Chapter -5 (10 marks)

a) Describe the working principle of three phase induction generator, Also explain how voltage build up in it. [4+4]

Derive torque developed by a 3-phase induction motor at running condition. Draw a Torque-slip characteristic and deduce the condition for maximum torque? [5+3]

Draw the equivalent circuit diagram of three phase induction motor. Explain how the torque is produced in three phase induction motor. [8]

a) Define slip. Why does the induction motor operates only in the linear portion of torque-slip characteristics? [4]

b) A three phase 6 pole, 50 Hz induction

a) Explain the T-S characteristic of 3-phase induction motor. Explain the effect of rotor resistance on T-S characteristic. [8]

(ii) efficiency [8]

a) Explain the operating principle of three phase induction motor with neat sketches. Why rotor speed is always less than synchronous speed. Justify. [6+2]

b) An alternator on open circuit generates

Explain the torque-slip characteristics of a three phase induction motor. Starting with the expression for torque as a function of slip, show that the value of maximum torque is independent of rotor resistance. [6]

a) Explain the torque-slip characteristics of an induction motor. Show the condition for which the maximum torque develops in the induction motor. [5+3]

b) Explain torque-slip characteristics of 3 phase induction. Deduce the condition for which maximum torque. Discuss the effect of variation of rotor resistance on this maximum torque.

Draw equivalent circuit of 3 phase induction motor at stand still and running conditions. Derive the expression for starting torque and running torque.

permeability of the core is 2000. [6]

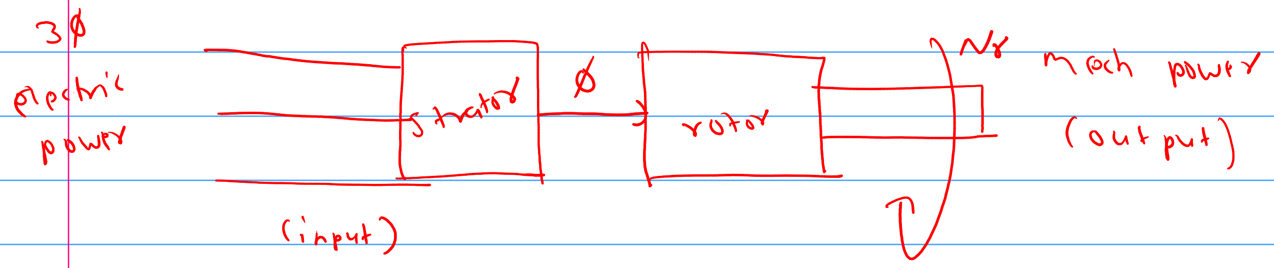
What will be the condition for maximum torque and explain torque slip characteristics of 3-phase induction motor. [8]

a) Explain the torque-slip characteristics of 3 phase induction motor. Show the condition for which the maximum torque develops in the induction motor. Discuss the effect of variation of rotor resistance on this maximum torque. [8]

3-phase induction machine

Construction → not asked

Operating of 3Ø induction motor (IOE)



→ 3Ø ac voltage is supplied to 3Ø stator winding
→ 3Ø ac current flows through it and they generate a rotational magnetic field (RMF)
→ The synchronous speed (Ns) of this field is determined by the supply frequency (f) and the no of poles (P)

$$N_s = \frac{120f}{P} \quad (\text{in RPM})$$

→ This rotating stator field cuts across the rotor conductors, inducing a emf (Faraday's law). And current flow through the rotor conductor.

→ Now, the current carrying rotor conductor are lying in the magnetic field so force will develop on the rotor conductor. ——— It produces a torque (Lorentz force) causing the rotor to spin in the direction of RMF.

→ This rotor cannot reach synchronous speed (N_s) because there would be no relative motion to induce currents. The difference between N_s and rotor speed (N_r) is called slip (s).

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

→ Slip is for torque production, at standstill (startup) slip is 1 (max), decreasing as the rotor accelerates.

