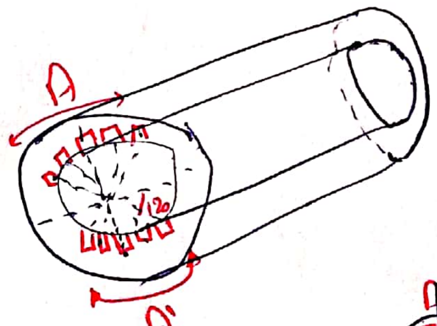
Rotating Field of Ac Machines

Both types of Ac Machines (Induction & Synchronans) have Identical Stator (Armature), where power generated or developed

- **Armeature Structure:-**

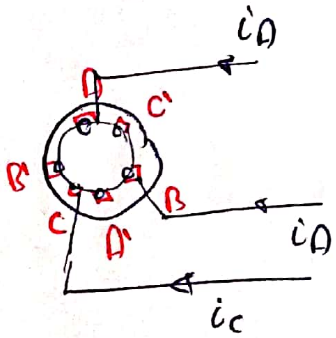
1) Ferromagnatic Core

- to Provide low-Reluctance Path for the magnatic field
- to hold the Windings of the armature



2) 3-Ph Windings:-

- 3-diffrent Sets of coils phisically displaced by 120° (Mech) (usually in slots)



3) 3-phase Power Supply (Balanc) (certain Sequances) ⟶ the rotating direction

the machine is [Motor]

3-Ph Balanced Supply

$i_A = I_m \cos(\omega t)$
$i_B = I_m \cos(\omega t - 120°)$ ⇒
$i_C = I_m \cos(\omega t + 120°)$ ⇒

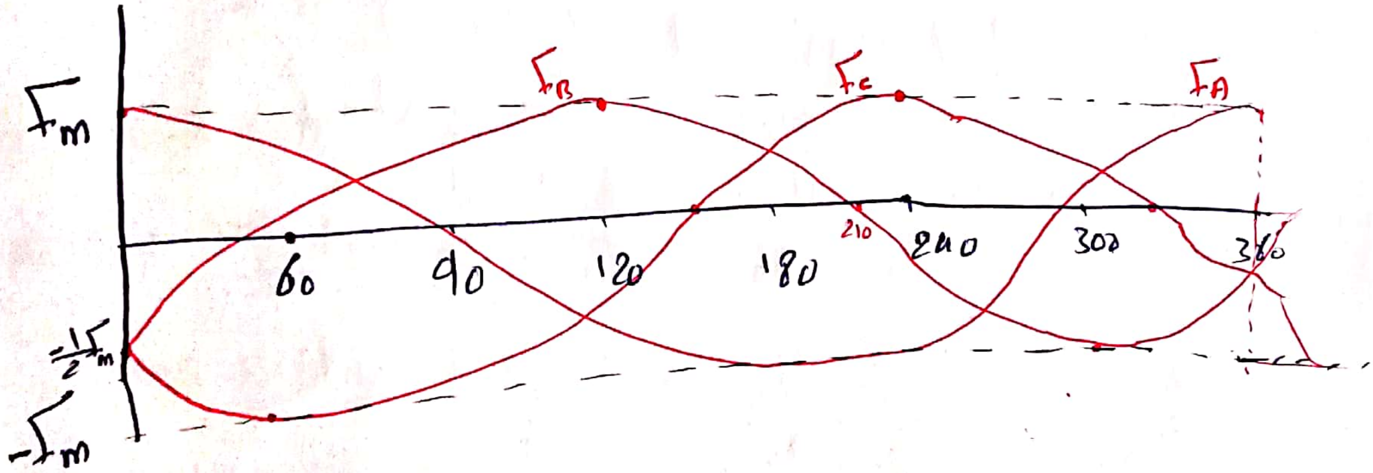
⇒ MMF $F_A = N_{ph} * i_A$
$F_B = N_{ph} * i_B$
$F_C = N_{ph} * i_C$

MMF Sets

$$F_A = N_{ph} I_m \cos(\omega t) = F_m \cos(\omega t)$$

$$F_B = N_{ph} I_m \cos(\omega t - 120°) = F_m \cos(\omega t - 120°)$$

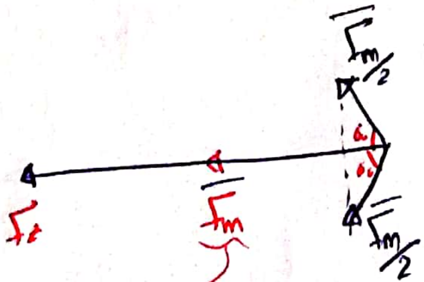
$$F_C = N_{ph} I_m \cos(\omega t + 120°) = F_m \cos(\omega t + 120°)$$



⊗ at $t=0$

$$\bar{F}_A + \bar{F}_B + \bar{F}_C = \bar{F}_t$$

$F_A = F_m \cos 0 = F_m$
$F_B = F_m \cos(-120) = -\frac{1}{2} F_m$
$F_C = -\frac{1}{2} F_m$



D.A تحت الرسم

$$\bar{F}_B + \bar{F}_C = \sqrt{F_B^2 + F_C^2 \pm \frac{1}{2} F_B F_C \cos(120)}$$
$$= \frac{1}{2} F_m$$

$$\boxed{F_t = 1.5 F_m}$$

3

* The rotating field has same Amplitude as the previous one i.e $\frac{3}{2} F_m$

* The Field Vector rotates in a certain direction decided by the Phase sequance of the supply If the direction is to be reversed phase sequance should be reversed

At $Wt = 90$

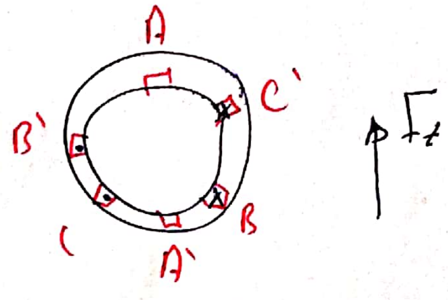
$F_{A} = 0 \Rightarrow \cos(90)$

$F_B = \frac{\sqrt{3}}{2} F_m \Rightarrow \cos(-30)$

$F_c = -\frac{\sqrt{3}}{2} F_m \Rightarrow \cos(210)$

* The Mech speed of the rotating Field Vector is refeired to as the Synchronanse speed which is a two-pole machine is Same as that of the electric Currents

$\boxed{W_m = W_e}$



The speed of the rotating field is known as N_s : synchronous speed (W_s)
rpm   rad/sec

$$N_s = \frac{60 \times f}{P}$$

where f: frequency in Hz or cycle/sec

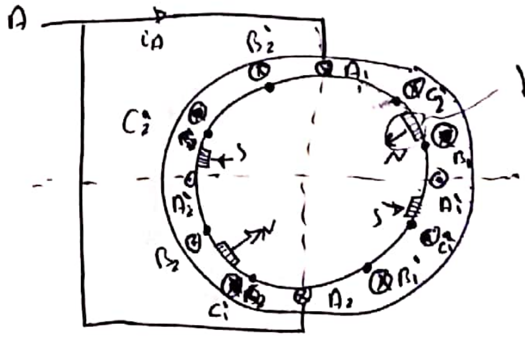
P:- No of pole pairs of the stator

50 Hz sys => 3000 1500 1000 750 . 600 500 ....

60 Hz sys => 3600 1800 1200 900 720 600 ....

Induction Asynchonous $N_m \neq N_s$

Synchonous $N_m = N_s$



between the ⊗ & ⊙

$W t = 0°$

W: electric freq (or speed)

4- Pole machine

To change N_s : the No of poles is to be changed from the (Design point of view)

But

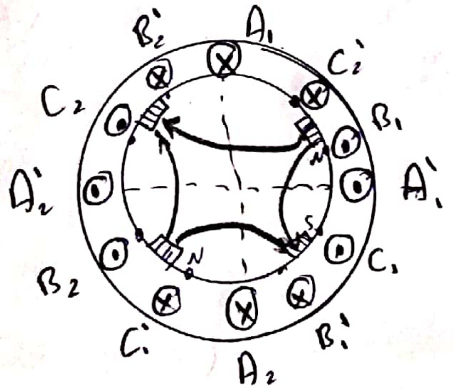
In Generatores N_s can be decided by the primemator speed (Thermal or Hydroelectric)

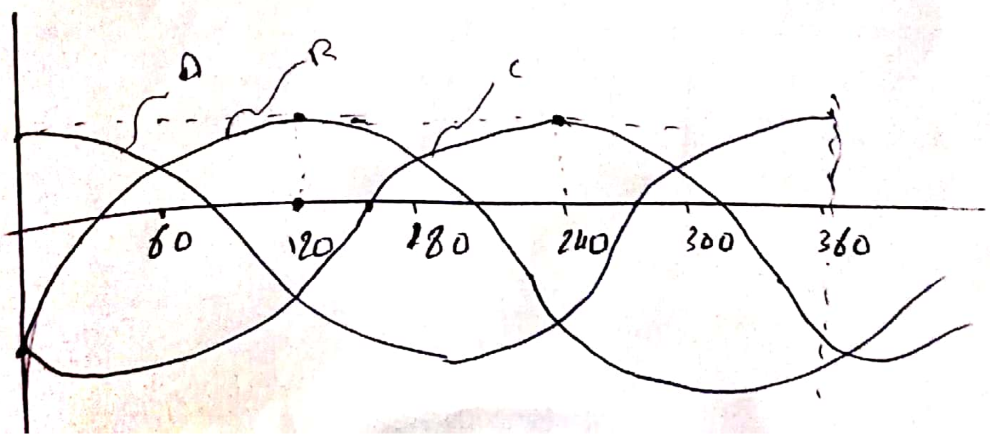
, High speed , low No of poles

, low speed , High No of poles

In motors: N_s can be controlled easily by frequency

Irrespective of P . Amplitude of the Rotating still $\frac{3}{2} I_m/ph$





* In motor N_s canbe controlled easialy by Frequancy Irrespective of P, the amplitude of the Rotating Field Still

$$\boxed{\frac{3}{2} F_m/ph}$$

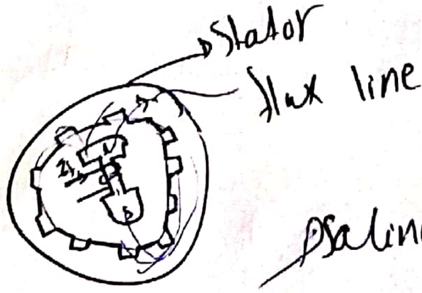
Synchronous Generotors

* two major Types:-
  - Salient-pole machine
  - round (or cylindrical) Rotor machine

} in both the Stator in the Same

~~Stator~~ Rotor:
a) permanent Magnet (small power)

b) Electric pole (Large power)



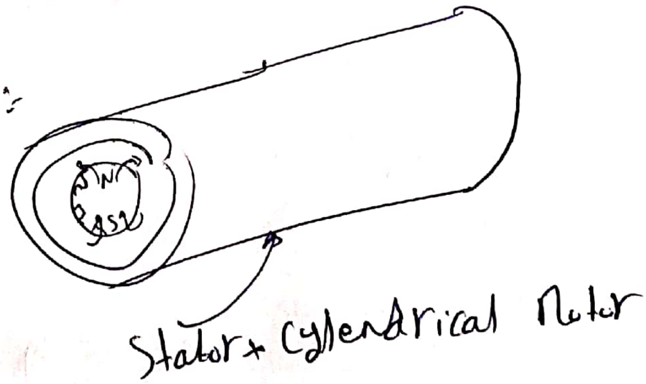
Saline-pole Machins

*) EF : the DC Field current
that usally Supplies ~~current~~ the rotor to create the flux

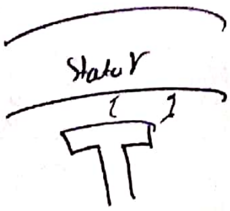
*) The stator is providing the close path for the flux ϕ
It is usally laminated to reduce Eddy current losses

*) The core (Rotor) is not lamminated?
because there is no change of the flux at the rotor
(Rotaters with the stater fields)
So => No eddy current

*) the airgap should be as small as possible :-
to reduce the Reluctance of the flux path

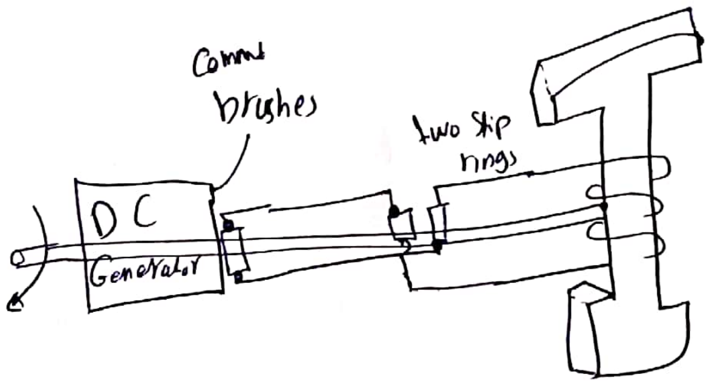


*) the airgap is usally not uniform. this
will help in creating pure sine function
(only in sline)

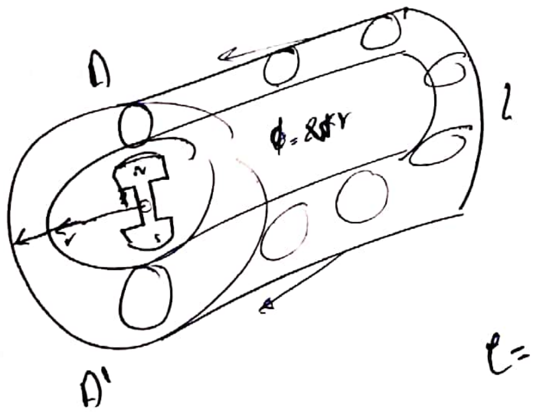


- Excitation

shaft
prime mover
(Steam or hydrolic ~~turbine~~ turbine)

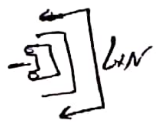


- EMF



the field power is 2% of the total power

$e = 4.44 N_{ph} \phi_m f$



$e = (\bar{V} \times \bar{B}) L$

$e = V . B_m \times L \times \sin\theta$ (ωt)

$e_{cond} = w_m . r . B_m . L . \sin wt \Rightarrow e_{coil} = \underbrace{2}_{\text{two sides}} \times r \times L \times \underbrace{N_{ph}}_{N \text{ turns}} \times \underbrace{w_m}_{w_m = \frac{w_e}{P}} \times B_m \times \sin wt$

$= 2 r L N_p \frac{w_e}{P} . B_m \times \sin wt$

$= \underbrace{\frac{2 r L \, B_m}{P}}_{\phi} . N_{ph} . w_e . \sin wt$

$\frac{2rL}{P} \Rightarrow$ area under one pole

So $B \times A = \phi$

$e_{coil} = N_{ph} . 2\pi f . \phi \sin wt \Rightarrow E_m = N_{ph} . 2\pi f \phi$

$E_{rms} = \frac{E_m}{\sqrt{2}} = 4.44 N_{ph} \phi f$

of Kw

the winding factor

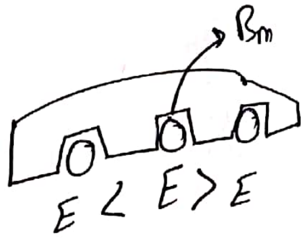
$$0.95 \le K_w < 1$$

$$E_{rms} = 4.44 \, K_w \, N_{ph} \, \phi f$$

Synch Machines can be

- → turbo machines → Steam (high speed - low poles. large diameter (short length)
- → Hydro machines → hydrolic machines (low speed - high no. poles 36 pole low diameter (low rolling length))

why Kw ??



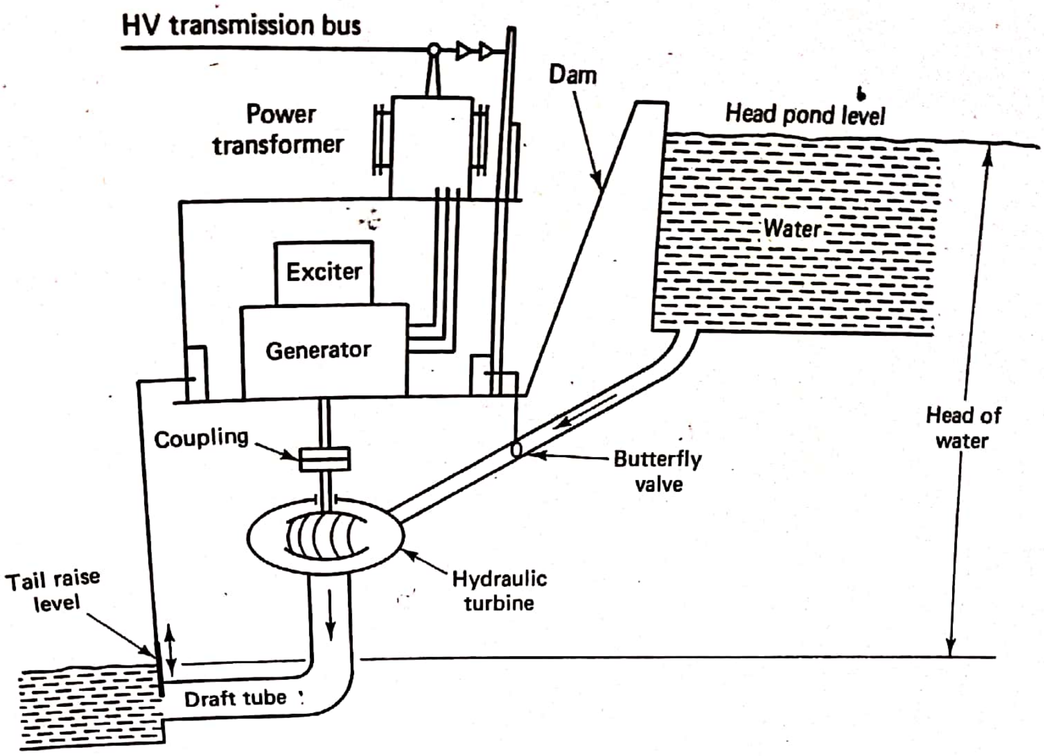


Figure 6-7 Typical hydrogenerating plant. Hydrogenerator is vertically constructed.

6-4 THREE-PHASE GENERATED VOLTAGES AND FREQUENCY

Rotor speed and frequency of the generated voltage are directly related. Let us now determine how. Consider the elementary two-pole ac generator of Fig. 6-9. To simplify things, there is only one coil shown, made up of two conductors in series, a and a'. When we have a single coil like this, we talk of a concentrated

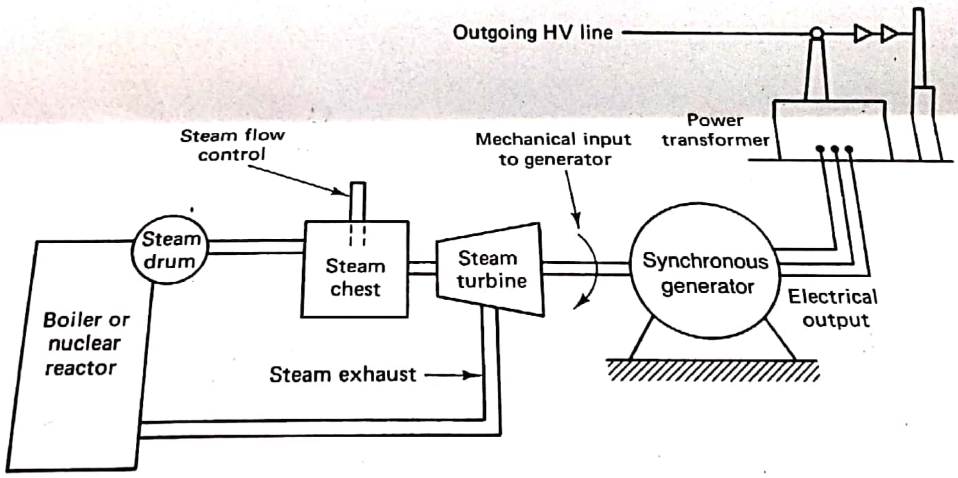


Figure 6-8 Simplified electric generating plant using horizontal construction of steam turbine generator.

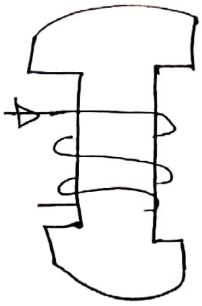
Speed → control the freq of the output
→ control the Real power

Field current ϕ → control the reactive power

* Excitation system:-

I_f ⇒ excitation current.

How to get it:



1) Isolated DC supply: (Isolated DC Generator)
↓
through slip rings and Brushes → field circuit

2) Isolated AC supply + Rectifier → Controlled
through slip rings + Brushes → field circuit → انا بتحكم بقيمة I_f

3) Brushless Excitation System.

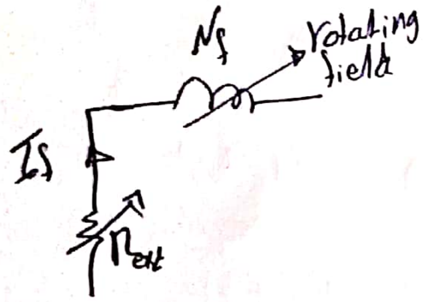
Commutator → to convert ac to DC

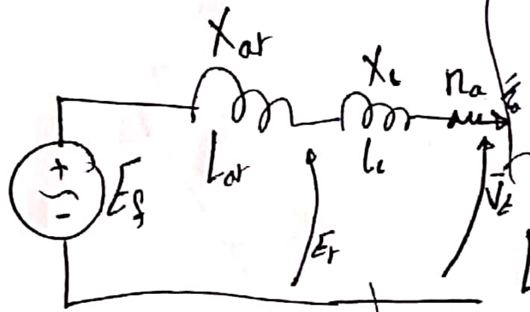
Brush → تجميع التيار

Brushless excitation:

- Pilot exciter ⟶ 3ph AC Generator (connected to the turbine shaft)

Equivalent Circuit / ph





internal induced EMF

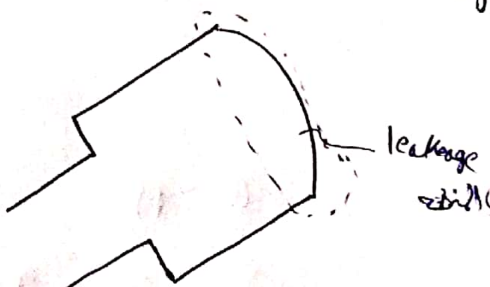
$E_f = 4.44\, K_w \cdot N_{ph} \cdot f \cdot \phi_p$

$L = \frac{N\phi}{I}$

X_{ar} ⇒ Armature Reaction Reactance

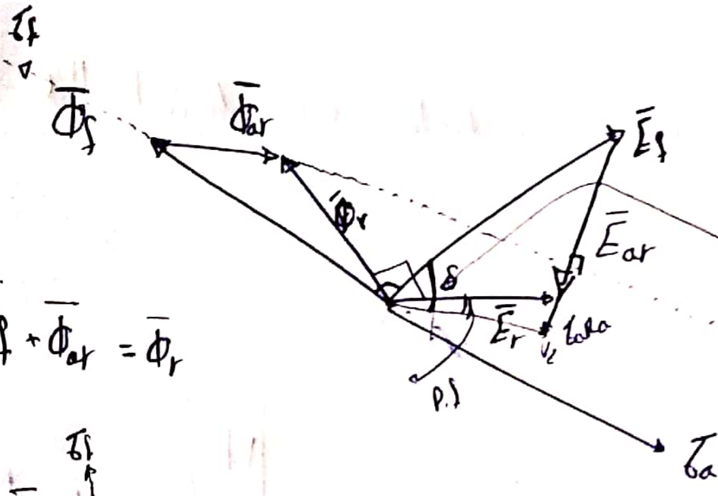
$X_{ar} = 2\pi f . L_{ar}$

X_L ⇒ flux leakeage نشأت عن



$\underbrace{\bar{E}_r}_{\text{resultant (airgap EMF)}} = \underbrace{\bar{E}_f}_{\text{main field}} + \underbrace{\bar{E}_{ar}}_{\text{Armature Reaction}}$

$$\boxed{X_s = X_{ar} + X_L}$$

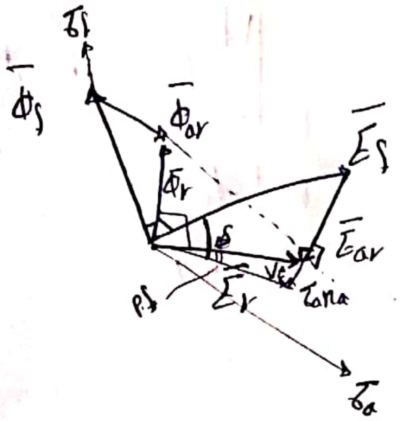


$\bar{\Phi}_f + \bar{\Phi}_{ar} = \bar{\Phi}_r$

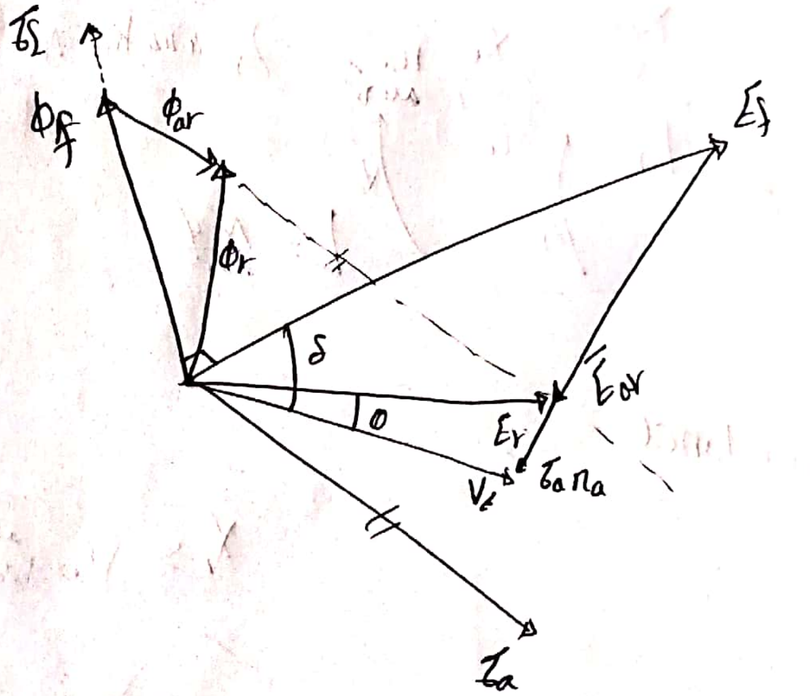
Power or Torque angle

$P = f(\delta)$

angle between V_t & $\bar{E}_f$



$I_a \parallel \bar{\Phi}_{ar}$



$\theta \Rightarrow$ pf

$\delta \Rightarrow$ power or Torqe angle

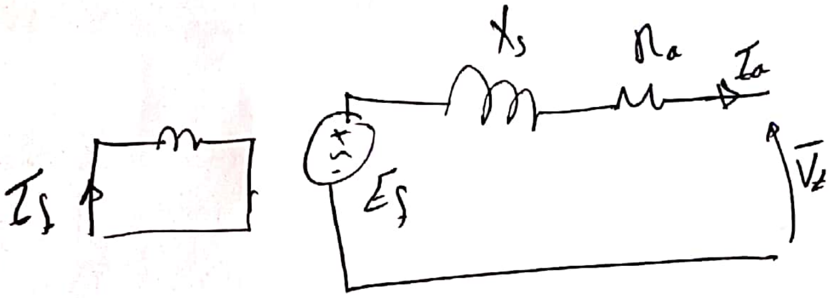
$X_s = X_{ar} + X_L$

↳ Synchronous reactance

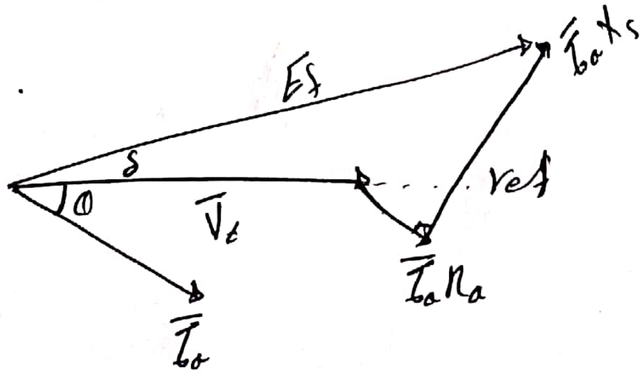
$X_{ar} >> X_L$

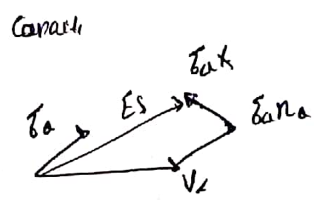
$X_s \longrightarrow$ Constant unless core saturation

$R_a <<< X_s$



inductive





$\delta \begin{cases} + & \text{Generators} \\ - & \text{Motors} \end{cases}$

$\bar{V}(t) = 200 \angle 30°$

$\bar{E}_f = 180 \angle 35°$

$\delta = \theta_{E_f} - \theta_{V_t}$

leading p.f

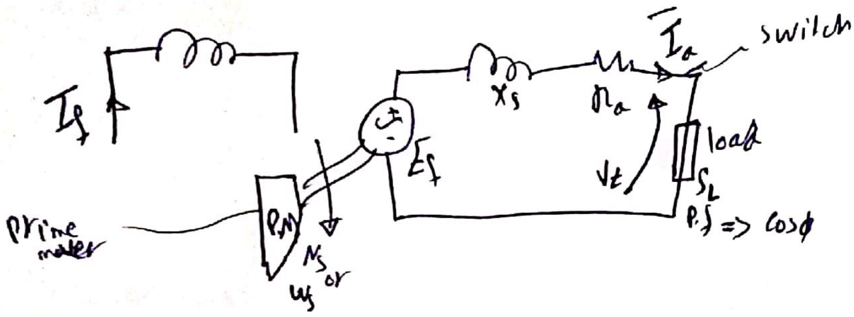
Generators

$E_f < V_t$

Scanned by CamScanner

Developed power by a synch. Generator :-

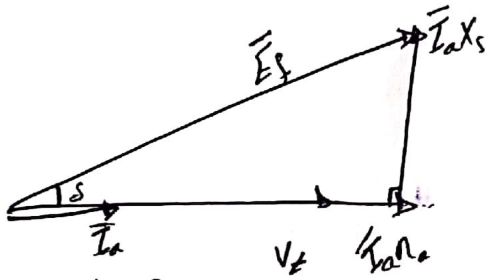
Start with phasor Diagram



a) Unity p.f load

δ angle between $\bar{V}_t$ and $\bar{E}_f$

b) ϕ angle between $\bar{V}_t$ and $\bar{I}_a$



$\phi = 0$
$\delta > 0$

$\bar{E}_f = \bar{V}_t + \bar{I}_a(r_a + jX_s)$

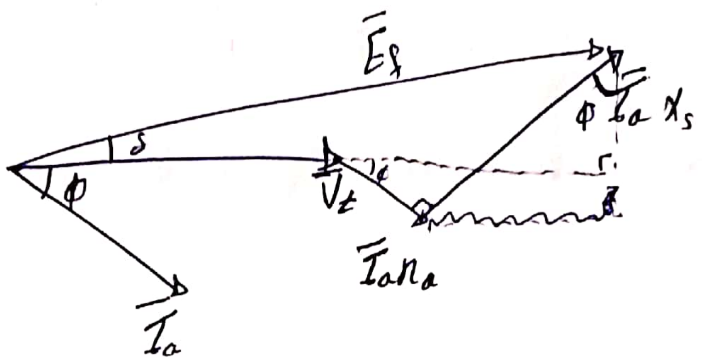
$r_a << X_s$

Voltage regulation :-

$$\frac{|E_f - V_t|}{V_t} * 100\%$$

Synch machine Voltage is around 20KV then To rise Voltage to Transmission

h) Inductive load



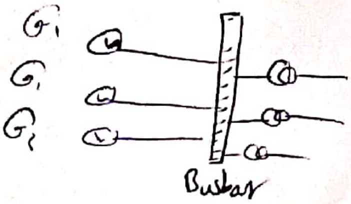
$$\boxed{S = 3 V_{rms} I_{rms}}$$

P_d => developed power transformer to the load

$P_d = 3 V_{t(ph)} I_{a(ph)} \cos\phi = \sqrt{3}\, V_{t(L)} I_{a(L)} \cos\phi$

* Synch. Generator are usually connected to a large power system or Network.

