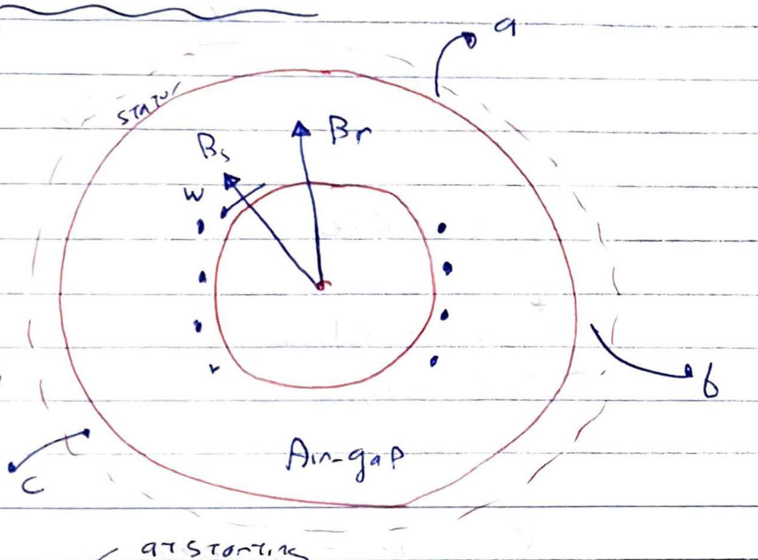
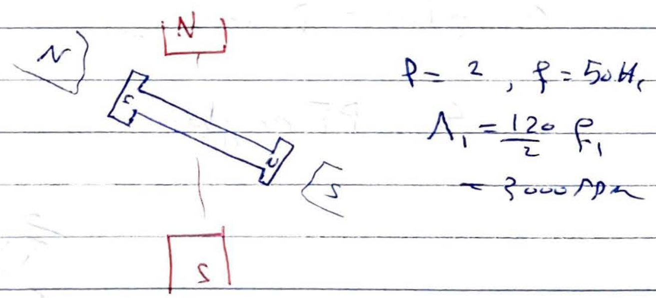
Chapter 5

Synchronous Motors

Operating principle



- The field current produces the rotor magnetic field $\vec{B_r}$.
- A set of 3ϕ voltages is applied to the stator windings which produces a set of 3ϕ currents to flow the stator windings.
- The ~~Rotor~~ current will produces $\vec{B}$, which rotates at ω_s. at starting
- The rotor is rotating by some external means to obtain a magnetic locking between the rotor & stator poles, and then produces a continuous induced torque ($T_{ind} = K \vec{B_r} \times \vec{B_s}$)

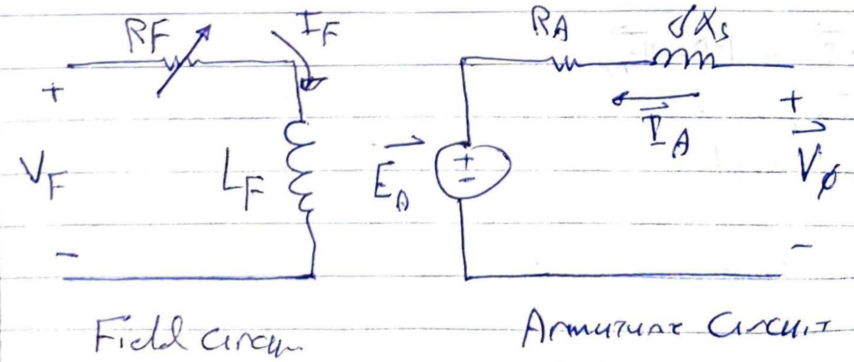


$P = 2$, $f = 50 Hz$

$n_1 = \frac{120}{2} f_1$

$= 3000$ rpm

equivalent circuit : (Per. phase)



