overload / no load protection.

In general 3 phase induction motors may be started either by connecting motor directly to the full voltage of supply or by applying a reduce voltage to the motor during starting period.

The following are the types of starters :-

1. Direct online starter } squirrel cage
2. Star Delta starter } squirrel cage
3. Auto transformer starter } squirrel cage
4. Rotor resistance starter } wound

① Direct online starter



In direct online method of starting cage motors. The motors is connected by a means of a starter across the full supply voltage. It consist of a coil operated contactor C controlled by start & stop push button. On starting the start push button $S_1$ (which is normally open by a spring), the coil is energised. The 3 main contacts M and auxiliary contact 'A' close and terminal 'a' and 'b' are short circuited. The motor is thus connected to supply.

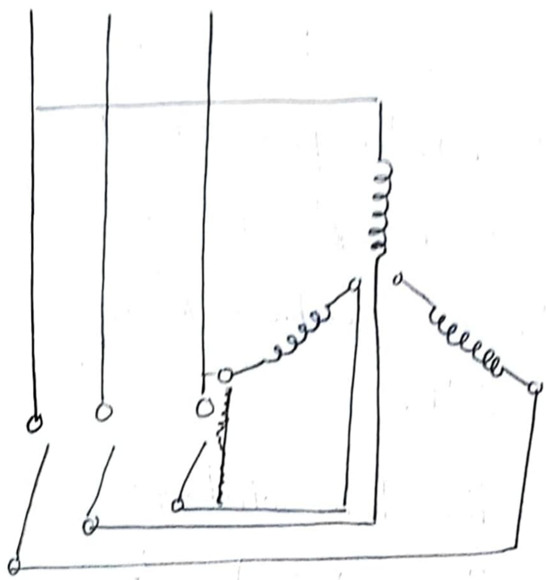
When stop push button $S_2$ is pressed the supply through the coil is disconnected. Since the coil c is deenergised the main contact M and auxiliary contact A are opened. The supply to the motor is disconnected and motor stops.

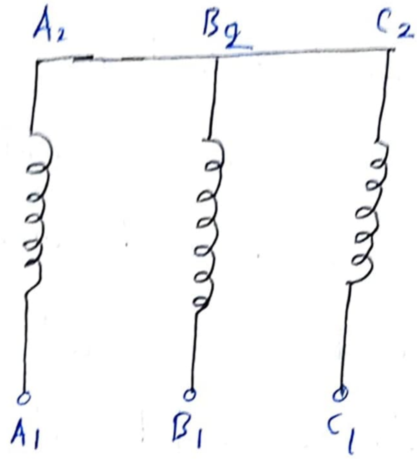
Undervoltage Protection:- When a voltage falls below a certain value or in the event of failure of supply during motor operation. The coil C is deenergised and the motor is then disconnected to the supply.

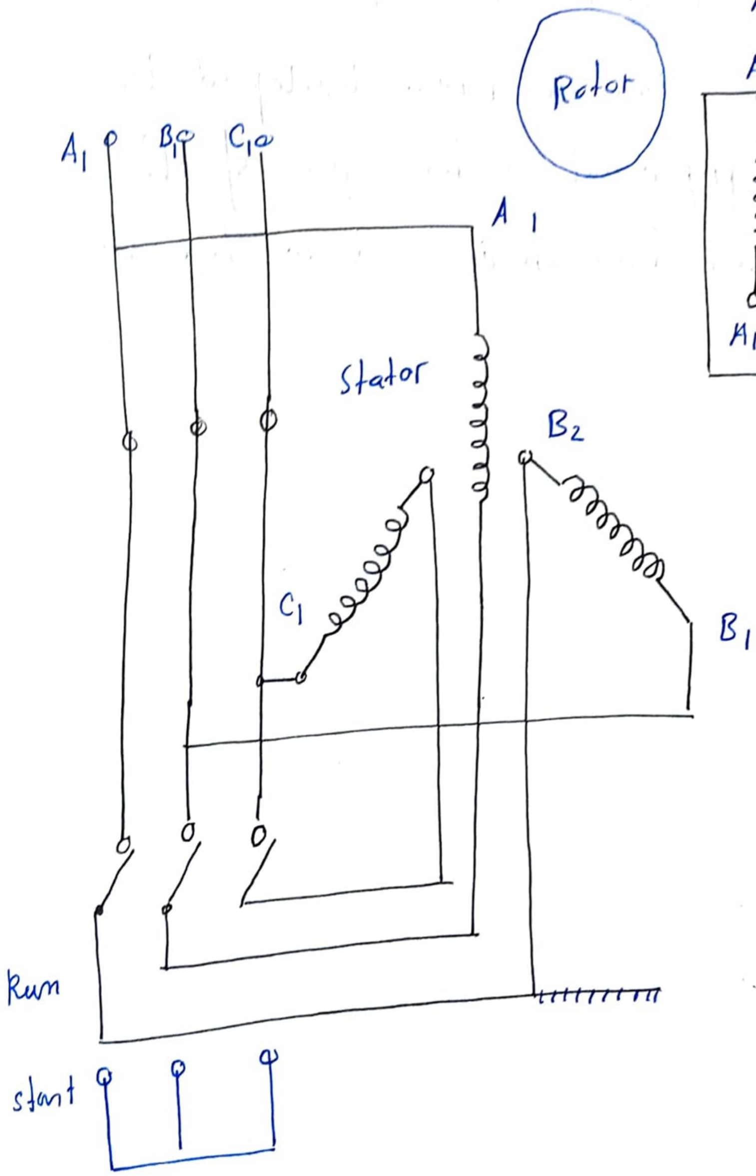
Overload protection:- In case of overload on the motor. OLC is energised the normally closed contact d is opened and coil c is deenergised to supply to the motor.

