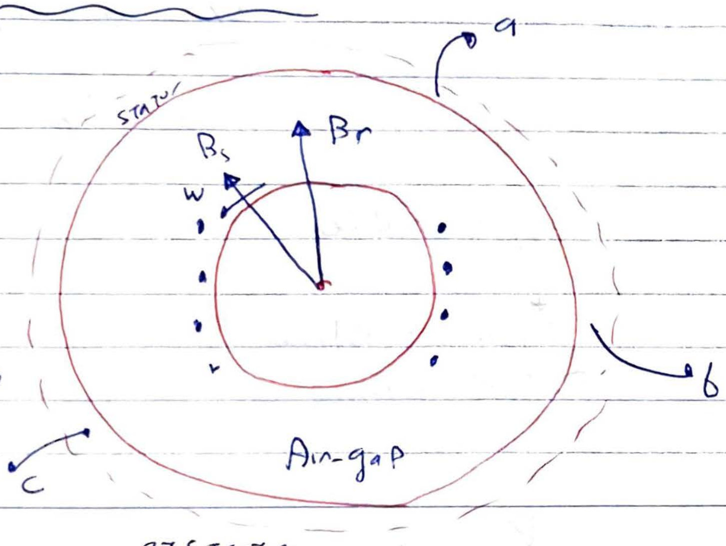
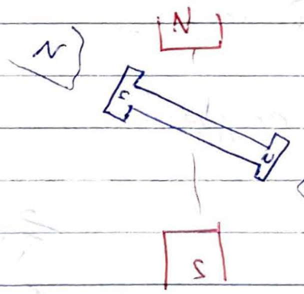
Chapter 5 Synchronous Motors

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 $(T_{ind} = K\vec{B_r} \times \vec{B_s})$

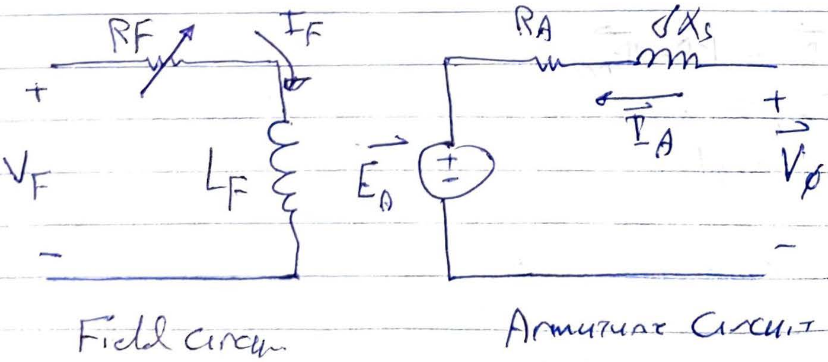


$P = 2$, $f = 50 Hz$

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

$= 3000 \, rpm$

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

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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 ~~of~~ voltage