R_A: armature resistance

X_s: Synchronous reactance

$X_s = X_A + X$

X_A → Reactance of stator windings

X → Reactance of armature reaction

V_ϕ : phase voltage

Y-connected $\longrightarrow$ $V_T = \sqrt{3}\, V_\phi$

Δ-connected $\longrightarrow$ $V_T = V_\phi$

$E_A = K \phi \omega_s$

↓

Induced voltage

Back emf voltage

emf

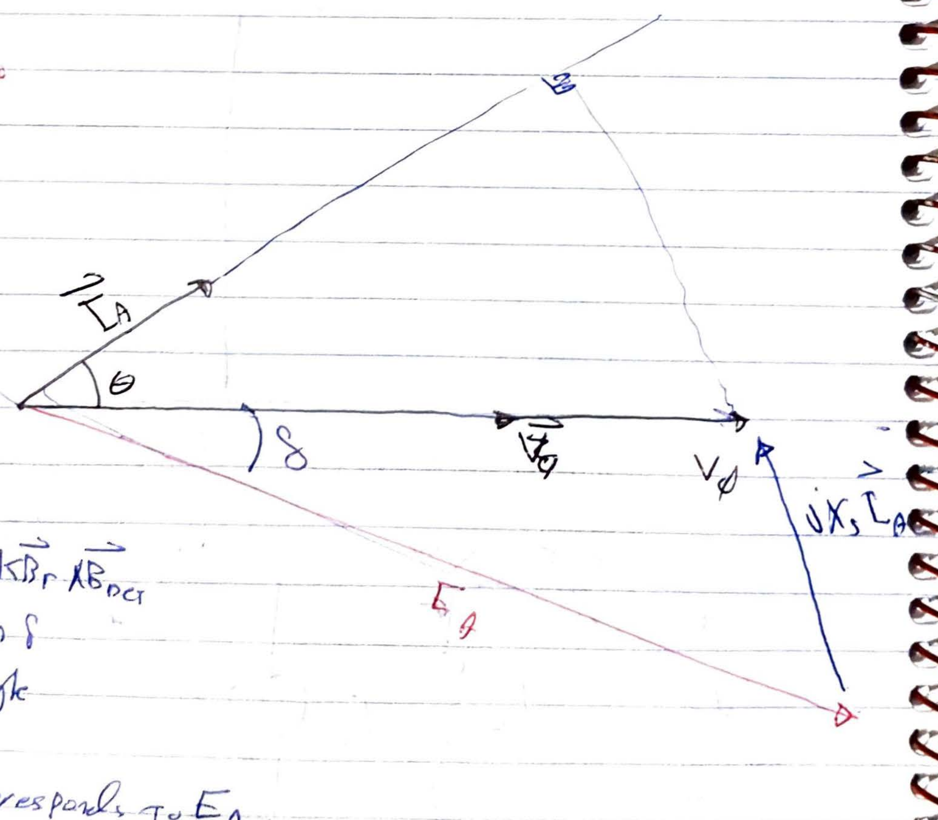
KVL in the armature circuit

$\vec{E}_A = \vec{V}_\phi - jX_s \vec{I}_A - R_A \vec{I}_A$

OR $\vec{V}_\phi = \vec{E}_A + R_A \vec{I}_A + jX_s \vec{I}_A$

* phasor Diagrams

θ : PF angle



$T_{ind} = K\vec{B}_r \times \vec{B}_s = K\vec{B}_r \times \vec{B}_{net}$

$T_{ind} = K B_r B_{net} \sin\delta$

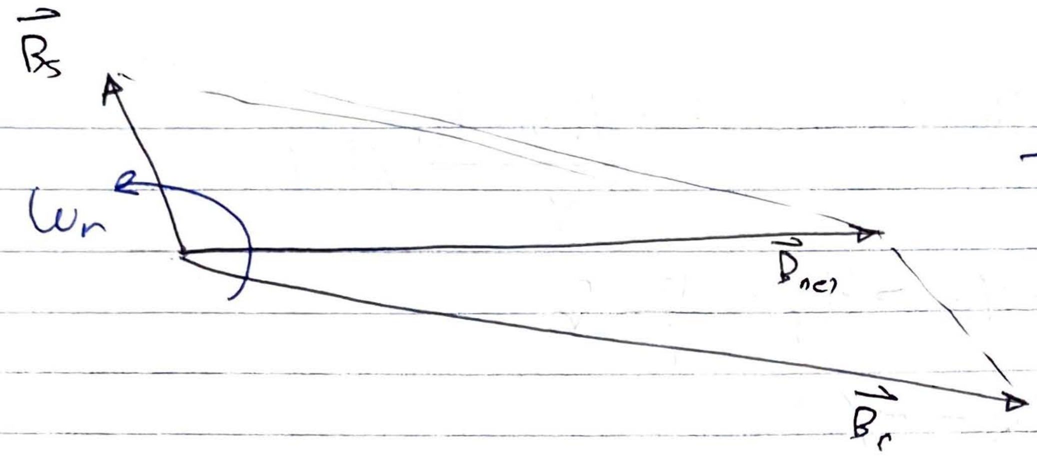
δ : Torque angle

$\vec{B}_r$: ~~same~~ corresponds to E_A

$\vec{B}_{net}$: correspond to $\vec{V}_\phi$

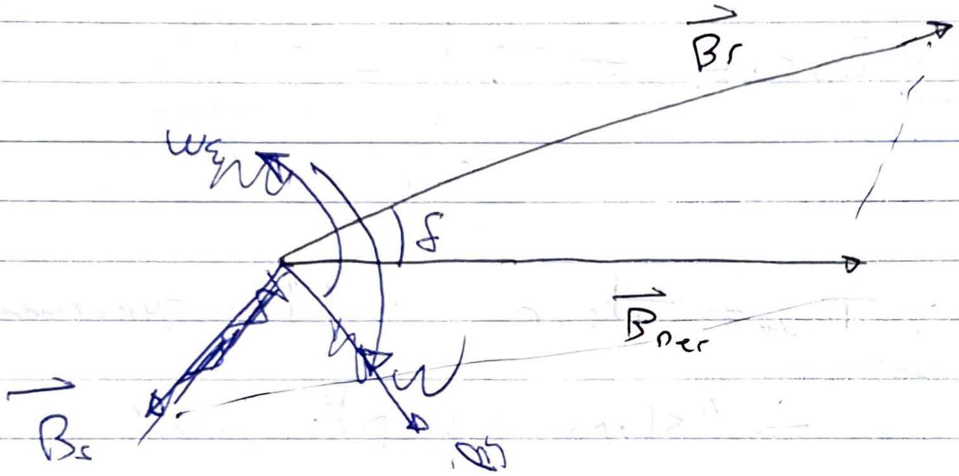
$\vec{B}_s$ = " " $(-jX\vec{I}_A)$

"Armature reaction"



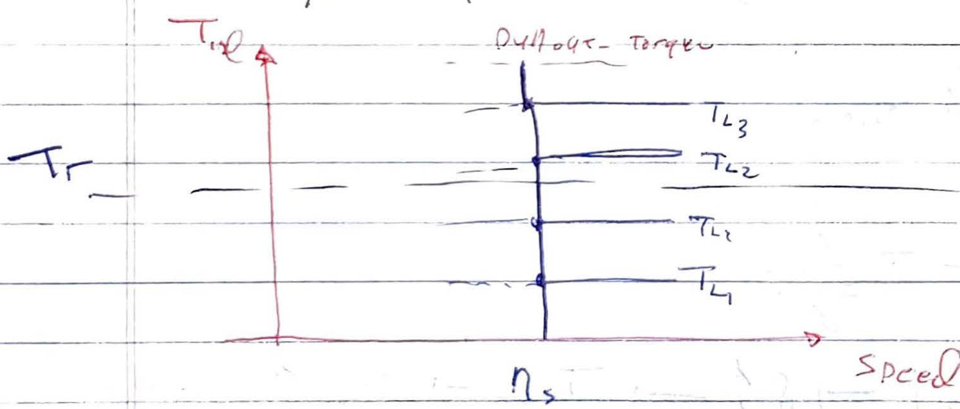
$T_{ind} = CCW$
$\omega_r = CCW$

"generator"



$T_{ind} = CW$
$\omega_r = CCW$