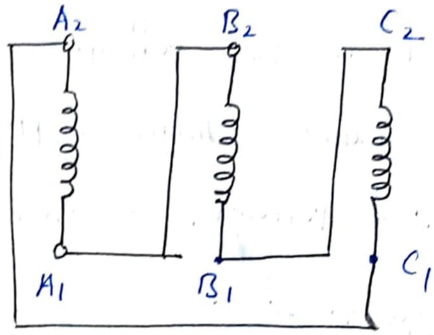
Fuses are provided for short circuit protection.

# (2) Star-Delta Starter





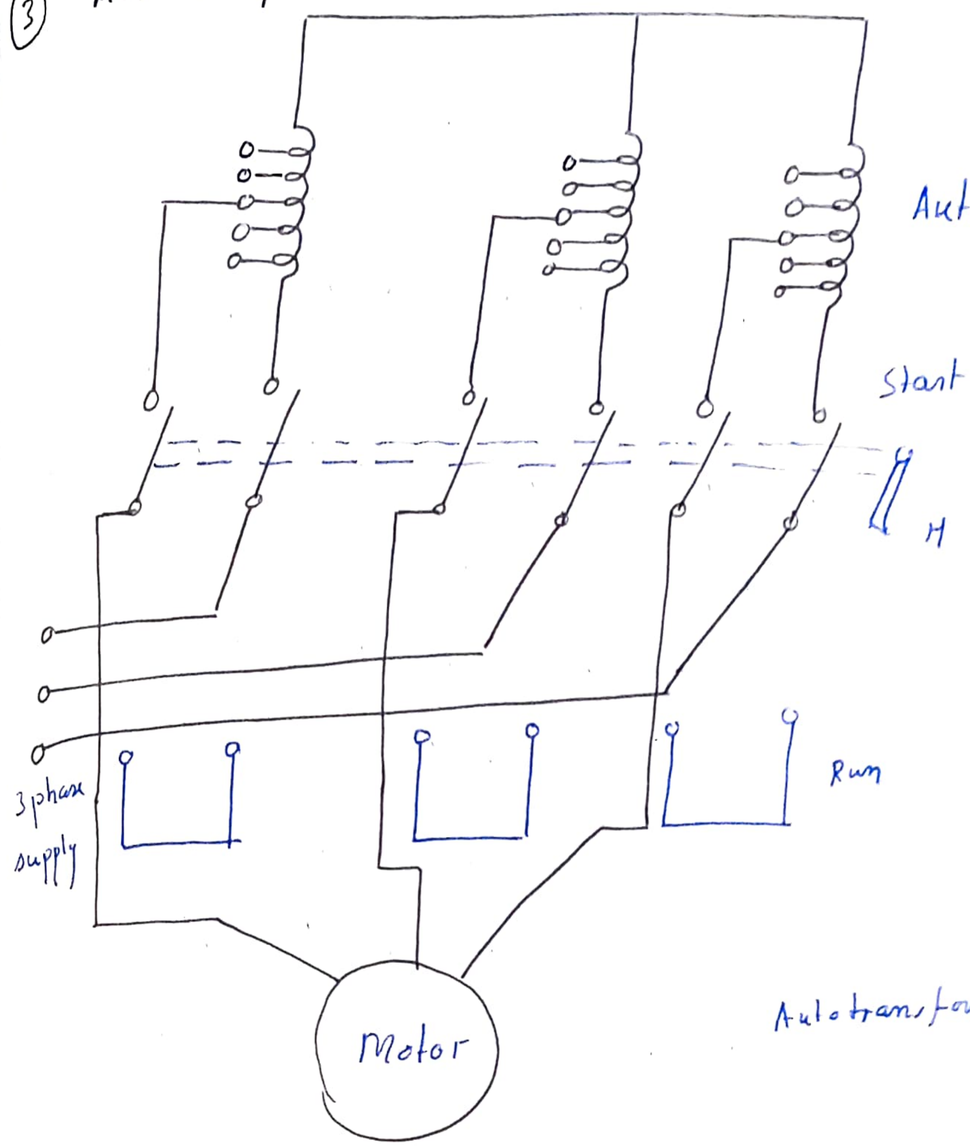




Delta

This is very common type of starter and extensively used compared to the other type of starter. When the switch S in start position the starter windings are connected in star as shown is fibgure '6'. When motor picks up speed around 80% of it's rated value the change over switch S is shown quickly to the run position which connects the stator ~~wdi~~ winding in delta

At the time of starting when the stator winding are star connected each stator phase voltage $(V_L/\sqrt{3})$ where $V_L$ is the line voltage. Since the torque developed by an induction motor is proportional to the square of the applied voltage, so star delta starting reduces the starting torque to $\frac{1}{3}$.