(Network is connected to an Infinite Busbar)

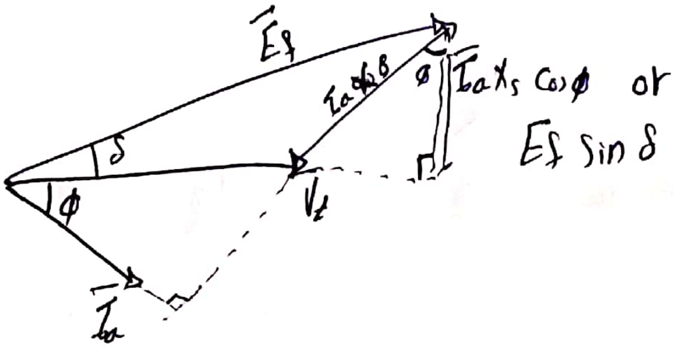


It means => Constant Voltage and frequency irrespective of load ~~variations~~ Variations

Assuming $V_t = \text{const}$

$$P_d \propto I_a \cos\phi$$

With $r_a \longrightarrow$ neglected



~~$I_a \cos\phi\, X_s$~~

$$I_a X_s \cos\phi = E_f \sin\delta$$

$$I_a \cos\phi = \frac{E_f \sin\delta}{X_s}$$

$$P_d = 3 V_t I_a \cos\phi$$

$$P_d = \frac{3 V_t E_f}{X_s} \sin(\delta)$$

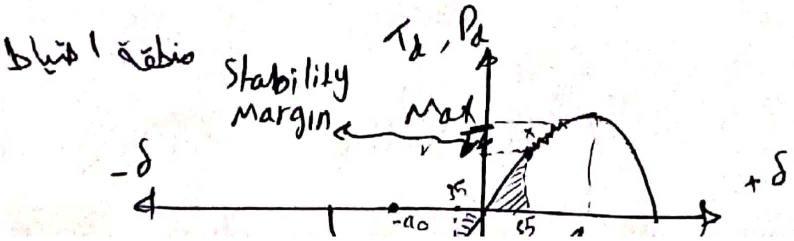
$$\boxed{P_d = \frac{3 V_t E_f}{X_s} \sin(\delta)}$$

δ is defined as the power angle since P_d is function this δ

developed Torq

$$T_d = \frac{P_d}{\omega_s} = \frac{P_d}{\text{Cons}} = \left(\frac{3 V_t E_f}{\omega_s * X_s} \right) \sin(\delta)$$

δ can be refeired to as the Torque angle



From the Theoretical point of View, δ is changing in the Range 17

$0^\circ \le \delta \le 90^\circ$ Generator

$\boxed{\text{ازا تعدى ال } 90^\circ \text{ يصبح Motor} \quad \delta > 90^\circ}$

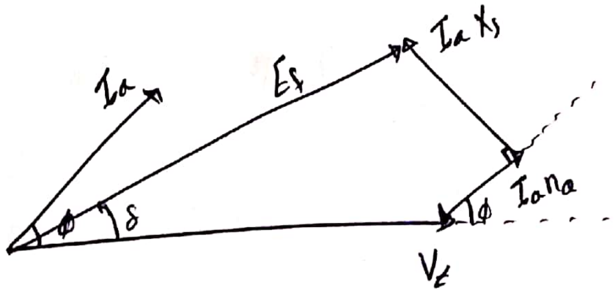
Practically

$10^\circ \le \delta \le 35^\circ$

If $\delta = 90^\circ \longrightarrow P_d = P_{max} = \dfrac{3 V_t E_f}{X_s}$

Stability margin $\Longrightarrow$ حتى لا ~~ندخل~~ ندخل المنطقة العليا
ويفصل ال Generator
ونفس الشيء ينطبق ع Motor

leading P.F



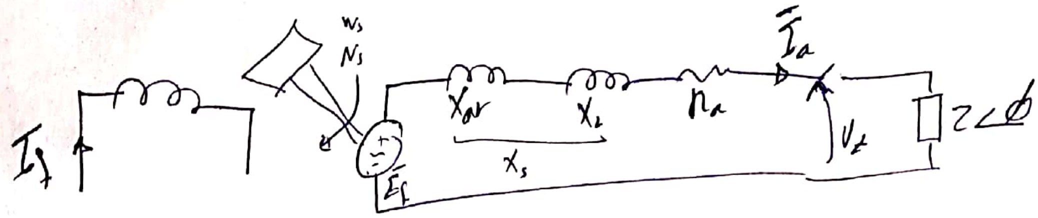
δ still $\oplus$

Reactive power depends on

$I_a \sin\phi$ $\boxed{Q = 3 V_t I_a \sin\phi}$

in Generators $\delta \to \oplus$

Synchronous Machines parameters

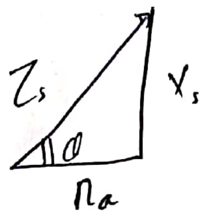


$\bar{E}_f, V_t, \bar{I}_a$ are per phase values

$r_a \Rightarrow$ Armature Resistance $\simeq 0.01$ pu

$X_l \simeq 0.1 - 0.2$ pu

$X_s \simeq 1$ pu



$$Z_s = \sqrt{r_a^2 + X_s^2} \angle \theta$$

$$\theta \lesssim 90^\circ$$

$$\theta = \tan^{-1} \frac{X_s}{r_a}$$

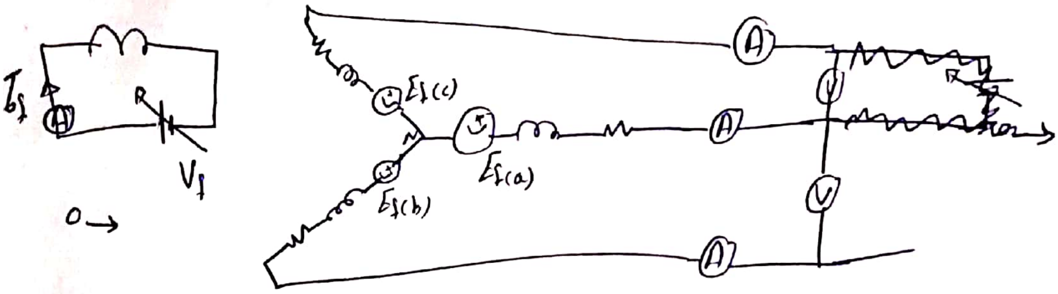
This is why r_a is neglected in the general analysis of S.M

for η calculation it is taken into account

ex) $P_d = \frac{3 V_t E_f}{X_s} \sin\delta \longrightarrow r_a \neq \infty$

$P_d (r_a \neq 0) = K + K'$ later on

S.M testing



DC test

To Evaluate R_a

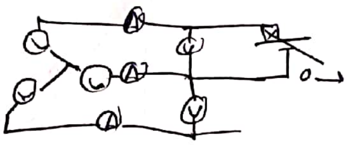
$N_s = 0$

$I_f = 0$

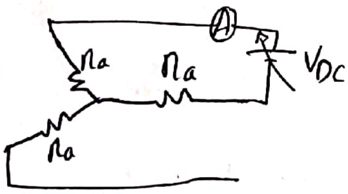
V_{DC}	V_{DC3}	V_{DC2}	V_{DC1}	V_{DC4}
I_{DC}	I_{DC1}	I_{DC1}	I_{DC3}	$I_a(r)$

$\rightarrow I_{DC4}$

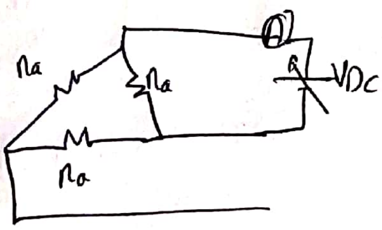
$I_{DC4} \leq I_a(r)$



eq



$R_a = \dfrac{V_{DC\,(av)}}{2 I_{DC\,(av)}}$, Y- connected



$2R_a // R_a = \frac{2}{3} R_a$

$R_a = \dfrac{3 V_{DC\,(av)}}{2 I_{DC\,(av)}}$

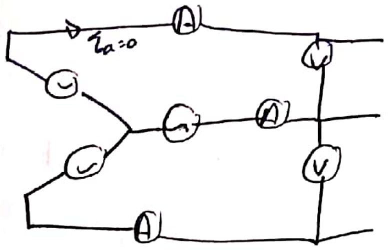
, If Δ- connected Armature

SEF → skin effector factor

$r_a(AC) = SEF * r_a(DC)$

to correct for skin effect

open Circuit test → No load



1) set

$I_f = 0$

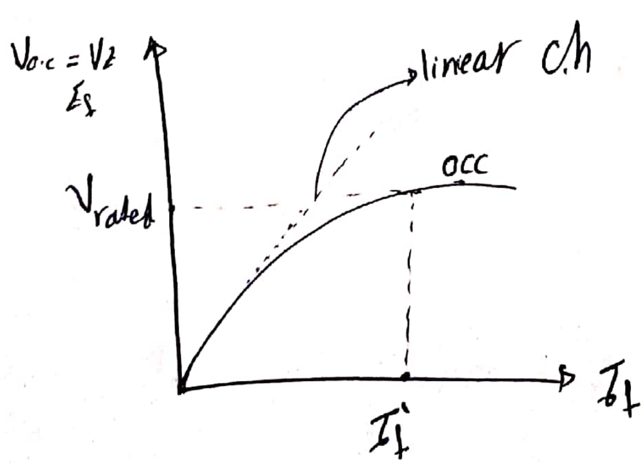
$\bar{E}_f = \bar{V}_\phi + \cancel{\bar{I}_a \bar{Z}_s}$

2) Run P.M at $\underline{N = N_s}$

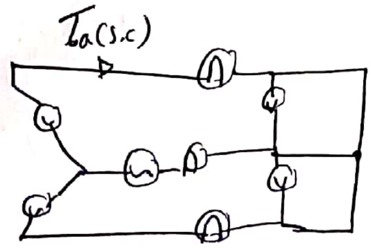
$I_a = 0$

I_f	0	I_{f1}	I_{f2}	...	
E_f : $V_{o.c}$	= 0				120% V_{r}

P.M ⇒ Prime mover



Short circuit test

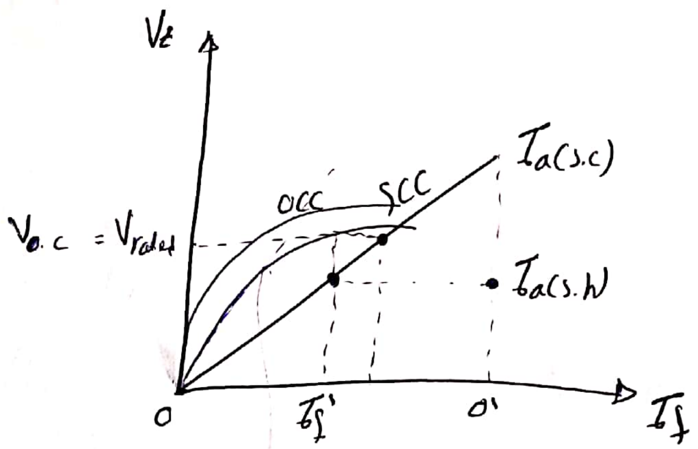


I_f at starting $= 0$

run P.M at N_s

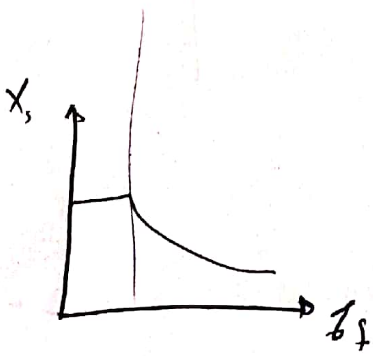
$I_a(av)$

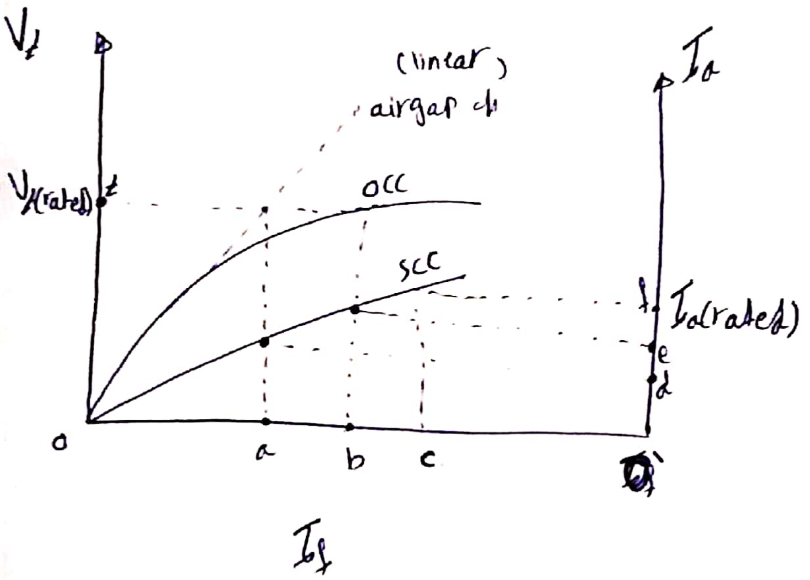
I_f	0	...	...	I_f
I_1	0			150% $I_{a(r)}$
I_2	0			
I_3	0			



$$Z_s = \frac{V_{(oc)}}{I_{a(s.c)}} \simeq X_s$$

$$X_s = \frac{V_{o.c}}{I_a(s.c)} \quad , \quad X_s = \sqrt{Z_{(s)}^2 - R_a^2}$$





$$X_s \simeq Z_s\,(sat) = \frac{ot\ (V/ph)}{o'e\ (A/ph)}$$

$$Z_s(sat) < Z_s\,(unsat)$$

$$X_s(unsat) = Z_s\,(unsat) = \frac{ot\ (V/ph)}{o'd\ (A/ph)}$$

Define the SCR (short circuit ratio)

$$SCR = \frac{\text{feild current the gives } V_t(\text{rated}) \text{ at OCC}}{\text{field current thes that gives } I_a(\text{rated}) \text{ at SCC}}$$

$$SCR = \frac{ob}{oc}$$

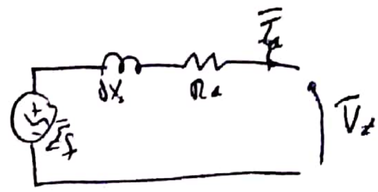
prove

$$SCR = \frac{1}{X_s(sat)\ (pu)}$$

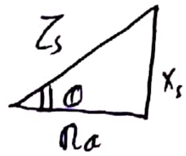
it can be proved that

$$S = \bar{V}_t * \bar{I}_a^*$$

$$\bar{I}_a = \frac{\bar{E}_f - \bar{V}_t}{Z_s \angle \theta}$$



$$\bar{I}_a = \frac{\bar{E}_f \angle \delta - V_t \angle 0}{Z_s \angle \theta}$$



$$Z_s = R_a + jX_s$$

$$= \sqrt{R_a^2 + X_s^2}$$

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right) \lesssim 90^\circ$$

$$= \frac{E_f}{Z_s} \angle \delta - \theta - \frac{V_t}{Z_s} \angle -\theta$$

$$= \frac{E_f}{Z_s}\left(\cos(\delta-\theta) + j\sin(\delta-\theta)\right) - \frac{V_t}{Z_s}(\cos\theta - j\sin\theta)$$

$$= \left(\frac{E_f}{Z_s}(\cos(\delta-\theta)) - \frac{V_t}{Z_s}\cos\theta\right) + j\left(\frac{E_f}{Z_s}\sin(\delta-\theta) + \frac{V_t}{Z_s}\sin\theta\right)$$

$$S = P + jQ = \bar{V}_t * \bar{I}_a^*$$

$$= \left(\frac{V_t E_f}{Z_s}\cos(\delta-\theta) - \frac{V_t^2}{Z_s}\cos\theta\right) - j\left(\frac{V_t E_f}{Z_s}\sin(\delta-\theta) + \frac{V_t^2}{Z_s}\sin\theta\right)$$

$$P = \text{Real power} = \frac{V_t E_f}{Z_s}\cos(\delta-\theta) - \frac{V_t^2}{Z_s}\cos\theta$$

$$Q = \text{Reactive power} = -\frac{V_t E_f}{Z_s}\sin(\delta-\theta) - \frac{V_t^2}{Z_s}\sin\theta$$

lets assume that $r_a \to 0$, $Z_s = X_s$, $\theta = 90^\circ$

$$P = \frac{V_t E_f}{X_s} \cos(\delta - 90^\circ) - \cancel{\frac{V_t^2}{X_s} \cos(90^\circ)}^{\,0}$$

$$\boxed{P = \frac{V_t E_f}{X_s} \sin(\delta)}$$

δ → Generator → P+
δ → Motor → P-

$$Q = -\frac{V_t E_f}{X_s} \sin(\delta - \theta) - \frac{V_t^2}{X_s} \cancel{\sin(90^\circ)}^{\,1}$$

$$\boxed{Q = \frac{V_t E_f}{X_s} \cos(\delta) - \frac{V_t^2}{X_s}}$$

Two Cases of Interests :-

when the Gen is connected to Infinite Busbar

(V_t = const, f = const irrespective of the load variations)

V_t → canbe controlled through I_f Governer.

$$\bar{V}_t = \bar{E}_f - j \bar{I}_a X_s$$

f → canbe controlled through the input energy Governer (to the turbine)

Case 1

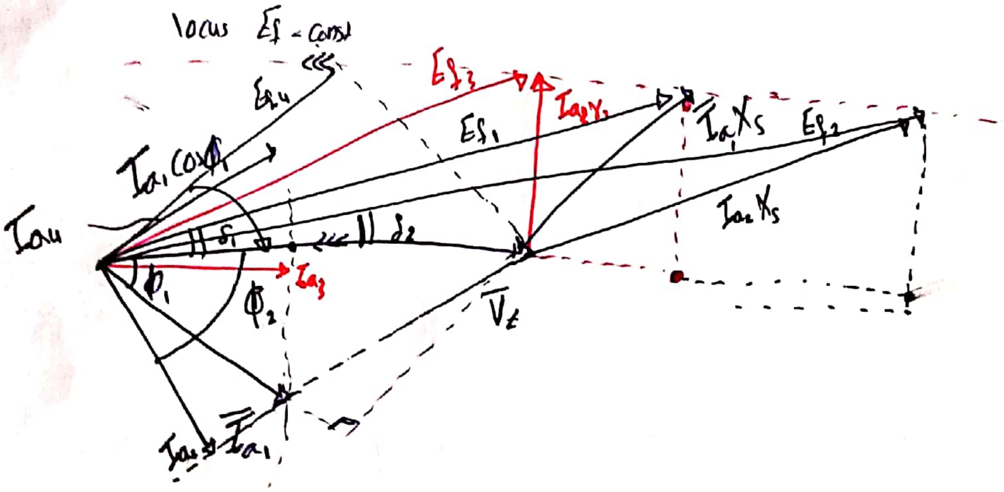
Infinite Busbar + constant $\underbrace{\text{real power}}_{P}$, $P_m \xRightarrow[\text{convert}]{\text{تتحول}} P$ real power

to Keep $P = \text{const}$

$$P = \frac{E_f V_t}{X_s} \sin\delta$$

$$P = V_t I_a \cos\phi$$

$$P = \text{const} \rightarrow I_a \cos\phi = \text{const}$$



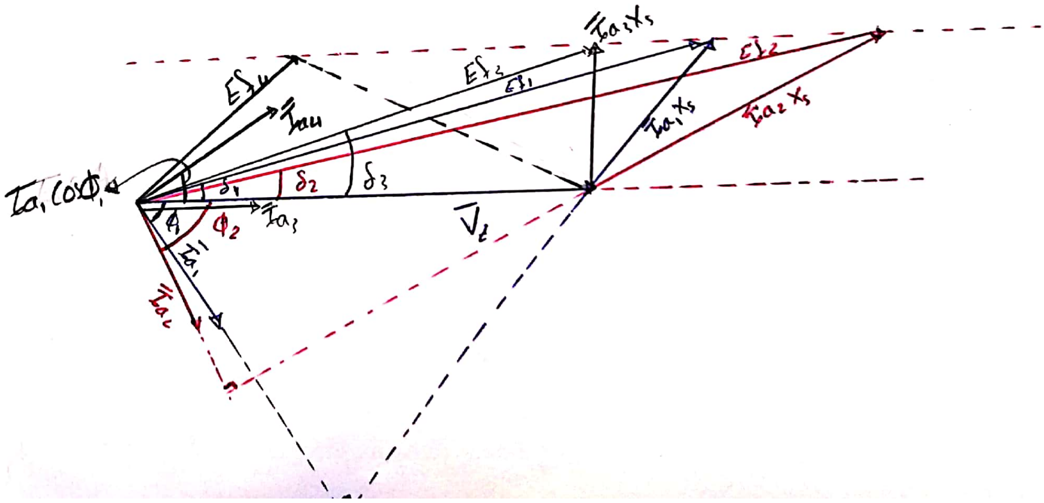
1) unity p.f , lagging , leading , constant

$$P = \frac{\bar{E}_f \, \bar{V}_t}{X_s} \sin \delta$$

$$P = \bar{V}_t \, \bar{I}_a \cos\phi$$

$P \rightarrow$ constant

$\bar{I}_a \cos\phi \rightarrow$ constant



case 2

Phasor Digram of Variable Real Power

at

$V_t = const$, $f = const$, $E_f = const$ $\rightarrow I_f = const$

locus of having E_f = constant $\Rightarrow$ Circle ; Center O ; radius E_f

$$P_1 = \frac{V_t E_f}{X_s} \sin \delta_1$$

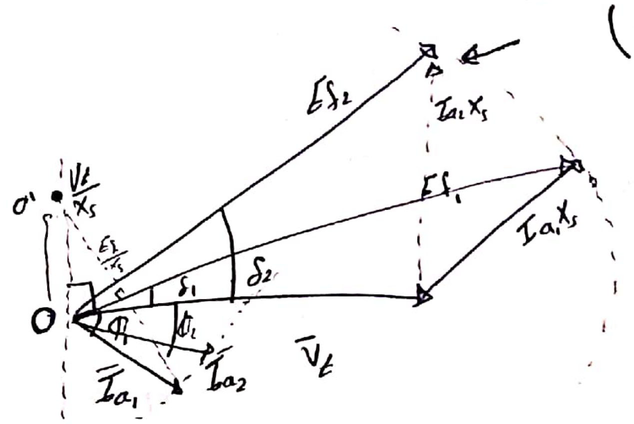
$$P_2 = \frac{V_t E_f}{X_s} \sin \delta_2 \Rightarrow \boxed{\frac{P_1}{P_2} = \frac{\sin \delta_1}{\sin \delta_2}}$$ Generator Side

load side

$$P_1 = V_t I_{a_1} \cos\phi_1$$

$$P_2 = V_t I_{a_2} \cos\phi_2 \Rightarrow \boxed{\frac{P_1}{P_2} = \frac{I_{a_1} \cos\phi_1}{I_{a_2} \cos\phi_2}}$$

locus of E_f=const (circle $\rightarrow$ O: center)



locus of I_a

Circle with O' center, $\frac{E_f}{X_s}$ radius

$$\bar{I}_a = \frac{\bar{E}_f - \bar{V}_t}{jX_s}$$

$$= \frac{-\bar{V}_t}{jX_s} + \frac{\bar{E}_f}{jX_s}$$

$$\bar{I}_a = \frac{j\bar{V}_t}{X_s} - \frac{j\bar{E}_f}{X_s}$$

$$= \frac{\bar{V}_t}{X_s} \angle 90^\circ$$

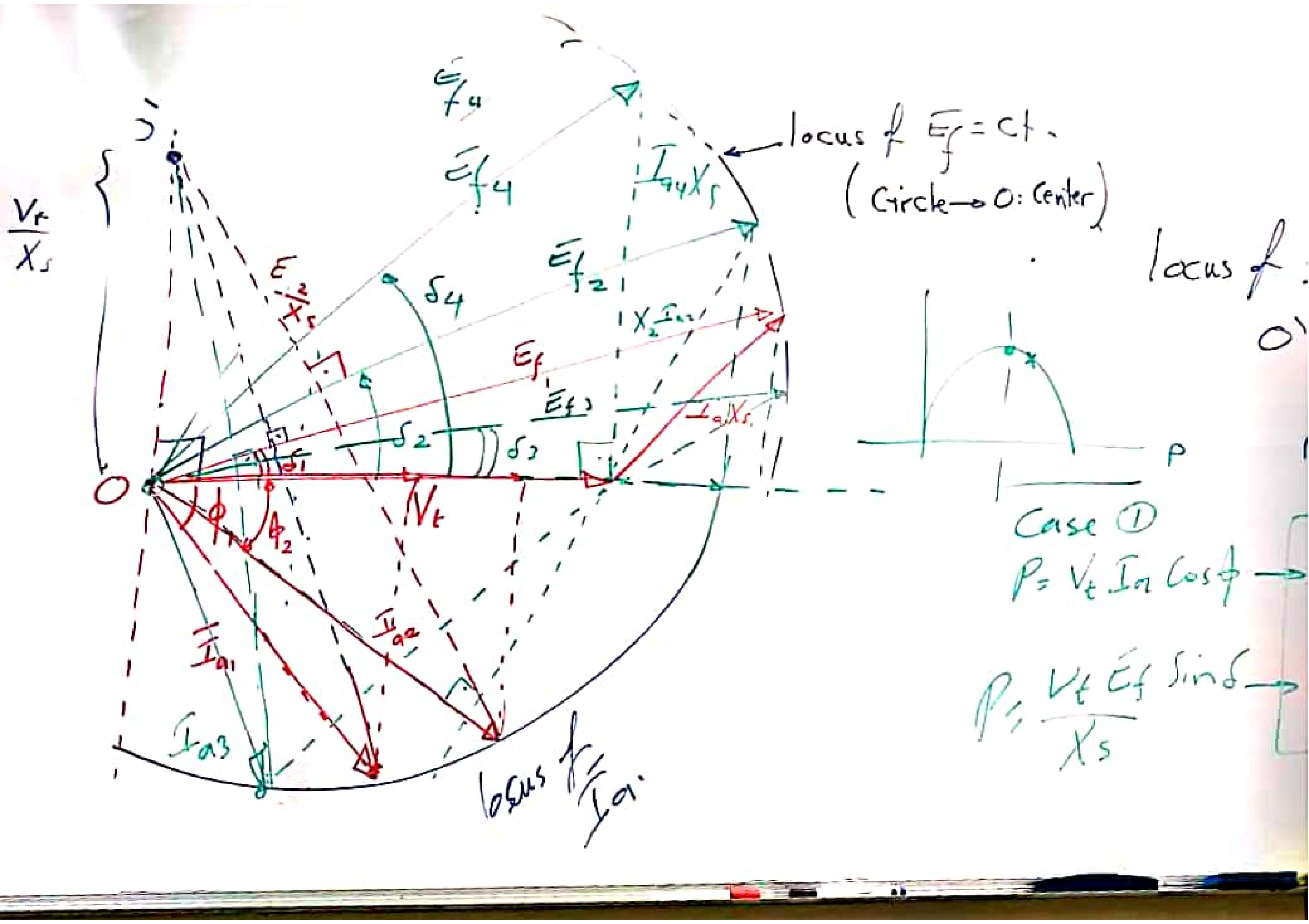
*Maximum power $\Rightarrow \delta = 90^\circ$

Power change E_f move same Amplitude

increas power increase $E_f \rightarrow \delta$

Case I $\quad P = \frac{V_t E_f}{X_s} \sin\delta \rightarrow E_f \sin\delta = const$

$P = V_t I_a \cos\phi \rightarrow I_a \cos\phi = const$



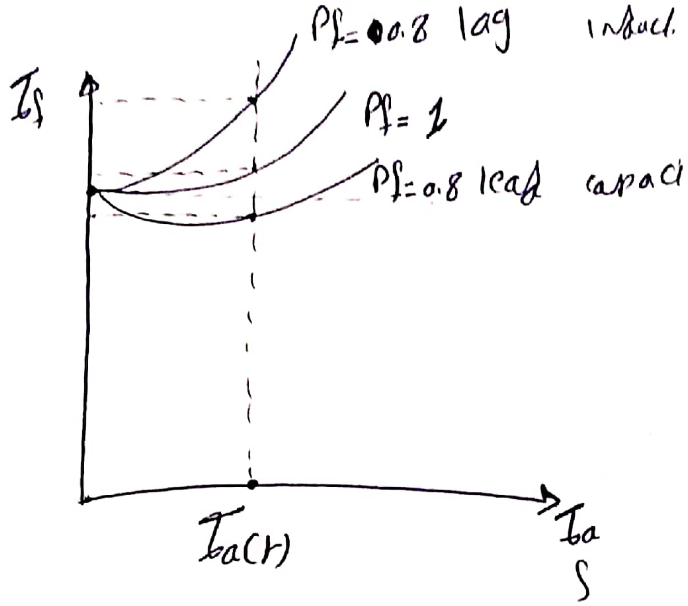
$\frac{V_t}{X_s}$
O
E_{f4}
$I_{a4}X_s$
locus of E_f = ct.
(Circle → O: Center)
locus of
E_{f2}
$X_s I_{a2}$
δ_4
E_f
E_{f3}
δ_2
δ_3
δ_1
V_t
ϕ_1
ϕ_2
I_{a1}
I_{a2}
I_{a3}
$I_a X_s$
locus of I_a
P
Case ①
$P = V_t I_a \cos\phi$
$P = \frac{V_t E_f \sin\delta}{X_s}$

Compound Curve of S.G

S.G ⇒ Relationship between I_a and I_f such that V_t = const and at constant P.f

change I_f
V_t = const

Voltage regulation
unity اقل ما يكون عند
P.f



Parallel operation of Generators:

$G_1 \rightarrow G_2$ ⇒ Isolated system

$G \rightarrow$ Infinite busbar

Conditions to be satisfied for connections in parallel ?