Torque - speed - characteristics.



Load Torque

$$T_{ind} - T_L = J \frac{d\omega_m}{dt}$$

Rated Torque (T_r)

↳ synchronous speed

Pull - out Torque : It's the maximum operating Torque of synchrones motor

$$T_{max} = (2.5 - 3)\, T_r$$

$$\text{Speed Regulation} = SR = \frac{n_{NL} - n_{FL}}{n_{FL}} \times 100\%$$

$$n_{NL} = n_{FL} = n_s = \frac{120}{P} f_e$$

$$\boxed{SR = 0\%}$$

Torque equations

$$T_{ind} = \frac{3 V_\phi E_A \sin\delta}{X_s \omega_s} \Rightarrow T_{max}\Big|_{\delta = 90} = \frac{3 V_\phi E_A}{X_s}$$

max

If $T_{Load} > T_{max} \Rightarrow$ The motor will lose synchronism

$\Rightarrow$ "slipping pole phenomenon"

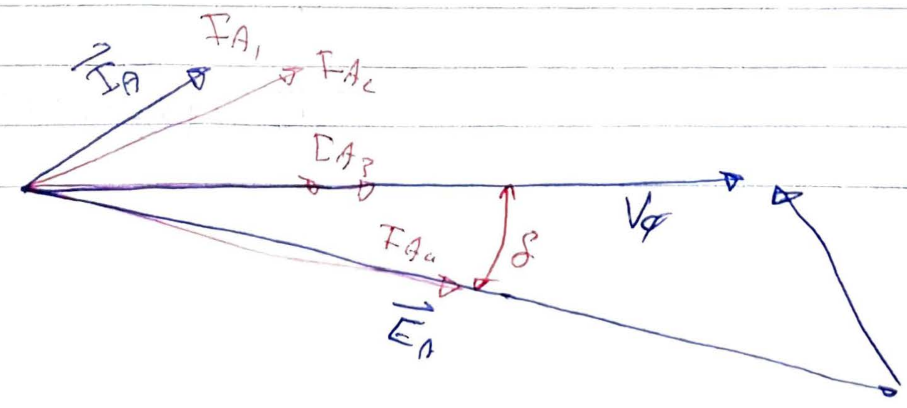
⊛ Effect of load changes :

$$T_{ind} = \frac{3 V_\phi E_A}{X_s \omega_s} \sin\delta$$

$$T_{ind} - T_{Load} = \underbrace{J}_{\text{inertia}} \frac{d\omega_m}{dt}$$

$T_{Load} \uparrow \Rightarrow \omega_m \downarrow \Rightarrow \delta \uparrow \Rightarrow T_{ind} \uparrow \Rightarrow \omega_m \uparrow$ until it Reaches synchronous speed