emf

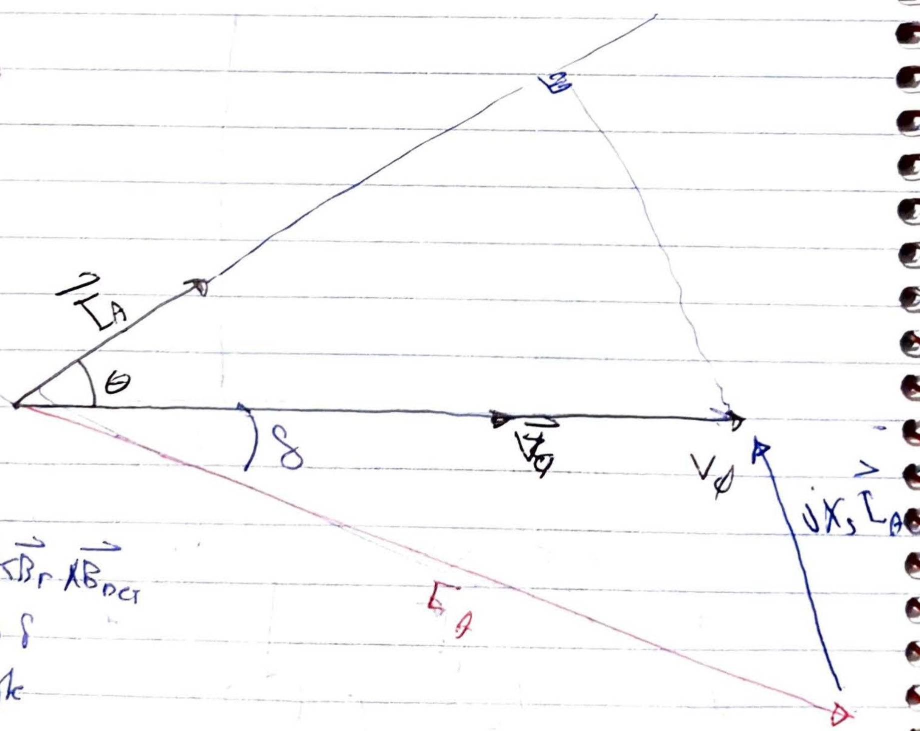
KVL in the armature circuit

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

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"

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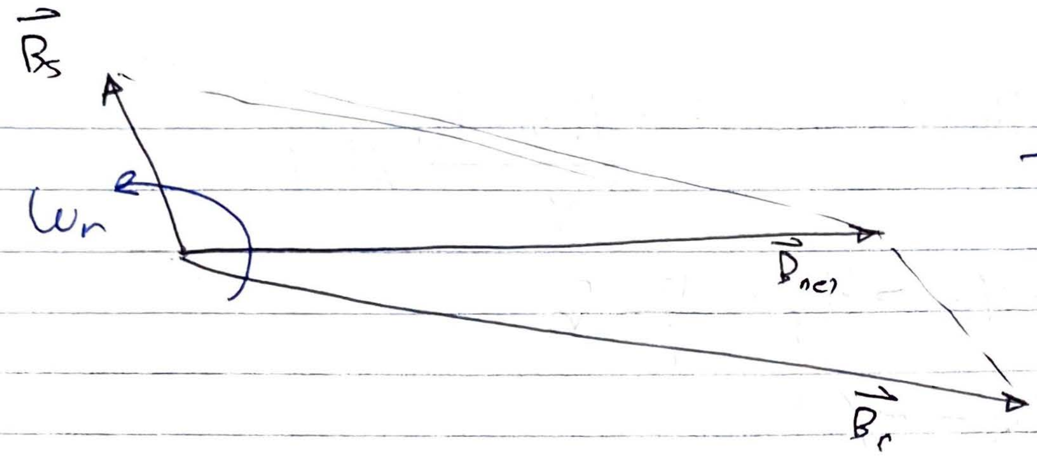
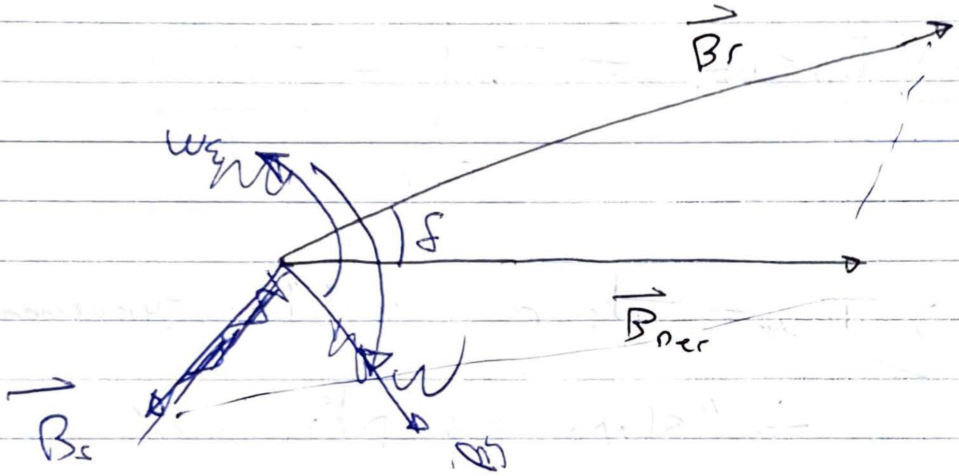