→ Under the action of the produced torque the rotor conductor will rotate with speed N_r.

$$(N_r < N_s)$$

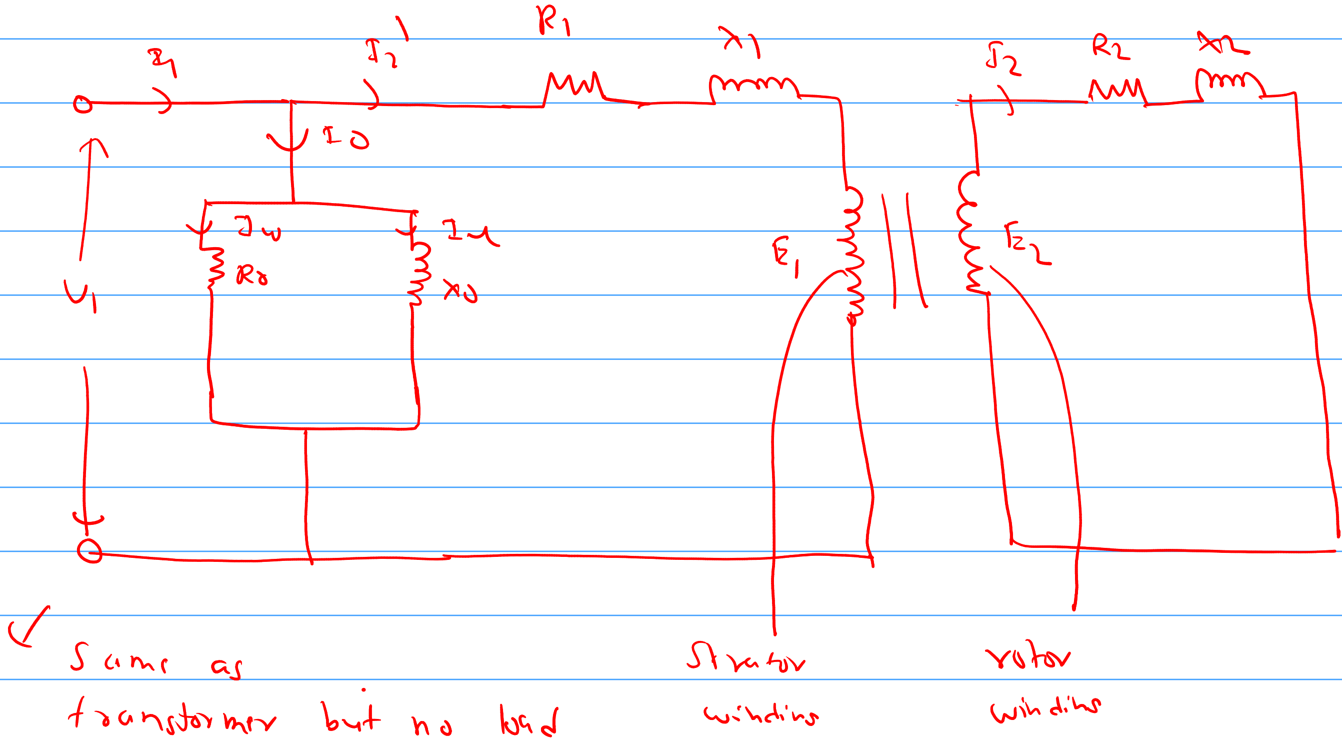
→ This is the basic operating principle of 3ϕ induction motor.

---

* Torque Equation (IOE)

→ The eqn ckt of 3ϕ induction motor is same as of 3ϕ transformer.

p.T.O



✓ Same as transformer but no load

fig: per phase equivalent ckt diagram of 3Ø induction motor

KVL in rotor winding

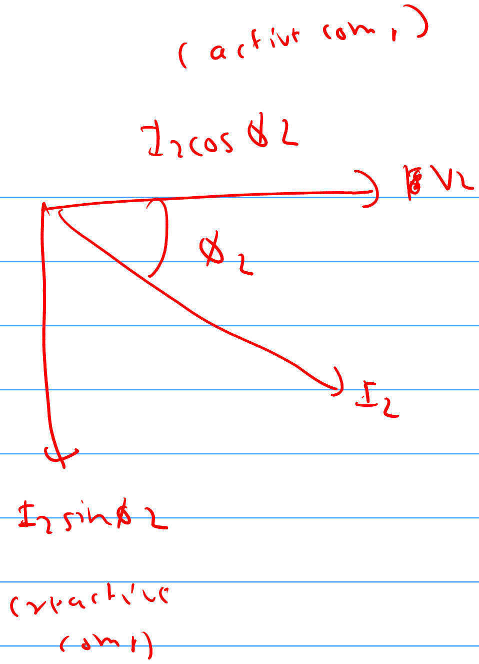
$$E_2 = I_2 R_2 + I_2 j X_2$$

or $$I_2 = \frac{E_2}{R_2 + jX_2} = \frac{E_2}{\sqrt{R_2^2 + (X_2)^2}} \quad \text{—— (i)}$$