⊛ phsor

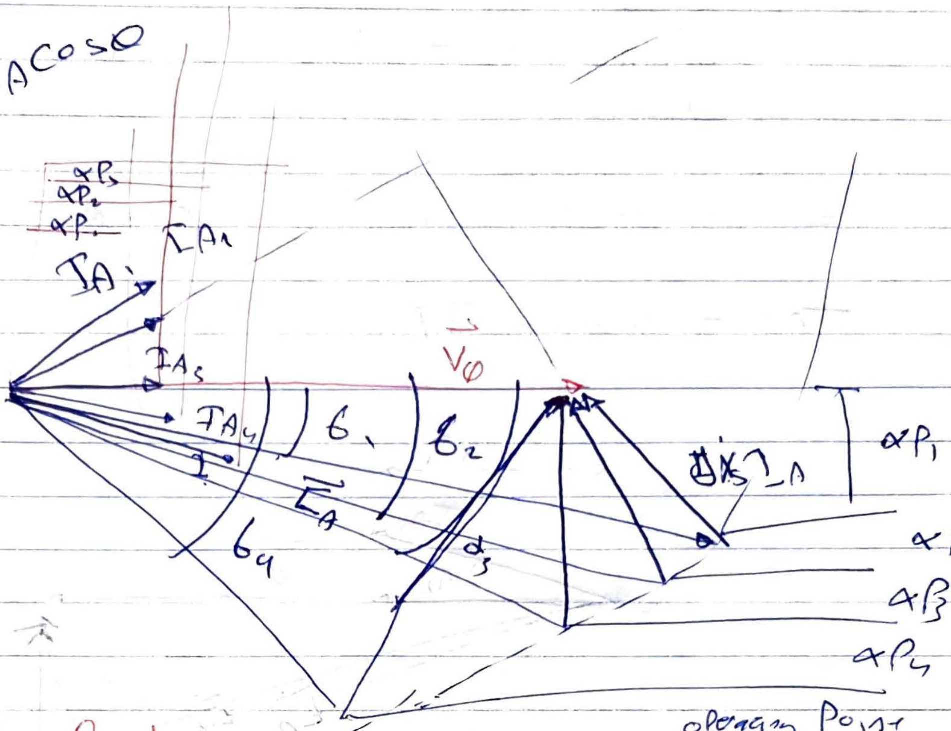


Video

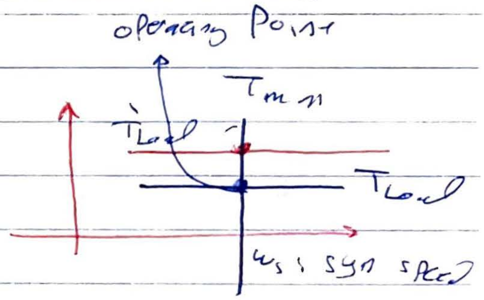
δ كل ما نزيد حتى يوصل I_A لـ T_{ind}

اما عند زيادة حمل Load I_A يزيد.

$P \propto I_A \cos\theta$



Effect of Load changes



$$T_{ind} = \frac{3 V_\phi E_A \sin\delta}{X_s \omega_s}$$

$T_{ind} - T_{Load} = J \frac{d\omega_r}{dt}$; $\omega_r \equiv$ Rotor speed

$T_{Load} \uparrow \Rightarrow \omega_r \downarrow \Rightarrow \delta \uparrow \Rightarrow T_{ind} \Rightarrow \omega_r \uparrow$ until it reaches ω_s, but at large δ

Load $\uparrow \Rightarrow$ the PF becomes less leading $\rightarrow$ unity $\rightarrow$ lagging $\rightarrow$ more lagging

الهدف التحكم بـ P ديكمه في المأخوذه والمعطاه.