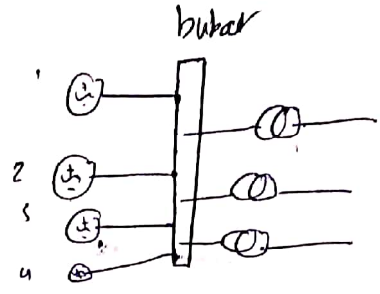
Parallel operation of synch. Machines:

Network

G + Infinite Busbar

Isolated

$G_1 + G_2$

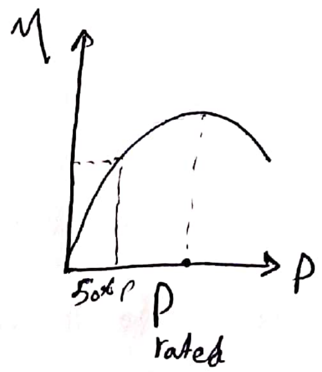


busbar (Infinite → V_t = fixed, f = fixed irrespective of load power flow)

* why Networks (parallel-connection Generator):

1) More Reliable

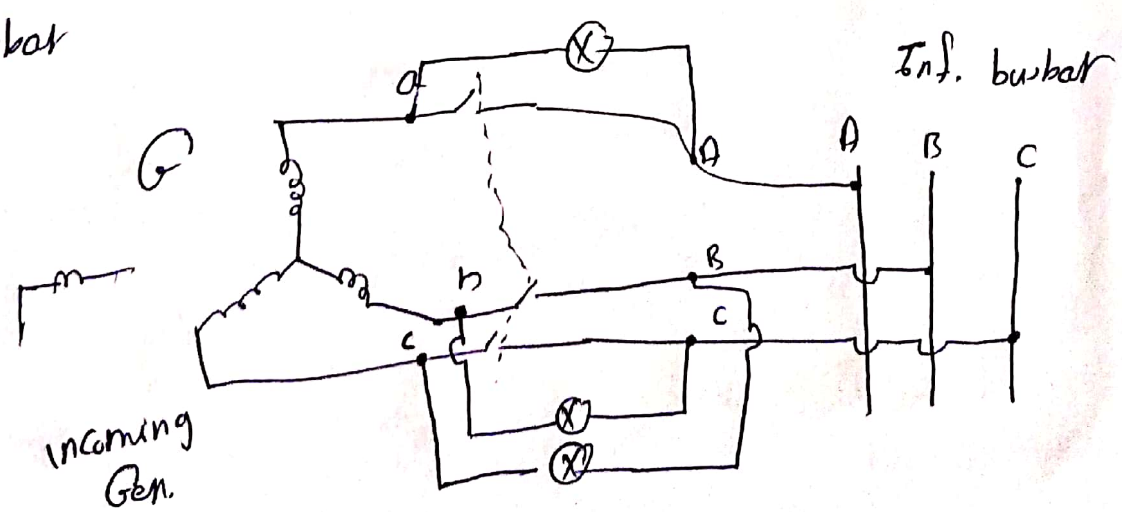
2) More (higher) effincy ~~(espece~~ (especially when the generator is under load)



3) More National security

Gen. [illegible]

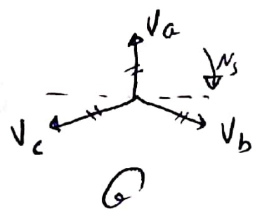
Conditions to be satisfied before Connecting anew Generator to the infinite busbar

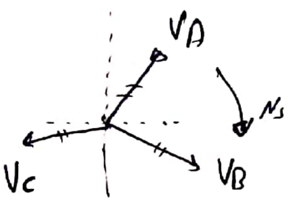


Condition :-

1) $E_f(G) = V_t(G) = V_{ab} \simeq$ ~~VAB~~ V_{AB} , Equal Voltages

2) Same phase sequence





- Using small 3-ph ~~induction~~ inductor motor
- Lamps
- Synchroscope

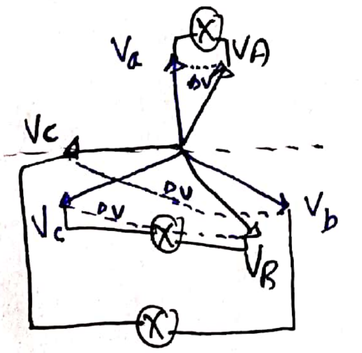
3) freq. of the Incoming Gene. should be equal or slightly higher then that of the busbar

4) Connection at the Instant at which the two Voltages are Inphase

الربط بيتم مع الشرط الرابع

Inphase

slight Brightness

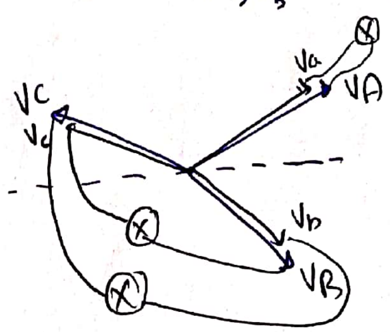


بعد فترة عندما يصبح Inphase

اللمبة بين Va & VA كطفي

اما Vb & VC phase shift 120°

Vc & VB dark

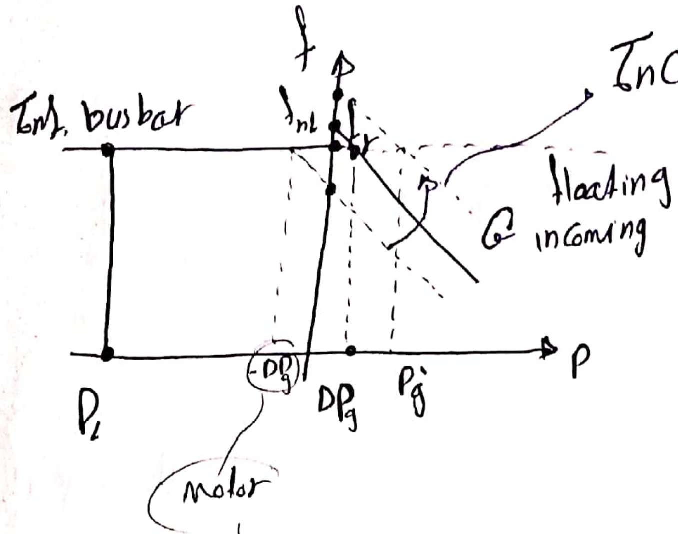


Instant of interconnection

1) freq/power curve
Active

2) Vt / reactive power curve

1)



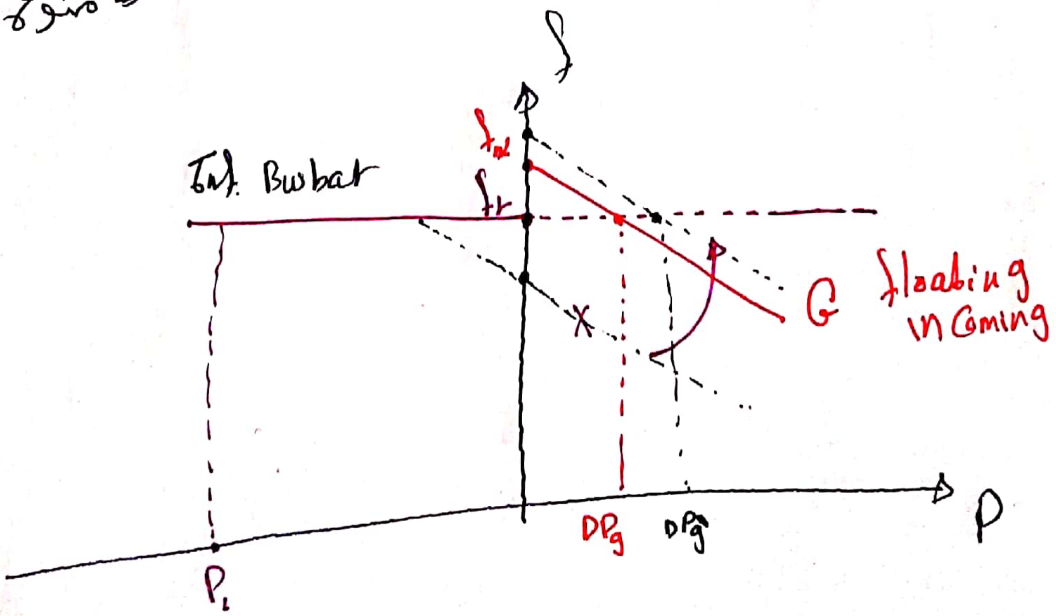
Increasing prime mover Gover set point

نفتح المصام و نزيد السرعه

Gover set point نغير موقع

اذا قللنا freq.

وهذا ممنوع



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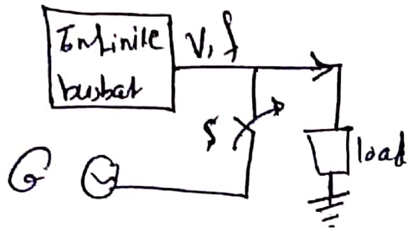
Parallel connections:-

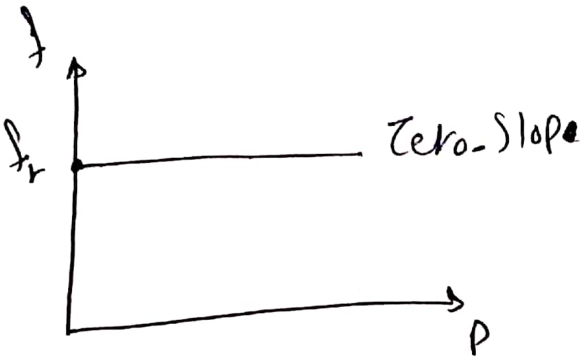
(A) Case 1:-

Generator to Infinite busbar

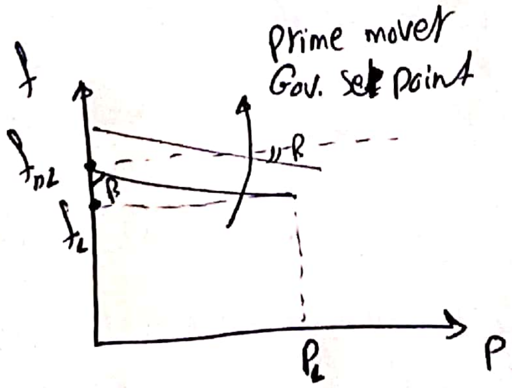


when S is closed, G is said to be floating. Housing Diagram:

f = Function of (P)



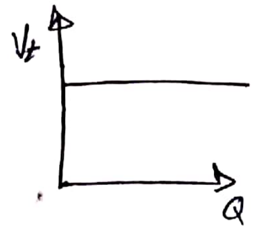
Infinite busbar



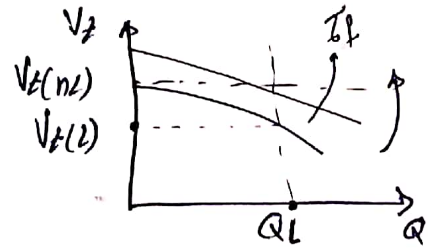
Single Generator

$P = slope * (f_{nl} - f_L)$, $slope = \tan\beta$

$V_t = f(Q)$



Infinite bus bar



V_t canbe controlled through I_f

After Floading:

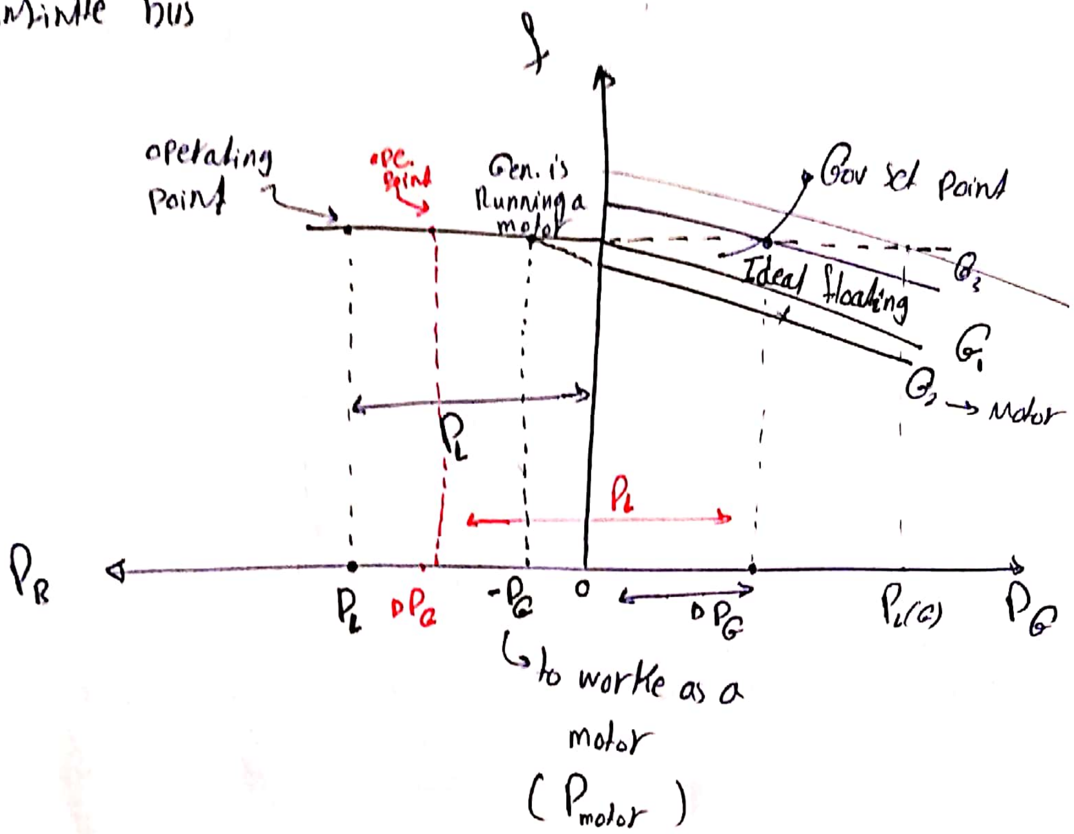
1) prime mover set point control to control the Real power the Gen. should share.

2) Generator field Current set point, to control the Reactive power

*) To make sure that the Incoming Machine is not working as a motor when S is closed, the freq of the Gen. output should be slightly grater than that Infinite bus

Infinite bus

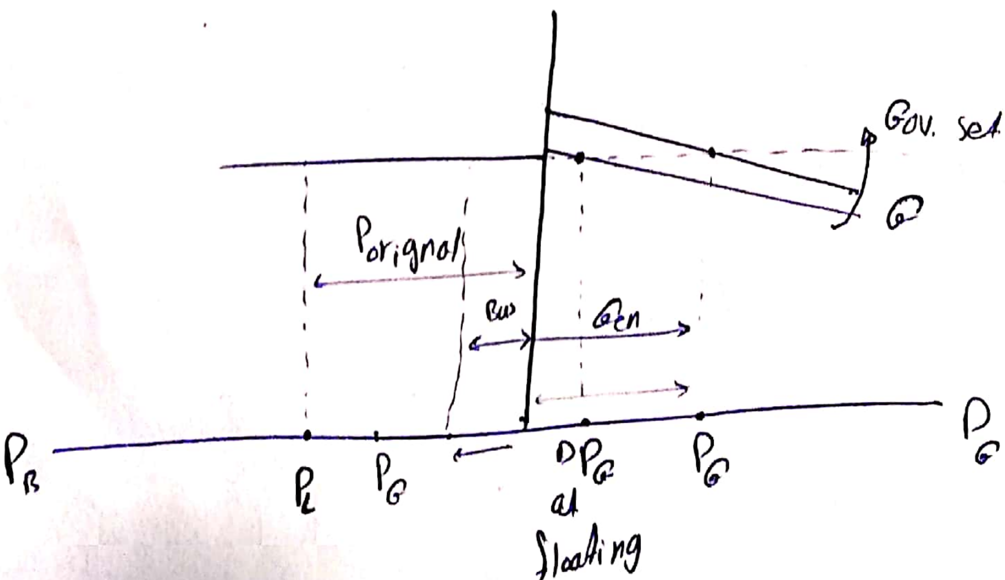
Incoming Machine



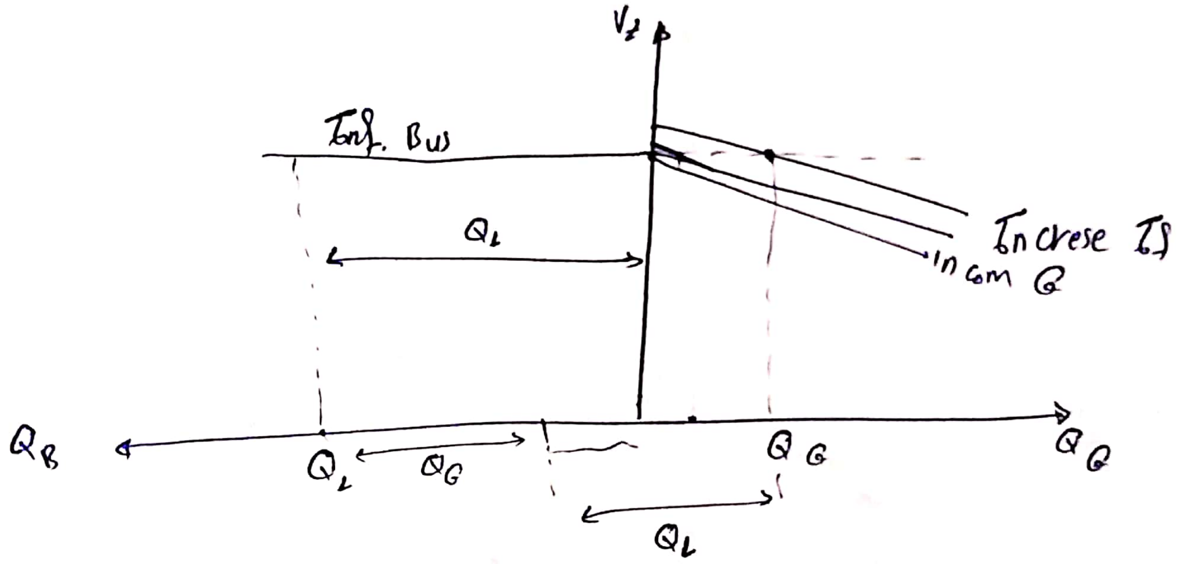
*) If this in not the case, a reverse - Power Trip facilities with open the switch S to avoid Motoring Action of the Gen.

*) In Case ③ (Normal Case) in practical life, G will share load power by DP_G
(Inf. bus) power will be $P_L - DP_G$

*) If the power need to be shared by G is to be increased, the P.M. Governer set point is increased.

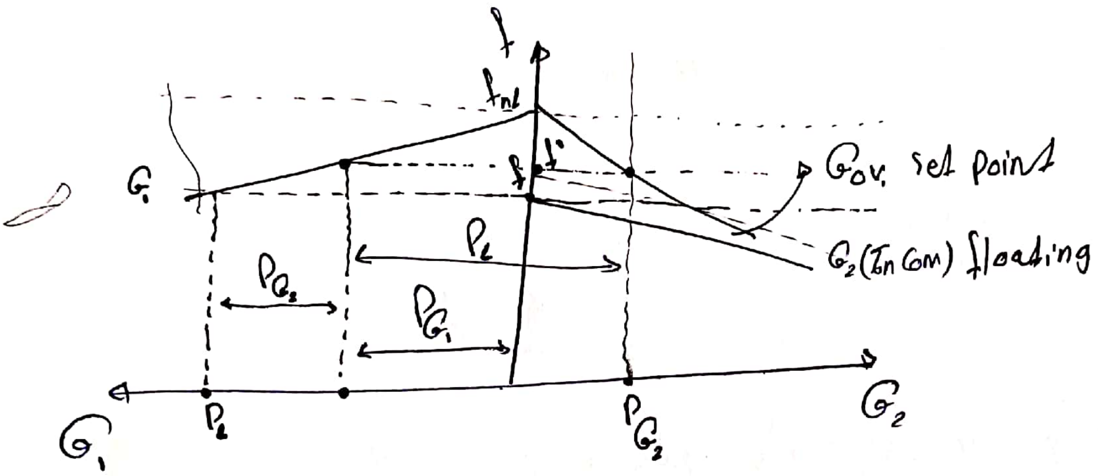


To control reactive power Q (and the power factor), the field current is to be controlled to maintain the ~~freq~~ req. Q (PS)



Case 2:

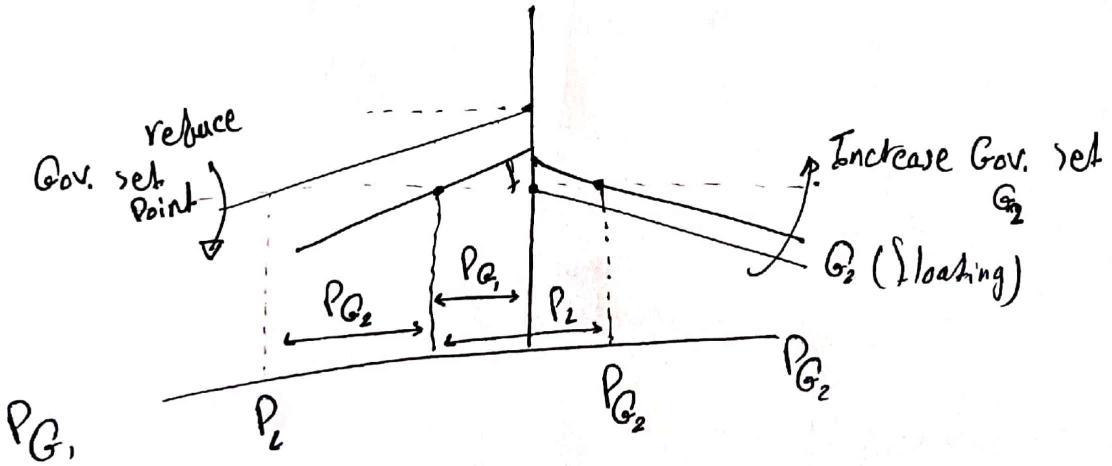
G_2 to G_1 in parallel V_t and $f \neq$ const.



How to keep freq constant ??!

*) when connecting G_2, freq of the system frequency increase (after load sharing)

*) If the freq is to be fixed at its original value



*) the Gov set point of G_1 is to be reduced and Gov. set point of G_2 should be increased.

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PROBLEMS

8-1. At a location in Europe, it is necessary to supply 300 kW of 60-Hz power. The only power sources available operate at 50 Hz. It is decided to generate the power by means of a motor-generator set consisting of a synchronous motor driving a synchronous generator. How many poles should each of the two machines have in order to convert 50-Hz power to 60-Hz power?

8-2. A 2300-V 1000-kVA 0.8-power-factor-lagging 60-Hz two-pole Y-connected synchronous generator has a synchronous reactance of 1.1 Ω and an armature resistance of 0.15 Ω. At 60 Hz, its friction and windage losses are 24 kW, and its core losses are 18 kW. The field circuit has a dc voltage of 200 V, and the maximum I_F is 10 A. The resistance of the field circuit is adjustable over the range from 20 to 200 Ω. The OCC of this generator is shown in Fig. P8-1.

(*a*) How much field current is required to make V_T equal to 2300 V when the generator is running at no load?

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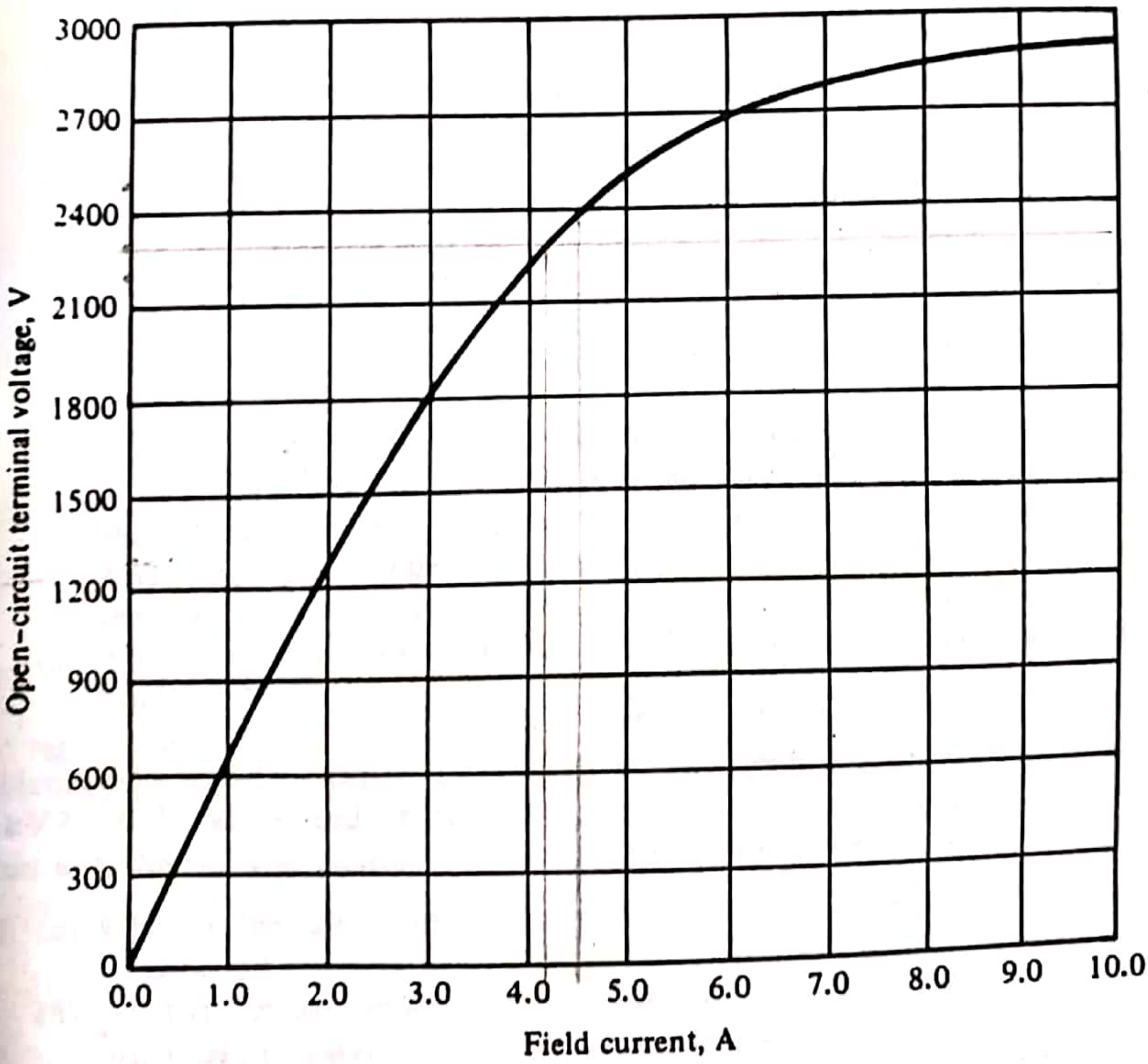
(*b*) What is the internal generated voltage of this machine at rated conditions?
(*c*) How much field current is required to make V_T equal to 2300 V when the generator is running at rated conditions?
(*d*) How much power and torque must the generator's prime mover be capable of supplying?
(*e*) Construct a capability curve for this generator.



speci
assump

FIGURE P8-1
The open-circuit characteristic for the generator in Prob. 8-2.