③ Auto transformer



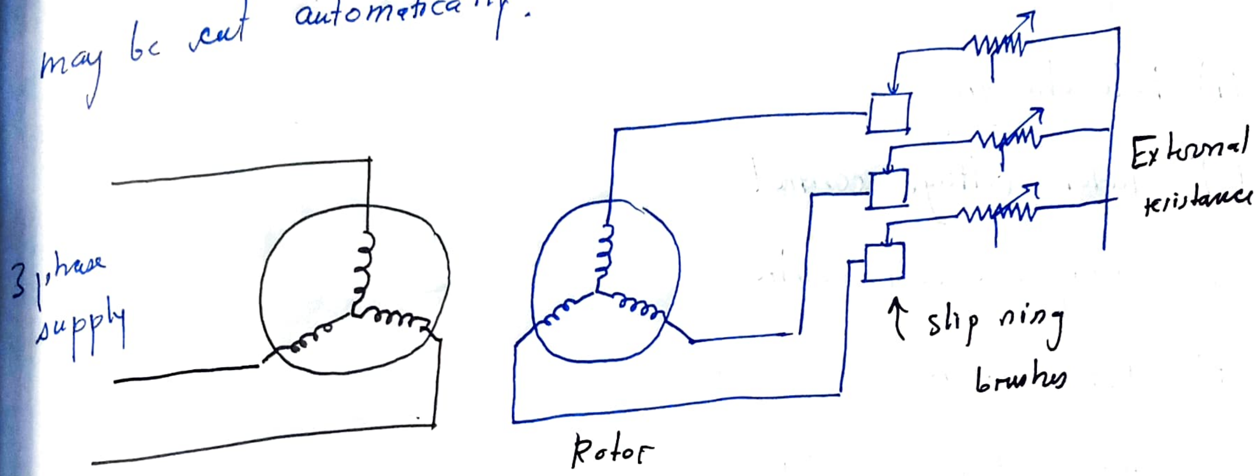

Autotransformer starter

An auto transformer starter is suitable for both star and delta connected motors. In this method, the starting current is limited by using a three-phase autotransformer to reduce the initial stator applied voltage. Fig. shows the motor with the autotransformer starter. The autotransformer is provided with a no. of tappings.

In practise, the starter is connected to one particular tapping to obtain the most suitable starting voltage. A double throw switch S is used to connect the motor in the circuit for starting. When the handle H of the switch S in the start position. the primary of the autotransformer is connected to the secondary of the autotransformer. When the motor picks up the speed, say to about 80% of the rated value, the handle H is quickly moved to H Run position. The autotransformer is disconnected from the circuit and the motor is directly connected to the line and gets its full rated voltage. The handle is held in the RUN position by the undervoltage relay. In case the supply voltage fails or falls below a certain value. the handle is released and returns to the OFF positions. Overload protection is given by thermal overload relays.

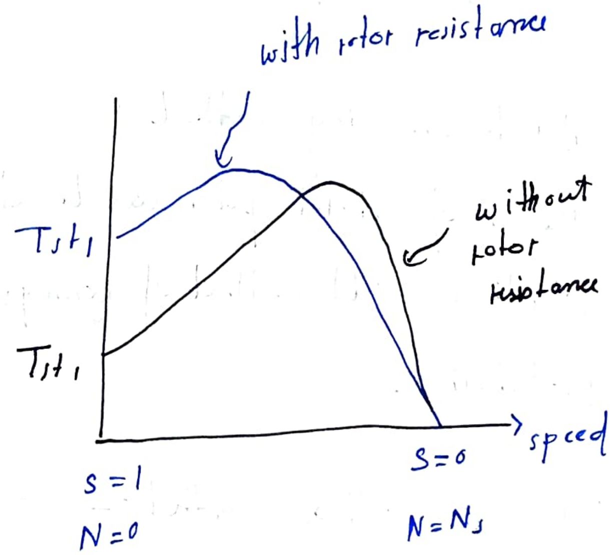
## (4) Rotor Resistance Starter (Slip ring induction motor) :-

In a slip ring induction motor, resistance can be added in series with each phase of the rotor through slip rings and brushes. Maximum resistance is kept while starting. As the motor picks up the speed, the resistance is gradually reduced. The operation may be manual or the resistance may be cut automatically.