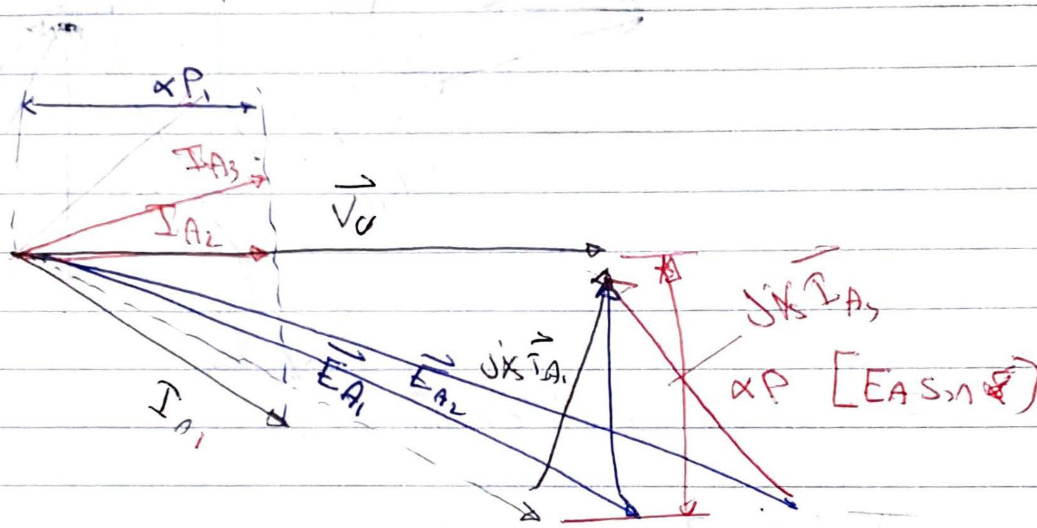
Effect of I_F changes:

Assume P is constant

$$P = \frac{3V_\phi E_A \sin\delta}{X_S} = 3V_\phi I_A \cos\theta = \text{constant}$$

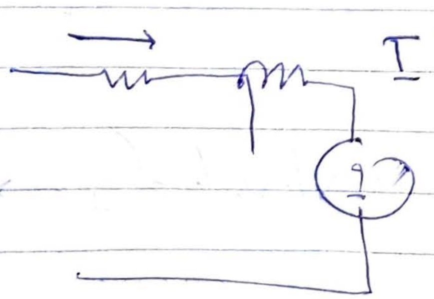
$$E_A \sin\delta = \text{constant} \;\&\; I_A \cos\theta = \text{constant}$$

viedee Try to increase I_F [E_A]



$E_A = K\phi\omega_s$

$I_F \uparrow \Rightarrow E_A \uparrow \Rightarrow$ PF becomes less lagging → unity → leading
→ More & More leading

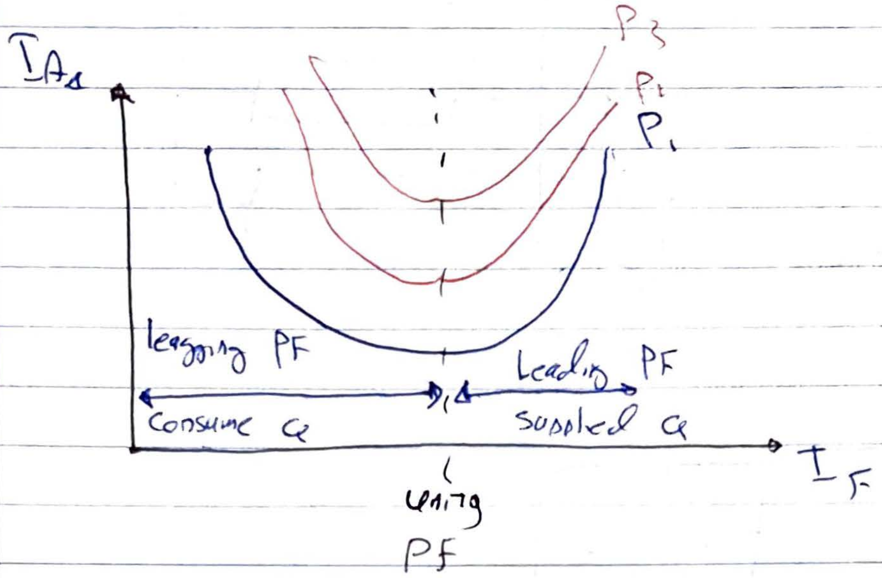


I^2R

$S\downarrow = VI\downarrow$

$S = \sqrt{P^2 + Q^2}$

V-curves of synchronous Motors.



$P_3 > P_2 > P_1$

its a data Represent the armature current and field current

when $E_A \cos\delta < V_\phi \Rightarrow$ Lagging PF $\Rightarrow$ Q is Connected
$\Rightarrow$ under-excited process