... adjusted to a

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(v)

Problem 1

300 KW at 60 Hz

Available freq is 50 Hz

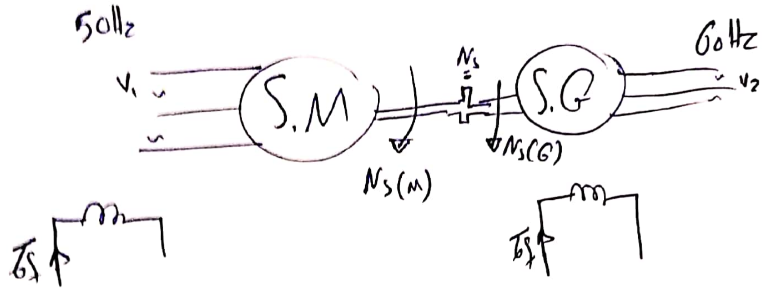
Power to be Gen by Motor-Generator set

synch → synch Gen

P_G, P_m = ??

How many poles should be convert from 50 to 60 Hz ?

Conventional M-G set



$$N_{s(m)} = N_{s}(G)$$

$$N_{s(m)} = \frac{60 f_m}{P_m}$$

$$N_{s(G)} = \frac{60 f}{P_G} = \frac{60 * 60}{P_G}$$

P_m	$N_{s(m)}$
1	3000
2	1500
3	1000
4	750
$\boxed{5}$	$\boxed{600}$
6	500
⋮	⋮

P_G	$N_{s(G)}$
1	3600
2	1800
3	1200
4	900
5	720
$\boxed{6}$	$\boxed{600}$
⋮	⋮

$P_G = 6 \Rightarrow 12$ Poles

$P_m = 5 \Rightarrow 10$ poles

Problem 2

A 2300 V, 1000 KVA, 0.8 p.f lag, 60 Hz, 2-pole

Y-connected synch. Generator $\Longrightarrow$ Nameplate Data

Nominal Value

Rated Value

$V_{L(r)} = 2300\,V$ / line

$S_r = 1000\,KVA \Rightarrow$ output

Prime mover $S = S_r +$ losses

$P.f = 0.8 \longrightarrow$

حاشي ~~شطب~~
تصنيف المادة $\rightarrow$ rated current

* $W_s = \frac{2\pi N_s}{60}$

$I_{a(r)L} = \frac{S_r}{\sqrt{3}\,V_r} = \frac{1000K}{\sqrt{3} \times 2300} = 251\,A$

$I_{a(r)ph} = I_{a(r)L} = 251\,A$

$V_r, f_r \Rightarrow \Phi_r \; (V_r = 4.44 N f_r \Phi_r)$

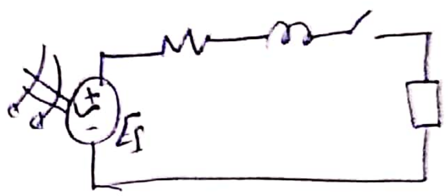
same example at 60 Hz, $P_{mech} = 24\,Kw$, $P_{core} = 18\,Kw$

field $V = 200\,V$, $I_{f_m} = 10\,A$, $R_f = 20 - 200\,\Omega$ OCC - given

$R_a = 0.15\,\Omega/ph$ $X_s = 1.1\,\Omega/ph$

a) $I_f = ??$ such that $V_t = 2300$ at no-load ($I_a = 0$)

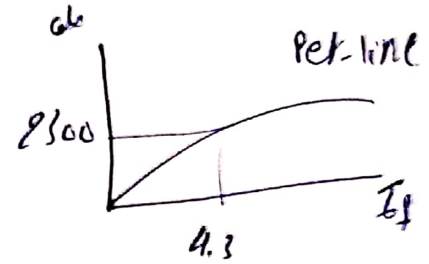
at no load $I_a = 0$



so $\boxed{V_t = E_f}$ => $E_f = 2300$ $\sqrt{3}$/line

from the curve

$I_f = 4.3$ A



b) internal generated voltage at rated loading conditions

$E_{f(r)_{ph}} = V_{t_{ph}} + I_{a(r)_{ph}} Z_s$ → allways per line

$V_{t_{ph}} = \frac{2300}{\sqrt{3}} \angle 0$, $I_{ph(r)} = 251 \angle -\cos^{-1} 0.8$

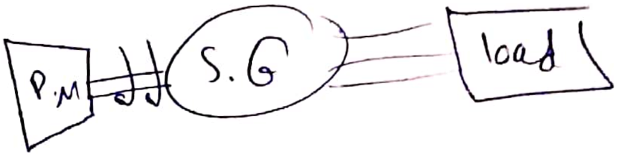
$I_{a(r)_{line}} = \frac{S_{(3ph)}}{\sqrt{3}\, V_{t(r)_L}} = \frac{10^6}{\sqrt{3}\, V_{t(r)_L}} = 251$ A $S_L = \sqrt{3}\, V_L I_L$

$E_{f(r)_{ph}} = 1536.6 \angle 7.4$ V_{ph} $Z_s = \sqrt{0.15^2 + 1.1^2} \angle \tan^{-1} \frac{1.1}{0.15}$

$L: \sqrt{3}\, E_f$ $1536 \cdot \frac{2300}{\sqrt{3}}$

% $E_f = 1536.6 \angle 7.42$ δ

3) Find P_{PM}



$P_{PM} = 24Kw + 18Kw + P_{cu} + P_{load}$

$P_{P.M} = \underbrace{\underbrace{P_{mech} + P_{core}}_{\text{No-load losses}} + P_{cu}}_{P\ \text{losses}} + P_{load}$

$P_{cu} = 3 I^2_{a(ph)} R_a$

$= 28.35\ Kw$

$P_{P.M} = 870.35\ Kw$

$Q = 600\ KVAR$

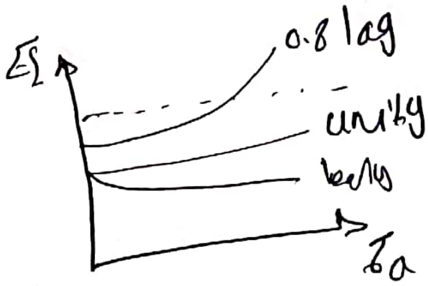
$S * P.f$

$10^6 * P.f$

$P_L = 800\ Kw$

4) $\eta = \dfrac{P_{out}}{P_{in}} = \dfrac{800\ Kw}{870.35\ Kw}$

5) capability curve



6) Torque by the prime mover $\Rightarrow T_q = \dfrac{P_{P.M}}{W_m} = \dfrac{P_{P.M}}{W_s}$

$W_s = \dfrac{2\pi N_s}{60}$, $N_s = \dfrac{60 f}{P} = 3600$

P → 1 (pairs)

$T_q = 2308$

7) the voltage regulation at rated conditions

$V.R = \dfrac{V_t(\text{line or phase})\ \text{no-load} - V_t(\text{load})\ \text{or full load}}{V_t(\text{load})}$

V.R i can use ~~the~~ line or phase

*) leading PF, rated condition

$V_{ph} + I_{a/ph} (Z_s)$

leading P.f

$E_f = \frac{2300\angle 0}{\sqrt{3}} + 251\angle + \cos(P.f) \times Z_s \angle 82.2$

$E_f = 1217.43 \angle 11.5$ New δ

$1217.43 \angle \frac{2300}{\sqrt{3}}$

$1217.43 * \sqrt{3}$

$V.Reg = \frac{2108 - 2300}{2300} = -8.3\%$

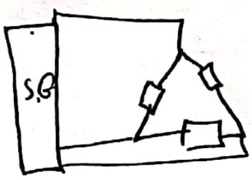
Unity P.f $\quad E_f = \frac{2300\angle 0}{\sqrt{3}} + 251\angle 0 \times Z_s$ $\quad 1.11\angle 82.2$

---

ex)

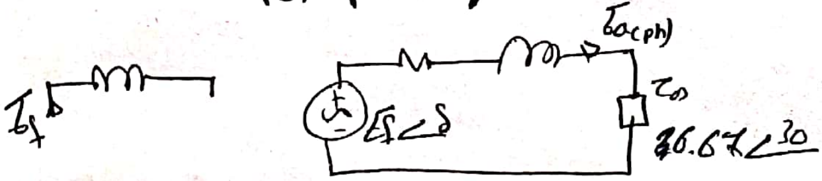
$I_f = 4.5A \xrightarrow[\text{curve}]{\text{from}} E_f = 2400V$ (the curve allways use the line)

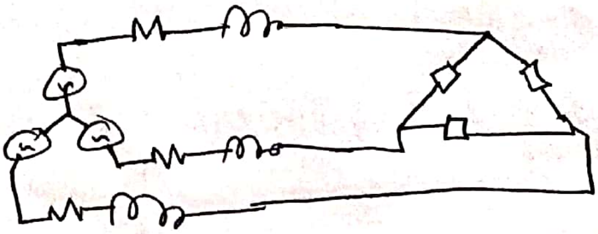
$\bar{V}_L = \bar{V}_L \angle 0 = ??$ Δ S.G



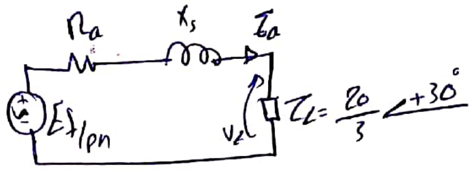
$Z_D = 20\angle 30° \Omega$

per phase eq





$Z_Y = Z_D/3$ (balanced)



يفضل التحويل من
$Y \leftarrow D$

Ef curve allways per-line

$I_f = 4.5A \xrightarrow[\text{curve}]{\text{from}} E_f = 2400\,V$

$V_t = E_f - I_a Z_s$

$V_t\angle 0 = E_f\angle\delta - 187.377\angle\delta - 36.8 * Z_s$

Per-phase

$I_a = \dfrac{E_f/\sqrt{3}}{Z_s + Z_L}$

$Z_s = \sqrt{R_a^2 + X_s^2}\ \angle \tan^{-1}\dfrac{X_s}{R_a}$

$= 1.11\angle 82.2^\circ\ \Omega/ph$

$I_a = \dfrac{1356.773\angle\delta}{1.11\angle 82.2^\circ + \frac{20}{3}\angle 30}$

$I_a = 187.377\angle\delta - 36.8\ A$

~~$V_t\angle 0 = E_f\angle\delta$~~

$V_t + j0 = 1356.773\cos\delta + j1356.733\sin\delta - \underbrace{(187.377\angle\delta - 36.8 * 1.11\angle 82.2^\circ)}_{207.88\angle\delta + 45.4^\circ}$

$V_t + j0 = [1356.773\cos\delta + 207.88\cos(\delta + 45.4^\circ)] + j[1356.733\sin\delta + 207.88\sin(\delta + 45.4^\circ)]$

~~$j0 = 207.88(\delta + 45.4^\circ)$~~

$j0 = j[1356.733\sin\delta + 207.88\underbrace{\sin(\delta + 45.4^\circ)}_{\sin\delta\cos 45.4^\circ - \cos\delta\sin 45.4^\circ}]$

$0 = 135.733\sin\delta + 207.88(\sin\delta\cos(45.4^\circ) - \cos\delta\sin(45.4^\circ))$

Divided by $\cos\delta$

$\cos 45.4 = 0.7$

$\sin 54.4 = 0.71$

$0 = 135.733\tan\delta + 145.516\tan\delta - 147.594$

$\tan\delta = 0.524$

$\therefore\ \boxed{\delta = 5.7^\circ}$

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Real part

$V_\phi = 15840.1 \ \Omega/ph$

$V_\phi = 2667.6 \ \Omega/$ line

13.8 KV, 10 MVA, 0.8 P.f lag, 60 Hz, 2-Pole, Y-connected, st. turbine

$X_s = 18\Omega/ph \quad R_a = 2\Omega/ph$

G → connected to Busbar (f, V_ϕ = constant)

1) $\bar{E}_f = ??$
2) δ

rated condition

3) I_f = const, $P_{max} = ??$, $P_{reserve}$ at full load.

$Q = ??$

$$I_{a(r)} = \frac{S_r}{\sqrt{3}\, V_{L(r)}}$$

$$= \frac{10\times10^6}{\sqrt{3}\times13.8\times10^3} = 418.37\angle\overset{lag}{-36.87^\circ}$$

$$E_f = \frac{13800}{\sqrt{3}}\angle 0 + 418.37\angle-36.87 \times 18.11077\angle 83.66^\circ$$

$$E_f = 13863\angle 25.53^\circ \ \Omega/ph$$

$E_f = 24011.87$ V/line

$E_{f\,line} = \sqrt{3}\, E_{f\,ph}$

$\delta = +25.53^\circ$

at any load

$$I_a = \frac{S}{\sqrt{3}\, \underbrace{V_{L(r)}}_{\text{Infinit bus}}}$$

$I_a = |I_a|\angle\theta$ — + lead, - lag, 0 unity

$$Z_s = \sqrt{2^2+18^2}\ \underbrace{\angle \tan^{-1}\frac{18}{2}}_{\theta}\ \Omega/ph$$

$Z = |Z_s|\angle\theta$

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$$P = \frac{3 V_{ph} E_{f}^{ph}}{X_s} \sin\delta \longrightarrow R_a = 0 \Rightarrow P_{max} \Rightarrow \text{when } \delta = 90$$

$$P = \frac{3 V_\phi E_f}{Z_s} \cos(\delta - \theta) - \frac{3 V_\phi^2}{Z_s} \cos\theta \longrightarrow R_a \neq 0$$

P_{max} if $R_a \neq 0$

$$\frac{\partial P}{\partial \delta} = 0 = -\frac{3 V_\phi E_f}{X_s} \sin(\delta - \theta)$$

$$\sin(\theta - \delta) = 0$$

$$\therefore \theta = \delta = 83.66^\circ$$

$$P_{max} = \frac{3 V_\phi E_f}{Z_s} * \cos(83.66 - 83.66) - \frac{3 V_\phi^2}{Z_s} \cos(83.66^\circ) = 17.6717 \text{ MW}$$

P_{max} at $R_a = 0 \Rightarrow P_{max} = 18.9$ MW

$R_a \longrightarrow 0$

$P_{max} = 18.9$ M

Reserve $= 18.9 - \underbrace{10(0.8)}_{S\,\text{p.f}} = 10.9$ MW

$\rightarrow$ Power rated

$R_a \neq 0$

Reserve $= 9.67$ MW

Synchronous Motors: SM non self starting Motor

*Reasons: for each current cycle from the supply the rotor vibrates with zero average torque. and since $E_f = 0$ → large armature current ≈ SCC
$V_t - E_f \approx V_t$.

Which can distroy the Motor is runs for a relatively long period of time.

* SM Can be Controlled to run at any pf (unity, leading or lagging).

This can be done by field control. (PF correction).

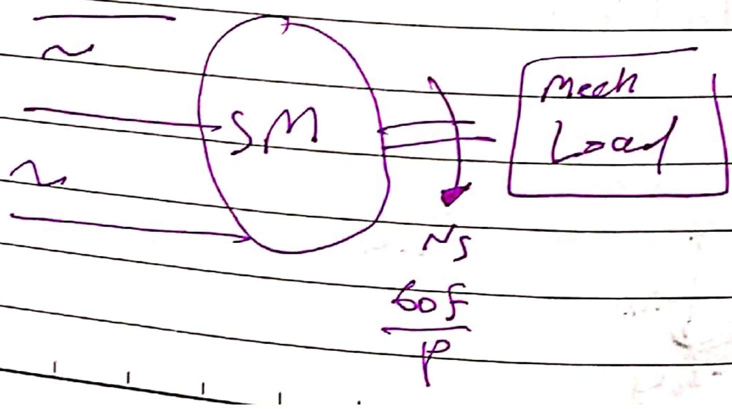
* SMs is expensive Motor (2-3) same size Induction motor.

* the only Motor that has zero speed regulation

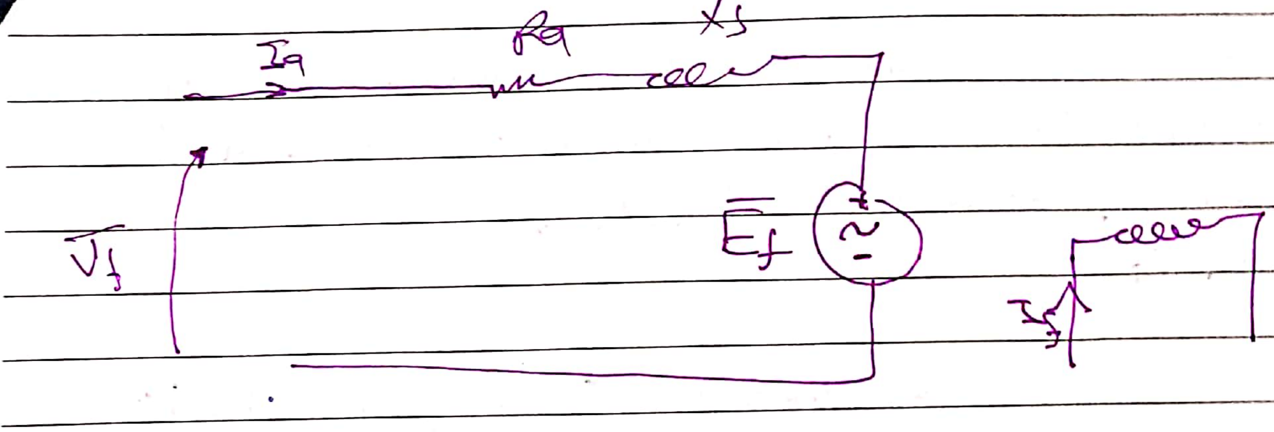
$N_m = N_{syn}$

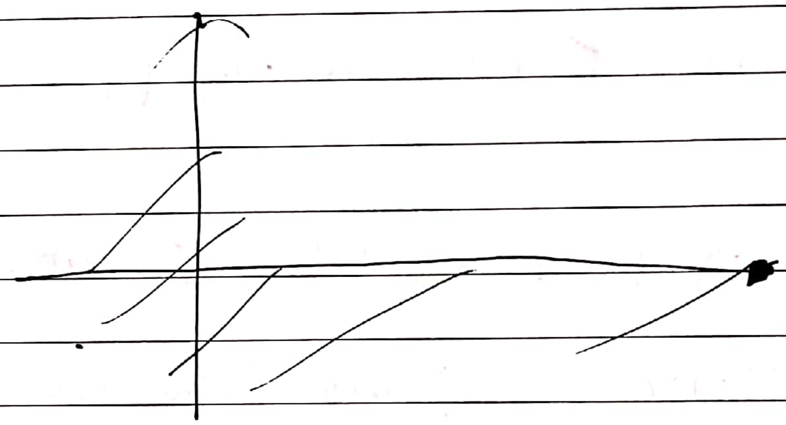
$$\text{Speed Reg} = \frac{N_{syn} - N_{mec}}{N_{syn}} \approx 0$$

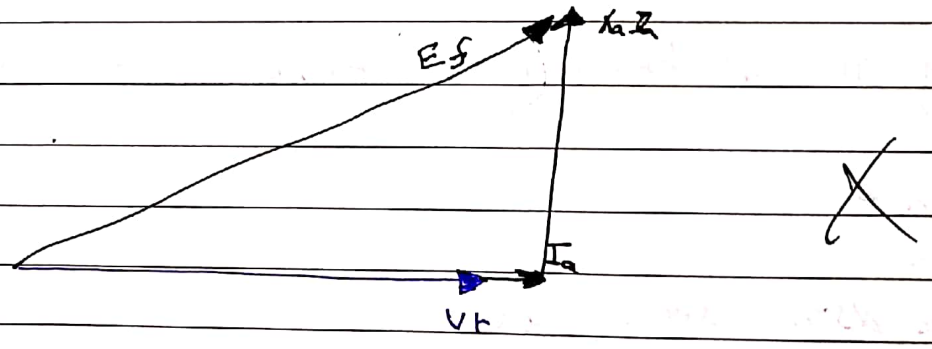
V, f



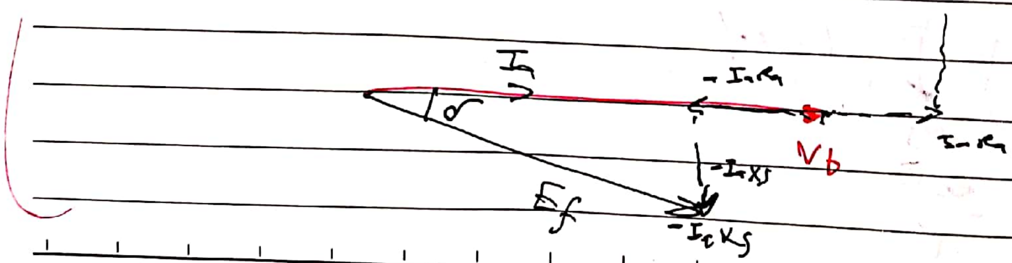
eqa CKT





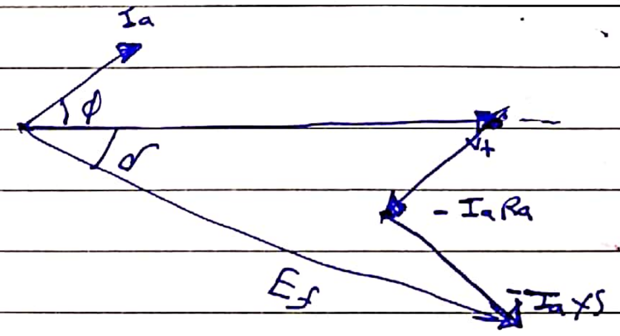


Normal Excitation



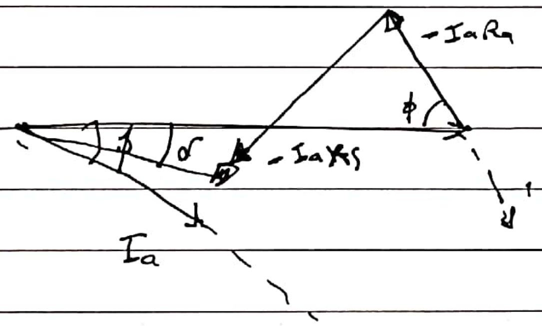
leading pf :-

over excitation

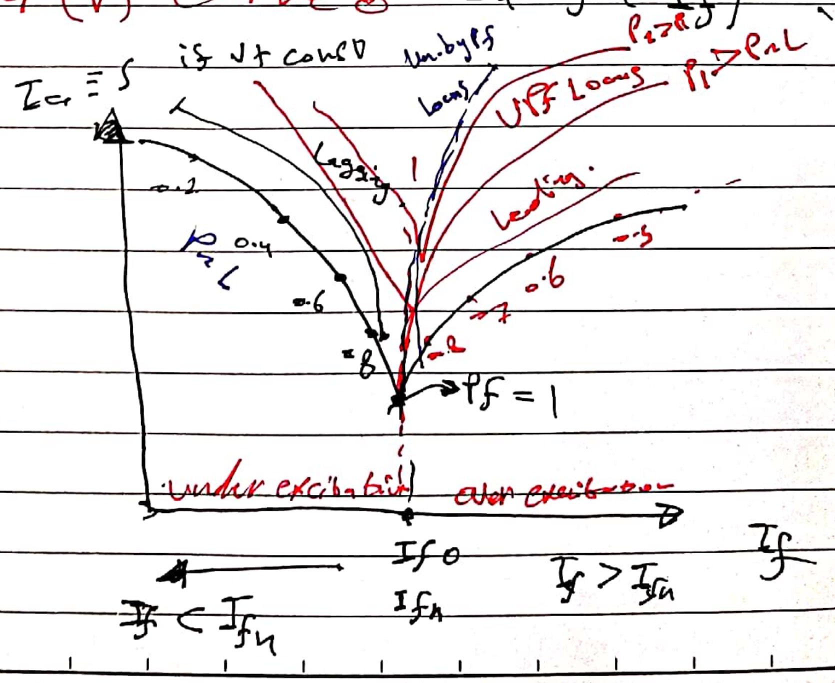


Lagging pf

small Emf Under excitation



(U) or (V) Curve :- $I_a = f(I_f)$



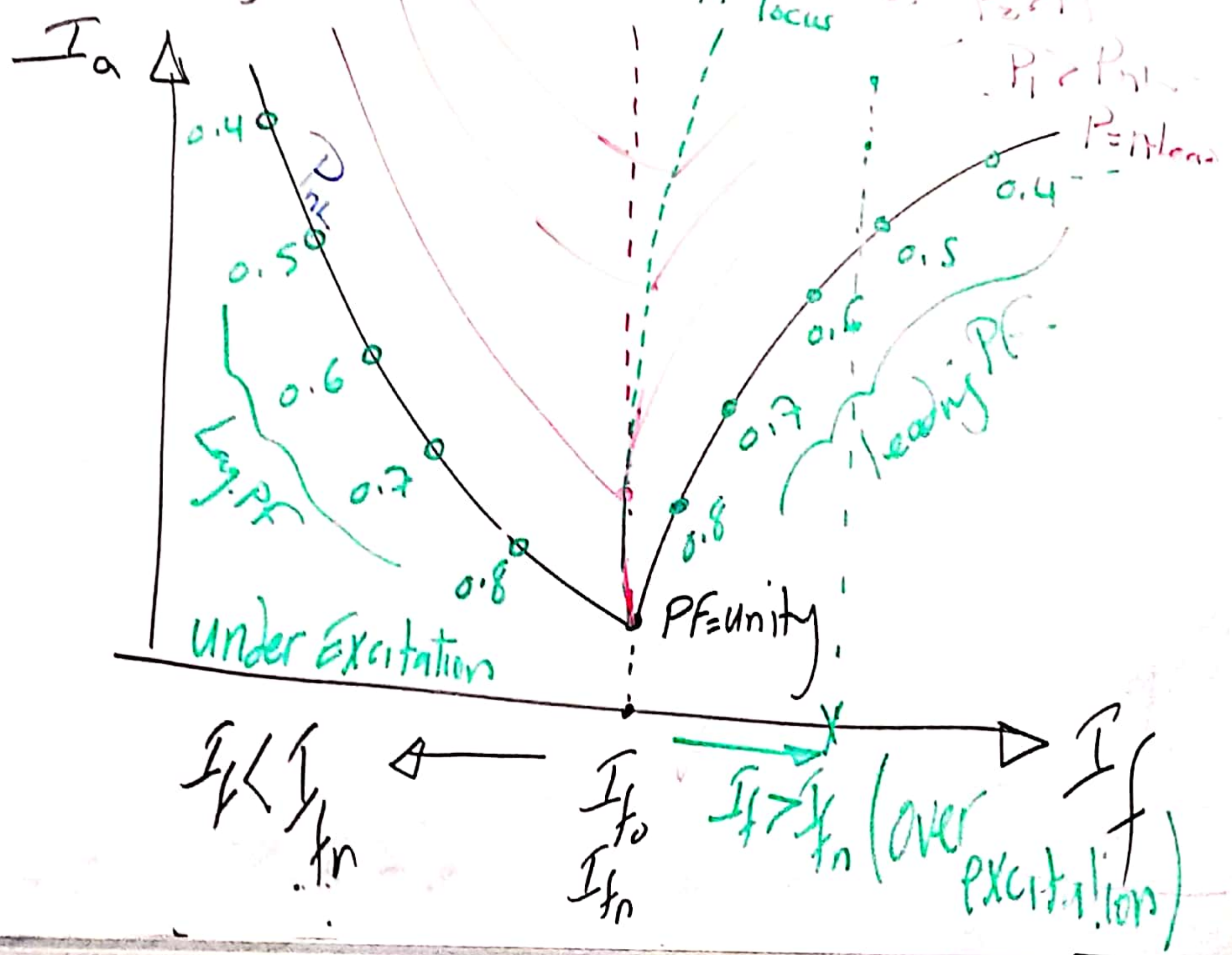
$I = \frac{P}{V \cos\theta}$ pf

I↑ pf ↓

N_s and P = const

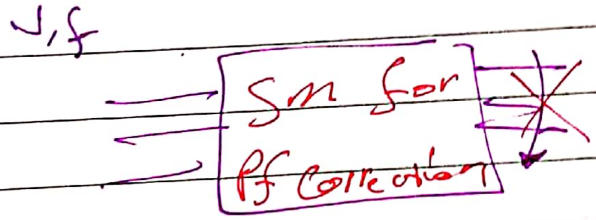
U or (V) Curve

$I_a = f(I_f)$.

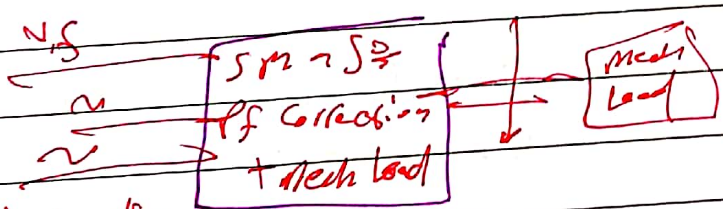


SM's can supply Reactive power only $P=0$, $Q \neq 0$ (+)
The motor in this case is known as synchronous capacitor. "Condenser".

Reactive power



& this motor can also be used to supply mech power to mech. loads while its power factor is leading (over excitation).



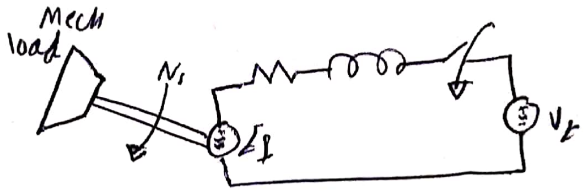
pf is leading

Ex: $V_t = 2300V$, $f = 50\ Hz$, $500\ kW$, 2 pole
synch motor $R_a = 0.1\Omega$, $X_s = 1\Omega/Ph$
If the motor is to supply rated power at [illegible] lead
find I_f (Given curve occ).

