INDUCTION MACHINE

Machine

- Induction motor
  - 3-ϕ
  - 1-ϕ
- Induction Generator

Q. Why the I.M is used most widely?

⇒ Following reasons -

i) Construction simple

ii) Easy maintenance

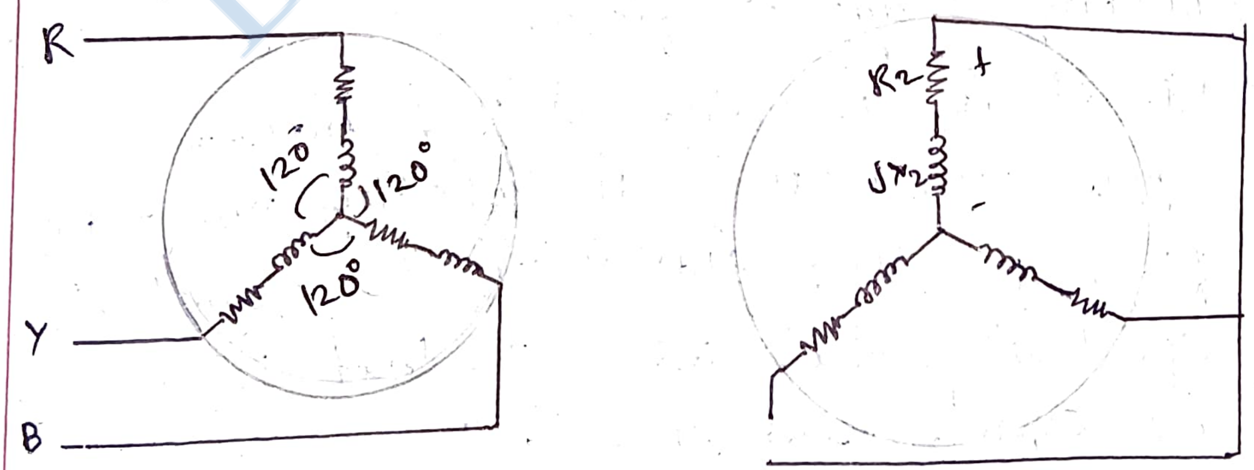
iii) No armature reaction effect

iv) Low cost.

3-ϕ Induction motor

It works on the principle of rotating magnetic field.

Note:- Induction machine is also known as rotating T/F.



Stator Rotor

$V_R = V_m \sin\omega t$
$V_Y = V_m \sin(\omega t - 120°)$
$V_B = V_m \sin(\omega t + 120°)$

Balance Supply
Same magnitude
Angle difference (120°)

→ Whenever a 3-φ supply 120° displacement with respect to time is applied across stator winding having displacement of 120° with respect to space, then a rotating magnetic field is produced and this magnetic field rotates at constant speed, which is known as synchronous speed.

$$N_s = \frac{120F}{P}$$ → Synchronous speed.

where
F = frequency
P = no. of pole

- **Working principle :-**

→ Induction motor works on the principle of rotating magnetic field.

→ जब stator winding को 3-φ balance supply दिया जाता है तो rotating magnetic field produce होता है जो एक constant speed से rotate करता है, that is known as synchronous speed.

→ When the stationary rotor cut the rotating magnetic field due to this E.M.F is induced in rotor winding and current starts to flow through the rotor winding.

→ As we know that when a current carrying conductor is placed in uniform magnetic field then it experience a mechanical force, which is known as lorentz force.

→ Hence there is torque on the rotor winding, which tends to rotate the rotor winding.

→ But as per lenz's law rotor will oppose for its rotation and rotates in the direction of rotating magnetic field.

Note :-

Rotor winding rotates in the direction of rotating magnetic field as per lenz's law to reduce the flux cutting action between the R.M.F. and rotor winding.

Hence, the rotating magnetic field cuts the rotor winding by relative speed of $(N_s - N_r)$

→ This relative speed is also known as slip speed.

→ Sleep speed is represented by (SN_s)

$$\therefore sN_s = N_s - N_r$$

$$\text{Slip} = \frac{N_s - N_r}{N_s}$$

→ Induction motor is also known as asynchronous motor because it never runs at synchronous speed because at synchronous speed there will be no flux cutting, no emf, no torque and hence the motor will not starts.

→ Induction motor always rotates below the synchronous speed.

$$s = \frac{N_s - N_r}{N_s}$$

<u>During starting</u>

$N_r = 0$

$$\therefore s = \frac{N_s - N_r}{N_s} = \frac{N_s - 0}{N_s} = 1$$

∴ At starting condition slip of induction motor is 1.

Operating slip = 1 % to 5 %

Q.) In 3-φ, 4-pole, 50 Hz Induction motor what is the speed of stator rotating magnetic field.

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

If F = 50 Hz

① $P = 2$, $N_s = \frac{120 \times 50}{2} = 3000$ rpm

② $P = 4$, $N_s = \frac{120 \times 50}{4} = 1500$ rpm

③ $P = 6$, $N_s = \frac{120 \times 50}{6} = 1000$ rpm

④ $P = 8$, $N_s = \frac{120 \times 50}{8} = 750$ rpm

⑤ $P = 10$, $N_s = \frac{120 \times 50}{10} = 600$ rpm.

Q. If A 3-φ, 4 pole, 50 Hz Induction machine run at 1450 rpm, then find persentage slip?

⇒ $N_r = 1450$ rpm.

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

$$\% \text{slip} = \frac{N_s - N_r}{N_s} \times 100$$

$$= \frac{1500 - 1450}{1500} \times 100 = \frac{50}{1500} \times 100$$

$= 3.33\%$ Ans

Q. If a 3-Φ 50 Hz Induction machine run at 950 rpm, find the no. of pole.

Soln:- As we know that the induction motor always rotates near the synchronous speed.

for P = 6

$N_s = 1000$ rpm

∴ No. of pole = 6.

Q. A 3-Φ 6 pole 60 Hz I.M has a slip of 5% than find the speed of rotor?

⇒ ~~Ns = 1000 rpm~~ $N_r = ?$

$N_s = \frac{120 \times 60}{6} = 1200$ rpm

$S = 0.05$

We know that

$S = \frac{N_s - N_r}{N_s} \Rightarrow SN_s = N_s - N_r$

$\Rightarrow N_r = N_s - SN_s$

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

$= 1200(1 - 0.05)$

$= 1200(0.95)$

$N_r = 1140$ rpm Ans

Effect of Slip on different parameters of rotor

(1) Effect on rotor frequency

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

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

stator frequency $(f) = \frac{N_s \cdot P}{120}$ — (I)

Rotor frequency $(F_r) = \frac{P(N_s - N_r)}{120}$ — (II)

Dividing eqn (II) by (I)

$$\frac{F_r}{F} = \frac{\frac{P(N_s - N_r)}{120}}{\frac{N_s \cdot P}{120}}$$

$$\frac{F_r}{F} = \frac{N_s - N_r}{N_s} \quad \left[\because \frac{N_s - N_r}{N_s} = s\right]$$

$$\frac{F_r}{F} = s$$

$$\therefore F_r = S \cdot F$$

Note :-

Rotor frequency becomes slip times of stator frequency.

Q. A 3-ϕ, 4-pole 50 Hz IM run at 1425 rpm than find the rotor frequency :-

Solution:

$N_s = 1500$ rpm

$N_r = 1425$ rpm

$\therefore s = \frac{N_s - N_r}{N_s} = \frac{1500 - 1425}{1500}$

$= \frac{75}{1500} = \frac{1}{20}$

$\therefore F_r = s \cdot F$

$= \frac{1}{20} \times 50$

$\boxed{F_r = 2.5 \text{ Hz}}$

Q. A 3-ϕ, 4 pole 50 Hz I.M has rotor frequency of 2 Hz, find rotor speed.

⇒ $\because F_r = sF$, $N_r = ?$

$N_s = 1500$ rpm.

$F_r = 2$ Hz

$F_r = sF$

$s = \frac{F_r}{F} = \frac{2}{50}$

$\therefore N_r = N_s(1 - s)$

$= 1500\left(1 - \frac{2}{50}\right)$

$$= \cancel{1500}^{30} \left(\frac{50-2}{\cancel{50}} \right)$$

$$= 30 \times 48$$

$$\boxed{N_r = 1440 \text{ rpm}}$$

(ii) Effect on rotor EMF

Induced EMF in rotor

$$\boxed{E_2 = \sqrt{2}\,\pi f \phi_m N_{ph} \cdot K_W}$$

where,
N_{ph} = No. of turns per phase
K_W = Winding factor

$$\boxed{E_2 \propto f}$$

$$\boxed{E_2' \propto sf}$$

$$\frac{E_2'}{E_2} = \frac{sf}{f}$$

where,
E_2 = EMF on standstill cond^n
E_2' = EMF on running cond^n

$$\boxed{E_2' = s \cdot E_2}$$

→ Rotor EMF becomes slip times of stator EMF.

(iii) Effect on rotor reactance

$$\boxed{X_2 = \omega L = 2\pi f L}$$

$$X_2 \propto f$$

$$\boxed{X_2' \propto sf}$$

$$\frac{X_2'}{X_2} = \frac{sf}{f}$$

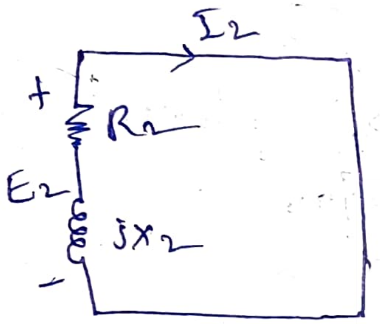
$$\boxed{X_2' = sX_2}$$

→ Rotor reactance becomes slip times of stator reactance.

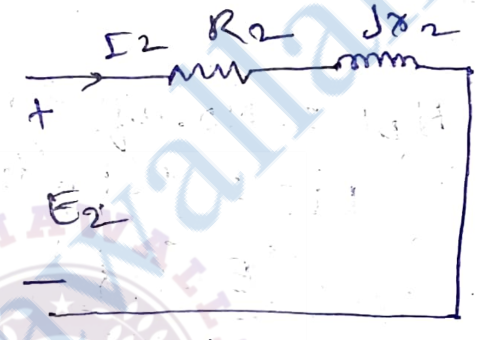
(iv) **Effect on rotor resistance**

No effect because rotor resistance does not depends on frequency.