I_2 lags behind E_2 by ϕ_2 (since inductive)

$$\phi_2 = \tan^{-1}\left[\frac{X_2}{R_2}\right]$$

Torque developed at standstill is :-

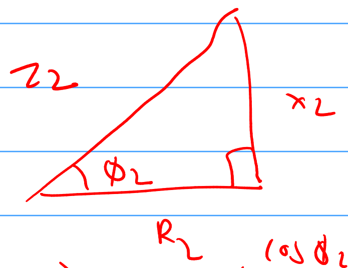


$$T_s \propto \phi_{air}\, I_2 \cos\phi_2$$

$$T_s \propto V_2 I_2 \cos\phi_2$$

$$T_s \propto E_2 I_2 \cos\phi_2$$

$$\therefore \boxed{T_s = k E_2 I_2 \cos\phi_2} \quad \text{— (ii)}$$



$\cos\phi_2 = \dfrac{R_2}{Z_2}$

from (i) and (ii)

$$T_s = k E_2 \left(\frac{E_2}{\sqrt{R_2^2 + X_2^2}}\right)\left(\frac{R_2}{\sqrt{R_2^2 + X_2^2}}\right)$$

$$\boxed{T_s = \frac{k R_2 E_2^2}{(R_2)^2 + (X_2)^2}} \rightarrow \text{torque developed at intial (stand still) condition}$$

At running condition mainly changes occurs in E_2, f and X_2

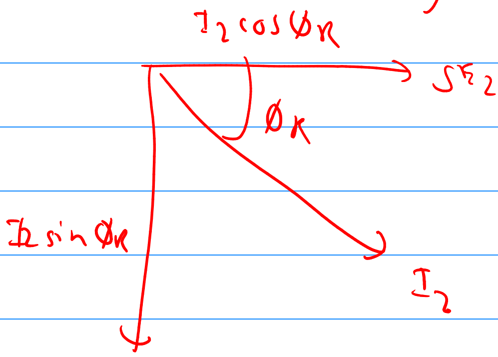
so, $\underset{\text{in rotor}}{E_R} = sE_2$, $f_R = sf$, $X_R = sX_2$

Now,

kvl

$$I_2 = \frac{sE_2}{R_2 + j(sX_2)} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad \text{—— (i)}$$

$$\phi_R = \tan^{-1}\left[\frac{sE_2}{R_2}\right] \quad \left(I_2 \text{ lags } sE_2 \text{ by } \phi_R \right)$$



Torque developed by rotor at running condition

$$T_R \propto \phi_{air} \cdot I_2 \cos\phi_R$$

$$T_R = k E_2 I_2 \cos\phi_R$$

Now,

$$T_R = kE_2 \cdot \left[\frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}}\right] \cdot \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$$

$$\boxed{= \frac{k \cdot s \cdot R_2 \cdot E_2^2}{(R_2)^2 + (sX_2)^2}}$$

At startup $N_r \to 0$ $\quad s = \frac{N_s - N_r}{N_s} = 1$

$$\boxed{T_s = \frac{kE_2^2 R_2}{(R_2)^2 + (X_2)^2}}$$

Torque - Slip Characteristics (IOE) VImp

→ Torque developed by the rotor during running condition is :-

$$T_R = \frac{s R_2 k E_2^2}{(R_2)^2 + s^2 X_2^2} \quad \text{—— (i)}$$

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

N_r — rotor speed

N_s → speed of rotating mag flux

$N_r < N_s$

at normal operating range

slip (s) is very small

s^2 = very small

$$s^2 X_2^2 << R_2^2$$

So,

$$T_R = \frac{s R_2 k E_2^2}{(R_2)^2} = \frac{k s E_2^2}{R_2}$$

$\therefore \boxed{T_R \propto s}$ (slip decreases as torque decreases and increases as torque increases)