E_f.

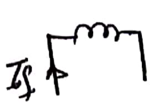
to find $I_f \longrightarrow E_f$

$$\bar{E}_f = \bar{V}_t - \bar{I}_a(R_a + X_s)$$



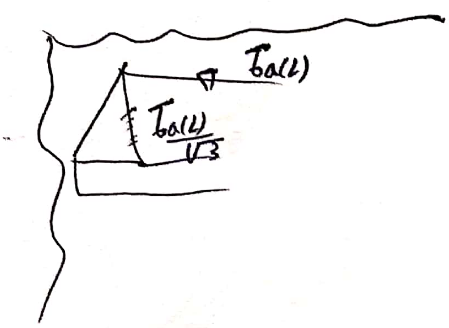
$$Z_s = (R_a + jX_s) = 0.1 + j1.0$$

$$= 1.0\angle 84 \ \Omega/ph$$



PF in = 0.6 load

$$I_{a_L} = \frac{P_{in}}{\sqrt{3} V_L \cos\phi} = \frac{500K}{\sqrt{3} * 2300 * 0.8} = 156.8 \text{ A/ph (A/line)}$$



$$\bar{I}_a = 156.8\angle +\cos^{-1} 0.6 = 156.8\angle 53.13^\circ \text{ A}$$

$\boxed{\text{Per phase } \frac{V_t}{\sqrt{3}}}$

$$E_f = \frac{2300}{\sqrt{3}}\angle 0 - 156.8\angle 53.13^\circ (1.01\angle 84.1)$$

$$E_f = 1448\angle -4.24^\circ \ V/ph \Rightarrow \boxed{\delta = -4.24}$$

$E_f = 1448 \ V/ph$

$E_f = 1448\sqrt{3} = 2508 \ V/line$

curve → from OCC ⇒ $I_f = 4.6A$

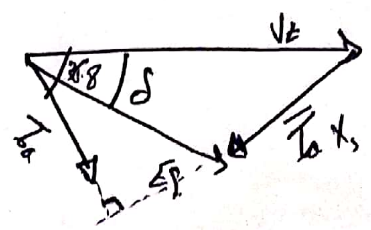
$$S_{in(rated)} = \frac{P}{P.f} = \frac{500k}{0.8} = 625 \ KVA\angle +36.87^\circ$$

$$= 500 + j315 \ KVA$$

$$S_L = \frac{500}{0.6} = 833.33 \ KVA\angle 53.13$$

$$= 500 - \underbrace{j666}_{Q_{new}} \ KVA$$

Neglected Ra



$$E_f = \frac{2300}{\sqrt{3}} - 156\angle -36.8 \times 1.01\angle 84^\circ$$

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ex)

3 Identical S. Gen are running in parallel.

rated 3MW at 0.78 P.F lagg

G_A: $f_{nl} = 61\ Hz$, speed Droop (A) = SD(A) = 3.4%

G_B: $f_{nl} = 61.5\ Hz$, speed Droop (B) = SD(B) = 3%

G_C: $f_{nl} = 60.5\ Hz$, speed Droop (c) = SD(c) = 2.6%

$$SD = \frac{speed_{nl} - speed_{fl}}{speed_{fl}} = \frac{N_{nl} - N_L}{N_L}\ \%$$

$$freq.\ Droop = \frac{f_{nl} - f_L}{f_L}$$

$$\boxed{N = \frac{60f}{P}}$$

S.D = freq Droop

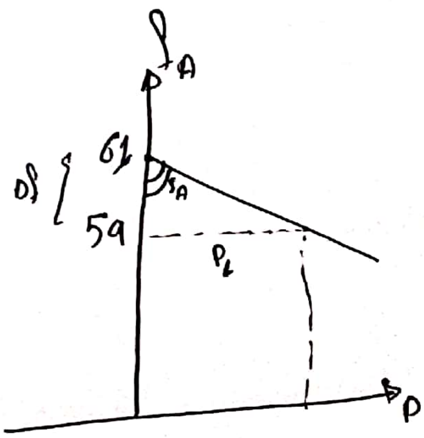
If

$P_L = 7MW \longrightarrow f = ??$ then

$P_A = ?$, $P_B = ?$, $P_C = ?$

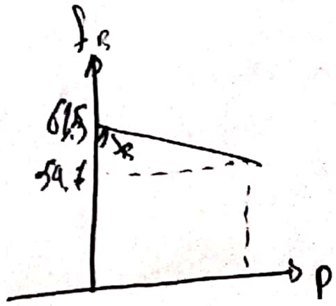
G_A

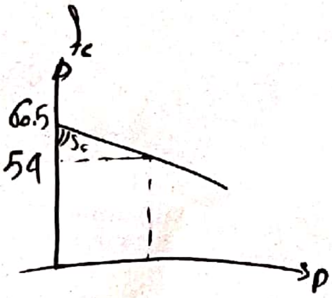
$$0.034 = \frac{61 - f_L}{f_L} \Rightarrow f_{L(A)} = 58.9 \approx 59\ Hz$$



G_B

$$0.03 = \frac{61.5 - f_L}{f_L} \Rightarrow f_{L(B)} = 59.7\ Hz$$





G_C:

$$0.026 = \frac{60.5 - f_L}{f_L} \Rightarrow f_{L(c)} = 59\ Hz$$

نرسم فقط واحد

S_A: Sloop of P/f ch. of Gen. A

$$S_A = \frac{3MW}{61-59} = \frac{3}{2} = 1.5\ MW/Hz$$

$$S_B = \frac{3MW}{61.5-59.7} = 1.67 MW/Hz$$

$$S_C = \frac{3MW}{60.5-59} = 2 MW/Hz$$

$$P_L = P_A + P_B + P_C$$

$$7M = 1.5[61-f] + 1.67[61.5-f] + 2[60.5-f]$$

$$f = 59.6\ Hz$$

$$\cancel{S_A}\ 1.5[61-59.6] = P_A$$

$$P_B = 1.67[61.5-59.6]$$

$$P_C = 2[60.5-59.6]$$

$\therefore$

$P_A = 2MW$

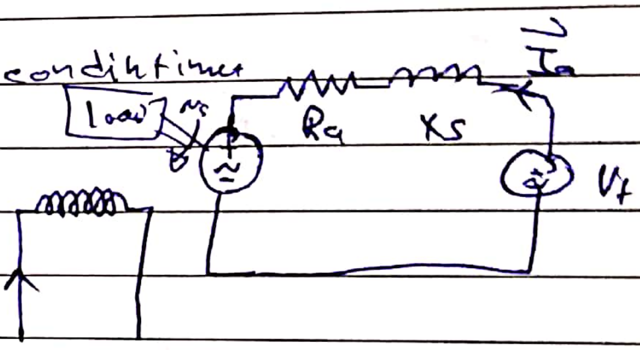
$P_B = 3.17\ MW \Rightarrow$ over load

$P_C = 1.8MW$

Δ connected

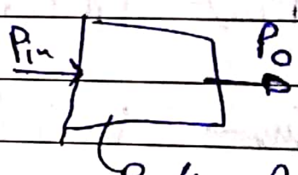
440 V, 50 Hz, 100 HP, 0.8 lead pf, 89% efficiency, synch motor has $R_a = 0.22\ \Omega/ph$, $X_S = 3.0\ \Omega/ph$, 4-pole

a) input current, Pin at rated conditions



$T_q(0) = ?!$

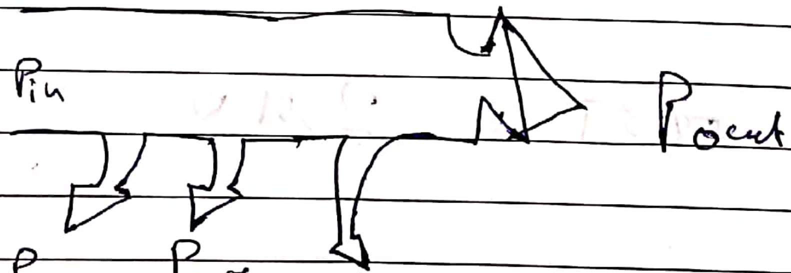
$P_o = \underbrace{100}_{HP} \times 746 = 74.6\ kW$



$\mu = \frac{P_o}{P_{in}}$

$P_{in} \rightarrow$ Rated power

$P_{in} = \frac{P_o}{\mu} = \frac{74.6}{0.89} = 83.82\ kW$



P_{cu} → $I^2 R$

P_{core} → constant

P_{mech} (windage & friction) → constant

* P_{mech} → constant since N_s → constant.

* P_{core} → constant since V_t & f are fixed.

* $P_{cu} = 3 \cdot I_{ph}^2 \cdot R_a$ "variable or load-dependent losses"

$P_{in} = \sqrt{3}\; I_{a(L)} * V_{t(L)} \cos\phi$

$I_{a(L)} = \dfrac{83.82 * 10^3}{\sqrt{3} * 440 * 0.8} = 137.5$ A/line

$I_{a(ph)} = \dfrac{137.5}{\sqrt{3}} = 79.375$ A

$P_{converted} = P_{in} - (P_{cu} + P_{core})$ & $(P_{out} + P_{mech})$

$Tq(o)_{sh} = \dfrac{P_o}{w_m} = \dfrac{P_o}{w_s}$

$W_m = W_s = \dfrac{2\pi\, N_s}{\cancel{60}\;\cancel{P}\,60}$

$N_m = N_s = \dfrac{60 f}{P} = \dfrac{\cancel{60}^{30} * 50}{2}$

$= 1500$ RPM

$Tq_{conv} = \dfrac{P_{conv}}{W_s}$

$= \dfrac{2\pi}{60} * \dfrac{60 f}{P} = \boxed{2\pi f}$

$Q = \sqrt{3}\; I_{a(L)} * V_t(L) * \sin\phi$

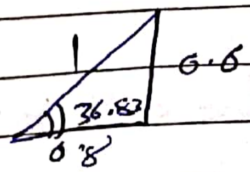
at full load

$\phi = \cos^{-1}(0.8) = 36.87°$

$\boxed{W_m = P W_s}$

$= \sqrt{3} * 137.5 * 440 * 0.6$

$= 62,865$ KVA



$S = 82.83 - J\,62.865$

b) δ at rated conditions

$P = \frac{3 V_t E_f}{X_s}$ & $E_f - I_f \angle \delta$

$\vec{E_f} = \vec{V_t} - \vec{I_{a(ph)}} Z_s$ → $\boxed{3.008 \angle 85.8^\circ}$

$= 440\angle 0 - 79.375 \angle +36.87^\circ \; (0.22 + J3)$

if $R = 0$ → $\boxed{3 \angle 90^\circ}$

$E_f = 603.34 \angle -19.46 \; V/ph$

$\boxed{motor}$

$\delta = -19.46^\circ$

c) If I_f is reduced by 10% (No sat)

→ $E_f = K \cdot I_f$

→ E_f

I_f

$\acute{E_f} = 90\% \; E_f$

new E_f

$(\acute{I_f} = 90\% \; I_f)$

New I_f

$\acute{E_f} = 0.9 * 603.34 = 543 \; V/ph$

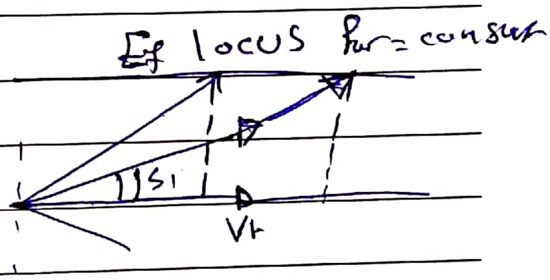
$\vec{\acute{I_a}} = \frac{\vec{V_t} - \vec{\acute{E_f}}}{Z_s} = \frac{440\angle 0 - 543\angle -21.7^\circ}{3.008\angle 85.8} = 70.35 \angle +22.42^\circ$

$Pf = \cos(22.42^\circ)$ leading $= 0.924$ lead p.f

* Criterion for ($P = ct$) (neglect R_a)

$E_f \sin(\delta) = \text{constant}$

$E_f \cdot \sin(\delta) = E_f' \cdot \sin(\delta')$



$$\sin\delta' = \left(\frac{E_f}{E_f'}\right)\sin(\delta)$$

$$= \left(\frac{E_f}{0.9\,E_f}\right)\sin(-19°)$$

$\delta_2 = -21.7°$

$Q' = -3 * 440 * 70.35 * \sin(22.4)°$

$= -34.37$ KVA

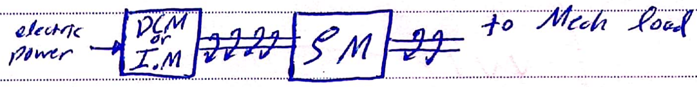
* Starting of Synch Motors (why?? ⇒ S-M is non-Self Starting)

How to Start the Motor??

i) Use a prime mover

- → DC Motor
- → Induction Motor

} Small



Steps (A) disconnect the Mech-load B) $I_f = 0$

c) Start the prime mover up to (almost) Synch-Speed

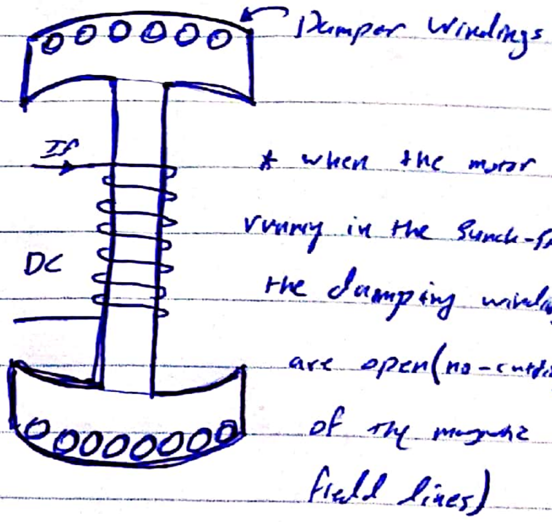
d) Connect the field Circuit (DO Synchronization) → [Connect 3ph-Source ⇒ Running as a motor → disconnect the small motor]

2) Damper Windings:

* I_f — $I_f = 0$, Stator Connected to 3ph-Supply it's run as an induction motor (unloaded)!!

then → Connect the I_f

* it also serves as a damping tool to any distanhance of motor speed (stability-tool)

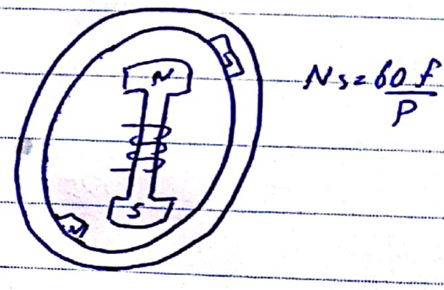


* when the motor vvary in the Synch-speed the damping windings are open (no-cutting of the magnetic field lines)

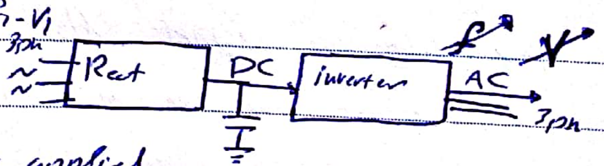
3) Starting by means of frequancy Control

* why the S.M is non ~~Cont~~ self-Starting
↳ the Rotating Field is alot faster than the mech load → every cycle the rotor is rotate then return every 10 ms

because of the mech loss → the Rotor is slipping and cant rotate with the field



* Freq-control can be done by the inverter



* Start at reduced freq (≈ 5 Hz) such that $\frac{V_r}{f_r}$ = const criterion is applied

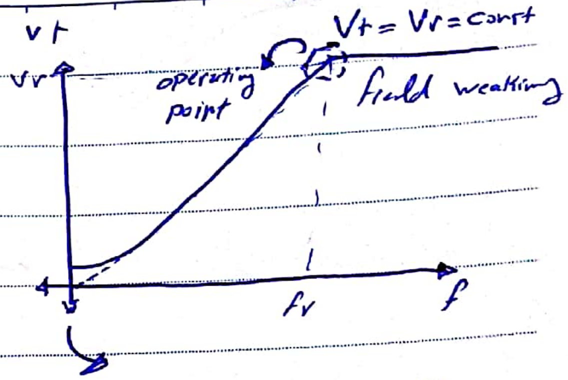
VVVF
↳ variable voltage variable frequency

unloaded

→ Note:
lower freq → lower X_s (ωL)
So, I need to lower the voltage

No.

*) --



* If I want to increase the freq → I can't increase Vt than Vr

↳ So use field weaking method

the curve is not linear because R don't change with the frequency

$V_t \approx E_f = 4.44 * K * N_{ph} * f * \phi$

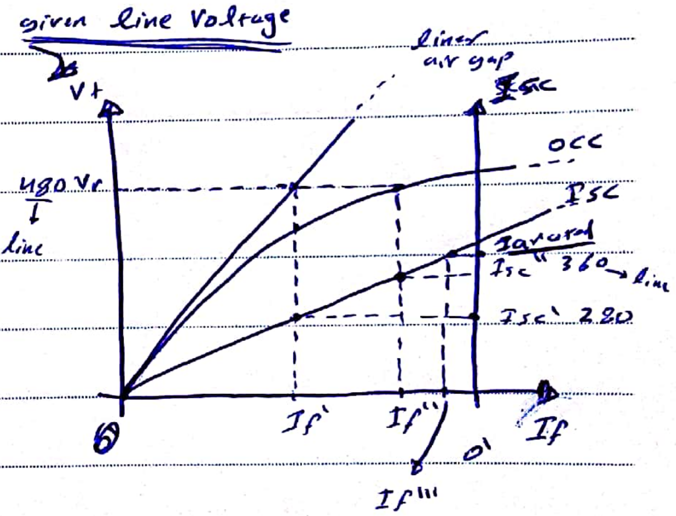
If $V_t \Rightarrow$ constant → $f\uparrow \to \phi\downarrow$

↳ $f\downarrow \to \phi\uparrow$

Ex) : (11-16) Y-connected $S = 300$ KVA

Find • $Z_s(sat)$

• $Z_s(unsat)$ • SCR



* $Z_s(unsat) = \frac{V_r(ph)}{(I_{sc}(ph))} = \frac{480/\sqrt{3}}{280}$

* $Z_s(sat) = \frac{480/\sqrt{3}}{360}$

* SCR (Short Circuit Ratio)

↳ $I\ rated = \frac{S_{rl}}{\sqrt{3}\ V_{rl}} = \frac{300\ KVA}{\sqrt{3}\ 480} = 360.8$

$SCR = \frac{I_f''}{I_f'''}$ → (If from the sat-curve with Vr) → (If from the I(f) with Isc-Test)

(pu) → $Z_{base} = \frac{V_r/ph}{I_r/ph}$ (Ω) , $Z(sat)_{pu} = \frac{Z_{sat}\ (\Omega)}{Z_{base}\ (\Omega)}$

Ex) in max power $\delta = 90°$ / when $R_a \neq 0$ $\theta_s - \delta$ (must be < 90°)

Ex) Const power variable field ⇒ $E_f \sin \delta = $ const

$E_f \sin(\theta_s + \delta) \to < 90°$

↓

θ

smile for life

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3-ph Induction Motors (Asynchronous) الحثي / التعريفي

*) Invented by Tesla

*) Construction ⇒

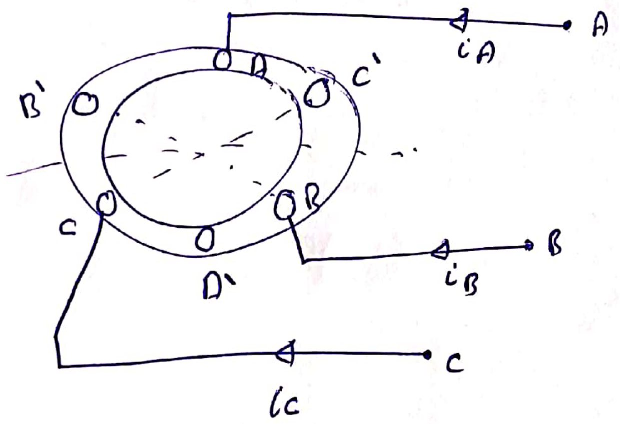
two Types:

1) squirrel-Cage

2) Wound-Rotor

In both cases:- Stator (where the 3-ph power supply is connected) called the Armature. The stator winding and construction is exactly identical to that of a synch. Machine.

3-ph balanced windings connected to create the required No. Poles.



3-ph Power supply
(f, v)

The supply to the windings creates the Rotating Field at the synchronous speed

$$N_s = \frac{60 f}{P}$$

$$W_s = \frac{2\pi N_s}{60} = \frac{2\pi \frac{60 f}{P}}{60} = \frac{2\pi f}{P}$$

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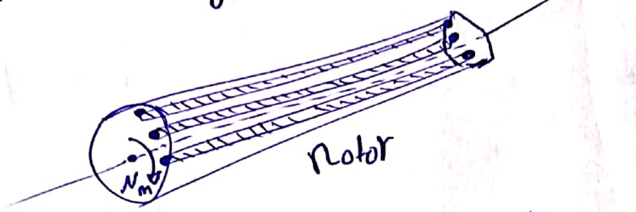
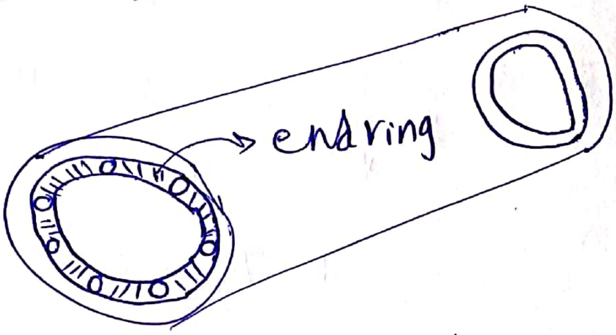
Rotor:

Squirrel- Cage

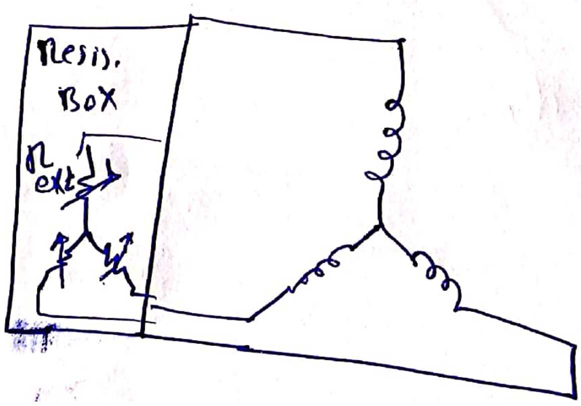




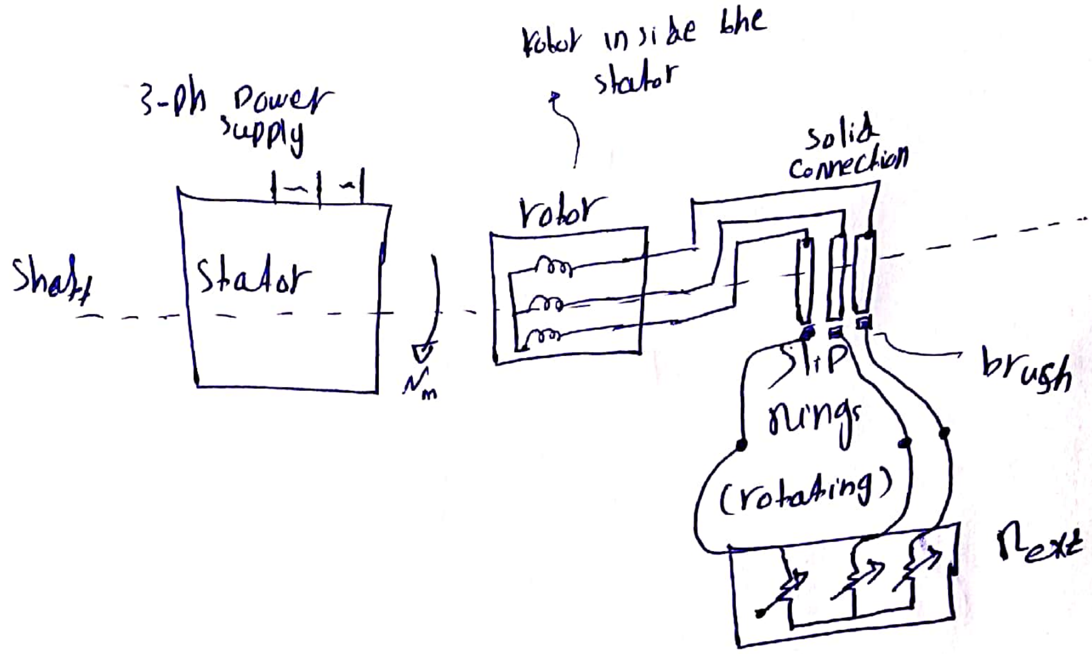
* قيمة المقاومة
صغيرة جدا

* Wound - Rotor Machine:-

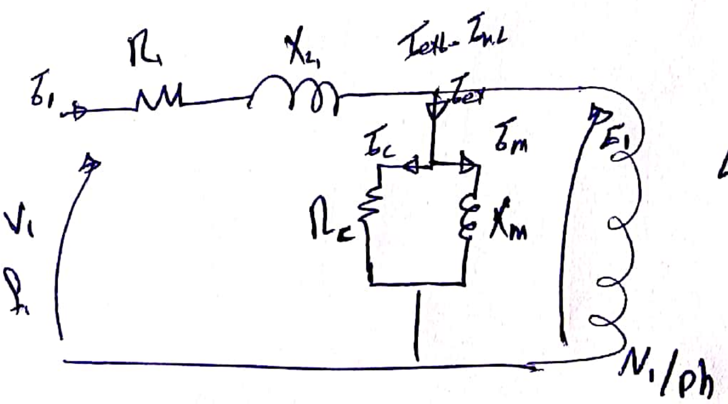
the rotor is wound exactly as the stator, but the ends of these windings are short- Circuited through 3-ph external Resistance Box



Wound Rotor



This Machine is referred to as (Rotating Transformer). the equivalent circuit of the stator of this Machine is exactly the same (in terms of its shape) to that of the transformer.



$E_1 = 4.44 * K_{w_1} * N_{1/ph} * f * \phi$

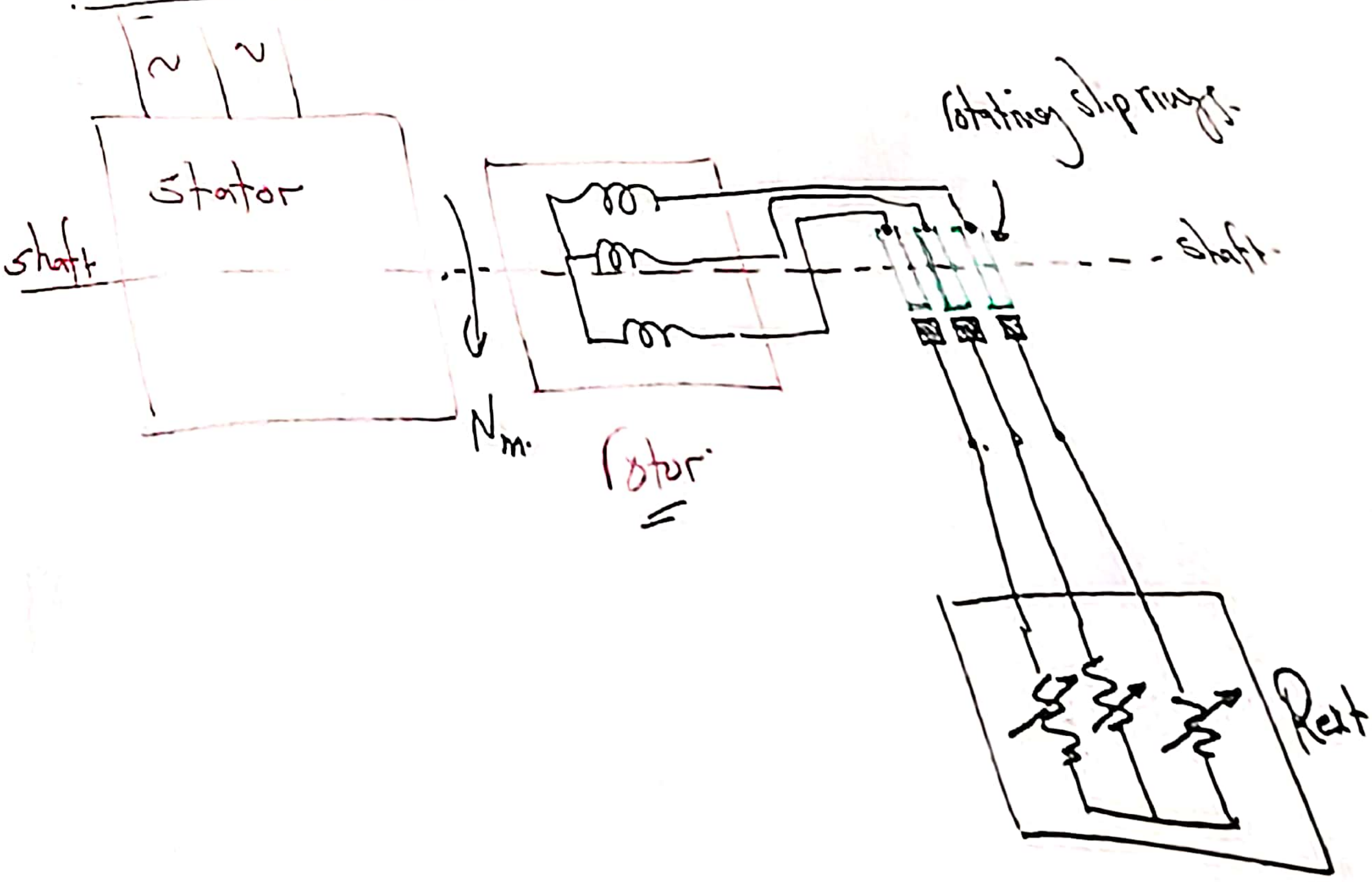
$K_w \Rightarrow$ Winding factor

$0.95 \leq K_w < 1$

P.f $\rightarrow$ lag

$\boxed{\text{allways } E_1 < V_1}$

Wound-Rotor Machine

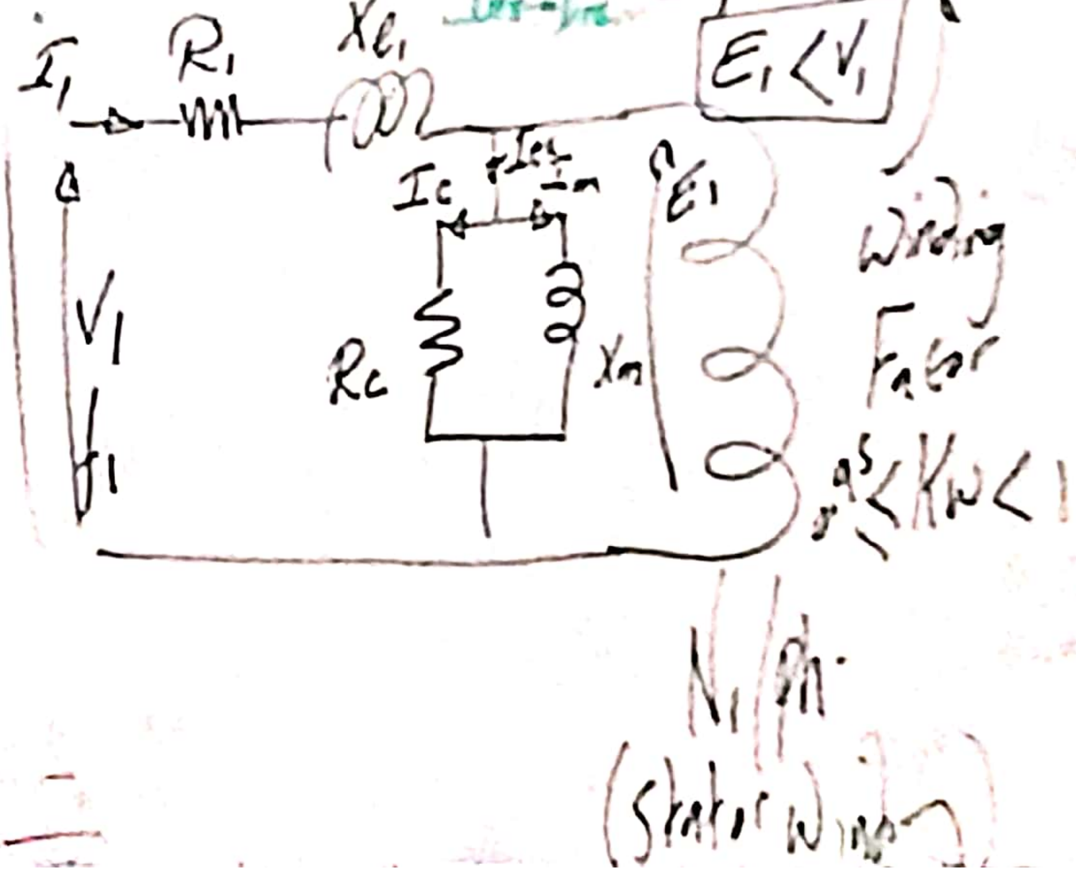


This Machine is Referred to as (Rotating Transformer).