(v) **Effect on rotor current of motor & rotor power factor.**



⇒



per-phase equivalent circuit of rotor.

starting condition

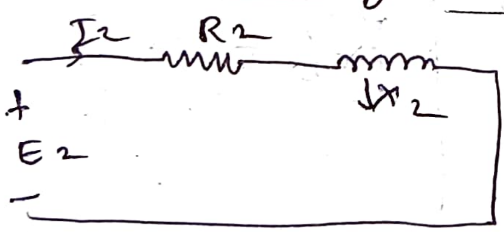
E_2 = Per phase EMF

R_2 = per phase resistance

X_2 = Per phase reactance

I_2 = Per phase current

starting → Standstill



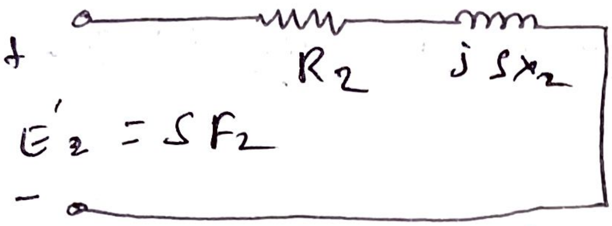
rotor current at standstill

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

Rotor Power Factor

$$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

At running condition



$$\text{rotor current } I_2' = \frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$$

Rotor power factor,

$$\cos\phi_2' = \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$$

Torque Calculations

Starting Torque (T_{st})

$$\text{Power} = T_{st} \cdot \omega = 3E_2 I_2 \cos\phi_2$$

$$T_{st} \cdot \frac{2\pi N_s}{60} = 3E_2 \left[\frac{E_2}{\sqrt{(R_2)^2 + (X_2)^2}}\right] \left[\frac{R_2}{\sqrt{(R_2)^2 + (X_2)^2}}\right]$$

$$T_{st} \cdot \frac{2\pi N_s}{60} = 3E_2 \left[\frac{E_2}{\sqrt{(R_2)^2 + (X_2)^2}}\right] \left[\frac{R_2}{\sqrt{(R_2)^2 + (X_2)^2}}\right]$$

$$T_{st} \cdot \frac{2\pi N_s}{60} = \frac{3E_2^2 \cdot R_2}{(R_2)^2 + (X_2)^2}$$

**

$$T_{st} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2 R_2}{(R_2)^2 + (X_2)^2}$$

Where,

$$K = \frac{3 \times 60}{2\pi N_s} \cdot E_2^2$$

$$T_{st} = K \cdot \frac{R_2}{R_2^2 + X_2^2}$$

Condition for maximum starting torque

$$\frac{dT_{st}}{dR_2} = 0$$

$$K \cdot \frac{d}{dR_2}\left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

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

$$\frac{K\left(R_2^2 + X_2^2 - 2R_2^2\right)}{R_2^2 + X_2^2} = 0$$

$$K\left(X_2^2 - R_2^2\right) = 0$$

$$R_2^2 = X_2^2$$

$$\therefore R_2 = X_2$$

⇒ Value of max^n starting torque

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2 X_2}{X_2^2 + X_2^2}$$

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2 \times X_2}{2 X_2^2}$$

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2}{2X_2}$$

Imp Point

(i) $$T_{st} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

(ii) Cond^n for maximum starting torque

$$E_2 = X_2$$

(iii) Value of maximum torque

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2}{2X_2}$$

Note:-
Maximum torque does not depends upon rotor resistance

$$T_{max} \neq f(R_2)$$

(iv) Power factor at maximum starting torque

$$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

At maximum torque

$$R_2 = X_2$$

$$\cos\phi_2 = \frac{X_2}{\sqrt{X_2^2 + X_2^2}} = \frac{X_2}{\sqrt{2}\, X_2} = \frac{1}{\sqrt{2}}$$

~~$$\cos\phi_2 = \frac{X_2}{\sqrt{X_2^2 + X_2^2}} = \frac{X_2}{\sqrt{\ }}$$~~

$$\cos\phi_2 = \frac{1}{\sqrt{2}} = 0.707 \text{ lagging}$$

Running torque or full load torque

$$\text{Power} = T_{F1}\cdot\omega = 3E_2' I_2' \cos\phi_2'$$

$$T_{F1}\frac{2\pi(N_s - N_r)}{60} = \frac{3\,sE_2\cdot sE_2}{\sqrt{R_2^2+(sX_2)^2}}\cdot\frac{R_2}{\sqrt{R_2^2+(sX_2)^2}}$$

$$\therefore N_s - N_r = sN_s$$

$$T_{Fl}\cdot\frac{2\pi N_s s}{60} = 3sE_2\cdot\frac{sE_2\cdot R_2}{R_2^2+sX_2^2}$$

$$T_{Fl} = \frac{3\times 60}{2\pi N_s}\cdot\frac{sE_2^2 R_2}{R_2^2+sX_2^2}$$

****

$$T_{Fl} = \frac{3\times 60}{2\pi N_s}\cdot\frac{sE_2^2 R_2}{R_2^2+(sX_2)^2}$$

$$T_{Fl} = K\cdot\frac{sR_2}{R_2^2+(sX_2)^2}$$

$$\text{where, } K = \frac{sR_2}{(R_2)^2+(sX_2)^2}$$

Condition for maximum full load torque

$$s\cdot\frac{d}{dR_2}\left[\frac{R_2}{R_2^2+(sX_2)^2}\right] = 0$$

$$\Rightarrow s\left[\frac{R_2^2+(sX_2)^2\cdot 1 - R_2(2R_2+0)}{R_2^2+(sX_2)^2}\right] = 0$$

$\Rightarrow R_2^2 + (sX_2)^2 - 2R_2^2 = 0$

$\Rightarrow (sX_2)^2 - R_2^2 = 0$

$\Rightarrow (sX_2)^2 = (R_2)^2$

$$\therefore R_2 = sX_2$$

Note: For maximum full load torque the rotor resistance must be equall to the slip times of rotor resistance.

$\Rightarrow$ Value of maximum full load torque

$$T_{max} = \frac{3 \times 60}{2\pi N_s} = \frac{s(E_2)^2 \cdot sX_2}{(sX_2)^2 + (sX_2)^2}$$

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \frac{s^2 E_2^2 \cdot X_2}{2 s^2 X_2^2}$$

**

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \frac{E_2^2}{2X_2}$$

Starting	Running
(i) $T_{st} = \frac{3 \times 60}{2\pi N_s} \frac{E_2^2 R_2}{(R_2)^2 + (X_2)^2}$	(i) $T_{FL} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2}$
(ii) Condition for T_{max}: $R_2 = X_2$	(ii) Condition for T_{max}: $R_2 = sX_2$
(iii) $T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2}{2X_2}$	(iii) $\frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2}{2X_2}$
(iv) Rotor power factor: $\cos\phi_2 = \frac{1}{\sqrt{2}}$ lagging	(iv) Rotor power factor

Imp points

(i) Tmax does not depends on rotor resistance

(ii) Slip at which Tmax occur depends on R_2.

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

(iii) **Ratio of starting torque**

$$T_{st} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2 R_2}{(R_2^2 + X_2^2)}$$

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2}{2X_2}$$

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

$$\frac{T_{st}}{T_{max}} = \frac{2R_2X_2}{(R_2)^2 + (X_2)^2}$$

$$\frac{T_{st}}{T_{max}} = \frac{2R_2X_2}{X_2^2\left[\frac{R_2^2}{X_2^2} + 1\right]}$$

$$\frac{T_{st}}{T_{max}} = \frac{\frac{2R_2}{X_2}}{\left[\frac{R_2^2}{X_2^2} + 1\right]} \quad \left[\because s = \frac{R_2}{X_2}\right]$$

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$$\frac{T_{st}}{T_{max}} = \frac{2s}{1+s^2}$$

Ratio of full load torque to maximum torque

$$T_{Fl} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

$$T_{max} = \frac{3 \times 60}{2\pi N_s} \cdot \frac{E_2^2}{2 X_2}$$

$$\frac{T_{Fl}}{T_{max}} = \frac{2 s R_2 X_2}{(R_2)^2 + (s X_2)^2}$$

$$\frac{T_{Fl}}{T_{max}} = \frac{2 s R_2 X_2}{X_2^2 \left[\left(\frac{R_2}{X_2}\right)^2 + s^2 \right]}$$

$$\because s_m = \frac{R_2}{X_2}$$

$$\frac{T_{Fl}}{T_{max}} = \frac{2 s R_2 / X_2}{\left[\left(\frac{R_2}{X_2}\right)^2 + s^2 \right]}$$

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$$\frac{T_{Fl}}{T_{max}} = \frac{2 s s_m}{s^2 + (s_m)^2}$$

Important points

$$\frac{T_{st}}{T_{max}} = \frac{2 s}{1 + s^2}$$

$$\frac{T_{Fl}}{T_{max}} = \frac{2 s s_m}{s^2 + s_m^2}$$

Ex- In a 3-φ I.M the max^n torque is 20 % of starting torque, then find the slip at which maximum torque occurs.

=> Given

$T_{max} = 2 \cdot T_{st}$

$$\boxed{\frac{T_{st}}{T_{max}} = \frac{1}{2}}$$

$$\therefore \frac{T_{st}}{T_{max}} = \frac{2s}{1+s^2}$$

$$\frac{1}{2} = \frac{2S_m}{1+S_m^2}$$

$$\boxed{S_m^2 - 4S_m + 1 = 0}$$

$$S_m = \frac{-b \pm \sqrt{D}}{2a}$$

$$S_m = \frac{4 \pm \sqrt{16-4}}{6 \times 1}$$

$$S_m = \frac{4 \pm \sqrt{12}}{2}$$

$$S_m = \frac{4 \pm 2\sqrt{3}}{2}$$

$$S_m = 2 \pm \sqrt{3}$$

$S_m = 2 + 1.732$

$S_m = 2 - 1.732$

$S_m = 3.732$ → Invalid | $S = 0.268$ → valid

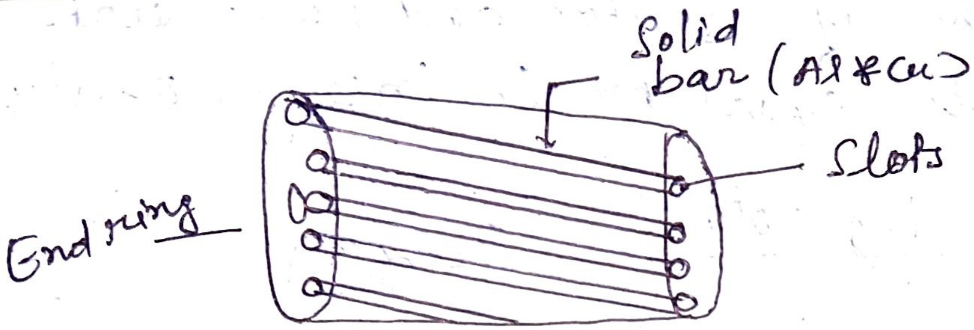
$S_m = 0.268$ Ans

Types of Rotors - Two types of rotor

(i) Squarell cage rotor

(ii) Slip ring rotor or wound rotor.