At overload condition.

slip (s) will not be small

s^2 will be significant

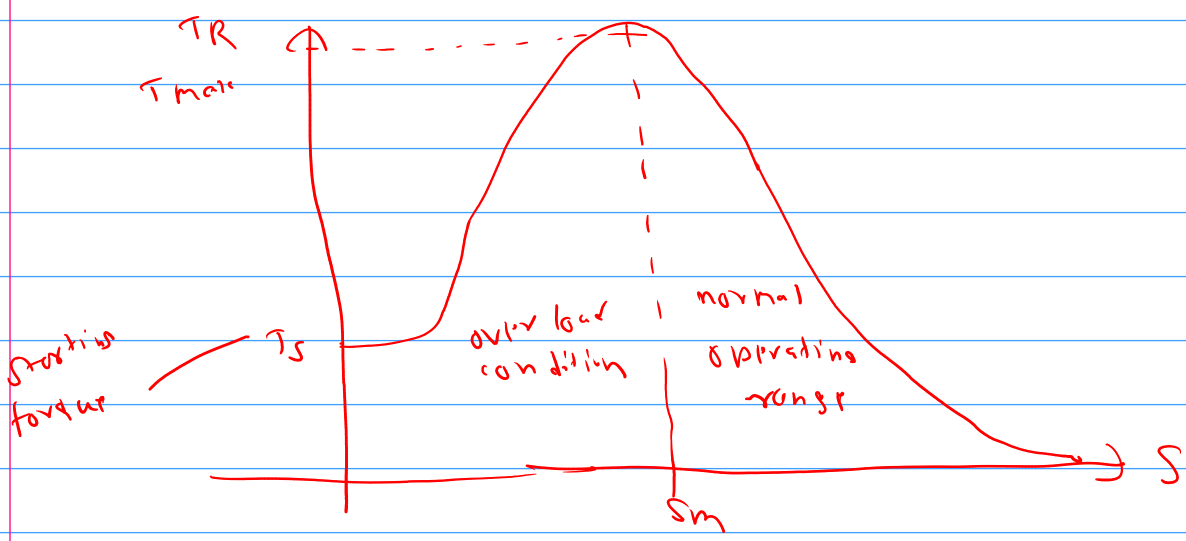
So, $R_2^2 << s^2 X_2^2$

eqn (i) become

$$T_R = \frac{k s E_2^2 R_2}{s^2 X_2^2} = \frac{k E_2^2 R_2}{s X_2^2}$$

$$\boxed{T_R \propto \frac{1}{s}}$$

as slip decrease, torque increase



Condition at max torque (Tok)

→ At a particular value of slip (S_m) the rotor will develop max torque (T_{max})

Let $y = \frac{1}{T_R} = \frac{1}{\frac{s R_2 k E_2^2}{R_2^2 + s^2 X_2^2}} = \frac{R_2^2 + s^2 X_2^2}{s R_2 k E_2^2}$

or, $$y = \frac{R_2^2}{s R_2 k E_2^2} + \frac{s^2 X_2^2}{s R_2 k E_2^2}$$

at $\frac{dy}{ds} = 0$, T will be max, that ⇒ s_m

$$\frac{dy}{ds} = \frac{R_2^2}{R_2 k E_2^2} \cdot \frac{d[s]^{-1}}{ds} + \frac{X_2^2}{R_2 k E_2^2} \frac{ds}{ds}$$

$$0 = \frac{R_2}{k E_2^2} (-1) \cdot s_m^{-2} + \frac{X_2^2}{R_2 k E_2^2}$$

or, $$0 = -\frac{R_2}{k E_2^2 s_m^2} + \frac{X_2^2}{R_2 k E_2^2}$$

or $$\frac{R_2}{\cancel{k} E_2^{\cancel{2}} s_m^2} = \frac{X_2^2}{R_2 \cancel{k} E_2^{\cancel{2}}}$$

or, $$\left(\frac{R_2}{X_2}\right)^2 = (s_m)^2$$

∴ $$\boxed{s_m = \frac{R_2}{X_2}}$$ at this s_m, torque will be max

$$T_{max} = \frac{s_m R_2 k E_2^2}{(R_2)^2 + (s_m X_2)^2} = \frac{\frac{R_2}{X_2} R_2 k E_2^2}{R_2^2 + \left(\frac{R_2}{X_2} \cdot X_2\right)^2}$$