Advantages:-

1 Starting torque is increases
2 Starting current is reduced
3 Power factor improved




# only can be used for slip ring induction motor

Speed control of Induction motor :-

$N_r = (1-s) N_s$ $\quad N_s = \frac{120f}{P}$ $\quad N_r = (1-s)\frac{120f}{P}$ → (i)

From eq (i) it is seen that motor speed via change in frequency 'f', 'p', 's'. Anyone or any combination of above methods may be used to change motor speed. The main methods used for speed control of induction motor are as follows:-

(1) Pole changing

(2) Stator voltage control

(3) Supply frequency control

(4) Rotor resistance control

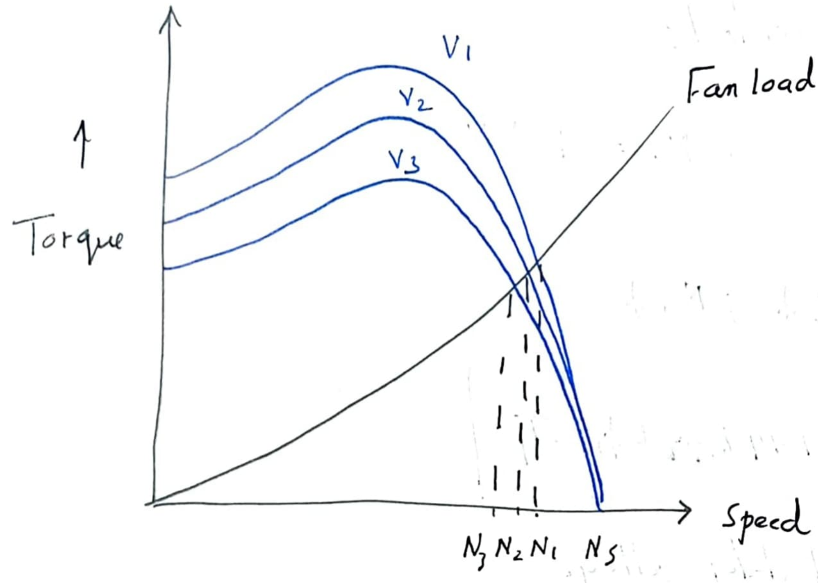
(5) Slip energy recovery.

(1) Pole changing methods :-

The no. of stator poles can be changed by (a) multiple stator windings (b) method of consequent poles (c) pole amplitude modulation.

(2) Stator voltage control :-

$$T_d \Rightarrow \frac{K.\,s.\,E_{20}^2.\,R_2}{R_2^2 + s^2 X_{20}^2} \quad \text{→ (ii)}$$




Torque speed characteristics for various terminal voltages :-

The speed of 3 phase induction motor can be varied by varying the supply voltage. eq (ii) shows that the torque developed is propotional to the square of supplied voltage and eq (iii) shows that slip at max torque is independant of supplied voltage. Variation of supplied volt. does not alter the synchronous speed. The graph (T. speed char. of 3 ...) as shown in fig.. This fig. also shows the torque speed characteristic of fan load.

This method of speed control is simple ~~to~~ low cost, and low maintenance but has limited use. bcz (i) the operation at voltages exceeding rated voltage is restricted by the magnetic saturation. (ii) A large change in voltage is required for small change in speed.