The equivalent circuit of the stator of this Machine is exactly the same (in terms of its shape) to that of the transformer

$E_1 = 4.44 \times K_{w1} \cdot N_{1ph} \cdot f \cdot \Phi$

$I_{ex} = I_m$



$X_m \longrightarrow$ Transformer $\quad X_{m(Tr)}$

$X_m \longrightarrow$ Induction Motor $\quad X_{m}(IM)$

the airgap in the induction Motor makes all differences

$$X_m(IM) << X_m(T.r)$$

prove

Due to airgap:

$$\Re_m(IM) >> \Re_m(T.r)$$

$$L_m(IM) << L_m(T.r)$$

$$I_{n2}(T.r) \approx (1-5)\%\, I_{rated}$$

$$I_{n2}(IM) \approx (25-40)\%\, I_{rated}$$

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Induction Motors:-

* Equivalent Circuit Development

N_s => the synchronous speed (RPM)

(speed of the Rotating field)

$$N_s = \frac{60 f}{P}$$

The rotor will move following the stator field at a speed N_m (Mech. speed)

$$\boxed{N_m < N_s}$$

Reason:-

friction and windage (Mech. losses),

with no source compensat for these losses.

The Rotor is slipping behined the stator field

*) Define S as the slip, where

S => Relative speed of Rotor compare that of the stator field:

$$S = \frac{N_s - N_m}{N_s} \quad (\text{pu or } \%)$$

$$0 < S \leq 1$$

$S = 0 \Rightarrow N_m = N_s$ (Impossible)

$\boxed{S \neq 0}$ => No Rotation

Min. Slip at No load

$S_{nL} = 0.005 \rightarrow 0.01$

$S = 1 \Rightarrow$ at $N_m = 0$ (at starting or when the Rotor is Blocked)

(equivalent to short circuit in Transformer)

$S_{normal} = S_{rated} = 0.03 \rightarrow 0.06$

In some cases S can reach 15% or 0.15

$N_s = \frac{60 f}{P}$, $S = \frac{N_s - N_m}{N_s}$ $\Rightarrow f = \frac{P}{60} N_s$

f => stator freq.
(supply freq.)

$DN = N_s - N_m$

Rotor freq $= f_{rotor} = f_r = \frac{P}{60}(N_s - N_m) = \frac{P}{60}(N_s * S)$

$$\boxed{f_r = S * f_s}$$

∴ Rotor freq = Slip * Stator freq

E_1 = Stator EMF/ph $= 4.44 K_{W} * N_{1ph} * \phi * f$

E_2 = Rotor EMF/ph $= 4.44 * K_{W_2} * N_{2ph} * \phi * f_r$

$\therefore E_{2s} = 4.44 K_{w2} \times N_{2/ph} \times \phi \times s f$

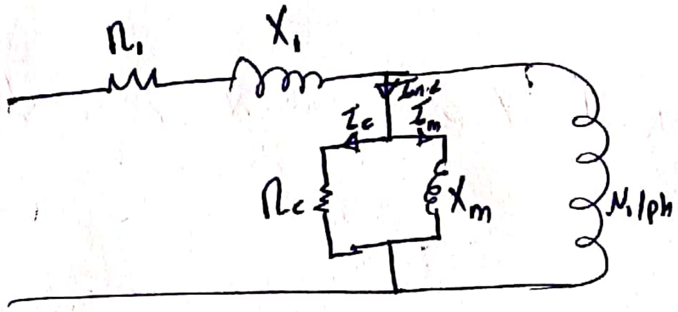
$E_{2s} = s\,(4.44 K_{w2} \times N_{2/ph} \times \phi \times f)$

E_{2s} => Rotor EMF /ph at Rotor freq

$E_{2s} = s \times E_2$, E_2 => Rotor EMF at supply freq.

Stator Eq. Circuit

at supply freq f



X_m => Magnetization Reactance /ph

X_1 => Stator leakage flux /ph

R_1 => Stator resistance /ph

R_c => core-loss equivalent Resis

I_{nL} => No load current

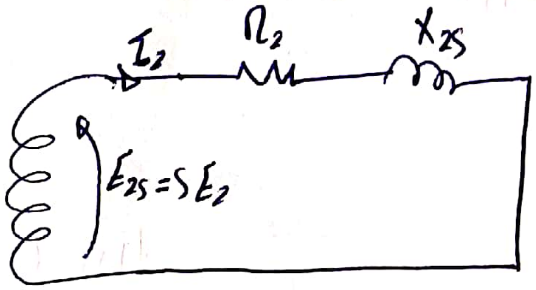
at
T.r $X_m < R_c$
I.M $X_m <<< R_c$

at

T.r $I_{o.c} = I_{n.L} \simeq (1-5)\%\ I_{rated}$

I.M $I_{n.L} \simeq (15\%-40\%)\ I_{rated}$

Rotor Eq. Circuit



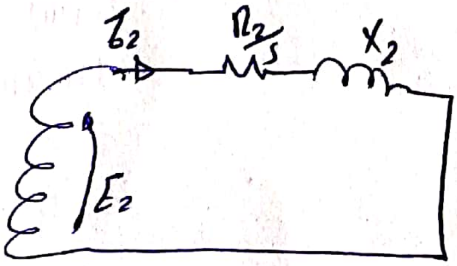
$$I_2 = \frac{E_{2S}}{R_2 + jX_{2S}}$$

$$X_{2S} = 2\pi f_r L_2 = 2\pi f S L_2$$

$\boxed{X_{2S} = S * X_2}$ ⇒ reactance at supply freq

$$I_2 = \frac{S E_2}{R_2 + j X_2 S} = \boxed{\frac{E_2}{\frac{R_2}{S} + jX_2} = I_2}$$

at supply freq

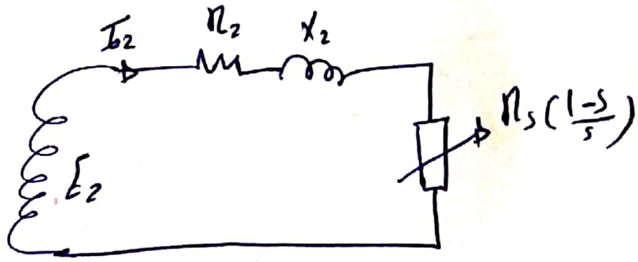


ii) $\frac{R_2}{s} = R_2 + ??$

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

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

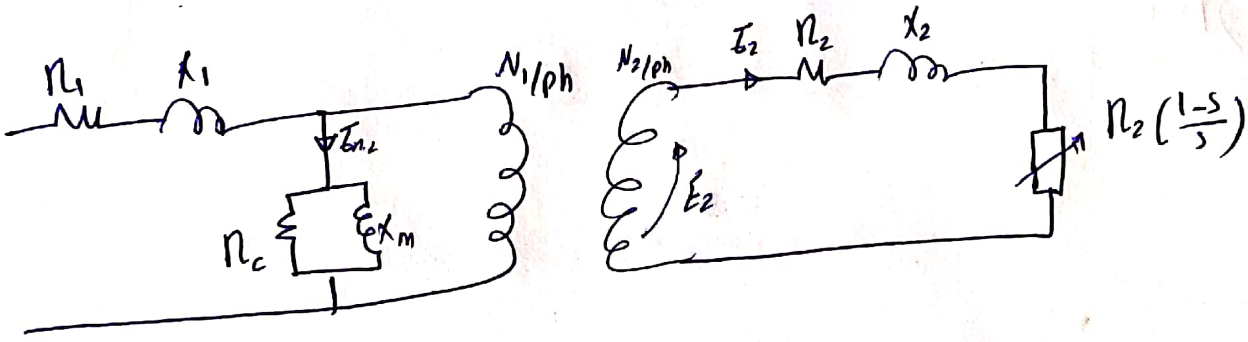
$= R_2\left(\frac{1-s}{s}\right)$



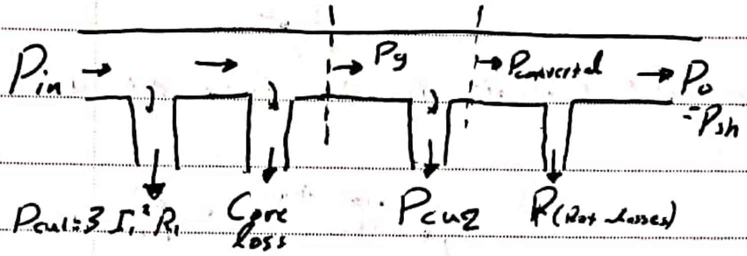
$R_2\left(\frac{1-s}{s}\right) \Rightarrow$ Mech load Equivalent Resistance

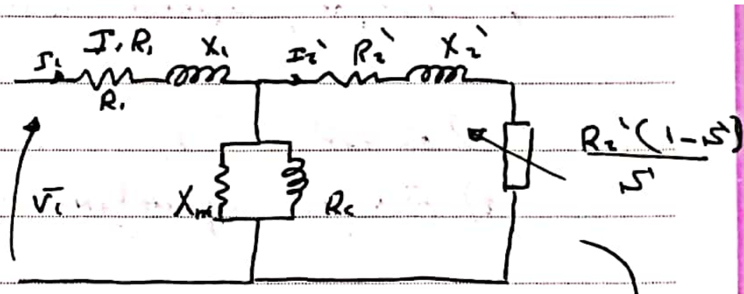
Now

at supply freq.



* Power Flow diagram





eq. Circuit Ref to Source Side

eq. Mech Power

* $P_{in} = 3 V_{1ph} * I_{1ph} * \cos\phi_1$

phase Shift V_1 & I_1

* $P_{conv} = P_g - P_{cu2}$

$P_{cu2} = I_2'^2 R_2'$

* P_{sh} : usful Shaft Power

* $\eta = \frac{P_{in} - P_{out}}{P_{out}}$

* $T_g = T_{dv} = T_{ind} = T_{electromagnetic}$

$T_g = \frac{P_g}{W_s}$, $W_s = \frac{2\pi N_s}{60}$

$T_g = \frac{3 I_2'^2 R_2'}{W_s \, S'}$

* $T_{conv} = \frac{P_{conv}}{W_m}$, $W_m = \frac{2\pi N_s}{60}$

$W_m = W_s (1-S)$

$\frac{P_g \cancel{(1-S)}}{W_s \cancel{(1-S)}}$

So $\boxed{T_{conv} = \frac{P_g}{W_s} = T_g}$

* P_g : Air Gap Power

or : Electromagnatic power

or : Developed power

$P_g = 3 I_2'^2 \left(R_2' + \frac{R_2'(1-S)}{S'} \right)$

$P_g = 3 I_2'^2 \frac{R_2'}{S'}$

* ~~$P_{converted} = P_g - P_{cu2}$~~

* or $P_{conv} = 3 I_2'^2 \left(\frac{1-S'}{S'} \right)$

$= \frac{3 I_2'^2 R_2'}{S} (1-S)$

$\boxed{P_{conv} = P_g (1-S')}$

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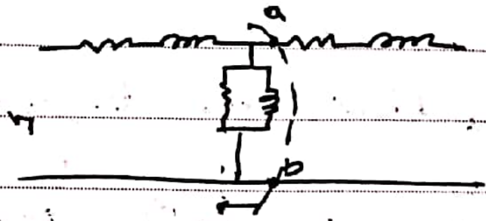
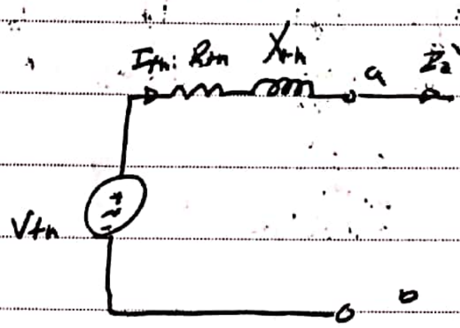
* Torque / Speed char



1) $R_c >>> X_m$

2) Find the equivalant thevenin's Circuit to the left of ab



$$* \ \bar{V}_{th} = V_1 * \frac{jX_m}{R_1 + jX_1 + jX_m}$$

$$= \frac{X_m \angle 90^\circ}{\sqrt{R_1^2 + (X_1+X_m)^2} \angle \tan^{-1}\frac{X_1+X_m}{R_1}} \bar{V}_1$$

Since $R_1 <<< (X_1 + X_m)$

$$V_{th} \approx \frac{\cancel{j}X_m}{\cancel{j}(X_1+X_m)} \bar{V}_1 \Rightarrow \boxed{V_{th} = \frac{X_m}{X_1+X_m} \bar{V}_1}$$

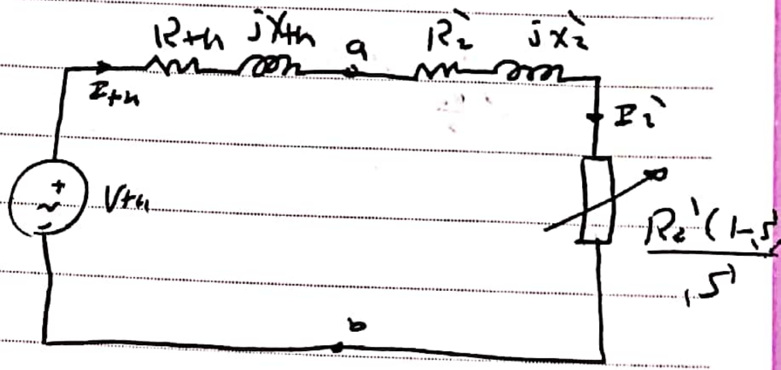
$$* \ Z_{th} = \underline{jX_m // (R_1 + jX_1)} = \frac{jX_m * (R_1 + jX_1)}{jX_m + R_1 + jX_1}$$

let $R_1 = 0$

$$\frac{X_m}{X_1+X_m}(R_1 + jX_1) = R_{th} + jX_{th}$$

$$\boxed{R_{th} = \frac{R_1 X_m}{(X_1 + X_m)}} \qquad \boxed{X_{th} = \frac{X_m X_1}{X_1 + X_m}}$$

* Modified Thevenins Eq. Circuit



So

$$I_2' = \frac{V_{th}}{\left(R_{th} + \frac{R_2'}{s'}\right) + j\left(X_{th} + X_2'\right)}$$

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

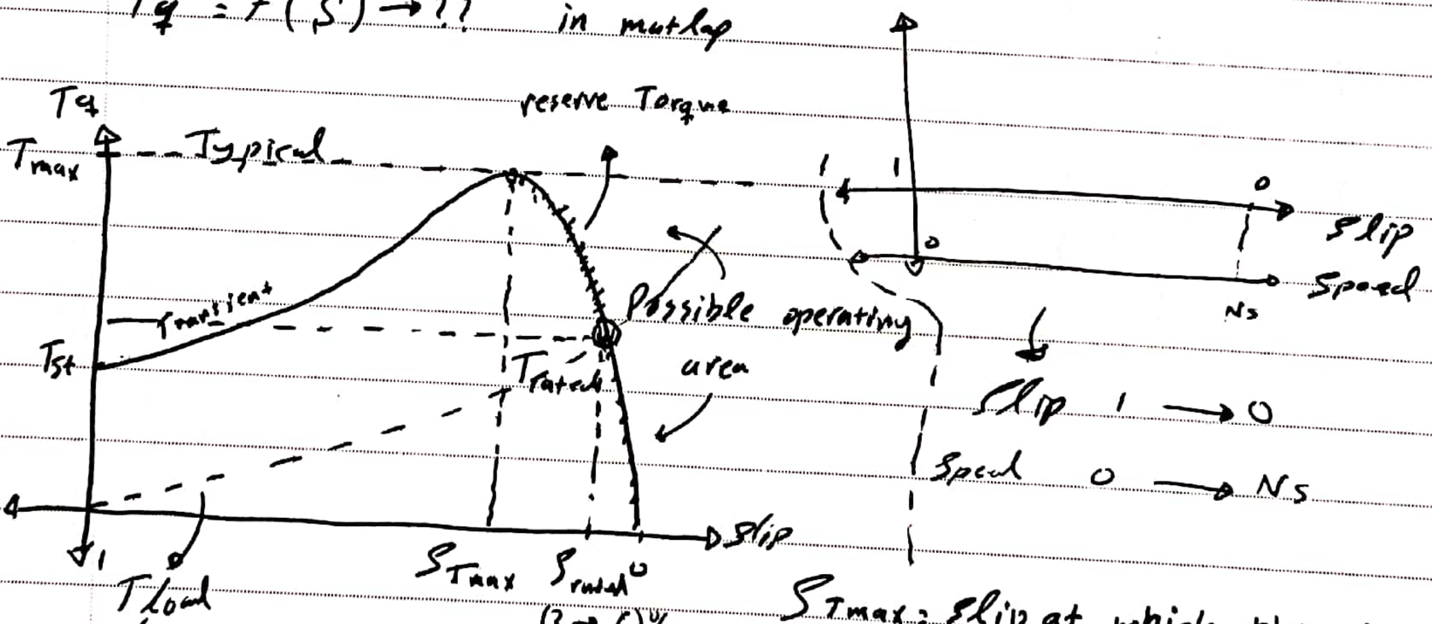
$$I_2' = \frac{\overline{V_{th}}}{\sqrt{\left(R_{th} + \frac{R_2'}{s'}\right)^2 + \left(X_{th} + X_2'\right)^2}} \angle \tan^{-1}\frac{X}{R}$$

→ for the Torque & power i need the amplitude

$$* \; P_g = 3 I_2'^2 \frac{R_2'}{s'} = 3 \frac{V_{th}^2 \quad R_2'/s'}{\left[\left(R_{th} + \frac{R_2'}{s'}\right)^2 + \left(X_{th} + X_2'\right)^2\right]}$$

$$* \; T_g = \frac{P_g}{w_s} = \frac{3 V_{th}^2}{w_s} \cdot \frac{R_2'/s'}{[\text{---}]}$$

$T_g = f(s') \rightarrow ??$ in matlap

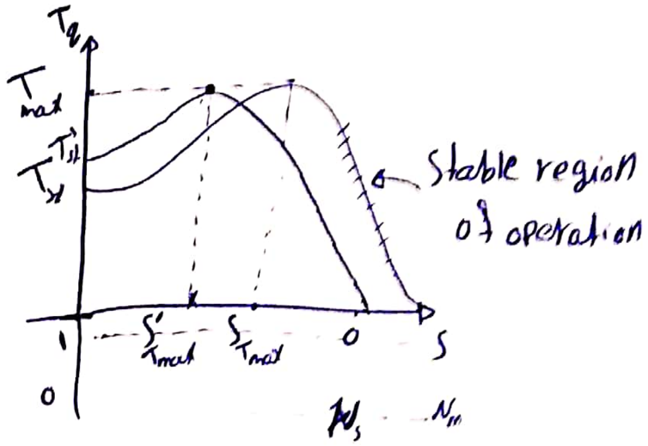


S_{Tmax}: slip at which the airgap Torque is Max.

T_{max} = Maximum Developed Torque

$$T_q = \frac{3V_{th}^2 \times R_2'/s}{w_s\left[(R_{th} + \frac{R_2'}{s})^2 + (X_{th} + X_2')^2\right]}$$

$$\frac{dT_q}{d(\frac{R_2'}{s})} = \sqrt{R_{th}^2 + (X_{th} - X_2')^2}$$



$$* \; S_{T_{max}} = \frac{R_2'}{\sqrt{R_{th}^2 + (X_{th} - X_2')^2}}$$

what does mean?

Slip at which the developed is Max depends on R_2', when R_2' is increased

(R_{ext} for the Wound-Rotor Motor)

By adding R_{ext} ⟶

$$S'_{T_{max}} = \frac{R_2' + R_{ext}}{\sqrt{R_{th}^2 + (X_{th} + X_2')^2}} \Rightarrow S'_{T_{max}} > S_{T_{max}}$$

(Stable Region of operation is increased)

Substit in T_q equation

$$T_{max} = \frac{3\,V_{th}^2}{2w_s\left[R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2')^2}\right]}$$

T_{max} is dependent on ??

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T_{max} is dependent on

1) $V_{th}^2 \longrightarrow (V_1^2) \longrightarrow$ square of the applied Voltage.

2) R_1, X_1, X_2' → by external components

it reduced T_{max}

3) freq control → almost $T_{max} \simeq$ constant if $f < f_r$

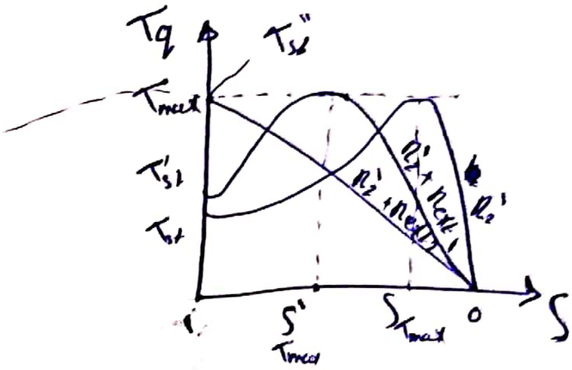
$T_{max} < T_{max(r)}$ if $f > f_r$

* T_{max} Independent of R_2'

$S_{T_{max}} = 1 \longrightarrow$ possible

$$1 = \frac{R_2' + R_{ext}}{\sqrt{R_{th}^2 + (X_{th} + X_2')^2}}$$

$$R_{ext} = \sqrt{R_{th}^2 + (X_{th} + X_2')^2} - R_2'$$

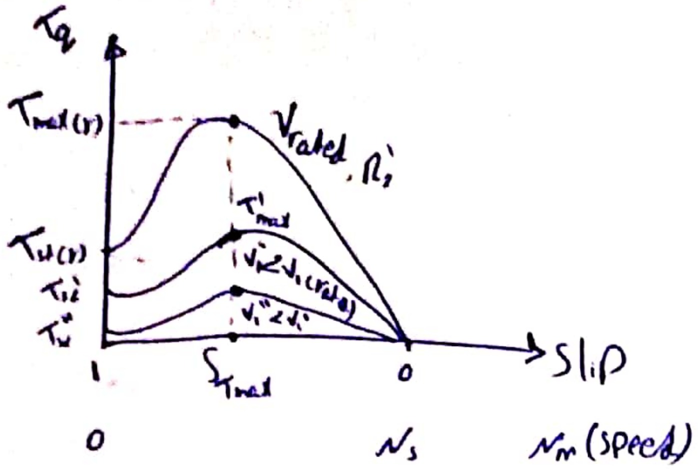


At such a condition, the Motor starts at Max Torque (Required for Traction system).

Motors with High T_{st} and wide Stability Region should be designed with higher R_2'. Solid-Rotor Motor is an example (No copper or Al. bus in the rotor)

T_q versus Voltage

* V_1 can be less than $V_{1(rated)}$



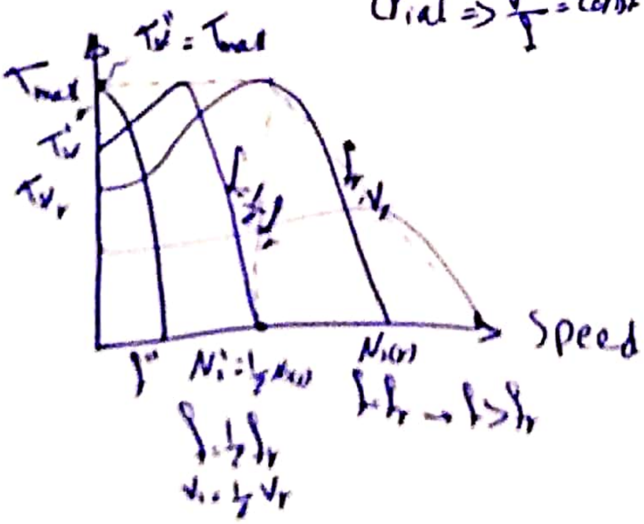
* $S_{T_{max}}$ is Independent of V_1

$S_{T_{max}} = \text{constant}$

* $T_{max} = f(V_1^2)$

T_q versus supply freq. (Modern speed control

Crial $\Rightarrow \frac{V}{f} = \text{const}$



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

$\boxed{\text{* } T_{max} \text{ is reduced}}$

at $f < f_r$ to keep $\phi = \text{const}$ (No saturation)

$\frac{V_1}{f} = \text{constant}$ to keep $\phi = \text{const}$

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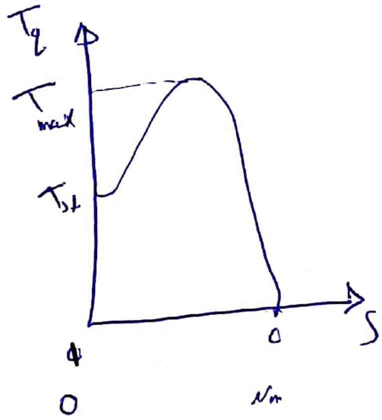
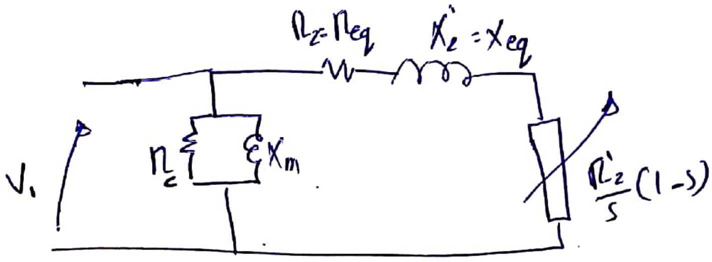
Induction Motor Starting

at starting

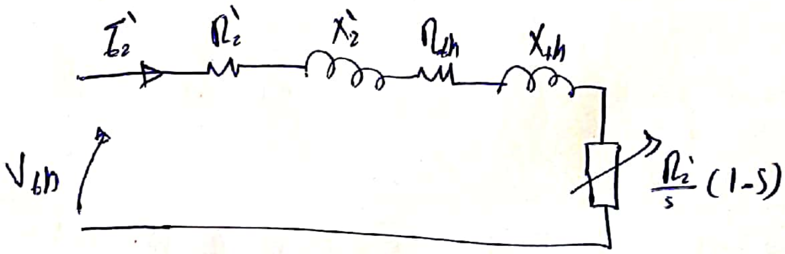
$S = 1 \Rightarrow S = \frac{N_s - N_m}{N_s}$

$= \frac{N_s - 0}{N_s}$





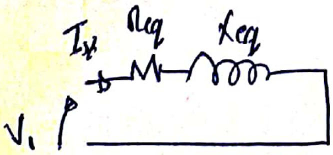
$\Downarrow$



at starting

$R_2'\left(\frac{1-s}{s}\right) \to 0$ [equivelant to short Circuit condition in Tr] ~~condition~~

$Z_{eq} \lll Z_{o.c}$



$$I_{st} = \frac{V_1}{\sqrt{R_{eq}^2 + X_{eq}^2}}$$

$$T_{st} = \frac{3\, I_{st}^2 \cdot R_2'}{W_s}$$, 3-ph $P = 3 I_{st}^2 R_2'$, $T = \frac{P}{W_s}$

$$T_q = \frac{3\, I_2' \; R_2'/s}{W_s}$$

$$I_{st} = \frac{V_1}{\sqrt{(R_1 + R_2')^2 + (X_1 + X_2')^2}}$$

$$\frac{I_{st}}{I_{2(r)}'} = (5 \rightarrow 20)$$

$$I_2' = \frac{V_1}{\sqrt{(R_{th} + \frac{R_2'}{s})^2 + (X_{th} + X_2')^2}}$$

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

ex)

from disin

$$\frac{I_{st}}{I_{2(r)}} = 5 \quad , \quad S_{rated} = 0.05$$

$$\frac{T_{st}}{T_{rated}} = 25 * 0.05 = 1.25$$

ex)

$$\frac{I_{st}}{I'_{2(r)}} = 10 \quad , \quad S_{rated} = 0.05$$

$$\frac{T_{st}}{T_{rated}} = 100 * 0.05 = 5$$ Not Acceptable

ex)

$$\frac{I_{st}}{I'_{2(r)}} = 5 \quad , \quad S_{rated} = 0.03$$

$$\frac{T_{st}}{T_{rated}} = 25 * 0.03 = 0.75$$

Starting:

The starting is large (up to 20 times rated circuit)

* If frequent starting this is not accibtable. (buring Motor)

* If $P_{rated} > 10$ Kw → Not Acceptable

T_{st} is affected by starting current!