$T_{ind} = CCW$

$\omega_r = CCW$

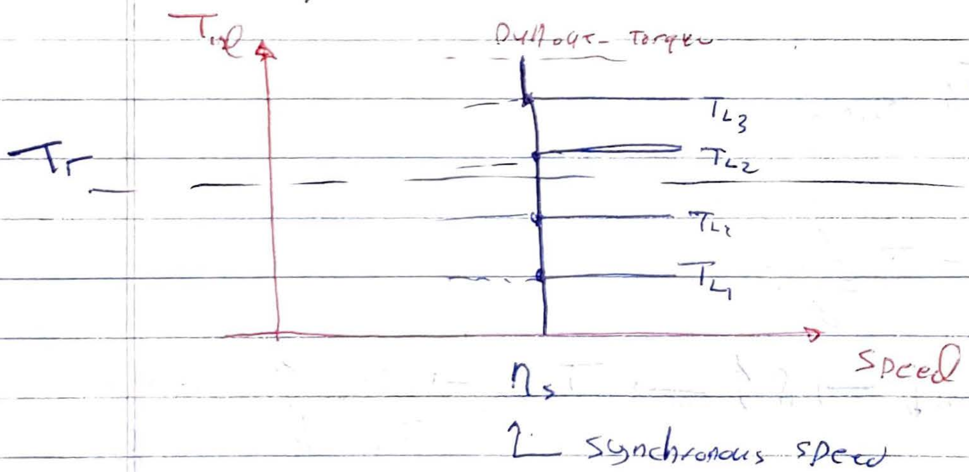
"generator"



$T_{ind} = CW$

$\omega_r = CCW$

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 synchronous motor

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

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

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

$\boxed{SR = 0\%}$

Torque equations

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

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

$\Rightarrow$ "slipping pole phenomenon"

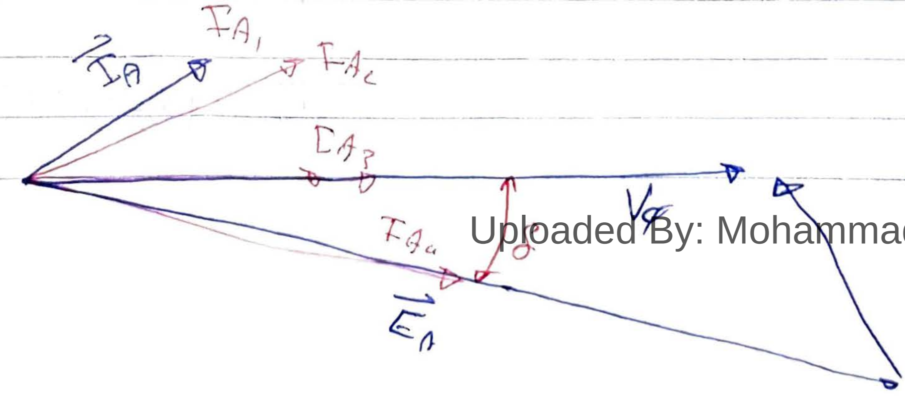
⊛ Effect of load changes :