(1) Squirrel Cage rotor



Imp. point

(i) It is a cylindrical shape structure having slots on its outer peripheral.

(ii) In these slots solid bars are used. which is made-up of copper aluminium

Al → Small rating machine

Cu → large rating machine

→ In this there is no winding on rotor hence we cannot change rotor resistance

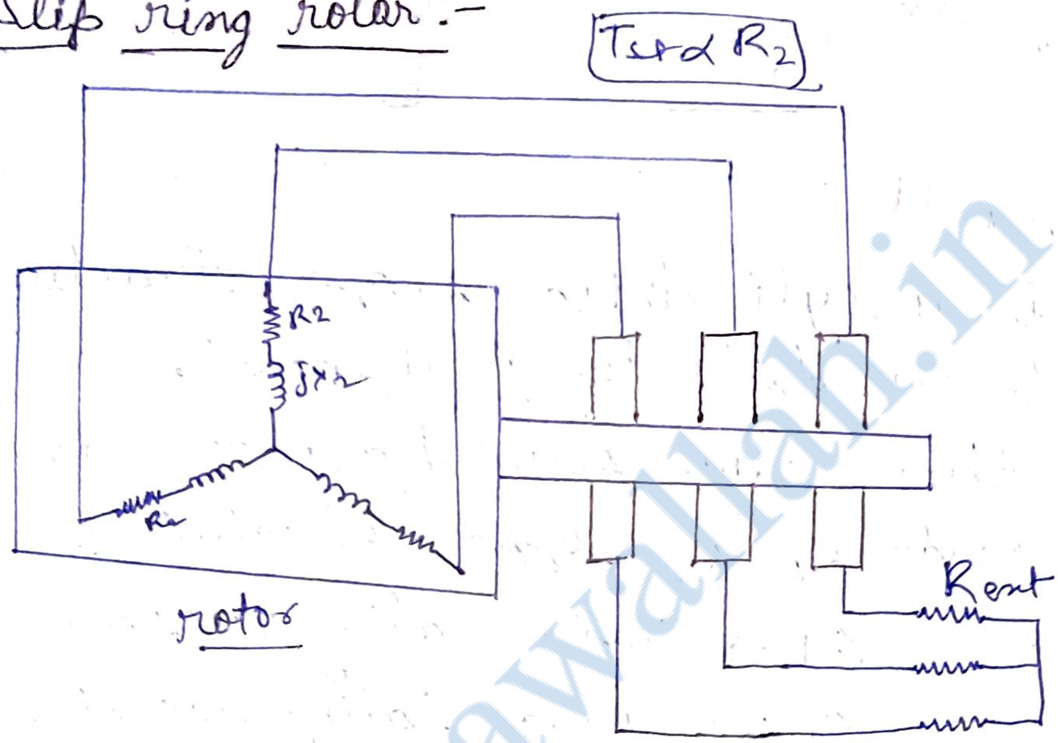
→ This is used for low starting torque application.

→ These solid bar are short circuited with the help of end ring, and it is also made-up of same material.

→ In this rotor the slots are slightly skewed (bending) in order to avoid the tendency of magnetic locking between stator and rotor teeth (cogging).

⇒ To avoid the logging problem the number of stator and rotor slots should not be equal or in integral multiple.

② Slip ring rotor :-



→ In this rotor the rotor winding is essentially star connected.

→ In this rotor with the help of three slip ring and external resistance is connected in series with rotor.

→ This rotor is used in high starting torque application.

→ The slip rings are made-up of phosphor Bronze or Graphite.

→ In order to disconnect the external resistance at running condition metal colour arangement is used.

The value of slip at which maximum torque occurs (S_m).

at maximum torque

$$R_2 = S X_2$$

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

The maximum torque does not depends on rotor resistance but the slip at which maximum torque occurs is depends on rotor resistance.

→ If the induction motor start with its maximum starting torque then

$$S_m = 1$$

→ In case of SRIM (Slip ring I.M.) if an external resistance ~~& reactance~~ is connected in series with rotor than

$$S_m = \frac{R_2 + R_{ext}}{X_2}$$

Q: A 3-φ, 4 pole, 50 Hz I.m. has standstill Impedance of (3+j5) Ω, then find the speed at which I.m. develop its maximum torque.

$$S_m = \frac{R_2}{X_2} = \frac{3}{5} = 0.6$$

⇒

$N_s = 1500$ rpm

$R_2 = 3\ \Omega$

$X_2 = 5\ \Omega$

$N_m = ?$

$$S_m = \frac{N_s - N_m}{N_s}$$

$$0.6 = \frac{1500 - N_m}{1500}$$

$900 = 1500 - N_m$

$N_m = 1500 - 900$

$N_m = 600$ rpm

Q: If a 3φ, 6 pole, 50 Hz I.m. has rotor resistance of 4 Ω and it develops it maximum torque at 400 rpm, than find the value of rotor reactance.

Solve

$N_s = 1000$ rpm

$R_2 = 4\ \Omega$

N_r ~~Tmax~~ $= 400$ rpm.

$X_2 = ?$

$$S_m = \frac{N_s - N_r}{N_s} = \frac{1000 - 400}{1000}$$

$$= \frac{600}{1000} = 0.6$$

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

$$0.6 = \frac{4}{X_2}$$

$$X_2 = \frac{4}{0.6}$$

$$X_2 = 6.67\ \Omega$$ Ans

Qn A 3-ϕ, 4 pole, 50 Hz I.M. develops its maximum torque of 100 N.m at 600 rpm than find starting torque.

Solve: Given:-

$N_s = 1500$ rpm.

$T_{max} = 100$ Nm

$N_{Tm} = 600$ rpm

$T_{st} = ?$

$$\Rightarrow S_m = \frac{1500 - 600}{1500} = \frac{900}{1500} = \frac{3}{5}$$

$$\therefore \frac{T_{st}}{T_{max}} = \frac{2 S_m}{1 + S_m^2} \Rightarrow \frac{T_{st}}{100} = \frac{2 \times \frac{3}{5}}{1 + \left(\frac{3}{5}\right)^2}$$

$$\Rightarrow T_{st} = \frac{2 \times \frac{3}{5} \times 100}{1 + \frac{9}{25}} = \frac{\frac{6}{5} \times 100}{\frac{34}{25}}$$

$$= \frac{600}{5} \times \frac{25}{34} = \frac{3000}{34}\ \text{Nm.}$$

$$\boxed{T_{st} = \frac{3000}{34}\ \text{Nm.}}$$

Torque slip characteristics

running cond^n

$s = 1\%$ to 5%

$= 0.01$ to 0.05

Starting cond^n

$N_r = 0$, $s = \frac{N_s - N_r}{N_s} = 1$

Case-I **Low slip region ($s = 1\%$ to 5%)**

$$T = \frac{3 \times 60}{2\pi N_s} \cdot \frac{3 E_2^2 \cdot R_2}{R_2^2 + (s x_2)^2}$$

$$R_2^2 >>> (s x_2)^2$$

$(s x_2)^2$ ← Neglect

$$T = \frac{3 \times 60}{2\pi N_s} \cdot \frac{s E_2^2 \cdot R_2}{R_2^2}$$

$$T = \frac{3 \times 60}{2\pi N_s} \cdot \frac{s E_2^2}{R_2}$$

$T \propto s$

at low slip region torque slip char. is a straight line (linear).

$R_2 = 2\Omega$,
$x_2 = 10\Omega$
$s = 0.9$
$(s x_2)^2 = (0.9 \times 10)^2 = 81$

Case-II **High slip region**

$$T = \frac{3 \times 60}{2\pi N_s} \cdot \frac{s E_2^2 \cdot R_2}{R_2^2 + (s x_2)^2}$$