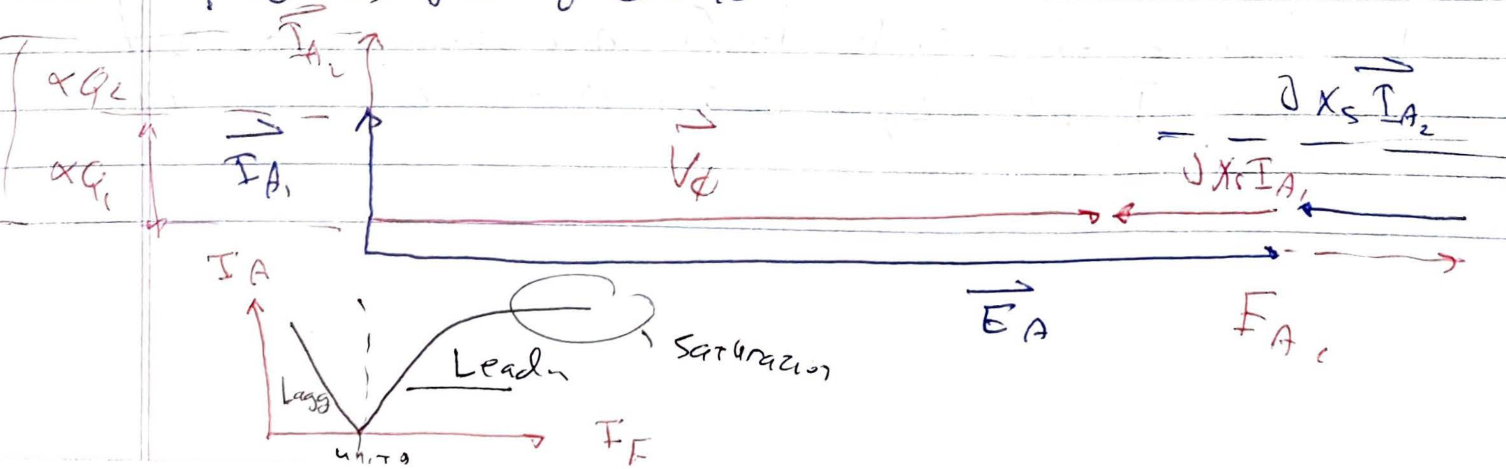
when $E_A \cos\delta > V_\phi \Rightarrow$ PF is Leading
$\Rightarrow$ Q is supplied
$\Rightarrow$ over-excited process

Synchronous Condenser OR synchronous Capacitor:

Its a synchronous motor without its shaft operated at no-load ($P=0$) & over excited (Q is supplied) it was used historically a power factor Correction Device.

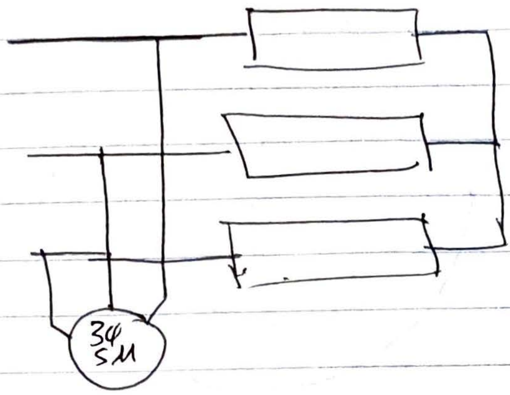
$$P=0 \Rightarrow P = \frac{3V_\phi E_A}{X_s}\sin\delta = 3V_\phi I_A \cos\theta$$

$P=0 \Rightarrow \delta=0$ & $\theta = 90°$

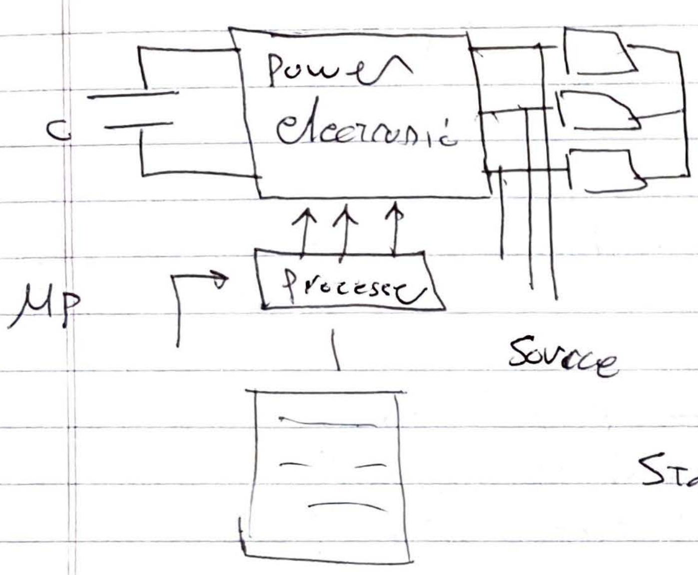


Power factor correction can achieved by :