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

$T_{ind} - T_{Load} = J \dfrac{d\omega_m}{dt}$ → inertia

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

⊛ phsor



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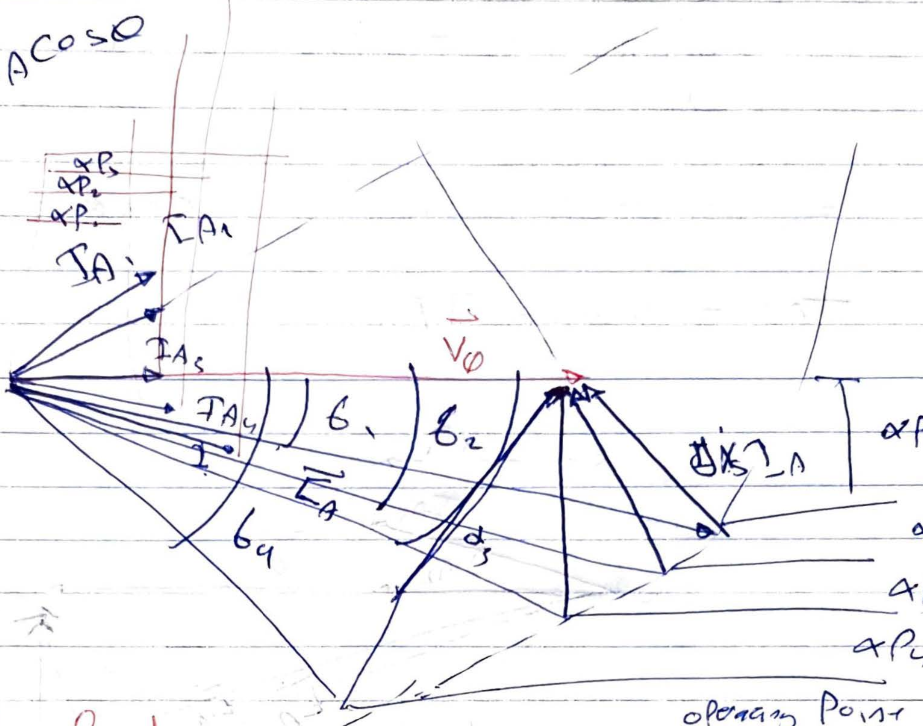
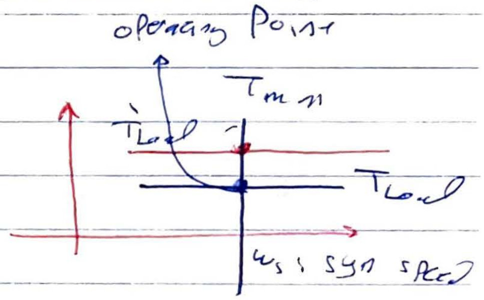
Video

δ بحب انه تزيد حتى تزود منه الـ T_{ind} I_A
ايضاً عند زيادة مع Load الـ I_A بزيد.

$P \propto I_A \cos\theta$



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

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لاهدف التحكم بـ P فيكم في المأخوذه والمعطاه.

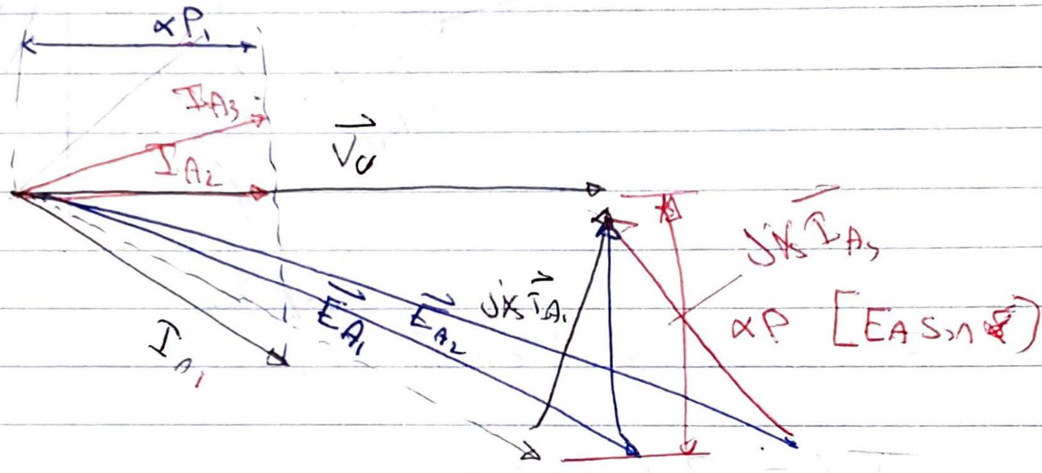
Effect of I_F changes:

Assume P is constant

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

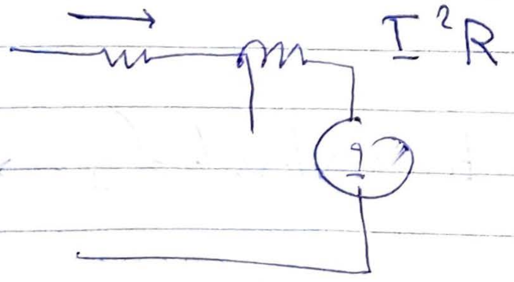
$E_A \sin\delta = \text{Constant}$ & $I_A \cos\theta = \text{Constant}$

Vector 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 $\rightarrow$ unity $\rightarrow$ leading
$\rightarrow$ More & More leading