at high slip

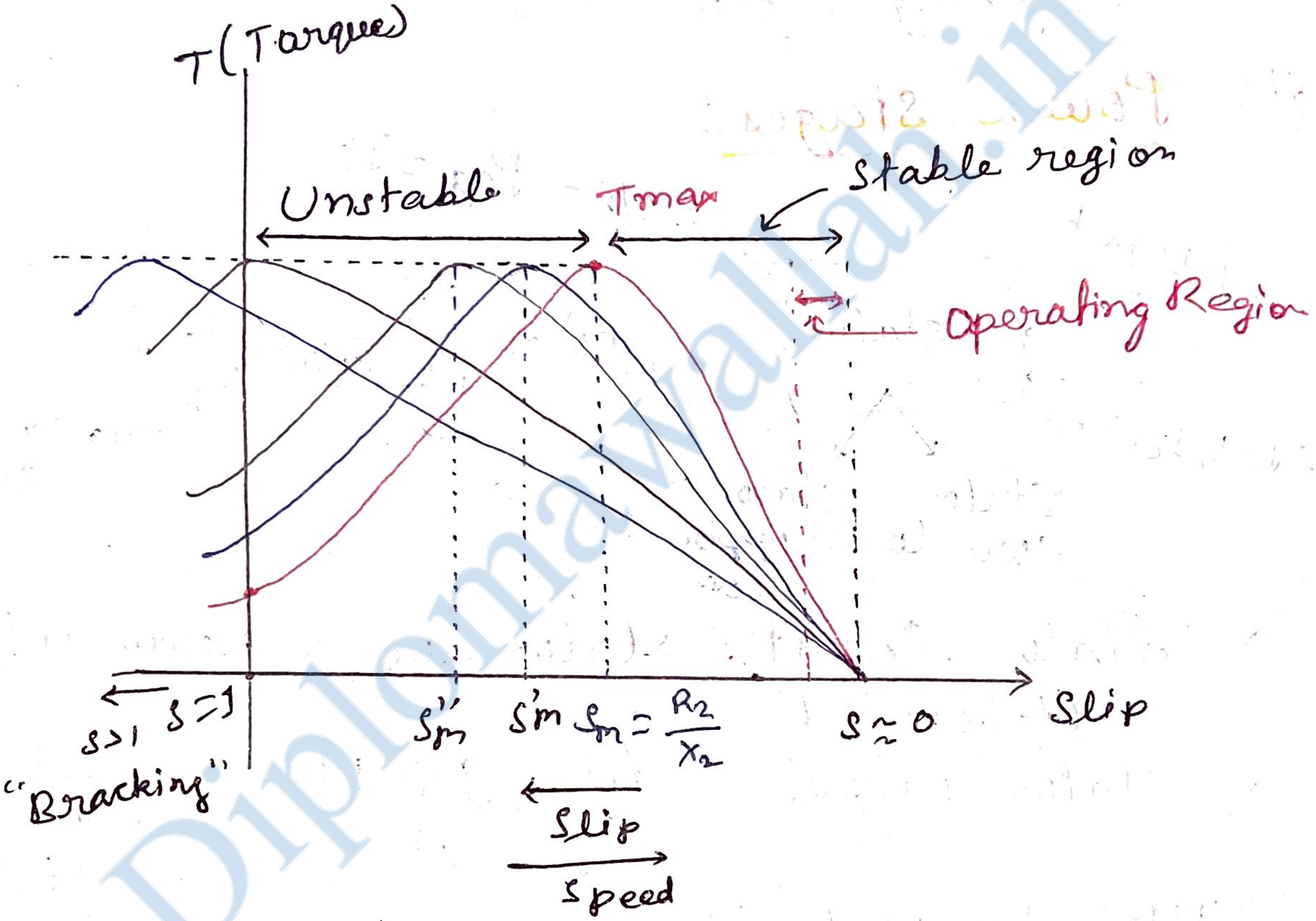
$$(s x_2)^2 >>>> R_2^2$$

R_2^2 ← Neglect

$$T = \frac{3 \times 60}{2\pi N_S} \cdot \frac{S E_2^2 R_2}{(S X_2)^2}$$

$$T = \frac{3 \times 60}{2\pi N_S} = \frac{E_2^2 \cdot R_2}{S X_2^2}$$

$$\boxed{T \propto \frac{1}{S}}$$



Imp. point

① If the load is increases than torque will also increases & I.M. will develop its maximum torque & if we increase load further than motor will stopped.

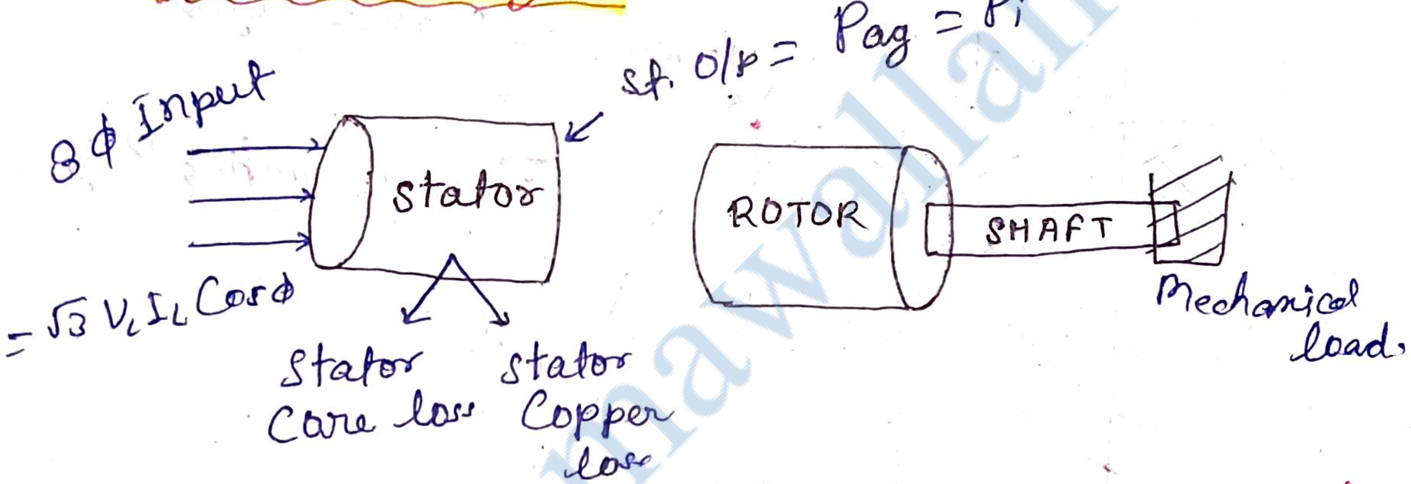
② In I.M. operating region is stable region But its opposite is not true.

→ If rotor resistance increases than starting torque will first increase & than Decreases.

→ For motoring region $0 < s < 1$

Breaking region $s > 1$

Power stages :-



→ Stator input − Stator loss = Stator output
($\sqrt{3} V_L I_L \cos\phi$)

→ Stator output = Air gap power = rotor power I/p
(P_{ag}) (P_i)

NOTE:- In Induction motor rotor core loss will not present because rotor freq. & EMF is negligible ($f_r = sf$, $E_2' = sE_2$)

→ Rotar input − rotor copper loss = rotor output
(P_i) (R.C.L.) (P_o)

→ Rotor power output = Mechanical power developed (P_{md})

→ Rotor power output − mechanical loss = shaft power output (P_{sh})

→ Efficiency (η) = $\dfrac{P_{sh}}{\sqrt{3} V_L I_L \cos\phi}$

⇒ Rotor power input (P_i) = $T_g \cdot \omega$ where T_g = generated torque

$P_i = T_g \cdot \dfrac{2\pi N_s}{60}$

⇒ Rotor power output $P_o = T_g \cdot \omega$

$= T_g \cdot \dfrac{2\pi N_r}{60}$

∴ rotor input − R.C.L. = rotor output (P_o) ①

R.C.L. $= P_i - P_o$

$= T_g \cdot \dfrac{2\pi N_s}{60} - T_g \cdot \dfrac{2\pi N_r}{60}$

$= T_g \cdot \dfrac{2\pi}{60}(N_s - N_r)$

R.C.L $= T_g \cdot \dfrac{2\pi}{60}(s N_s)$

$= s\left[T_g \cdot \dfrac{2\pi N_s}{60}\right]$

V.V.I

R.C.L. = s × Rotor power input (P_i)

by eqⁿ ①

Rotor power input (P_i) – S. rotor power input = rotor power o/p

$$P_i - S.P_i = P_o$$

$$P_i(1-S) = P_o$$

V.V.I

$$\boxed{\frac{P_o}{P_i} = 1-S}$$ → Efficiency.

Q. A 3-ϕ, 4-pole, 50 Hz, I.M. run at 1450 rpm. The power input to motor is 10 kW, stator loss are 1 kW & mechanical loss are 800 W, than find.

(i) Air gap power
(ii) Mechanical power developed
(iii) Shaft power o/p
(iv) Efficiency.

Solu- Given $P = 4$, $f = 50$ Hz, $N_r = 1450$ rpm.

Stator power input = 10 kW,

Stator loss = 1 kW

Mechanical loss = 800 W = 0.8 kW.

$N_s = 1500$ rpm

$$S = \frac{N_s - N_r}{N_s} = \frac{1500 - 1450}{1500} = \frac{50}{1500} = \frac{1}{30}$$

Stator power output = 10 KW − 1 KW

Stator output = 9 KW ← Airgap power

Rotor power input = 9 KW.

→ ∵ R.C.L. = s × rotor power input

$= \frac{1}{3\phi} \times 9000$ (300)

= 300 watt

= 0.3 kW.

→ Rotor power output = P_1 − R.C.L.

= 9 − 0.3 = 8.7 kW.

→ Shaft output = rotor output − Mech. loss

= 8.7 − 0.8

= 7.9 KW

→ Efficiency $\eta = \frac{P_{sh}}{Input} = \frac{7.9}{10} \times 100 = 79\%$

Q. A 3φ 6 pole, 50 Hz I.M. run at 980 rpm, the shaft power output is 20 kW, Mech. loss = 2 kW & stator loss are 1 kW, than find.

(a) Rotor power input

(b) R.C.L

(c) Stator I/p

(d) Efficiency.

⇒ Rotor o/p − Mech. loss = shaft o/p

Rotor o/p = shaft o/p + Mech loss

= 20+2 = 22 kW.

→ $\frac{\text{rotor o/p}}{\text{rotor I/p}} = 1-s$

rotor I/p = $\frac{\text{rotor o/p}}{1-s} = \frac{22}{1-\frac{1}{20}} \Rightarrow \frac{22\times 20}{19} = \frac{440}{19}$

= 23.15 kW

→ Rotor copper loss = s.P_i

$= \frac{1}{20} \times 23.15$

= 1.157 kW.

⇒ Stator I/p = st. output + stator loss

= 23.15 + 1

= 24.15 kW.

⇒ $\eta = \frac{P_{sh}}{\text{stator i/p}} = \frac{20}{24.15} \times 100$

Q. A 3ϕ, 8 pole, 50 Hz, I.M. run at 700 rpm & develop at shaft torque at 100 N.m, the torque lost in friction is 10 N.m. & stator loss are 500 watt, than find -

(i) rotor o/p

(ii) R.C.L.

(iii) rotor power I/p

(iv) Efficiency.

Solve:- Given:-

$P = 8, \; f = 50\,Hz, \; N_r = 700\ rpm, \; N_s = \frac{120f}{P}$

$= \frac{120 \times 50}{8} = 750\ rpm.$

$s = \frac{N_s - N_r}{N_s} = \frac{750 - 700}{750} = \frac{50}{750} = \frac{1}{15}$

$\Rightarrow$ Rotor power output $(P_o) = (100 + 10) \times \frac{2\pi \times 700}{60}$

$= \frac{110 \times 2\pi \times 700}{60} = 8.063\ kW.$

$\Rightarrow \frac{P_o}{P_i} = 1 - s$

$P_i = \frac{P_o}{1-s} = \frac{8.063}{1 - \frac{1}{15}} \Rightarrow \frac{8.063 \times 15}{14}$

$\Rightarrow$ R.C.L. $= s \cdot P_{i/p}$

$= \frac{1}{15} \times \frac{8.063 \times 15}{14} = 0.576\ kW.$

$\rightarrow$ Stator i/p $= \frac{8.063 \times 15}{14} + 0.5$

$= 9.139\ kW$

$\rightarrow$ Efficiency $= \frac{P_{sh}}{\text{stator i/p}} = \frac{7.33}{9.139} \times 100$

$\rightarrow P_{sh} = T_{sh} \cdot \omega$

$= T_{sh} \times \frac{2\pi N_s}{60} = 100 \times \frac{2\pi \times 700}{60}$

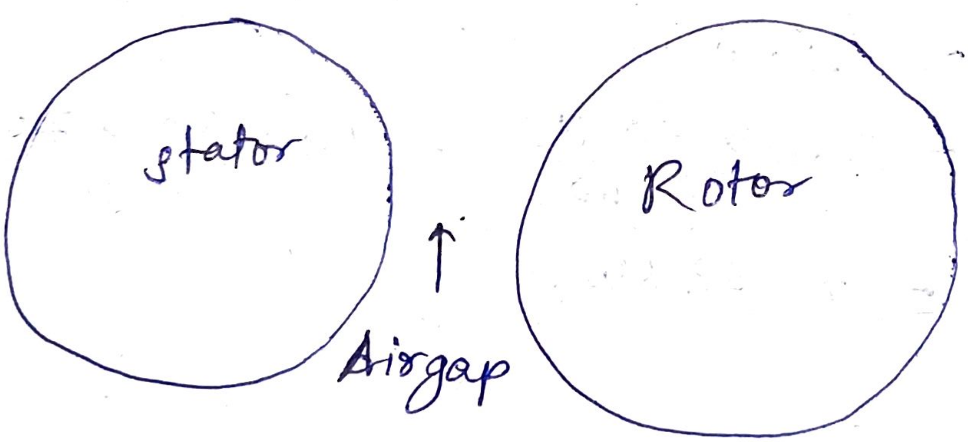
$= 7.33\ kW.$

Effect of change in supply voltage on Starting torque

The starting torque is directly proportional to the square of the supply voltage ($T_s \propto V^2$).