$$T_{max} = \frac{\frac{(\cancel{R_2})^2}{X_2} \cdot K \cdot E_2^2}{2 \cancel{R_2^2}}$$

$$= \frac{K E_2^2}{2 X_2}$$

$$\therefore \boxed{T_{max} = \frac{K E_2^2}{2 X_2} \quad \text{at } s = s_m = \frac{R_2}{X_2}}$$

effect of Rotor resistance on torque - slip (TOE)

→ If R_2 is increased $R_2(\text{new}) > R_2(\text{old})$

previous
both area

at operating

$$T_R = \frac{K s E_2^2}{R_2(\text{new})}$$

$R_2(\text{new}) \uparrow$ $T_R \downarrow$

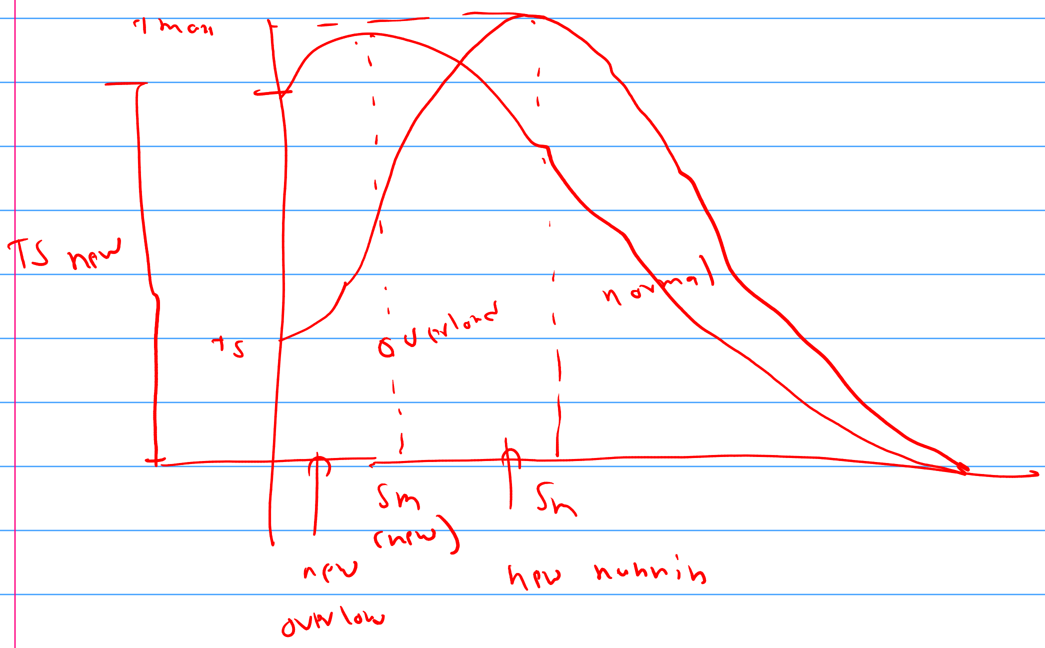
at overload