$S\downarrow = V I \downarrow$

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

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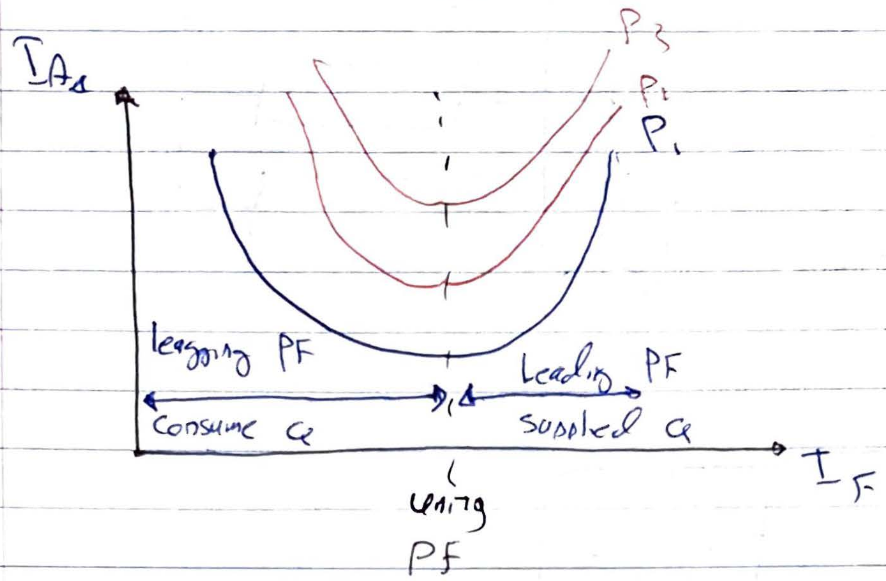
V-curves of synchronous Motors.



$P_3 > P_2 > P_1$

its a data Represent the armature current and field current

when $E_A \cos\delta < V_\phi \Rightarrow$ Lagging P F $\Rightarrow$ Q is Consumed
$\Rightarrow$ under - Excited process

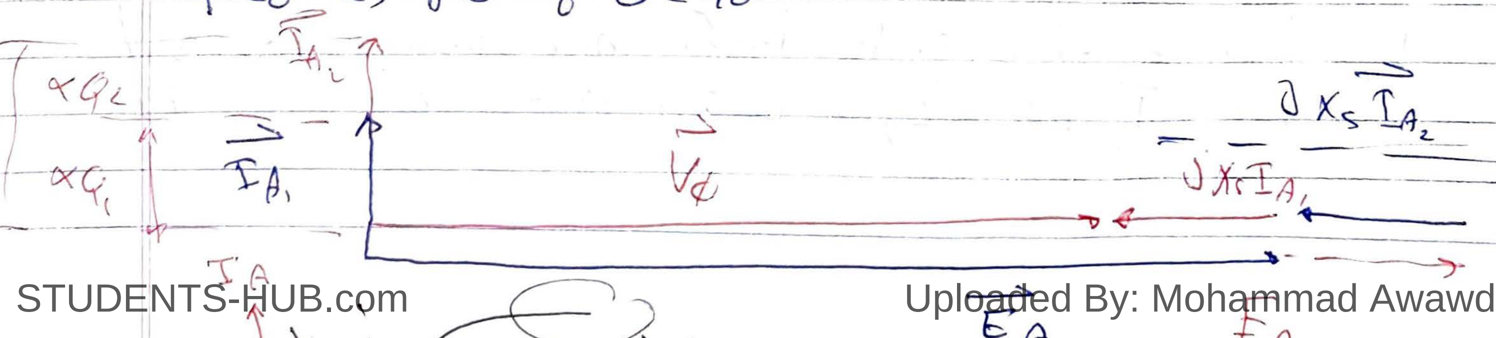
when $E_A \cos\delta > V_\phi \Rightarrow$ PF is Leading
$\Rightarrow$ Q. is supplied
$\Rightarrow$ over - excited process

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.