Motors should start carfully such that

$$I_{st} \lesssim I_{rated}$$

How to reduce I_{st} ?!

1) If normally Δ-Connected, start the motor as Y (Y-Δ Starting)

This imply that

$$\frac{I_{st}(Y)}{I_{st}(\Delta)} = \frac{1}{\sqrt{3}} = 58\%$$

$$\frac{T_{st}(Y)}{T_{st}(\Delta)} = \left(\frac{V_{(Y)}}{V_{(\Delta)}}\right)^2 = \frac{1}{3}$$

$$I_{st} = \frac{V_1}{Z_{eq}}$$

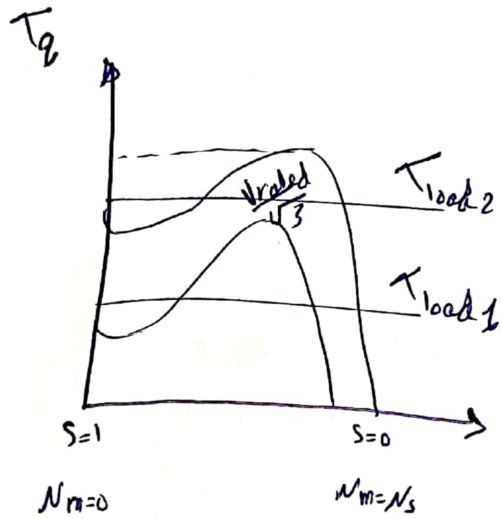
$$I_{st}(Y) = \frac{V_r/\sqrt{3}}{Z_{eq}}$$

$$I_{st}(\Delta) = \frac{V_r}{Z_{eq}}$$

$$T_{st} = \frac{3V_1^2}{Z_{eq}}$$

$$T_{st}(Y) = \frac{3(V_r/\sqrt{3})^2}{Z_{eq}}$$

$$T_{st}(\Delta) = \frac{3V_r^2}{Z_{eq}}$$

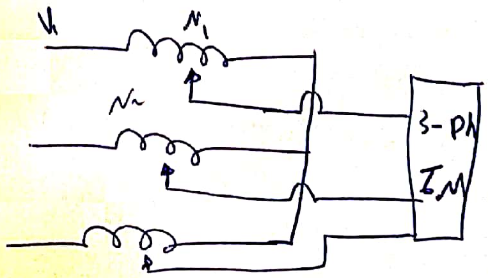


2) Starting at reduced Voltage using

Auto transformer

$$a = \frac{N_1}{N_2} > 1$$

$$V_{st} = \frac{V_{rated}}{a}$$



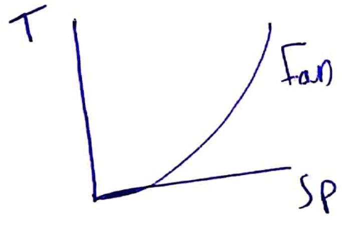
Sameside effect same as (λ-D)

a → Variable (Not $\sqrt{3}$ ably as λ (D)

* load ⇒ Fan type

Can the reduced Voltage apply ~~as~~ efficiently?!

Since T_{st} is very small.



③ Add R_{ex} to the stator

$$I_{st(New)} = \frac{V_1}{\sqrt{(R_{th} + R_{eq} + R_2')^2 + (X_{th} + X_2')^2}}$$

$I_{st(New)} < I_{st}$

* but this is inefficient due to copper losses in R_{ext}.

④ Add X_{ext} to the stator circuit

$$I_{st(New)} = \frac{V_1}{\sqrt{(R_1 + R_2')^2 + (X_1 + \underbrace{X_{ext}}_{\text{external}} + X_2')^2}}$$

$I_{st(New)} < I_{st(rated)}$

$T_{st(New)} < T_{st(rated)}$

$I_{st(New)} < I_{st}$

$T_{st(New)} < T_{st(r)}$

* but much lower P.f at starting

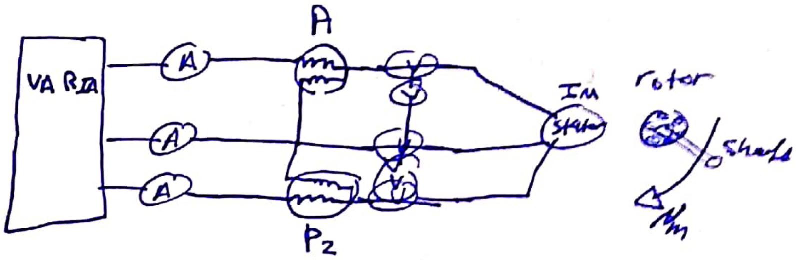
Scanned by CamScanner

* Inducting Motor Testing :-

1) No load test

2) Blocked-Rotor Test

* wiring diagram

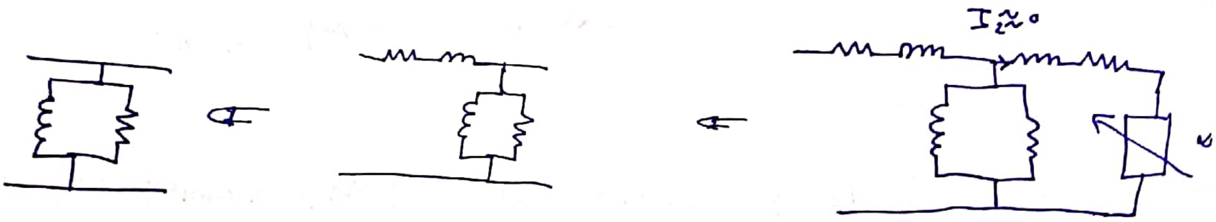


* No load test :- equal to open circuit Test

rotor is free to run without mech load

$N_m \approx N_s \rightarrow S = 0$

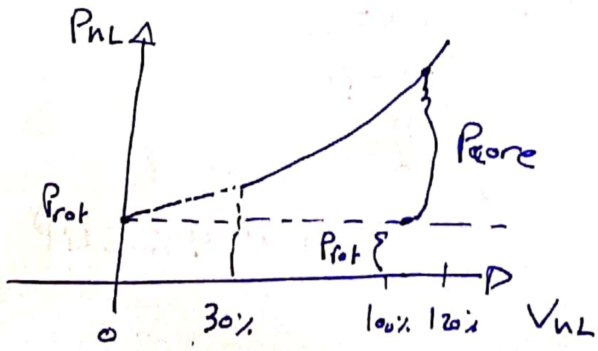
$R_2' \left(\frac{1-s}{s}\right) \rightarrow \infty$ (rotor ⇒ open circuit)



from this Test, X_m & R_c can be evaluated $P_{core} + P_{rot\ loss} = P_{o.c}$

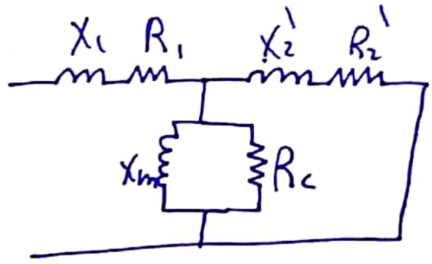
* To separate P_{core} & P_{rot}

V_{NL}	30%	40	50	60	...	120%
P_{NL}						



Blocked-Rotor Test:-

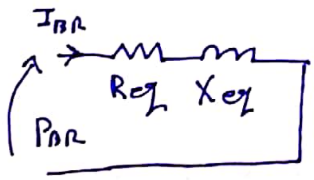
$N_m = 0 \rightarrow S = \frac{N_s - 0}{N_s} = 1$



$R_2' \left(\frac{1-S}{S}\right) \rightarrow 0$

$Z_{oc} \gg \underbrace{R_2' + jX_2}_{Z_2'}$

* Z_o can be omitted



* can be calculated $\leftarrow \begin{cases} R_{eq} = R_1 + R_2' \\ X_{eq} = X_1 + X_2' \end{cases}$

~ . ~ . ~ . ~ .

Ex: 400 V, 6-Pole, 50 Hz Y-connected 3-Ph IM, Running light (No-load) at rated voltage:- 7.5 A, 700 W

$\frac{X_1}{X_2'} = \frac{1}{0.5}$

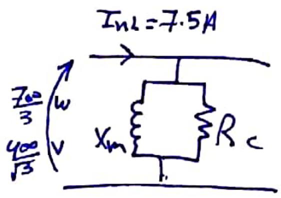
* اذا ما اعطاني بفرض انهم متساويات

* Blocked-Rotor:- 150 V, 35 A, 400 W
(stator & rotor copper loss are equal)
$R_1 = R_2'$

— find:-
1) $P_{sh} = ?!$
2) $P_o = ?!$
3) $T_g = ?!$, $T_o = ?!$
4) $\eta = ?!$ at 4% slip

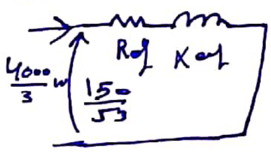
Scanned by CamScanner

No-load Test



$\Rightarrow$

Blocked-Rotor

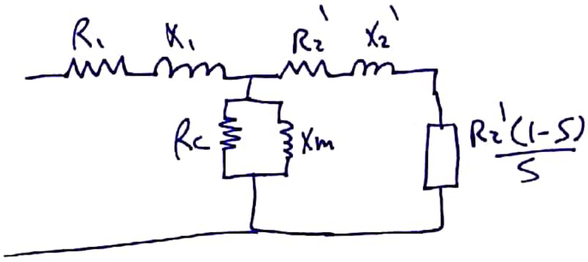


$R_1 = R_2' = R_{eq}/2$

$X_{eq} = X_1 + X_2' = X_1 + 0.5X_1$

$= 1.5X_1$

$X_1 = \frac{X_{eq}}{1.5}$, $X_2' = X_{eq} - X_1$



$S = 0.04$

$Z_{in} = Z_{oc} // \left(\frac{R_2'}{S} + jX_2'\right)$

$I_1 = \frac{V_1}{Z_{in}}$, $I_2 = \frac{I_1(Z_0)}{Z_0 + \left(\frac{R_2'}{S} + jX_2'\right)}$

Ex) 460 V, 25 hp, 60 Hz, 4-pole, Y connected 3-ph induction motor

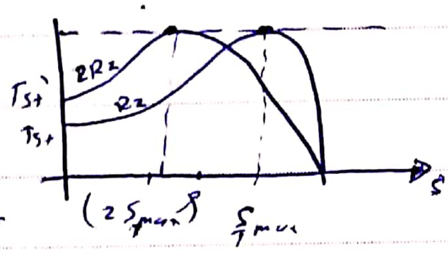
$R_1 = 0.641\ \Omega/ph$, $R_2' = 0.332\ \Omega/ph$, $X_1 = 1.106\ \Omega/ph$, $X_2' = 0.464\ \Omega/ph$

$X_m = 26.3\ \Omega/ph$, $R_c \rightarrow$ large enough (can be omitted) 1750 RPM

$P_{rot} = 1100\ W = const$

Find 1) T_{st}, I_{st}, T_{max}

2) If R_2 is doubled Recalculate T_{st}, I_{st}, T_{max}



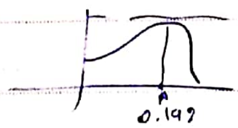
by using the eqv. cct

Sol) 1)

$* \ V_{th} = V_{ph} \dfrac{X_m}{X_m + X_1} = \dfrac{460}{\sqrt{3}} \left(\dfrac{26.3}{26.3 + 1.106} \right) = 254.8\ V$

$* \ X_{th} = X_1 = 1.106\ \Omega/ph \qquad R_{th} = R_1 \left(\dfrac{X_m}{X_m + X_1} \right)^2 = 0.59\ \Omega/ph$

$S_{Tmax} = \dfrac{R_2'}{\sqrt{R_{th}^2 + (X_{th} + X_2')^2}} = 0.198\ pu$ or 19.8%



$* \ \text{Speed } N_m \Big|_{T_d = T_{dmax}} = N_m = N_s(1 - S) = 1443\ RPM$

$* \ S = \dfrac{N_s - N_m}{N_s}$

$* \ T_{d\,max} = \dfrac{3 V_{th}^2}{2 \omega_s \left(R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2')^2} \right)} = 229\ N.m$

$* \ N_s = \dfrac{60 f}{P} = 1800\ RPM$

$T_{st} = \dfrac{3 V_{th}^2 R_2'}{\omega_s \left[(R_{th} + R_2')^2 + (X_{th} + X_2')^2 \right]} = 104\ N.m$

$\boxed{T_{st} < T_{max}}$

$\omega_s = \dfrac{2\pi}{60} N_s$

$$I_{st} = \frac{V_{th}}{\sqrt{(R_{th}+R_2')^2+(X_{th}+X_2')^2}} =$$

$$T_{st} = \frac{3\, I_{st}^2\, R_2'}{w_s}$$

$$T_{FL} = 3 I_2'(FL)^2\, R_2' / S_{FL}$$

full load ⇒ rated value

S_{FL} ⇒ at rated speed 1710

$$S_{FL} = \frac{N_s - 1710}{N_s}$$

$$T_{st} = \frac{3 I_{st}^2 R_2'}{w_s}$$

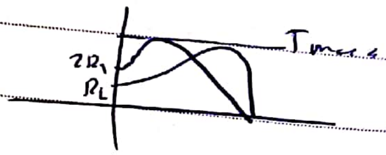
$$\frac{T_{FL}}{T_{st}} = \left(\frac{I_2' fL}{I_{st}}\right)^2 * \frac{1}{S_{FL}}$$

* after adding Rext ($R_{ex} = R_2$

* $$S_{Tmax}' = \frac{R_2' + R_{ext}'}{\sqrt{R_{th}^2 + (X_{th}+X_2')^2}} = \frac{2R_2'}{\sqrt{R_2^2 + (X_{th}'+X_2')^2}} = 2 * S_{tmax} = 0.396 \text{ pu}$$

* $N_m = N_s(1 - S_{tmax}') = 1800(1 - 0.396) = \ldots$

* T_{max}' = the same = 229 constant T_{max} is independent of R_2'



* $$T_{st}' = \frac{3\, V_{th}^2 (R_2' + R_{ext}')}{w_s\left[(R_{th}+R_2'+R_{ext})^2 + (X_{th}+X_2')^2\right]}$$

$= 170$ N.m

$$I_{st}' = \frac{V_{th}}{\sqrt{(R_{th}+R_2'+R_{ext}')^2 + (X_{th}+X_2')^2}}$$

Q) $R_{ext}' = ??$ If $I_{st} = I_{max}$??

$S=1$

$$1 = \frac{R_2' + R_{ext}'}{\sqrt{R_{th}^2 + (X_{th}+X_2')^2}}$$

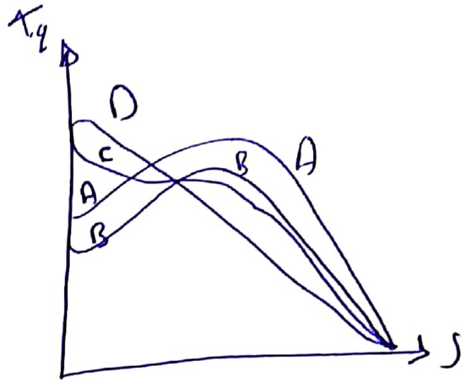
Classes of I.M :-

Class A

Class B

Class C

Class D



Differences :

$\frac{T_{st}}{T_{rated}}$, $\frac{T_{max}}{T_{rated}}$, $\frac{I_{st}}{I_{rated}}$, $S_{T_{max}}$, S_{rated}

Class A ⇒ Classic Motor

$\frac{T_{st}}{T_r} \simeq 175-200\%$ $\frac{T_{max}}{T_r} \simeq 250-300\%$ $S_r \leq 0.05$

$\frac{I_{st}}{I_r} \simeq 500-1000\%$ $S_{T_{max}} \simeq 15-20\%$

Class B

$\frac{T_{st}}{T_r} \simeq 100-150\%$ $\frac{T_{max}}{T_r} \simeq 200\%$ $S_r \leq 0.05$

$\frac{I_{st}}{I_r} \simeq 700-1200\%$ $S_{T_{max}} \simeq 15-20\%$

Class C

(Special Design of Squiriel - cage Motor)

[Deep bars or Double-cage I.M]

$\frac{T_{st}}{T_r} = 275-300\%$ $\frac{T_{max}}{T_r} \simeq 300\%$ $S_r \simeq 5\% - 7\%$

$S_{T_{max}} \simeq$ up to 25% $\frac{I_{st}}{I_r} \simeq 300\% - 500\%$

Class D

Mostly wond Rotor I.M, with high R_2. Rext can be add to achieve the goal or the more is basicly designed with high R_2.

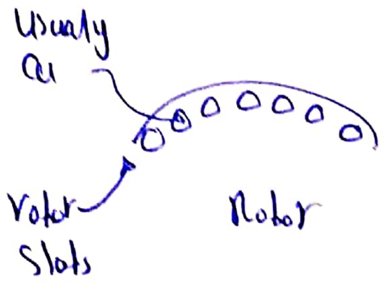
ex) use Al insead of copper in the rotor bars or use solid rotor without copper or Al bars

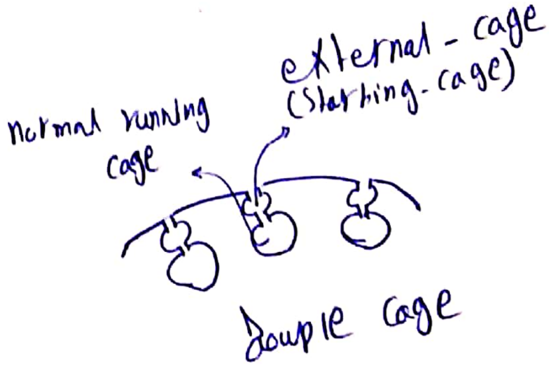
$S_{T_{max}} = 100\%$ S_r = up to $7-11\%$ [less efficient]

$\frac{T_{st}}{T_r} \simeq \frac{T_{max}}{T_r} \simeq 275-350\%$ [usefull for Tranction Application]

$\frac{I_{st}}{I_r} \simeq 300\% - 500\%$

Deep bar or double - Cage Motor





Starting cage ⇒ Small cross-sectional area
mode of high resistivity material

Normal running cage ⇒ large cross-sectional area
mode of low resistivity material

At starting $S = 1 \Rightarrow f_r = sf \approx f$

*) at starting Rotor reactance is Mech larger that its value at normal running.

*) rotor bars flux is concentrated in the Innier part or [the normal-running cage]
→ (implying high reactance)

this reactance reduces as we approach the outer part of the rotor
(Near the air gap)

Also,

$f_r = f$ [the highest - Value ever)

This implies that the rotor current flows in relatively low cross sectional area in the [outer part or starting cage] Implying High R_2, leading to low starting current, High starting torque.

As S reduces to reach $\simeq 5\%$ of it's starting value, the interal reactance reduces [in the same ratio]

* [In case of double-cage the electric resistance of the cage is much lower than that of starting one]. Then the rotor current is driven back to the normal running cage [or more uniformally distributed in the deep bar ratio].

This impiles that R_2 is ~~bees~~ becoming lower. leading to High effiency Normal running

~~~~~~~~~~

Modern Starting Feching of I.Motor

$$I_{st} = \frac{V_{th}}{\sqrt{(R_{th} + R_i)^2 + (X_{th} + X_i)^2}} = \frac{V_{th}}{\sqrt{(R_{th} + R_i)^2 + f^2(2\pi X_{th} + 2\pi L_i)^2}}$$
~~~~~~~~~~

*Ex 208 V, 60 Hz, 6-pole, Y con, 25 hp Design B Ind Machine

tested: consider $\boxed{X_2' = 0.4\, X_{eq}}$

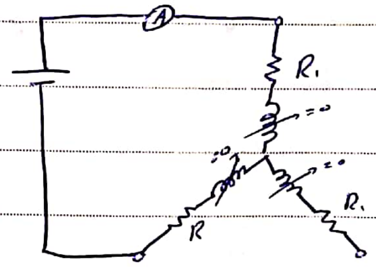
No load 208 V, 22 A, 1200 W, 60 Hz

Blocked Rotor 24.6 V, 64.5 A, 2200 W, 15 Hz

DC Test 13.5 V, 64 A

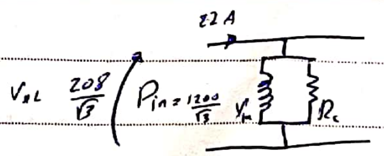
Sol Find every thing

① DC test



$2R_1 = V_{DC}/I_{DC} \Rightarrow R_1 = 0.1055\ \Omega/ph$

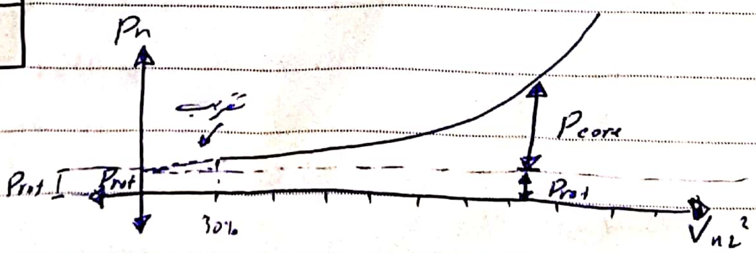
② No-load Test



$R_c = 41,327\ \Omega$, $X_m = 5,507$

to Find P_{rot}

V	30%	40%	50%	--	120%
P_{nL}					

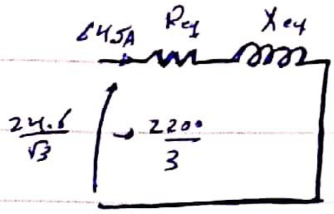


at $V=0$ ($P_{core}=0$)

so $\Rightarrow P_{V=0} = \cancel{P_{core}} + P_{rot}$

$P = P_{rot}$

Blocked Rotor test



$R_{eq} = 0.1763\ \Omega/ph$

$X_{eq} = 0.13147\ \Omega/ph$
(15 Hz)

$X_{eq(60\,Hz)} = 0.13147 \times \left(\frac{60}{15}\right) = 0.528$

* why $f \neq f_r$ at BRT ??
for more convenient result
↳ to reduce the (skin effect) Factor
$f \downarrow \rightarrow$ skin effect $\downarrow$
(correction factor)

So $X_2' = 0.4\, X_{eq}$ → given

$X_2' = 0.3167\ \Omega/ph$, $X_1 = 0.2112\ \Omega/ph$

ex) 208 V, 4 pole, 10 HP, 60 Hz, Y-conn, 3-ph IM

Full load Torque at 3.8 % slip at 60 Hz and 208

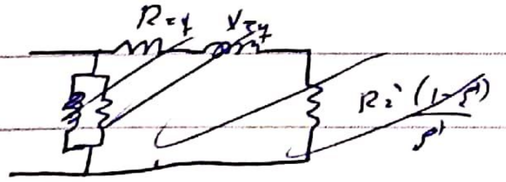
$R_1 = 0.33\ \Omega$, $X_1 = 0.42\ \Omega$, $X_2' = 0.42\ \Omega$, $X_m = 15$.

$P_{mech} \rightarrow 0$

Find $R_2' = ?$, $s_{T_{max}}$, N_m (T_m (max torque)) $T_{st} = ?$

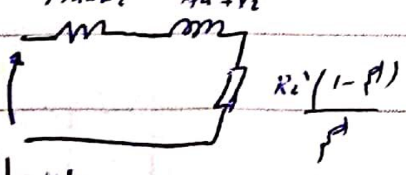
$R_{th} = R_1 \left(\frac{X_m}{X_m + X_1}\right)^2$

$X_{th} = X_1$



$V_{th} = \frac{V_1 X_m}{X_1 + X_m} = 128.9\ V$

$Z_{th} = 0.374 + j\,0.464$



~~P~~ P_o ($P_{mech(rot)} \rightarrow 0$) $= 10 \times 746 = 7.46\,kw$

$T_g = \frac{P_g}{w_s} = \frac{P_{conv}}{w_m}$

$w_m = \frac{2\pi f}{2} \Rightarrow W_s(1-s) = w_m$

$w_m \Rightarrow$ ✓

$= \frac{P_o}{w_s(1-s)} = \frac{P_o}{w_r} = 41.1\ N_m$

$$\boxed{T_g = \frac{3\, V_{th}^2\, R_2'/s}{w_s\left[\left(R_{th} + \frac{R_2'}{s}\right)^2 + \left(X_{th} + X_2'\right)^2\right]}}$$

Solve

$R_2' = 0.195$ ✓ → مقبول

$R_2'{}_2$ -- ✗

208 V, 4-pole, 10 hp, 60 Hz, Y-conn. 3-ΦIM

Full-Load developed Torque at 3.8 % slip at 60 Hz and 208 V

$R_1 = 0.36\,\Omega$, $X_1 = 0.47\,\Omega$, $X_2' = 0.47\,\Omega$, $X_m = 15.5\,\Omega$

$P_{mech} \to 0$.

1. $R_2' = ??$
2. T_{max}, $S_{T_{max}} = ??$ Nm (at Max Torque)
3. $T_{st} = ??$

$P_{rot} \to 0$

$$T_g = \frac{P_g}{\omega_s} = \frac{P_{conv}}{\omega_m} = \frac{P_o}{\omega_m}$$

$P_o = 10 * 746 = 7.46$ kW.

$\omega_s = \frac{2\pi f}{2} =$

$\omega_m = (1-s')\,\omega_s$

$$T_g = \frac{P_g}{\omega_s} = \frac{P_{conv}}{\omega_m} =$$

$$= \frac{P_o}{\omega_s(1-s')} = \frac{P_o}{\omega_m} = 41.1 \text{ Nm.}$$

$$T_g = \frac{3V_{th}^2 R_2'/s'}{\omega_s\left[\left(R_{th} + \frac{R_2'}{s'}\right)^2 + (X_{th} + X_2')^2\right]}$$

$V_{th} = 128.9$ V.

$Z_{th} = 0.339 + j0.464$

$R_2' = 0.195$

$S_{T_{max}} = 0.196$

$T_{max} = 99.2$ Nm.

$T_{st} = 44.5$ Nm.