$$T_R = \frac{K E_2^2 R_2(\text{new})}{s X_2}$$

$R_2 \uparrow$ $T_R \uparrow$

$$\uparrow s_m = \frac{R_2(\text{new})}{X_2} \uparrow$$

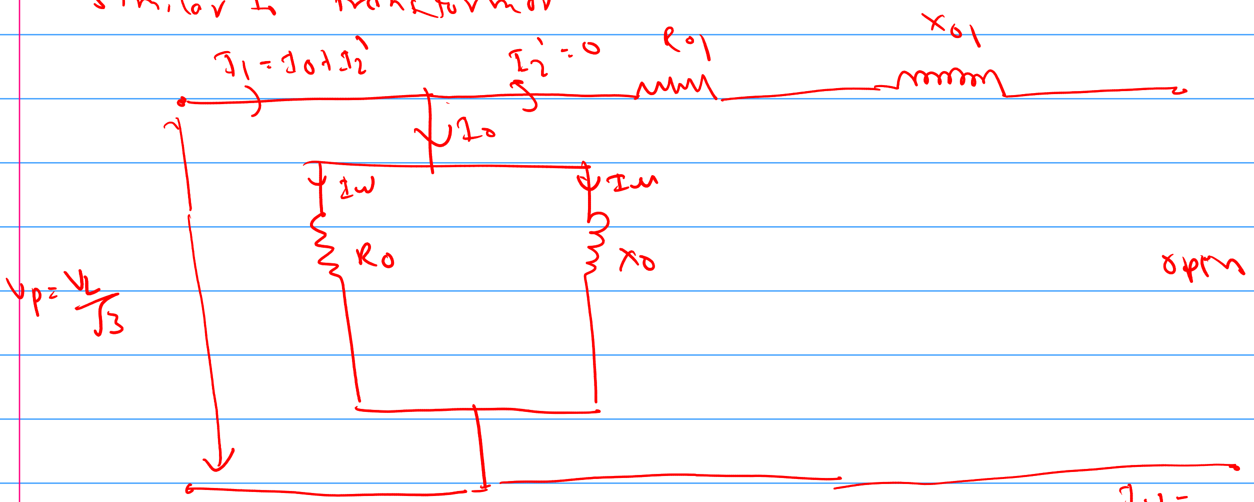
→ starting torque increases
→ running torque decreases



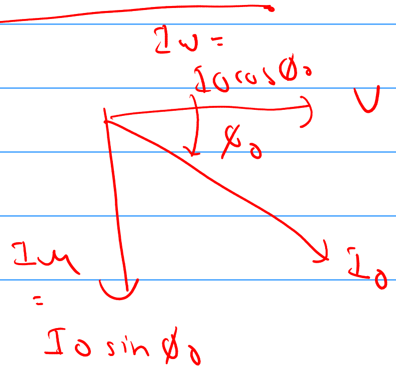
Testing (not main priority)

① No-load test (iron loss)

Similar to transformer



$$W_0 = W_1 + W_2 = \sqrt{3}\, V_p I_0 \cos\phi_0$$



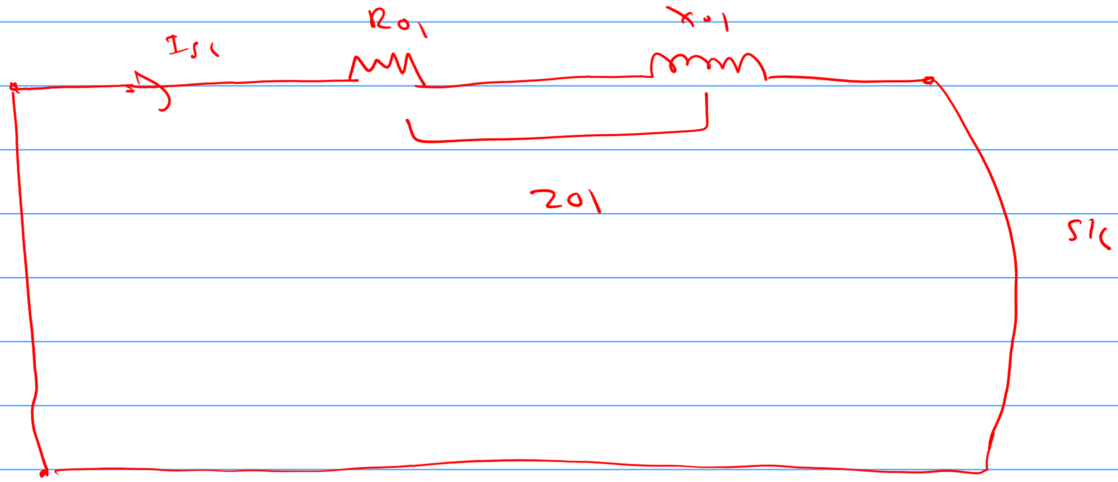
$$\cos\phi_0 = \frac{W_0}{\sqrt{3}\, V I_0}$$