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

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



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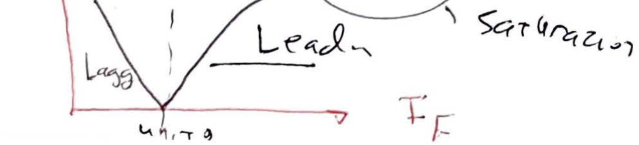
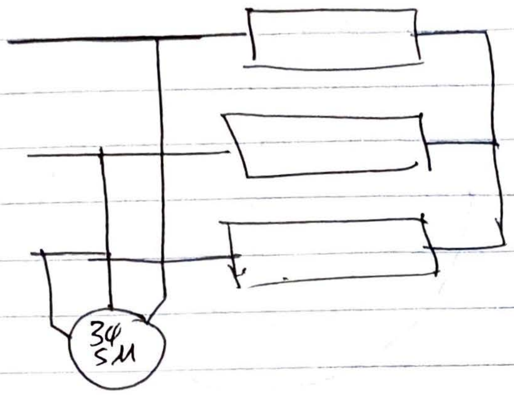
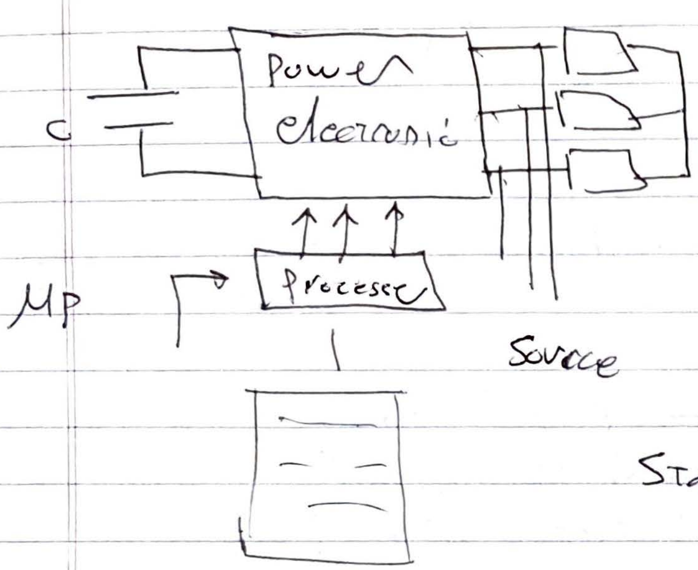


Power factor correction can achieved by :

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



③



φ

STATIC VAR compensator

Example 208V , 45KVA , 0.8 PF leading , Δ-connected , 60 Hz , 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 motors 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 $\vec{I_\phi}$, I_L & $\vec{E_A}$, what is the new motor PF ?

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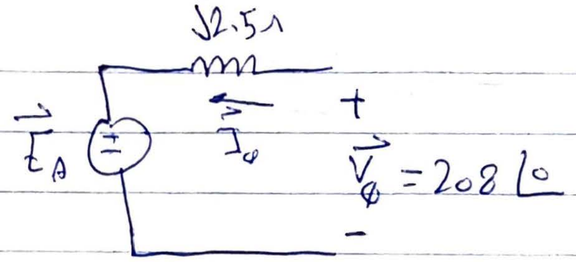
a)



KVL in the Armature Circuit:

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

$$P_{out} = (15)(746) = 11.19\ KW$$

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

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

$$\vec{E}_A = 255\angle -12.4^\circ\ V$$

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

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

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

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

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

$$\delta' = 23^\circ$$

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$$\vec{E}_A = 255\angle -23^\circ\ V$$

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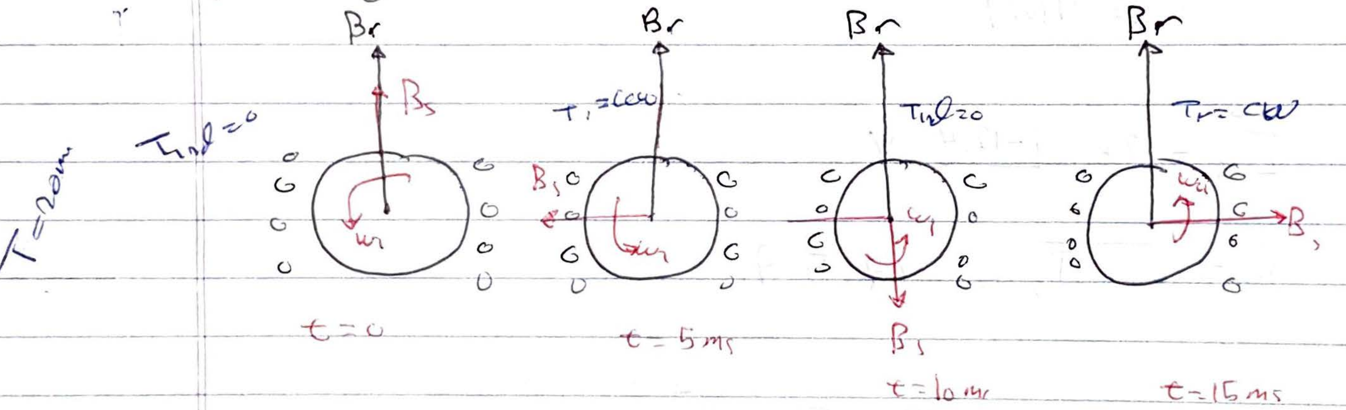
$$\vec{I}_{\phi} = \frac{202 - 255\angle -23^{\circ}}{j2.5} = 41.2\angle 15^{\circ}$$