(3) Supply frequency control :-

$$N_s = \frac{120f}{P} \quad \& \quad N_r = (1-s) N_s$$

If $f \downarrow$ ; $N_s \downarrow$ ; $N_r \downarrow$

$$\boxed{E_1 = 4.44\, k_w\, f\, \phi_m \cdot T_p}$$

where $E_1$ is induced stator voltage

$T_p$ is no. of turns / phase

$k_w$ is the winding factor

If stator voltage drops are negligible than $E_1 \approx V_1$

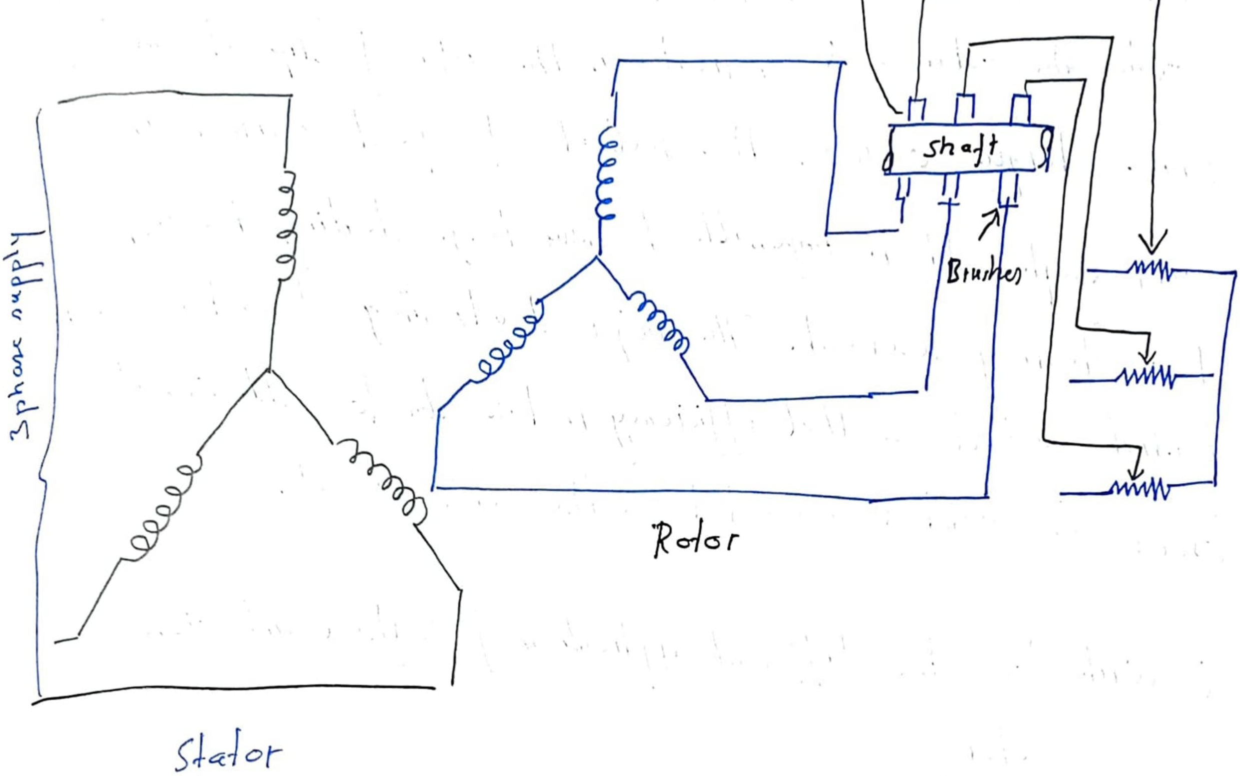
$$V \approx \phi_m f$$

$$\phi_m \propto \frac{V}{f}$$

# We must change frequency in such a way along with $v$ so that $\phi_m$ remains constant.

When $f$ is reduced $\phi_m$ will increase which will produce saturation causing high iron loss and large magnetising current. In order to avoid saturation and to minimise loss motor is operated around rated air gap flux by varying terminal voltage, with frequency so as to maintain $\frac{V}{f}$ ratio constant. This type of control is known as constant volt / Hertz. Thus the speed control of an induction motor using variable frequency requires a variable voltage source.

(4) Rotor resistance control :-




The speed of wound induction motor can be controlled by connecting external resistance in the rotor ckt through slip rings as shown in figure.

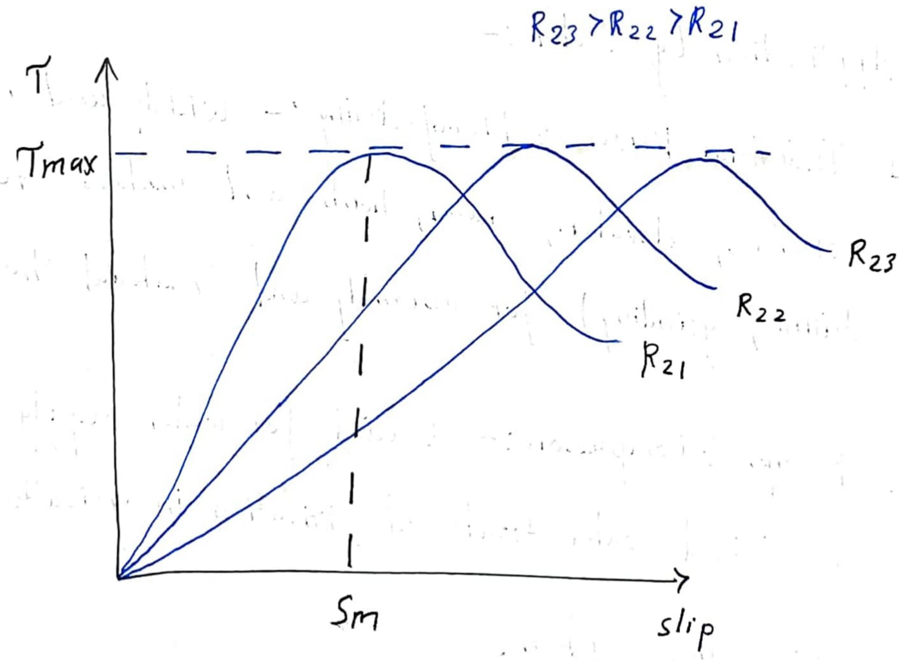



Fig (2) shows the torque slip curve for various values of ~~external~~ rotor resistance.

It is seen that the max. torque is independant of rotor resistance. Greater the value of $R_2$, greater is the value of slip at which max. torque occurs. This method of speed control is very simple. It is impossible to have large starting torque, low starting current. The major disadvantage of rotor resistance control method is that efficiency is low due to additional losses in resistor connected in the rotor circuit.

Q Write down the different application of 3 phase induction motor?