$\phi_0 = ?$

$$\boxed{R_0 = \frac{V_p}{I_w}} \qquad \boxed{X_0 = \frac{V_p}{I_\mu}}$$

(ii) Blocked Rotor test → S/C test of transformer

$V_p = \frac{V_{sc}}{\sqrt{3}}$



$$\boxed{Z_{01} = \frac{V_p}{I_{sc}} = \frac{V_{sc}}{\sqrt{3}\, I_{sc}}}$$

$$\boxed{R_{01} = \frac{W_0}{I_{sc}^2}} \qquad \boxed{X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}}$$

$$\boxed{Cu\text{-}loss = I_{sc}^2 \times R_{01}}$$

#4 η of 3ϕ induction motor

i/p power to rotor $= T_R \times \frac{2\pi N_s}{60}$

o/p power by rotor $= T_R \times \frac{2\pi N_r}{60}$

$$\boxed{\text{Rotor Cu-loss} = s \times \text{input power to rotor}}$$

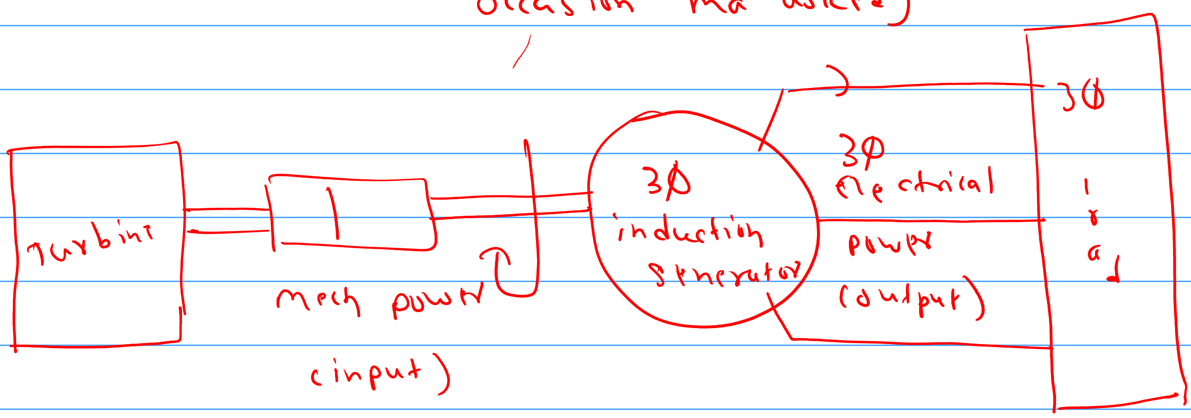
$$\text{rotor } (\eta_r) = \frac{\text{Power developed by rotor}}{\text{Input power to rotor}}$$

$$\boxed{\eta_r = \frac{N_r}{N_s}}$$

$$\boxed{\text{Overall } \eta_o = \frac{\text{Power developed by shaft}}{\text{Input power to stator}}}$$

3Ø induction Generator

#1 Working (IOE) → (motor is main focus tara vari occasion ma asked)



→ A turbine provides mech power to the rotor

→ The rotor starts rotating at speed higher than Synchronous spee ($N_r > N_s$).

→ In normal induction motor, slip (s) is positive

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

→ In generator mode, the rotor moves faster than the synchronous speed, making slip negative.

$$S = \frac{N_s - N_r}{N_s} < 0$$

→ This negative slip reverse the power flow, converting mechanical into electrical energy.

→ The rotor has a rotating magnetic field due to residual mag flux

→ as the rotor spins faster, it cuts the strator windings, inducing an opposite direction emf in strator coils.

→ The induced voltage in the strator windings causes current flow, producing a three-phase ac output.

→ This is the basic operation of 3Ø induction generator

Voltage Build up - process for 3Ø induction generator (sometimes) (IOE)

→ The rotor has a small amount of leftover mag field from previous operation.

→ A turbine spins the rotor at high speed.

→ As the rotor spins, its residual magnetic field moves past the strator windings, inducing a small emf in it.

→ Capacitors are connected in stator terminals allowing a leading current to flow due to small emf.

→ The stronger mag field induces an even higher emf in the stator windings.

→ This process repeats in a positive feedback loop - higher the emf leads to more current which increases the magnetic field further until the magnetic core ~~stat~~ saturates, stabilizing the voltage.

→ Once stabilized, the generator produces a steady 3-phase AC voltage at the stator terminals, ready to power a load.