- If Voltage increases:-
  Torque increases rapidly.
  - ex:- If voltage increased by 10%.
    $T_s \propto (1.1)^2 = 1.21$
    so torque increases by 21%
- If voltage decreases:-
  Torque decrease significantly.
- for ex:-
  If voltage drop by 10%.
  $T_s \propto (0.9)^2 = 0.81$
  so torque reduces by 19%.

Equivalent circuit of an Induction motor



NOTE:- If the airgap b/w stator & rotor is increased.

$\downarrow \phi = \frac{MMF}{rel. \uparrow}$ $\uparrow Rel = \frac{\uparrow l}{\mu A}$ ← length of air gap

then magnetizing current will increase & power factor will decrease.

Notations.

E_1 = induced emf in stator per phase

E_2 = Rotor induced emf per phase (on standstill)

$$\left[K = \frac{\text{Rotor turns}}{\text{Stator turns}}\right]$$

$$\left[K = \frac{E_2}{E_1}\right]$$

E_{2r} = Rotor induced emf in Running condn per phase.

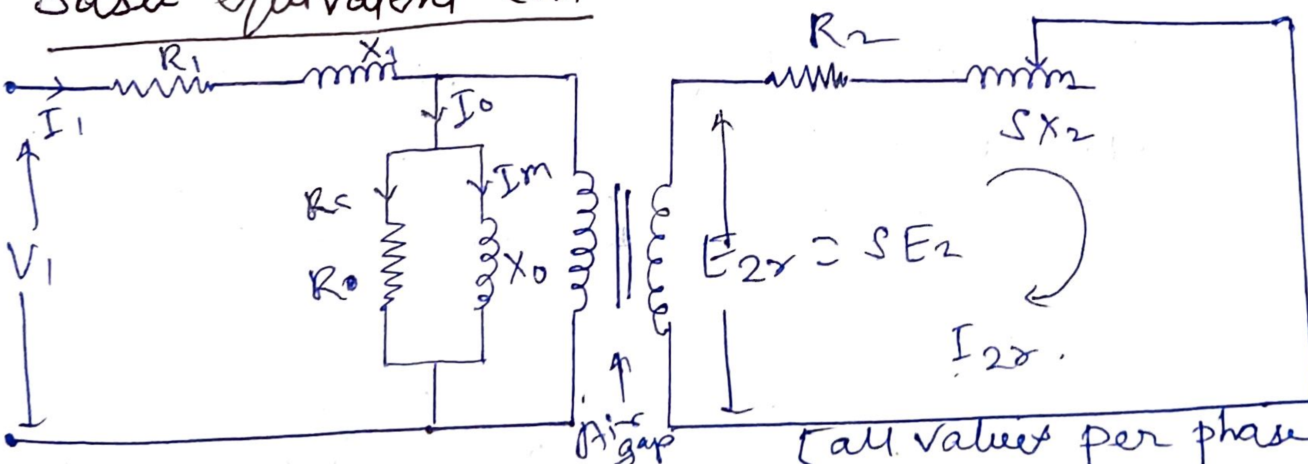
R_2 = Rotor Resistance per phase

X_{2r} = Rotor reactance per phase in running condn

R_1 = Stator resistance per phase

X_1 = Stator reactance per phase

Basic equivalent Ckt



[all values per phase]

I_{2r} = Rotor current in running condition

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

[NOTE :- As load on motor changes, the motor speed changes, Thus slip changes. As slip changes the reactance X_{2r} changes.
· Hence $X_{2r} = sX_2$ is shown variable]

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

[Hence it is assumed that equivalent rotors. ckt in running condition has fixed. Reactance X_2, fixed voltage E_2 but a variable resistance $\frac{R_2}{s}$]

imp.

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

$$= R_2 + R_2\left(\frac{1}{s} - 1\right) = R_2 + R_2\left(\frac{1-s}{s}\right)$$

[so variable rotor resistance $\frac{R_2}{s}$ has 2 parts.]

1. Rotor resistance R_2 itself which represent copper loss.
2. $R_2\frac{(1-s)}{s}$ which represent load resistance R_2.

so it is electrical equivalent of mechanical

Testing of Induction motor

→ There are two methods:

ⓐ No load test

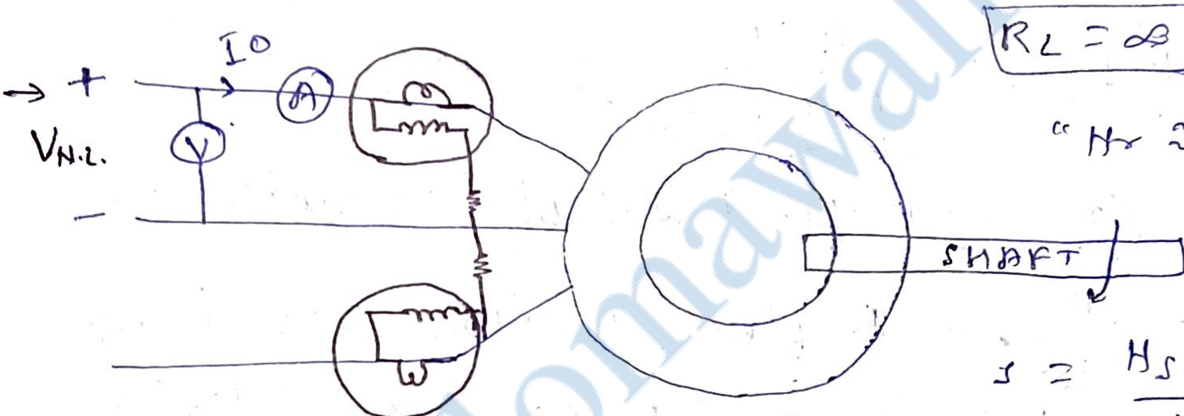
ⓑ Blocked rotor test.

① **No load test:-** In this test there is no load is connected to shaft But shaft is freely rotate.

$R_L = R_2\left(\frac{1}{s} - 1\right)$

$R_L = \infty$ → open ckt.

" $N_r \simeq N_s$ "



No load

$s = \frac{N_s - N_r}{N_s}$

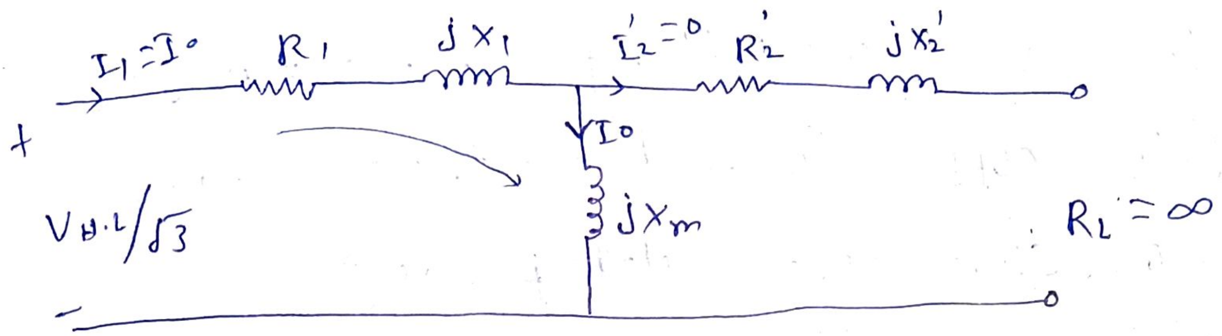
$s \simeq 0$

→ This test is performed at a rated voltage & rated frequency.

→ In this No load current will flow from stator side which is $I_0 = (30\% \text{ to } 40\%)$ of rated current.

→ In this test for power measurement two wattmeter method is used.

→ In this test the P.F. is highly lagging (0.1)



- Stator core loss = Present (Because V & f → rated)
- Stator copper " = Present (Because $I_0 = 30\%$ to 40%)
- rotor core loss = Not present ($E_2' = sE_2$, $f_r = sf$ & $s \approx 0$)
- rotor copper loss = Not present ($I_2 = 0$)
- Mechanical loss = Present (shaft rotate)

② Blocked rotor test :-

→ In this test the shaft will not rotate

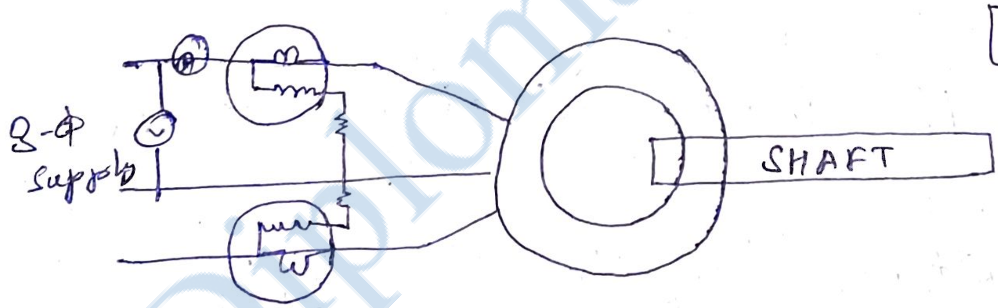
$R_L = R_2\left(\frac{1}{s} - 1\right)$

$R_L = 0$ short circuit

will not rotate

"$N_r = 0$"

$s = 1$



→ This test is equivalent to short circuit test of T/F

→ This test is performed at a reduced voltage & freq. & rated current will flow.