.328

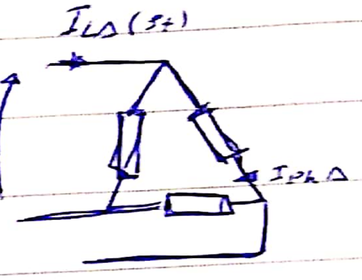
$X_1 = 0.2112\,\Omega/ph$

$X_2' = 0.3167/\Omega ph.$

* $Y \rightarrow \Delta$ Starting

Motor: 208 V, Δ Connected, $2P = 2$, 25hp, 60 Hz, 3ph IM

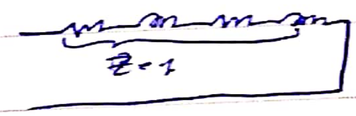
in Δ



$$I_{ph\Delta}(st) = \frac{V_{ph\Delta}}{Z_{eq}}$$

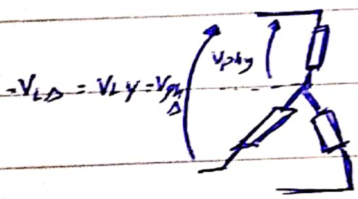
$$I_{L\Delta}(st) = \frac{V_{ph\Delta}}{Z_{eq}} * \sqrt{3}$$

at Starting $\boxed{S = 1}$



$$Z_{eq} = \sqrt{(R_{th} + R_2')^2 + (X_{th} + X_2')^2}$$

* Starting at Y



$$I_{LY}(st) = I_{phY}(st) = \frac{V_{ph\Delta}}{Z_{eq}\sqrt{3}} \qquad V_{phY} = V_{ph\Delta}/\sqrt{3}$$

* Motor Side

$$\frac{I_{phY}(st)}{I_{ph\Delta}(st)} = \frac{V_{ph\Delta}/\sqrt{3}}{\cancel{Z_{eq}} \cdot \frac{V_{ph\Delta}}{\cancel{Z_{eq}}}} = \frac{1}{\sqrt{3}} \quad \left(\frac{1}{3} \text{ less losses } P_{cu} = I^2 R\right)$$

* line Side

$$\frac{I_{LY}(st)}{I_{L\Delta}(st)} = \frac{V_{ph\Delta}/\sqrt{3}}{Z_{eq}\sqrt{3}\,\frac{V_{ph\Delta}}{Z_{eq}}} = \frac{1}{3} \quad \left(\frac{1}{9} \text{ less losses}\right)$$

* Starting torque

$$T_{st} = \frac{3V^2 R_2'}{\omega_s Z_{eq}^2} = \frac{3}{\omega_s} I_{phY(st)}^2 R_2'$$

$$T_{st(\Delta)} = \frac{3}{\omega_s} I_{ph\Delta(st)}^2 R_2'$$

$$\frac{T_{stY}}{T_{s\Delta}} = \left(\frac{I_{phY(st)}}{I_{ph\Delta(st)}}\right)^2 = \frac{1}{3}$$

EX) 460, 50 Hp, 6-poles, Δ-connected, 3-ph IM

$S_r = 4\%$, $\eta_n = 91\%$, PF = 0.87 ~~leading~~ lagging

at Starting, $T_{st} \approx 1.75\, T_{rated}$ / $I_{st} = 7\, I_{rated}$

phase values

An auto Transformer is to be used to start the motor such that

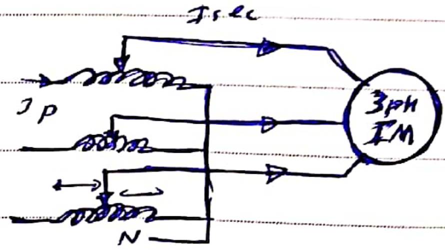
$T_{st}' = T_{rated} \Rightarrow a = ??$, $\frac{I_{st}'}{I_{rated}} = ?$, $I_{st\,Primary}' = ??$

Sol

$I_{rated} = \frac{P_{in}}{\sqrt{3}\, V_{L-L}\, PF} = \frac{40.98\,kW}{\sqrt{3} * 460 * 0.87}$ $\quad P_{in} = \frac{P_{out}}{\eta} = 40.98\,kW$

$= 59\,A/line$

$I_{ph} = \frac{59}{\sqrt{3}} = 34.1\,A/ph$



per phase auto transformer

$\frac{V_r}{V'} = a$

$\frac{T_{st}}{T_r} = 1.75$, $\frac{T_{st}'}{T_r} = 1$ $(T_{rated} = T_{st})$

$\frac{T_{st}'}{T_{st}} = \frac{1}{1.75}$

$\frac{I_{st}'}{I_{st}} = \sqrt{\frac{T_{st}'}{T_{st}}}$ $\Rightarrow$ $T_{st} = \frac{3}{\omega_s} \frac{I'^2}{\ } \frac{R_2'}{\ }$

$I_{st}' = \ldots$

$= \sqrt{\frac{1}{1.75}} = 0.76$

$a = \frac{1}{0.76} \left(\frac{V}{V'}\right)$

Single-ph Induction Motors:-

This the most important Existing Single-ph Motor.

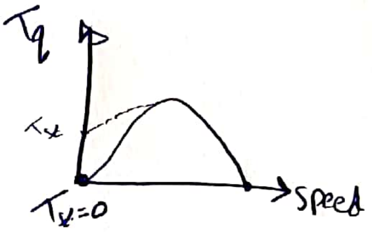
Used in:

Washing Machines, ~~fan~~ fans, pumbs, Kitchen tools,....

It is a special Motor.

Wrost feture:- it is a non-self starting Motor. $\Rightarrow (T_{st}=0)$

Certain arrangements required to start the motor.



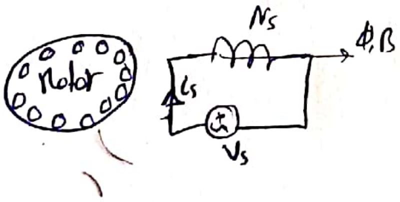
The basic construction features:-

Rotor:-

Usally squirel-cage [same as that of 3-ph Motors]

Stator:-

Single winding supplied by single phase current.



$B = B_m \cos(w_s t)$, $w = 2\pi f$

α axis angle of the rot element

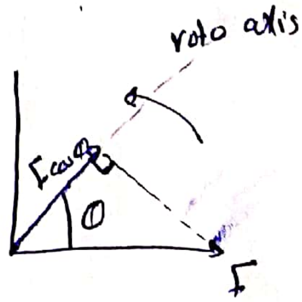
$F = F_{max} \cos(w_s t)$ $\quad \phi = \phi_m \cos(w_s t)$

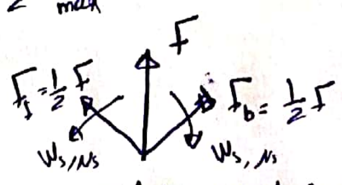
$\phi, B, F \Rightarrow$ pulsaiting, rather than fixed rotating field in 3-ph Motors.

$F = F_m \cos w_s t = F_m \cos(w_s t) . \cos \theta$

$= \frac{F_m}{2} \cos(w_s t - \theta) + \frac{1}{2} F_m \cos(w_s t + \theta)$

$F(t, \theta) = \frac{1}{2} F_{max} \cos(\theta - w_s t) + \frac{1}{2} F_{max} \cos(\theta + w_s t)$





This implies that the pulsating field can be considered as two componants [Rotating Field rotating opposite to each other.

1) $F_f \Rightarrow$ Forward Rotating Field (Rotor rotates in the same direction as F_f)

define $S_f = \frac{N_s - N}{N_s}$ Forward slip

2) $F_b \Rightarrow$ Back Rotating Field (In opposite direction of F_f)

Define $S_b \Rightarrow$ Slip of the back rot. Field F_b

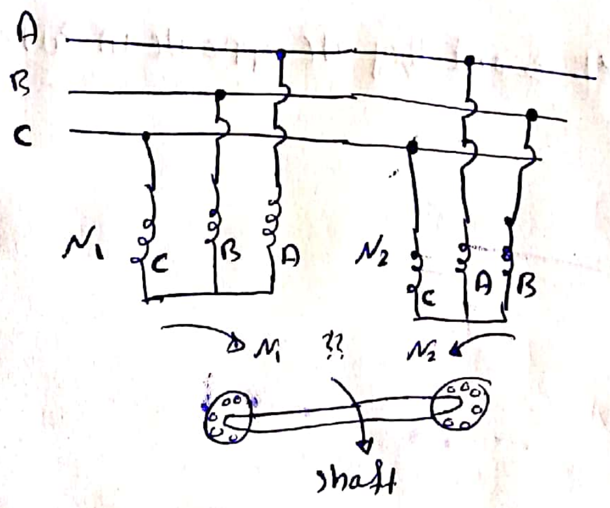
$$S_b = \frac{N_s - (-N)}{N_s} = \frac{N_s + N_f}{N_s}$$

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

$$\therefore S_b = 2 - S_f$$

$S_b \overset{??}{=} S_f \Rightarrow$ This is if $S_f = 1 \Rightarrow$ Starting Instant

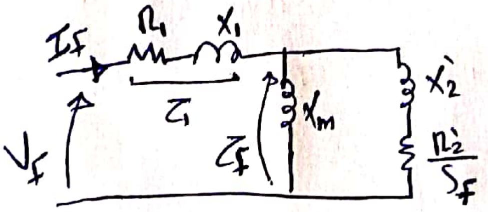
This is equivalent to



*) This is the two 3-ph equivalent structure of the single-phase I.M

Equivalent Circuit Development :-

Forward Field :-

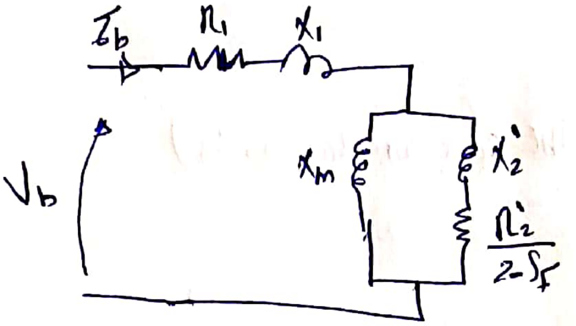


$I_s \Rightarrow$ Stator current [single phase] $= \bar{I}_f + \bar{I}_b$

$$Z_f = \frac{jX_m \left(\frac{r_2'}{S_f} + jX_2'\right)}{\frac{r_2'}{S_f} + j(X_m + X_2')}$$

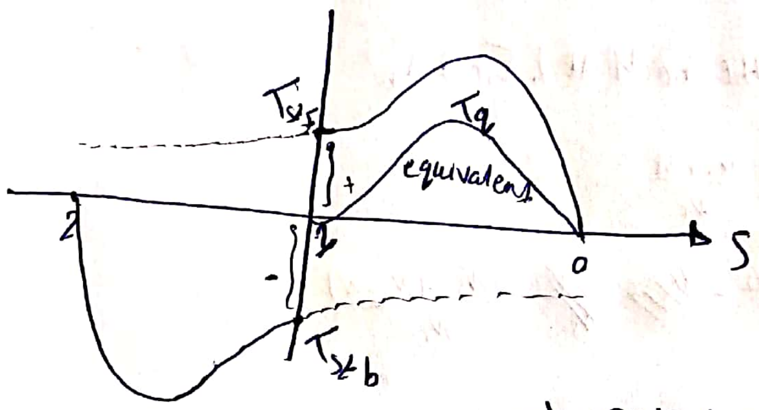
$$\bar{V}_f = \bar{I}_f (Z_1 + Z_f)$$

Backward Field:-



$$\bar{Z}_b = \frac{jX_m\left(jX_2' + \frac{R_2'}{2-S_f}\right)}{\frac{R_2'}{2-S_f} + j(X_m + X_2')}$$

$$\bar{V}_b = \bar{I}_b(\bar{Z}_1 + \bar{Z}_b)$$



→ operating areas

Total torque

$$T_q = T_f + T_b$$

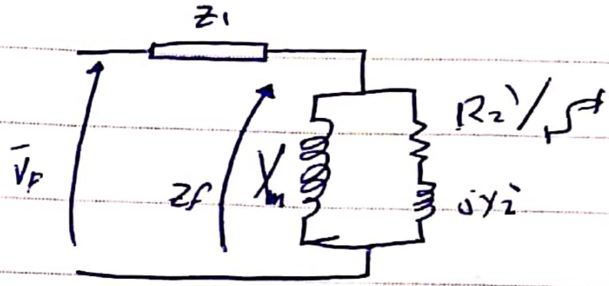
$T_{st} = 0 \Rightarrow$ Since $T_{stf} = T_{stb} \Rightarrow$ and they are opposite in directions

* Equivalent Circuit

Forward Field

define $s = s_f \to$ hence $s_b = 2 - s$

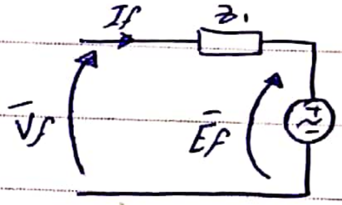
$Z_1 = R_1 + jX_1$



* $Z_f = jX_m \,//\, \left(\frac{R_2'}{s} + jX_2'\right)$

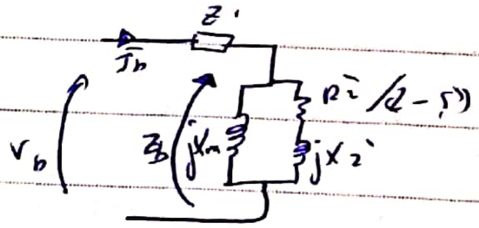
$= R_f + jX_f$ $\qquad \bar V_f = \bar I_1 Z_1 + \bar E_f$

$E_f = I_f * Z_f$

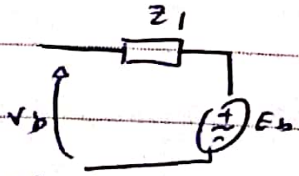


Backward

$Z_b = \ldots // \ldots$



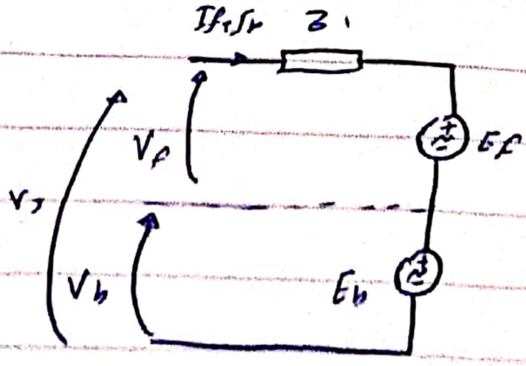
$\bar V_b = \bar I_b * Z_1 + \bar E_b$



* the two circuits can be combined into one circuit

$V_s = I_s Z_1 + \bar E_f + \bar E_b$

$= I_s Z_1 + I_s(Z_f + Z_b)$



* at stand still

$S_f = S_b = S \to Z_f = Z_b$

$B(\theta, \dot\theta)_f = B_{max} \cos(\theta)$

$B(\theta, \dot\theta)_b = B_{max} \cos(\theta)$

$\boxed{E_f = E_b}$

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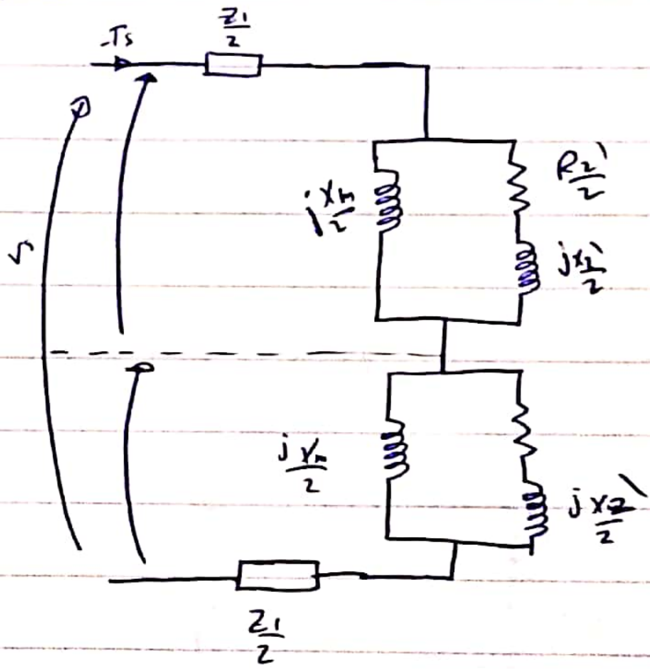
$Z_f I_f = Z_b + I_b$

Since $Z_f = Z_b \Rightarrow I_f = I_b \Rightarrow I_f = I_b = \frac{I_s}{2}$ $\quad (I_s = I_f + I_b)$

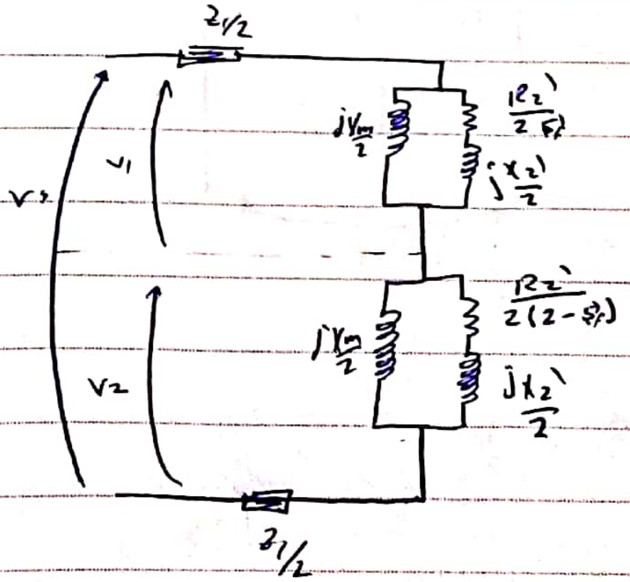
$V_s = I_s Z_1 + I_s (Z_f + Z_b)$

$= Z_1 \frac{I_s}{2} + Z_1 \frac{I_s}{2} + \frac{I_s}{2} Z_f + \frac{I_s}{2} Z_b$

only at Stand still $\Rightarrow$



In General

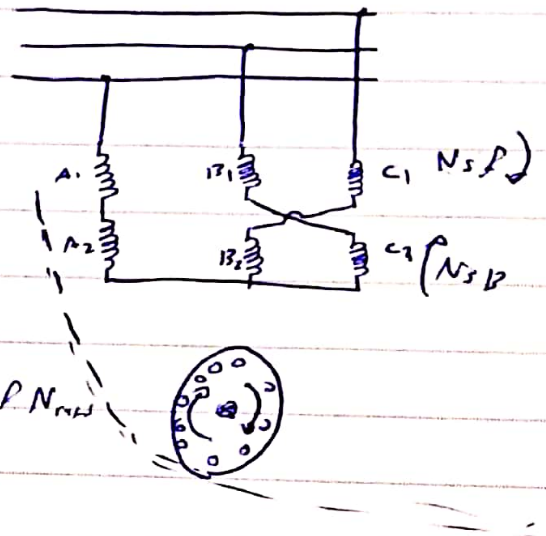


* Starting of Single phase I-M

$T_{gf} = \frac{I_s^2}{w_s} \frac{R_f}{2}$, $T_{gb} = \frac{I_s^2}{w_s} * \frac{R_b}{2}$ $Z_f = R_f + jX_f$

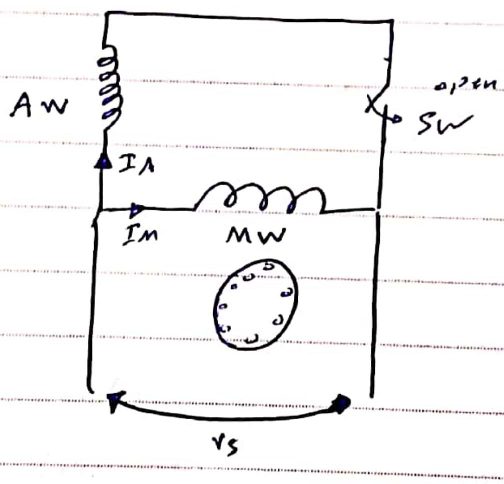
$T_{overall} = T_f - T_b = \frac{I_s^2}{2w_s} (R_f = R_b)$ at starting

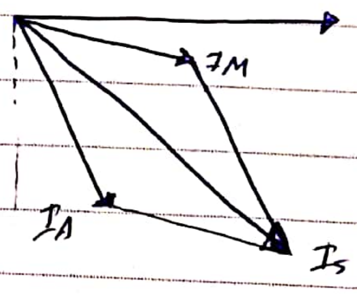
$\boxed{T_{st} = 0}$



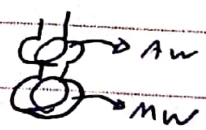
Problem: Starting Torque = 0

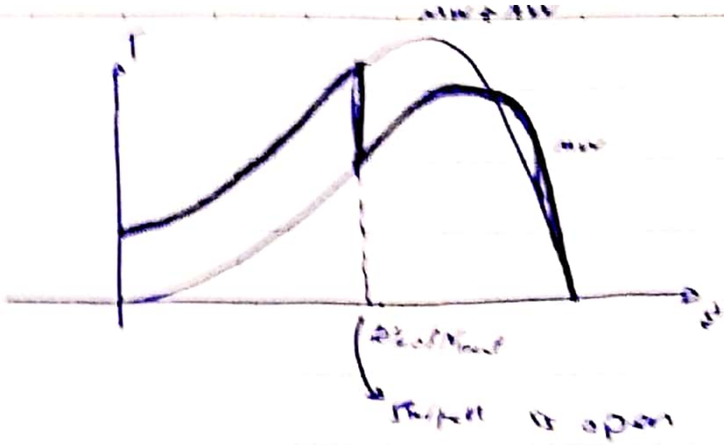
① use split-phase IM





AW has $\frac{R_a}{X_A}$ larger than that in MW
(then wire, outer part of the rotor)
R↑ X↓

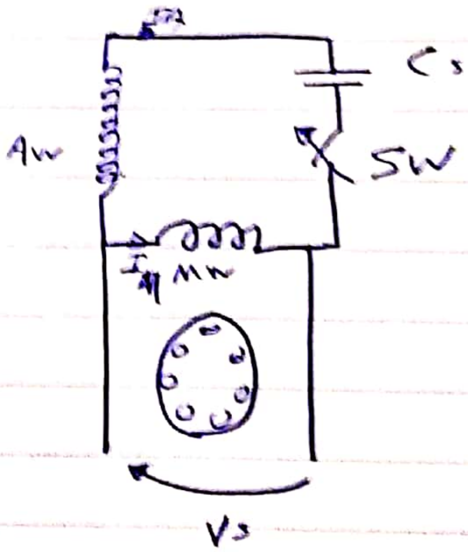


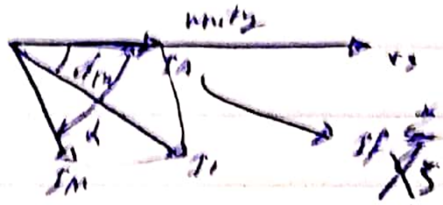


→ at starting
- low PF
- high current
- low η

② Capacitor – Start ~~Split~~ Single phase IM

a Capacitor C_s is added in series with the AW

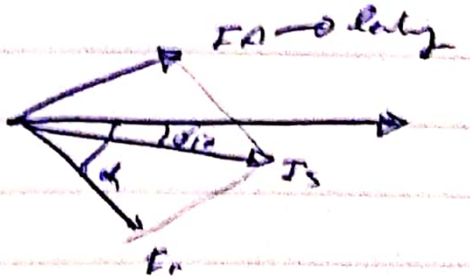




$X_S = X_w$

for $X_C > X_{Aw}$

preferred to set $\alpha = \frac{\pi}{2}$



Sw is open at (70–80)%.

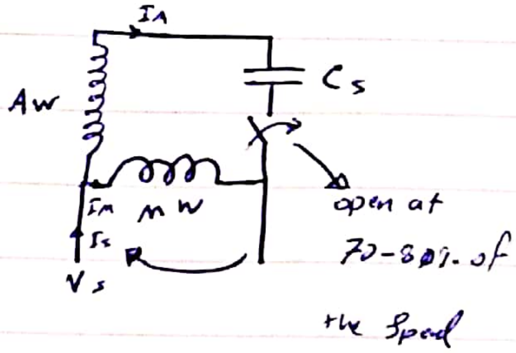
* Capacitor - Run Motor

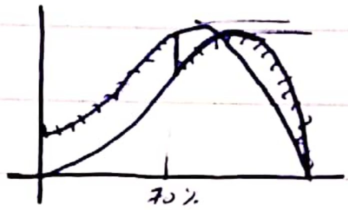
* with C_s

$T_{st} > 0$

$PF_{in} \uparrow$ → at starting

$\eta \uparrow$

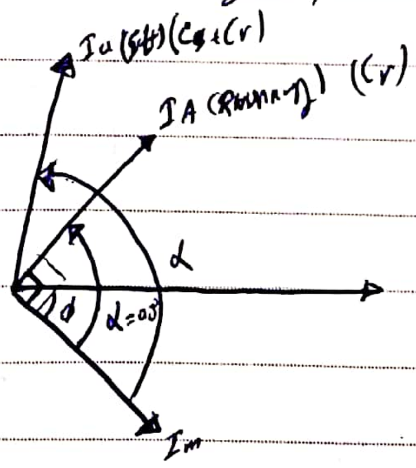


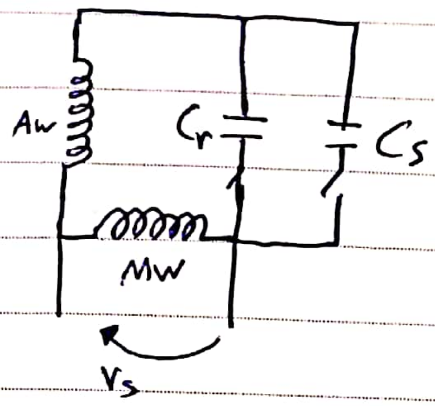


③ Capacitor Start, Capacitor Run Motor

C_s : Starting Capacitor

C_r: normal running capacitor   * α designed to be greater than 90°





* the parameters are selected such that when C_s is removed $\alpha = 90^\circ$

$PF \uparrow$ $\eta \uparrow$ } ⇒ normal running

$T_{st} = 2.5 - 3\ T_{rated}$ } ⇒ ~~Fastest~~ at starting

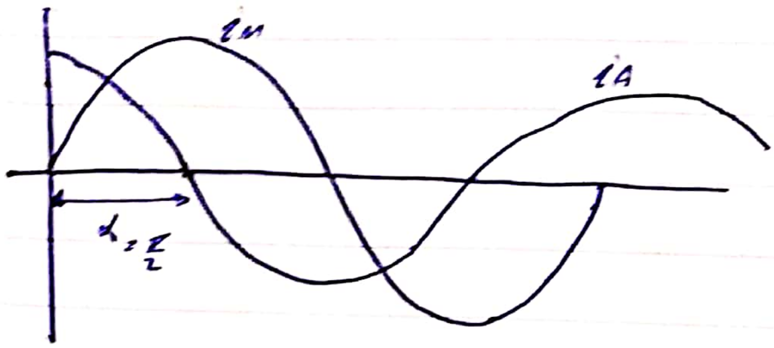
The Rotating Field

@ t = 0

$i_A = I_m \cos(\omega t)$ $F \propto i N$

$F_A = F_m \cos(\omega t)$

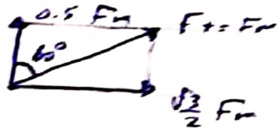
$F_M = F_m \sin(\omega t)$



@ ωt = 60°

$F_A = 0.5\ F_m$

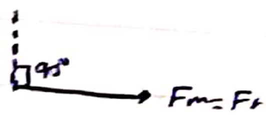
$F_M = \frac{\sqrt{3}}{2}\ F_m$ ⇒



$(\sqrt{\frac{1}{4}^2 + \frac{\sqrt{3}}{2}^2}$

@ ωt = 90° $F_A = 0$

$F_B = F_M$ ⇒



↳ The Field has Fixed amplitude ~~Fmt~~ and Rotating in the Same Speed as ωs of the supply Current

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* Problem

1 KW, 4-pole, 215 V, 50 Hz Single Phase IM

has the parameters $X_m = 110.2\ \Omega$. $X_1 = X_2' = 4.02\ \Omega$

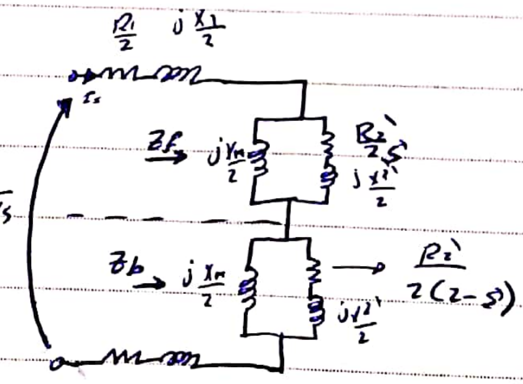
$R_1 = 1.6\ \Omega$ $R_2' \approx 3.1\ \Omega$

- Draw the motor equivalent circuit with all the parameters being shown
- Determine the input Current, PF, η, Shaft torque, when running at $\underline{1440\ RPM} \longrightarrow N_m$

Sol

$S_{forward} = S$ at the normal running

$S = \dfrac{1500 - 1440}{1500} = 0.04$ $N_s = \dfrac{60f}{P} = 1500\ RPM$



$\dfrac{R_2'}{2S} = 38.75\ \Omega$, $\dfrac{R_2'}{2(2-S)} = 0.79\ \Omega$

* $Z_f = j\dfrac{X_m}{2} \parallel \left(\dfrac{R_2'}{2S} + \dfrac{jX_2'}{2}\right)$

$= \underbrace{23.73}_{R_f} + j\underbrace{19.63}_{X_f} = 30.8\angle 39.36^\circ\ \Omega$

* $Z_b = \text{---} \parallel \left(\dfrac{R_2'}{2(2-S)} + \text{--}\right)$

$1.37 + j\ 3.78 = 4.02\angle 70.0^\circ\ \Omega$

$Z_{rotor} = Z_f + Z_b$, $Z_{stator} = R_1 + jX_1$, $Z_{total\ in} = Z_{rot} + Z_{stator}$

$Z_{in} = \text{-----} = 26.7 + j\ 27.43 = 38.28\angle 45.77^\circ$

$I_s = \dfrac{V_s}{Z_{in}} = \dfrac{215\angle 0^\circ}{38.28\angle 45.77} = 5.62\angle -45.77^\circ$

$PF_{in} = \cos(\phi_{vs} - \phi_{is}) = \cos(0^\circ - (-45.77)) = 0.7$ lagging

* at Starting use the other equ-cct
  ↳ to find $T_{(st)}$, $I_{(st)}$

at starting $S = 1$

$f\ \dfrac{R_2'}{2*S} = b\ \dfrac{R_2'}{2*S}$

$\boxed{Z_f = Z_b}$ → at starting

* The Torque depends on $\boxed{R_f}$

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$* \eta \Rightarrow$

$P_{shaft} = P_o = P_{conv} - \cancel{P_{rot}} \rightarrow 0$

$= 674.9 \text{ watt}$

$\eta = \frac{P_o}{P_{in}} = \frac{674.9}{845.8} = 80\%$

$P_{in} = V_s I_s \cos\phi_{in}$ 11-

$= 215 * 5.67 * 0.7$

$= 845.81 \text{ W}$

$P_{g_{out}} = I_s^2 * (R_f - R_b)$

or

$I_f^2 * R_f \Rightarrow$

$P_{g_{out}} = 5.62(23.73 - 1.37)$

$= 706.23 \text{ W}$

$P_{conv} = P_g(1-s) = 677.9 \text{ W}$

$\textcircled{*}$ $T_{sh} = \frac{P_o}{w_m} = \cancel{\boxed{4.5 \text{ Nm}}}$

$w_m = \frac{2\pi}{60} * N_m$

$= 150 \text{ rad/s}$

$T_{gap} = \frac{P_g}{w_s}$

$w_s = \frac{2\pi}{60} * w_m =$