→ 3 phase induction motors are the workhorse of industrial and commercial applications, utilized for its robustness, efficiency, and self starting capacity :-

Application by Sector :-

1 Industrial Drives & Manufacturing :- Widely used in conveyer belt, crushers, elevators, cranes, hoists and machine tools (lathes, drilling, grinding) for assembly and material handling.

2 Pumps & Compressors :- Crucial for water supply systems, municipal water treatment, irrigation in agriculture, and refrigeration system.

3 Mining & Excavators :- Used for powerful heavy duty equipment like excavators, mining rollers, and transport machinery due to their durable construction.

4 Transportation :- Employed in electric trains, suburban trains, and commercial Electric vehicles (EVs).

5 Fans & HVAC :- Utilized in large scale air conditioning units ventilation systems, and industrial blowers.

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+2

# Synchronous Motors :-

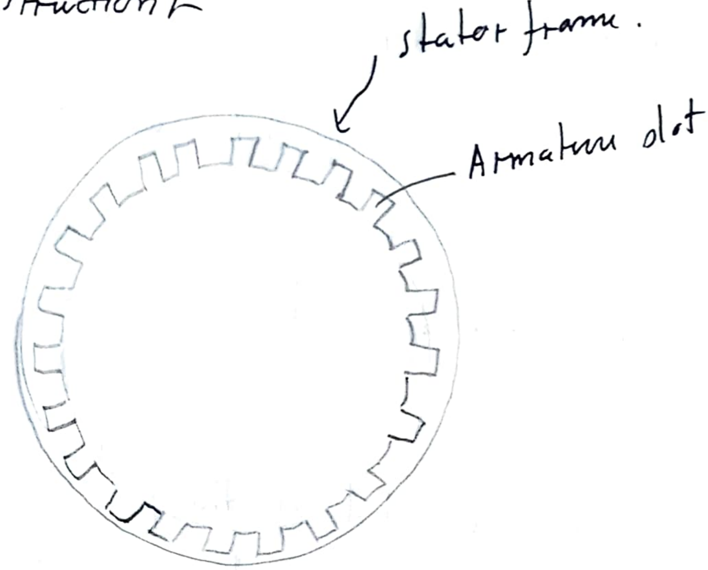
## Introduction :-

Like most rotating machine a synchronous machine can also operate as both generator and motor. A synchronous motor is a machine that converts A.C electrical power to mechanical power at a constant speed called synchronous speed. A synchronous motor is a doubly excited machine its rotor poles are excited by DC at its stator winding are connected to the A.C supply. The air gap flux is therefore the resultant of fluxes due to both rotor current and the stator current.

## Construction :-

Similar to the other rotating machines it consist of 2 main parts stator and rotor. The stator is the stationary part and the it carries the armature winding in which the voltage is generated. The output of machine is taken from the stator. The rotor is the rotating part of machine. The rotor produces the main field flux.

Stator construction :-




The various parts include stator frame, core, windings and cooling arrangements. The frame may be made of cast iron in order to reduce stresses and eddy current losses. The stator core is assembled with high grade silicon steel lamination. A 3 phase winding is put in slot as shown in figure. When current flows in a winding it produce emf.

Rotor construction :- There are 2 types of rotor construction
① Salient - Pole rotor ② Cylindrical Pole rotor

Salient Pole rotor :-

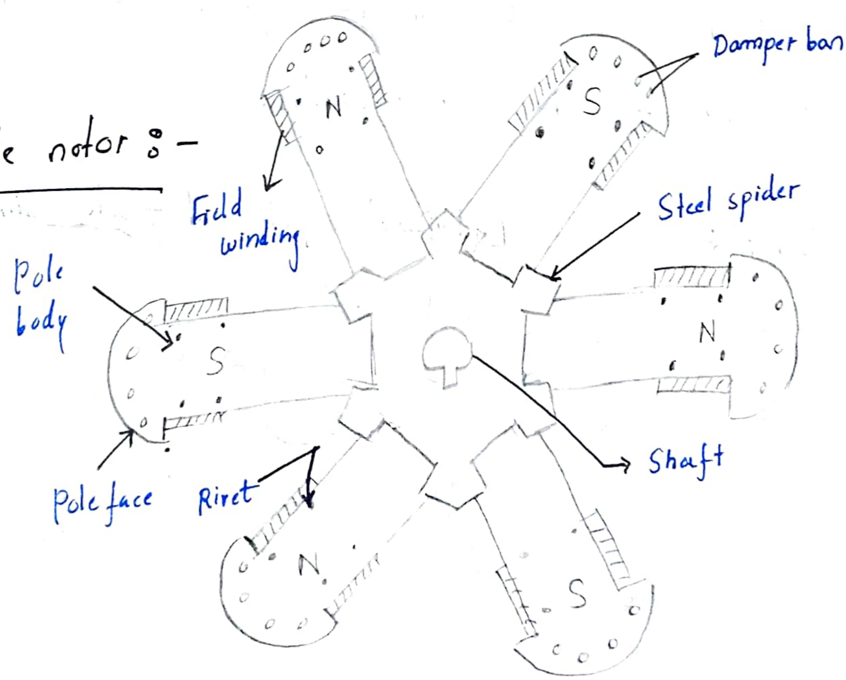


Fig shows the end view of a typical 6 pole salient pole rotor

Salient pole rotor are used for rotor with 4 or more poles

Since the rotor is subjected to changing magnetic fields, it is made of thin steel laminations to reduce eddy current losses.