(i) Stator core loss → Not present (V & F reduced)
(ii) Stator copper loss → Present (I → rated)
(iii) rotor core loss → Not present
(iv) rotor copper loss → Present (I → rated)
(v) Mechanical loss → Not present (shaft will not rotate)

Necessity of starters :-

When an induction motor is started directly ~~by~~ by connecting it to the full supply voltage, it draws a very high starting current (5 to 7 times full load current).

This high current can:

- Damage the motor winding due to overheating
- Cause voltage drop in the supply system
- Disturb other equipment connected to the same supply.

Therefore, starters are required to :-

- Limit the starting current
- Provide smooth acceleration
- Offer motor protection (against

overload, phase failure, etc.)

Types of starter OR starting method

1. Direct On - Line Starter
2. Stator resistance starter
3. Auto Transformer starter
4. Star-Delta starter
5. Rotor resistance starter.

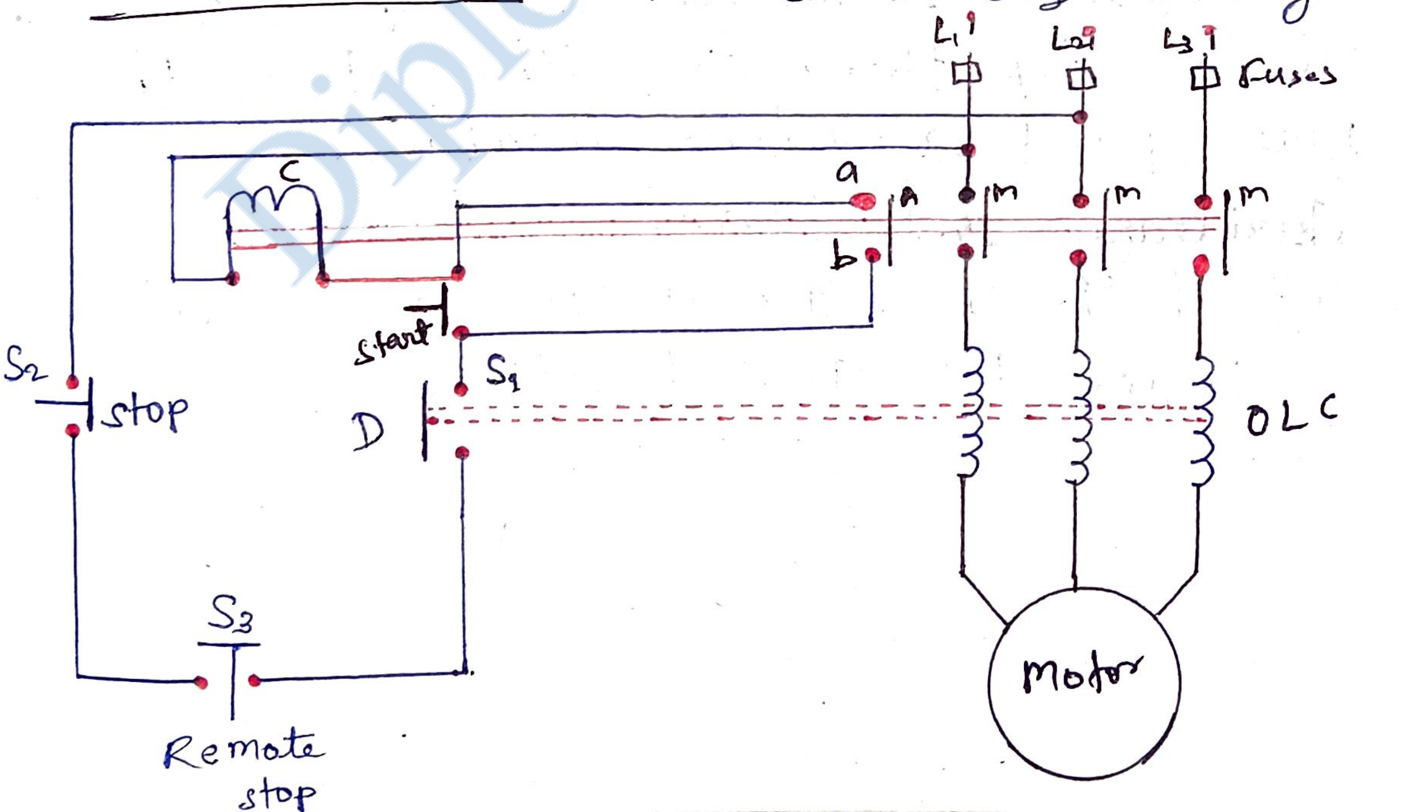
1. DOL Starter:-

→ A DOL starter is the simplest and most commonly used starter for starting squirrel cage induction motors.

→ It directly connects the motor terminals to the full supply voltage.

∘ This method is not a reduced voltage starting method.

Construction :-



1. Three - Phase supply (L_1, L_2, L_3) :-
It provides the electrical power to the motor.

2. Fuses: These protects the circuit from short - circuits and overcurrent.

3. Contactor (C) :-
An electromagnetic switch that connects or disconnects the power to the motor.

4. Overload Relay (OLC) :-
It protects the motor from overloading. if current exceeds the limit, it trips the circuit.

5. Start Button (S_1) :-
A Push - button switch used to start the motor.

6. Stop Button (S_2) and Remote stop (S_3) :-
Used to stop the motor either from the main panel or remote location.

7. Auxiliary contact (a) :-
It holds the circuit ON even after releasing the start button.

Working :-

→ When the start button (S_1) is pressed, current flows through the stop button (S_2), Remote stop (S_3), and energizes the contactor coil (C).

→ The contactor closes its main contacts (M), and the 3-phase supply is given directly to the motor.

→ At the same time, an auxiliary contact (a) closes and keeps the contactor coil energized even after the button is released. This is called the "holding circuit."

→ The motor continues to run untill :

- The stop button (S_2) or Remote stop (S_3) is pressed, or
- The motor draws overload current, which activates the Overload Relay (OLC) and opens the circuit.

→ Once the coil is de-energized, the contactor opens and the motor stops.

Advantages :-

- Simple design
- Low cost
- Easy to operate

Disadvantages:-

- High inrush current
- Not suitable for large motors due to voltage dip and torque shock to mechanical load.

Troubleshooting of starter

1. Motor does not start

- Cause:-
  - No power supply (main switch off or fuse blown)
  - Faulty start button (S1)
  - Contactor coil is damaged.
- Solution:-
  - Check and ensure 3-phase supply is available
  - Check the fuse and replace if blown
  - Check start push button with a multimeter
  - Test the contactor coil and replace if faulty.

2. Motor starts but stops immediately

- Cause:-
  - Holding contact (auxiliary contact 'a') is not working
  - Loose wiring
  - Overload relay tripped.

Solution:-

- → Check the auxiliary contact and wiring.
- → Tighten all terminal connections
- → Reset the overload relay

3. Contactor makes noise or vibrates

· Cause:-

- → Low voltage supply
- → Coil is not getting enough power
- → Contactor armature is dirty or struck

Solution:-

- → Check supply voltage
- → Clean and adjust the contactor
- → Replace coil if necessary.

4. Overload Relay trips frequently

Cause:-

- · Motor is overloaded
- · Motor bearings jammed or faulty
- · Wrong setting of overload relay

Solution:-

- · Reduce motor load
- · Check motor for mechanical faults
- · Set the ~~ovet~~ overload relay properly (as per motor current).

5. Motor runs in reverse direction

Cause:-
- Any two supply phases (L_1, L_2, L_3) are reversed.

Solution:-
Swap any two phases to correct the direction.

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

$$T_{Fl} \propto \frac{I_{Fl}^2}{S_{Fl}}$$

$$\frac{T_{st}}{T_{Fl}} = \left(\frac{I_{st}}{I_{Fl}}\right)^2 \cdot S_{Fl}$$

Q. In a 3-ϕ Induction motor the starting current is 8 times the full load current & full load slip is 5% than find the ratio of starting torque to full load torque