1) syncronous condunser
2) static capacitors
3) using power electronics



③



$\overbrace{\text{VAR}}^{Q}$

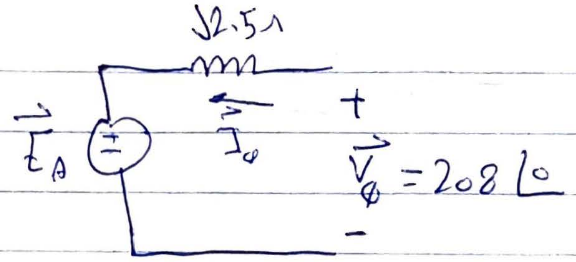
STATIC VAR compensator

Example 208V, 45KVA, 0.8 PF leading, Δ-connected, 60Hz, synchronous machine has $X_s = 2.5\,\Omega$ & $R_A = 0$ its friction and windage losses are 1.5 kW, & its core losses are 1kw, initially the shaft is ~~lagging~~ supplying a 15 hp Load, and the motor PF is 0.8 Leading

$1hp = 746W$

a) Find the values of $\vec{I}_\phi$, I_L & $\vec{E}_A$?

b) Assume that shaft load is now increased to 30 hp, Find I_ϕ, I_L & E_A, what is the new motor PF ?

a) 

KVL in the Armature Circuit:

$208\angle 0° = j2.5\vec{I}_\phi + \vec{E}_A$

$P_{OUT} = (15)(746) = 11.19$ KW

$P_{in} = 11.19 + 2.5 = 13.69$ KW $= 3 V_\phi I_\phi PF$

$$I_\phi = \frac{(13.69 \times 10^3)}{(3)(208)(0.8)} \angle +\cos^{-1}(0.8) = 27.4\angle 36.87 \text{ A}$$

$\vec{E}_A = 255\angle -12.4°$ V

$I_L = \sqrt{3}\,\vec{I}_\phi = 47.5$ A

b) $208\angle 0 = j2.5\,\vec{I}_\phi + \vec{E}_A$ → $K\phi\omega = E_A = \text{constant}$

$$P_{in} = \frac{3 V_\phi E_A \sin\delta}{X_s}$$

$P_{in} = (30)(746) + 2.5 \times 10^3 = 24.88$ KW

$$24.88 \times 10^3 = \frac{(3)(208)(255)\sin\delta'}{2.5}$$

$\delta' = 23°$

$\vec{E}_A = 255\angle -23°$ V

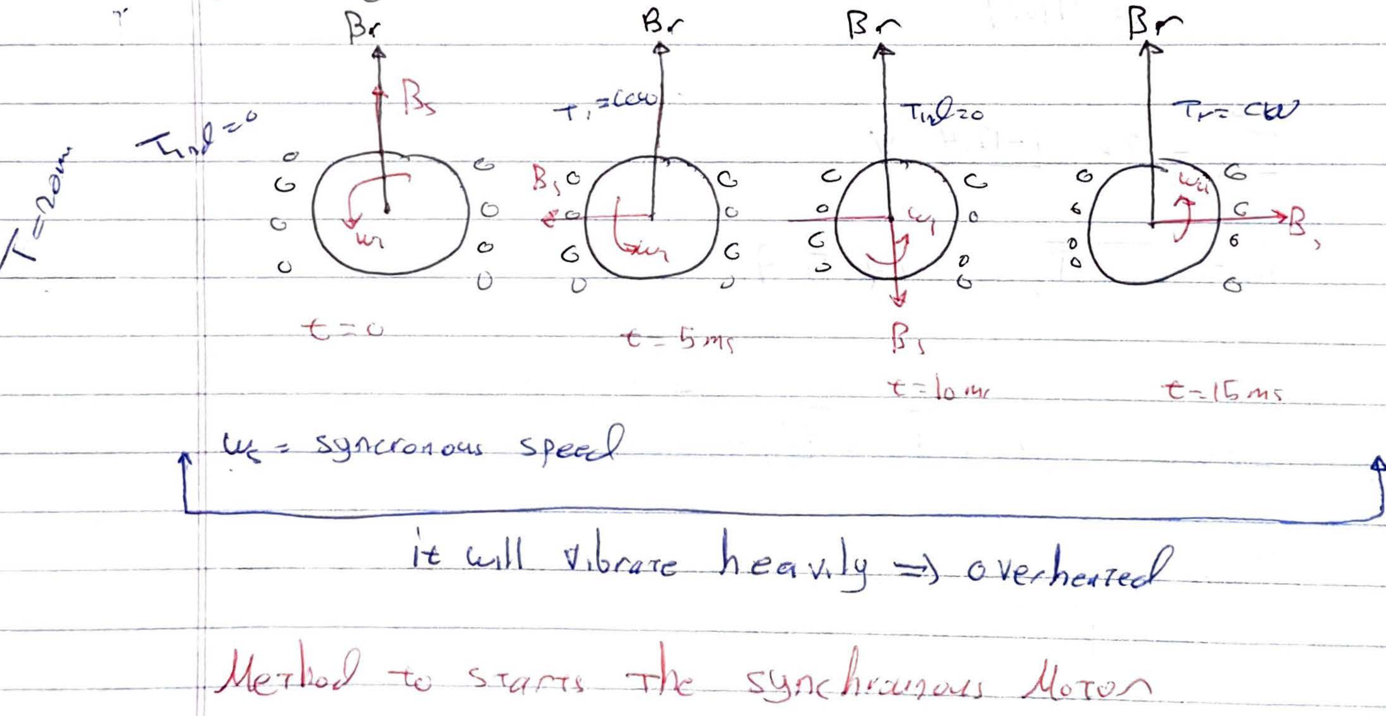
$$\vec{I}_\phi = \frac{208 - 255\angle -23^\circ}{j2.5} = 41.2\angle 15^\circ$$