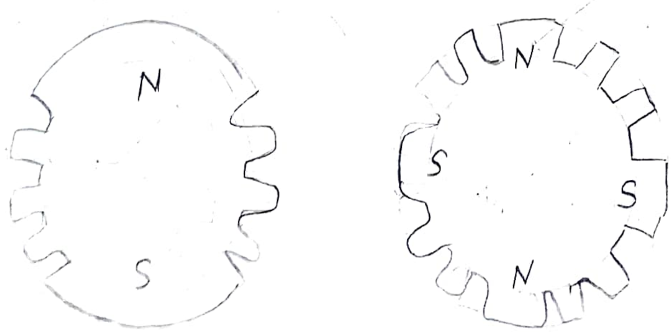
Damper bars are usually inserted in the pole faces to damp out the rotor oscillations during sudden change in load conditions. A salient pole synchronous machine has a non-uniform air gap. The air gap is minimum under the pole centres and it is maximum in between the poles.

The individual field pole winding are connected in series to give alternate north and south polarities. The ends of the field windings are connected to a dc source through the brushes of the slip rings.

They are used to carry current to or from the rotating part of the machine via carbon brushes.

<u>Cylindrical Rotor</u> :-

End view of 2 pole and 4 pole cylindrical rotors



A cylindrical - rotor machine is called a non salient pole rotor machine. Cylindrical rotor are made from solid forgings of high grade nickel chrome - molybdenum steel. at regular intervals and parallel to the shaft. The dc field winding are accomodated in these ~~shafts~~. slots.

Construction of 3$\phi$ ~~induction~~ synchronous motor :-

The construction of a 3$\phi$ induction motor is essentially the same as that of synchronous generator. An additional set of windings called the damper winding is mounted on the rotor. This winding is placed in slots located in the pole phases and parallel to the shaft as shown in Fig.

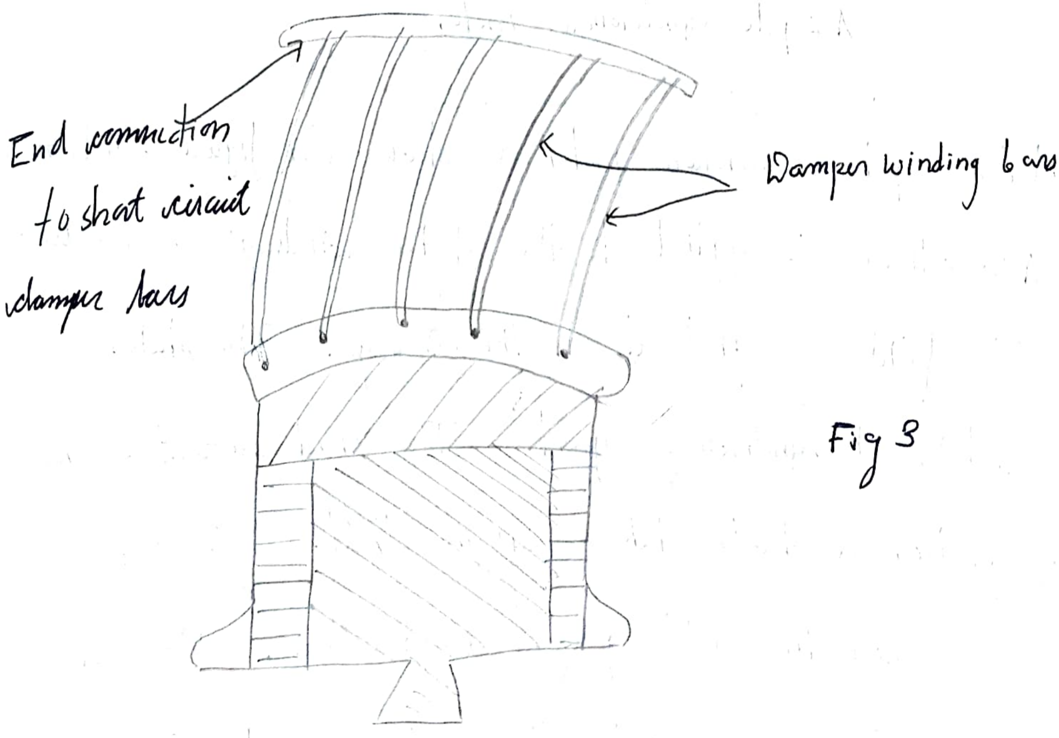
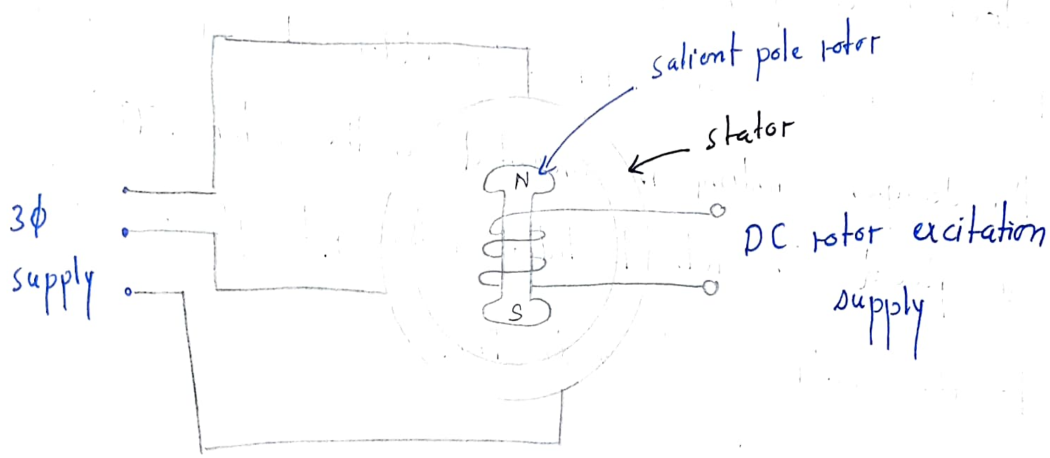