$$\frac{T_{st}}{T_{Fl}} = \left(\frac{I_{st}}{I_{Fl}}\right)^2 \cdot S_{Fl}$$

$$= (8)^2 \times 0.05 \Rightarrow 64 \times 0.05$$

$$\Rightarrow 3.2 \text{ Ans}$$

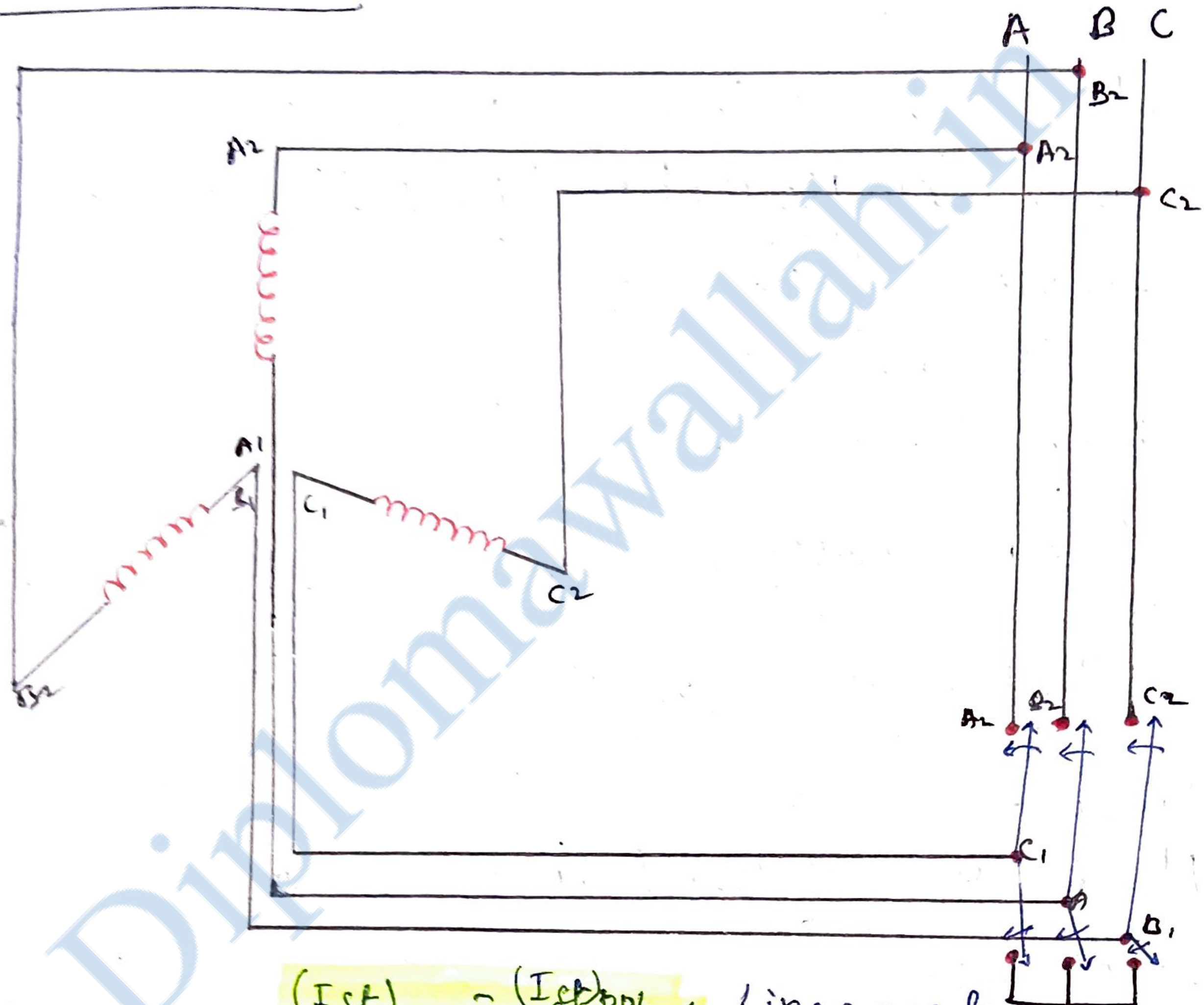
Star-Delta Starter

→ It is a reduced voltage starting method.

→ In this method TPDT switch is used

→ Most widely used method.

Construction:-



$(I_{st})_{Y-\Delta} = \frac{(I_{st})_{DOL}}{3}$ ← Line current

$(I_{st})_{Y-\Delta} = \frac{(I_{st})_{DOL}}{\sqrt{3}}$ ← Phase current

Working:-

- **Starting (star connection)**

→ When the motor starts, the star contactor and main contactor close.

→ The motor windings are connected in a star configuration (low voltage across each winding).

→ This reduces the starting current and torque.

- Running (Delta connection)

→ After a 70 to 80% of the rated speed, the star contactor opens and the delta contactor closes.

→ The motor windings now connect in a delta configuration (full line voltage across each winding).

→ The motor runs at full speed with normal torque.

Troubleshooting of star-delta starter

1. Motor does not start

Cause :-

- No power supply / loose connections

Solutions :-

- Check incoming 3-ϕ supply
- Check MCB, fuses and all wiring
- ~~Check MCB, fu~~
  Tighten loose terminals.

2. Motor starts in star but does not change to Delta

. Cause:-
Faulty timer or delta contactor not working.
. Solution:-
. Check the timer setting and wiring
. Replace or repair the delta contactor
. Ensure proper time delay

3. Overload relay trips Immediately After start

. Cause:-
. Motor overload
. Faulty overload relay
Solution:-
. Check for mechanical load on the motor
. Reset or replace the overload relay
. Ensures correct overload setting.

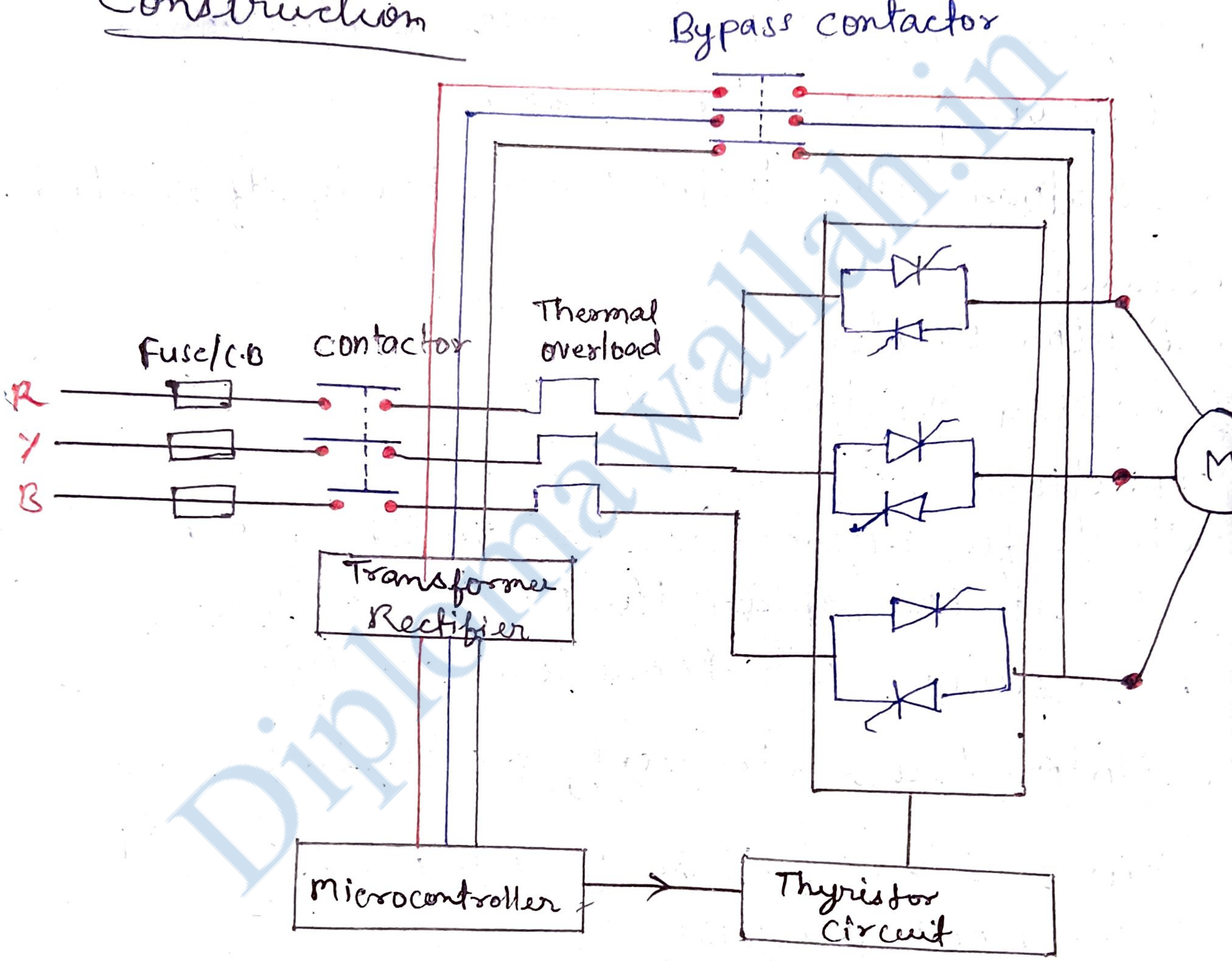
4. Motor Runs Unevenly or vibrates.

. Cause:- Phase failure or one winding not connected properly.
Solution:-
. Check motor terminal connections
. Ensures all three phases are present
. Test motor windings with a multimeter.

③ # Soft Starter :-

- A Soft starter is an electronic device used to start and stop induction motor smoothly by controlling the voltage applied to the motor during startup and shutdown.

Construction



- Power supply Terminals (R, Y, B) :- These are the three-phase input terminals connected to the supply.
- Fuse / Circuit Breaker :- These protect the system from overcurrent or short circuit conditions,
- Contactor :- It allows or disconnects the power to the motor, acting as a main switch.
- Thermal Overload Relay :- Protects the motor from overcurrent due to overload condition
- Thyristor circuit (Back to Back SCR Configuration) :- These are silicon controlled Rectifiers connected in an anti-parallel (back to back) configuration for each phase. ~~Thrys~~ Thryistors control the voltage supplied to the motor by delaying the firing angle during startup.
- Bypass contactor :- After the motor reches full speed, the thyristor is bypassed using this contactor to reduce heat and power losses.
- Transformer & Rectifier :- They convert AC to DC and supply power to the control circuit.

- **Microcontroller:-** It control the firing angle of thyristors, enabling smooth voltage control during motor startup and stopping.

Working:-

- **Startup:** When the motor is started, the microcontroller gradually increases the firing angle of the thyristors, slowly allowing more voltage to pass to the motor. This smoothly ramps up the motor speed, reducing inrush current and mechanical stress.
- **Running:** Once the motor reaches full speed, the bypass contactor is activated. It bypasses the ~~thy~~ thyristors and connects the motor directly to the supply to avoid heating of the SCRs during continuous operation.
- **Stopping:** During stopping, the microcontroller gradually decreases the voltage, allowing for soft stopping of the motor, which is especially useful in applications like pumps to avoid water hammering.

Advantages :-

- Reduces mechanical stress on motor and equipment.
- Limits inrush current during motor startup.
- Provides smooth acceleration and deceleration.
- Increases the lifespan of motor and connected equipment.

Applications :-

→ Pumps, conveyors, Fans & blowers, compressors, HVAC system.

Troubleshooting of soft starter

① Motor does not start :-

Cause – No power supply, faulty SCR; blown fuse

Solution –
Check supply, inspect SCRs, replace fuse.

② Motor starts with high jerk :-

Cause :- Ramp time set too short
Solution – Increase ramp-up time

③ Overheating of soft starter :-

Cause :- Cooling fan not working, high ambient temp.