$PF_{new} = \cos(0^\circ - 15^\circ) = 0.966$ Leading

لو كبرنا ⓐ [illegible]
PF و

Starting of synchronous Motor

Assume that a 50Hz power is supplied to a two poles synchronous Motor



ω_s = syncronous speed

it will vibrate heavily ⇒ overheated

Method to starts the synchronous Motor

① Using external prime mover

- Run the machnes as generator using the prime moves.
- Increase the Rotor speed up To ω_s
- Disconnect the Prime mover.

② Using damper or amortisseur windings

This method will start up the synchronous motor like 3ϕ induction motor

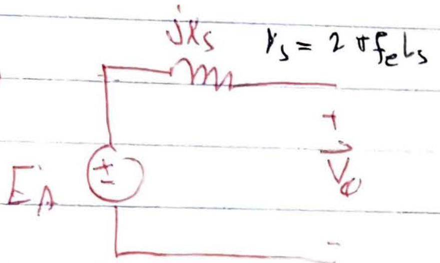
③ Reducing the electric frequency

$$n_s = \frac{120}{P} f_e$$

لذلك نريد انه محرك ركب الـ Motors
من خلالها سيحرك الـ Loads

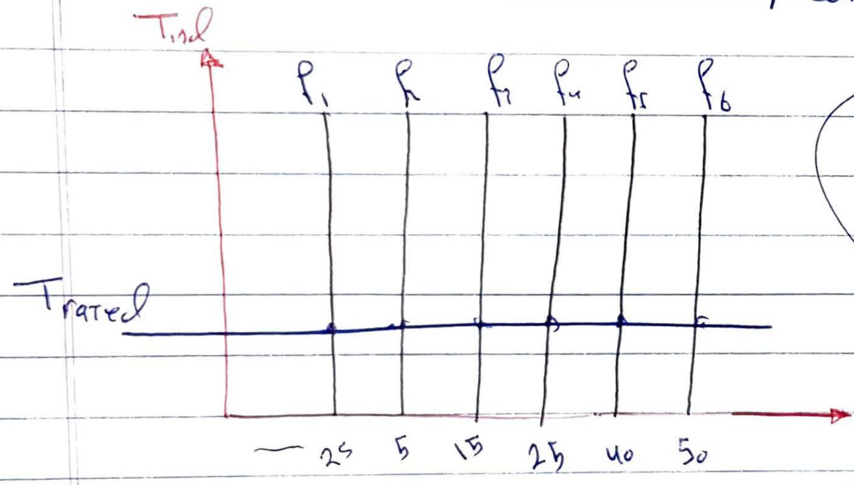
when f_e is small $\Rightarrow$ the speed of B_s, will be also small ($n_s = \frac{120}{P} f_e$)
$\Rightarrow$ The Rotor can ~~acce~~ accelerate and lock in with B_s.
$\Rightarrow$ when the motor is started increase the electric frequency gradually up to its normal value.

Note:



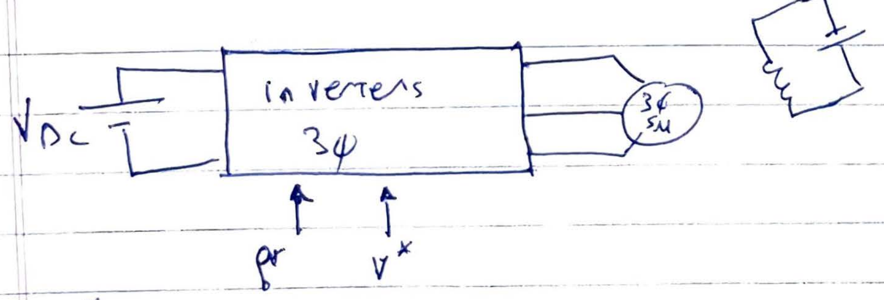
$$V_\phi \cong E_A = K\phi\omega_s \quad \propto f_e$$

$\phi \propto V/f_e \Rightarrow$ Two voltage must decrease with f_e by the same factor to keep ϕ constant & not let it saturated.



$$\frac{V}{f} = \text{Constant}$$

VVF Drive



So you can work at Rated Torque at all speeds

f^*: reference frequency
V^*: references voltage

CH5 problems: 1, 2, 3, 7, 9, 10, 14, 17, 18, 19