Fig 3

This ends of Cu bar are short circuited in the same manner as a cage rotor of Induction motor,

Damper windings provide a means of starting the synchronous motor. They also serve to increase the stability of rotor during load

Principle of Operation :-




A 2 pole synchronous motor

Consider a 2 pole synchronous motor as shown in figure. When a 3ϕ A.C. voltage is applied to the stator windings a rotating magnetic field is produced in the air gap. The stator field rotates at synchronous speed. The field current of the motor produces a steady state magnetic field. Therefore there are 2 magnetic field present in machine. The rotor will tend to align with the stator field just as two bar magnets will tend to align if placed near each other. Since the stator magnetic field is rotating, the rotating magnetic field and the rotor will tend to rotate with the rotating field of the stator. In order to develop a continuous torque the 2 field must be stationary w.r.t each other. This is possible when the rotor also rotates at synchronous speed. The basic principle of synchronous motor operation is that rotor chases the stator magnetic field. In other words the stator rotating magnetic field tends to drag the rotor along as if north pole.

When a pair of rotating stator pole sweeps across the stator poles at the synchronous speed. The stator poles will tend to rotate the rotor on the one direction and then in other direction. However bcz of the Rotor inertia the stator field slides by so fast that rotor can not follow it. Consequently the rotor does not move and we say that a synchronous motor is not self starting.

Q Write down the application of synchronous motor?

-) Synchronous motors are utilised across various industries due to their unique ability to run at a constant speed regardless of load, high efficiency, and capability for power factor correction.

Application by sector:-

1 Power Generation and Utilities:-

Synchronous Condensers:- Over excited synchronous motor running without mechanical load to improve power factor and regulating voltage at the end of long transmission lines.

Generator Driving:- Used in power plant to drive large exciters.

2 Manufacturing & Processing:-

· Mining and Mineral Processing:- Used in rock crushers, ball mills and rod mills often at low speed with high horsepower requirements.

3 Automation & Precise Engineering:-

Robotics and Actuators:- High precision magnet synchronous motor are used as servo motors for robotic arms, CNC machines etc.

4 Marine and Transportation:-

· Ship Propulsion:- High power, low synchronous speed synchronous motors are used for driving propellers in large ships.

...mer Applications :-

Timing Devices :- Small synchronous motors are used in clocks, timers, recording instruments, utilising the A.C frequency for precise timing.

## Starting of Synchronous Motors :-

A synchronous motor is not self starting. It can be started by the following two methods :-

1. Motor Starting with an external Prime mover :-

In this method an external motor drives the synchronous motor and brings it to synchronous speed. The synchronous machine is then synchronized with the bus bar as a synchronous generator. The prime mover is then disconnected. Once, in parallel, the synchronous machine will work as a motor. Since load is not connected to the synchronous motor before synchronising, the starting motor has to overcome inertia of the synchronous motor at no load. Therefore the rating of the ~~synchronous~~ starting motor is much less than the rating of synchronous motors.

At present most large synchronous motors are provided with brushless excitation systems mounted on their shafts

These excitors are used as starting motor.

2 Motor starting with Damper windings :-

Today the most widely used methods of synchronous motor is to use damper windings. A damper winding consist of heavy Cu bars inserted in slots of the pole face of the rotor as shown in Fig 3. These bars are short circuited by end rings at both ends of the rotor. Thus, these short circuited bars form a squirrel cage winding. When a 3 phase supply is connected to the stator, the synchronous motor with damper wire will start as a 3$\phi$ induction motor. As the motor approaches synchronous speed, the dc excitation is applied to the field windings. The rotor will then pull into step with the stator magnetic field.