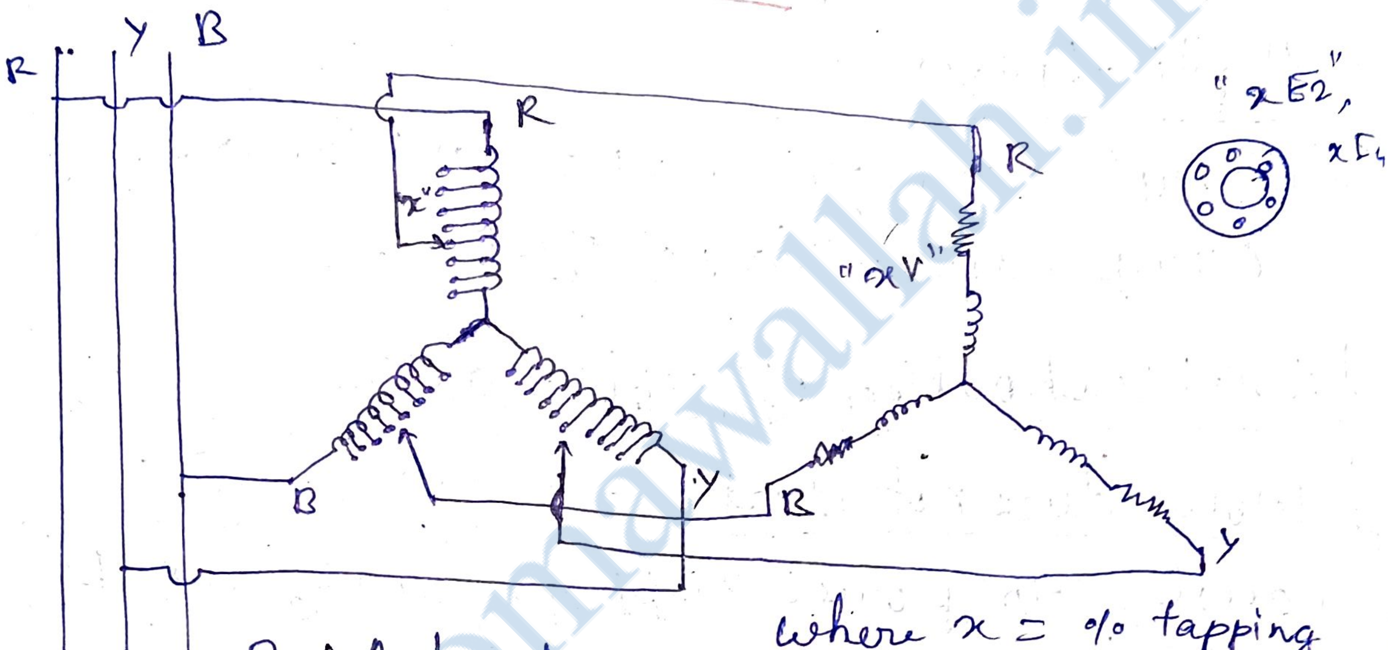
Solu :- Check fan, improve ventilation.

(6) Motor not reaching full speed :-

Cause :- Incorrect voltage setting or load too high.

Solu :- Adjust voltage settings, check motor load

(7) Auto T/F starting



3-ϕ Auto T/F.

where x = % tapping Auto Transformation ratio

$$\frac{T_{st}}{T_{Fl}} = \left[\frac{x I_{st}}{I_{fl}}\right]^2 \cdot S_{Fl}$$

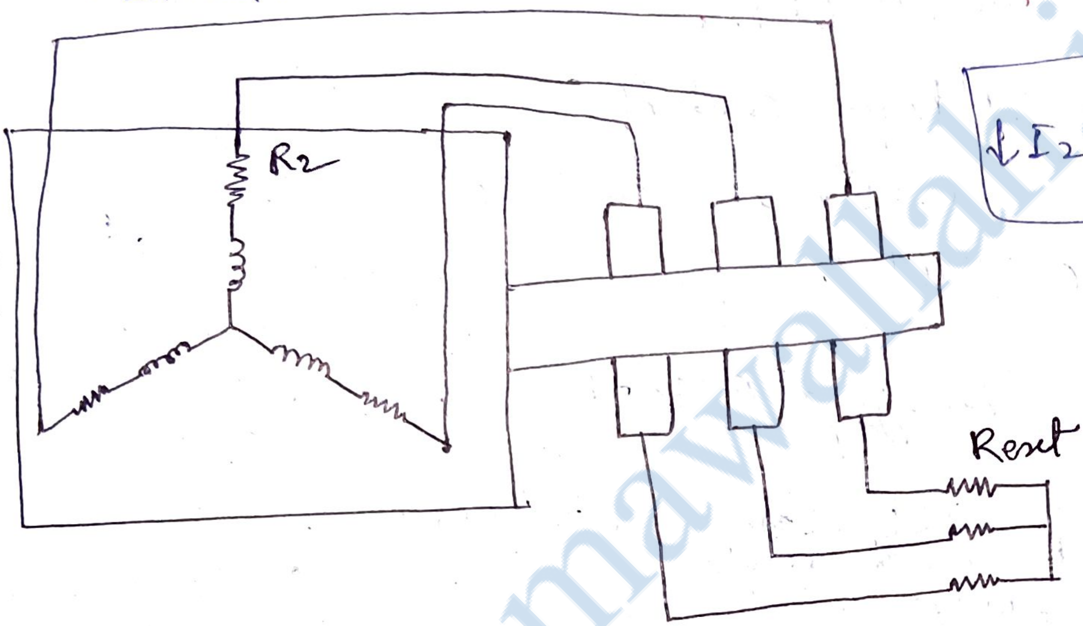
$$\frac{T_{st}}{T_{Fl}} = x^2 \left[\frac{I_{st}}{I_{Fl}}\right]^2 S_{Fl}$$

Note :- If $x = \frac{1}{\sqrt{3}} = (57.7\%)$ than the ratio of starting torque to full load in both star-delta starting method & auto T/F starting method is become equal.

- → It is a reduced voltage starting method
- → Cost is very high.
- → For smooth starting this method is used.

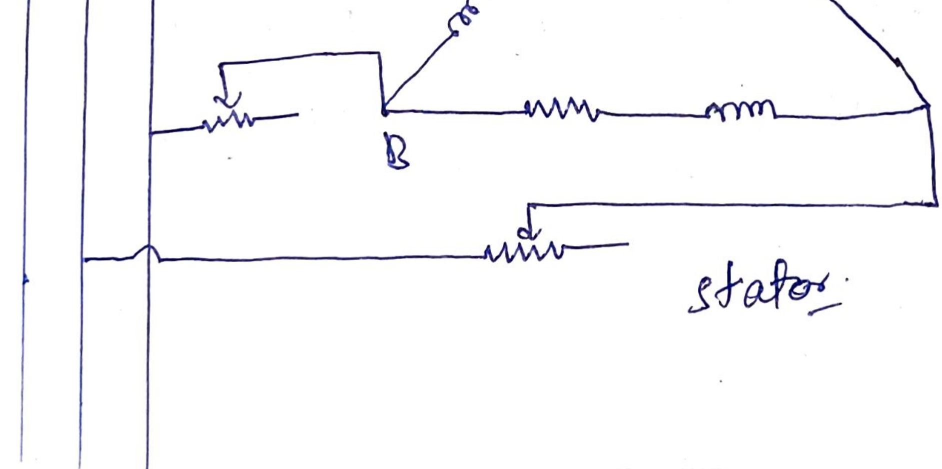
(5) Rotor resistance starting :-

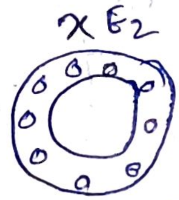
- → It is applicable only for slip ring I.M.
- → This method is not a reduced voltage starting method.



$$\downarrow I_2 = \frac{E_2}{R_2 + jX_2 + R_{ext}\uparrow}$$

(6) Stator Resistance starting method :-





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

$$I'_{st} = \frac{x E_2}{\sqrt{R_2^2 + X_2^2}} = x I_{st}$$

$$\frac{T_{st}}{T_{Fl}} = \left(\frac{x I_{st}}{I_{Fl}}\right)^2 \cdot S_{Fl}$$

$$\boxed{\frac{T_{st}}{T_{Fl}} = x^2 \left(\frac{I_{st}}{I_{Fl}}\right)^2 S_{Fl}}$$

→ This method is reduced voltage starting method.

Speed Control Method

1. Supply voltage control
2. Stator resistance control
3. $\frac{V}{f}$ control or frequency control
4. Pole changing method.

} Both for Squirrel cage & slip ring IM.

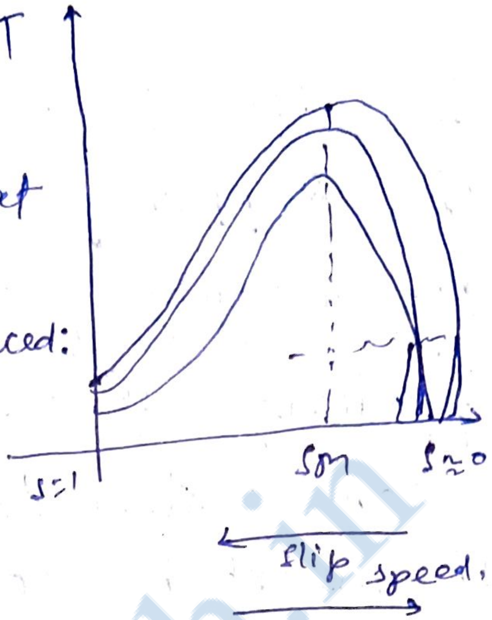
5. Rotor resistance control (Rheostat control method)
6. Slip power recovery
7. Cascading

} only for Slip ring I.M.

1. Supply voltage control

The change of applied voltage method is a speed control technique in which the voltage applied to the stator of an induction motor is varied to control its speed and torque.

$\downarrow T_{max} \propto E_2^2 \propto V^2 \downarrow$



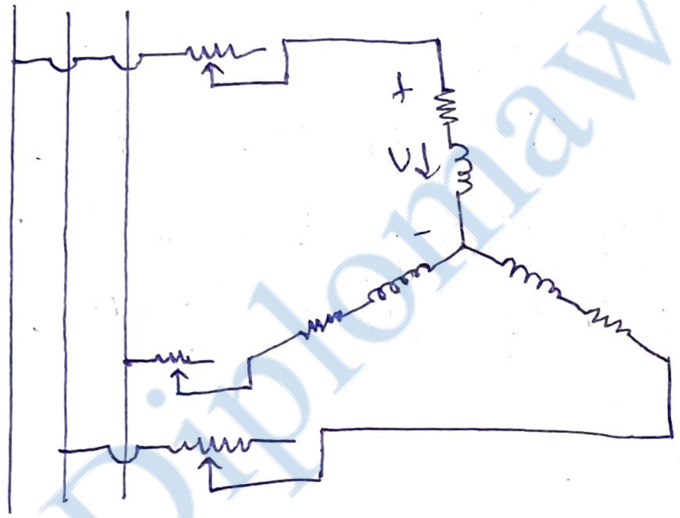
→ when full rated voltage is applied → Motor runs at full speed.

→ When the voltage is reduced: than the torque is also reduced.

→ Speed drops when the motor is lightly loaded.

→ So, by reducing voltage, we can reduce speed.

② Stator resistance control method



→ This method is similar to supply voltage control method.

③ frequency control OR V/f control :-

⇒ The frequency control method is a very effective way to control the speed of an induction motor. This motor works by changing the supply frequency to the motor.