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

لو كبرنا ال PF (a) حسب كلام موجود

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 machines as generator using the prime mover.
- Increase the Motor speed up to ω_s
- Disconnect the prime mover.

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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 نزيد الـ سنكرونس Motors as

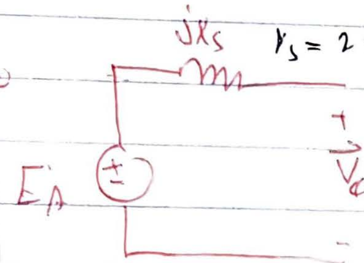
من خلالها بنتحكم بـ Load

when f_e is small $\Rightarrow$ the speed of B_s, will be also small $\left(n_s = \frac{120}{P} f_e\right)$

$\Rightarrow$ The Rotor can ~~accel~~ accelerate and lock in with B_s.

$\Rightarrow$ when the motor is started increase the electric frequency gradually up to its normal value.

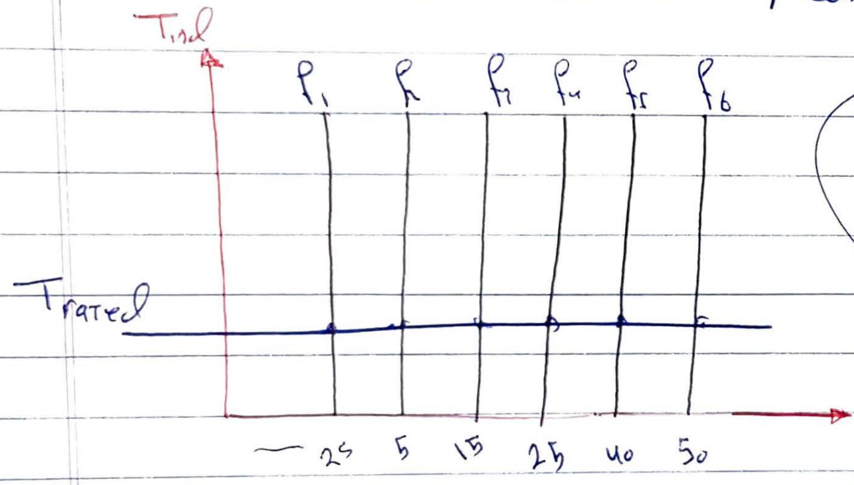
Note:



$X_s = 2\pi f_e L_s$

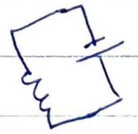
$$V_\phi \cong E_A = K\phi\omega_s \propto f_e$$

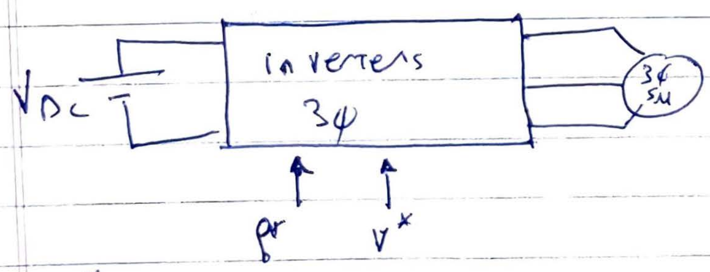
$\phi \propto V/f_e \Rightarrow$ Two voltage must decrease with f_e by the same factor to keep ϕ constant & not let it saturated.



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

VVF Drive





So you can work at Rated Torque at all speeds

f^*: reference frequency

V^*: references voltage

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

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