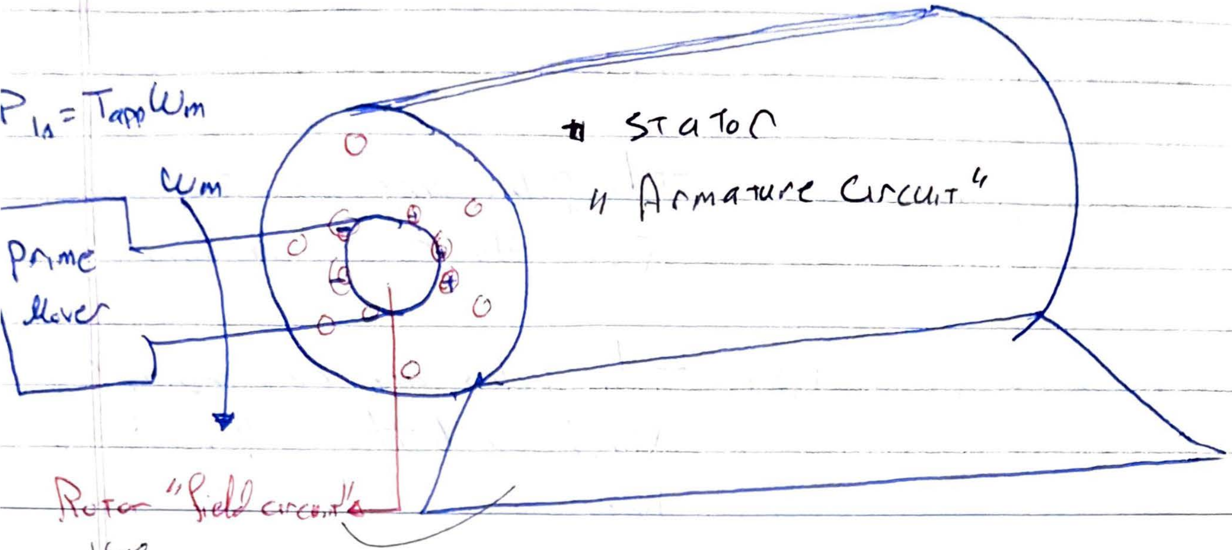
H4

Synchronous Generator (SG_s)



مسؤول عن ال flux

Prime mover: its the initial source of mechanical energy, it's any machine that converts fuel steam into a mechanical energy.

⊛ The synchronous generator has two main windings:
(ينتج منه ال flux)

1) Rotor or field winding where the machine flux is produced.

2) Stator or armature windings where the 3-ϕ voltage are induced (المكان الذي يؤخذ منه 3ϕ فولتية)

⊛ operating Principles:

⊛ ~~Ac Dc magnetic~~

⊛ A Dc current is supplied to the rotor coil to produce a rotor magnetic field.

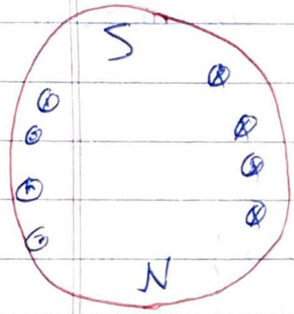
⊛ The Rotor rotates by means of external prime mover to produce a rotating magnetic field.

* The rotating magnetic field will Induce 3-φ Voltage accross the stator (armature) winding,

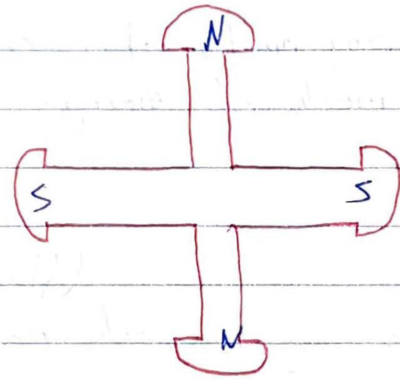
* Types of Rotor In Synchronous generator:

① salient poles rotor :- The poles are sticking out from the rotor surface.

② Cylindrical Rotor Types:- The poles are constructed flush with the surface of the Rotor.



$P=2$, Cylindrical Type.

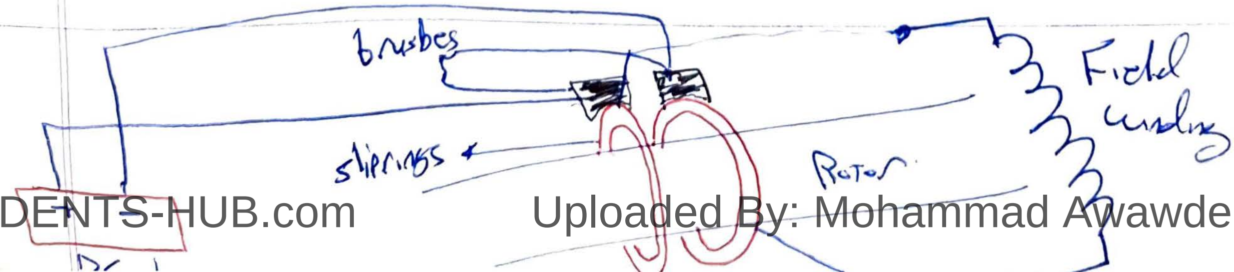


$P=4$
Salient-Pole Type

Note :- when $P>4$ Salient pole machine is selected
when $P=2,4$ Cylindrical is usually used.

* Methods to feed the Rotor or field Circuit

① slip rings & brushes :-
slip rings :- Metal rings, encircling the shaft, but insulated.



Brushes: it's a block of carbon compound that conducts electricity freely, but has very low friction.

This arrangement has two main problems:

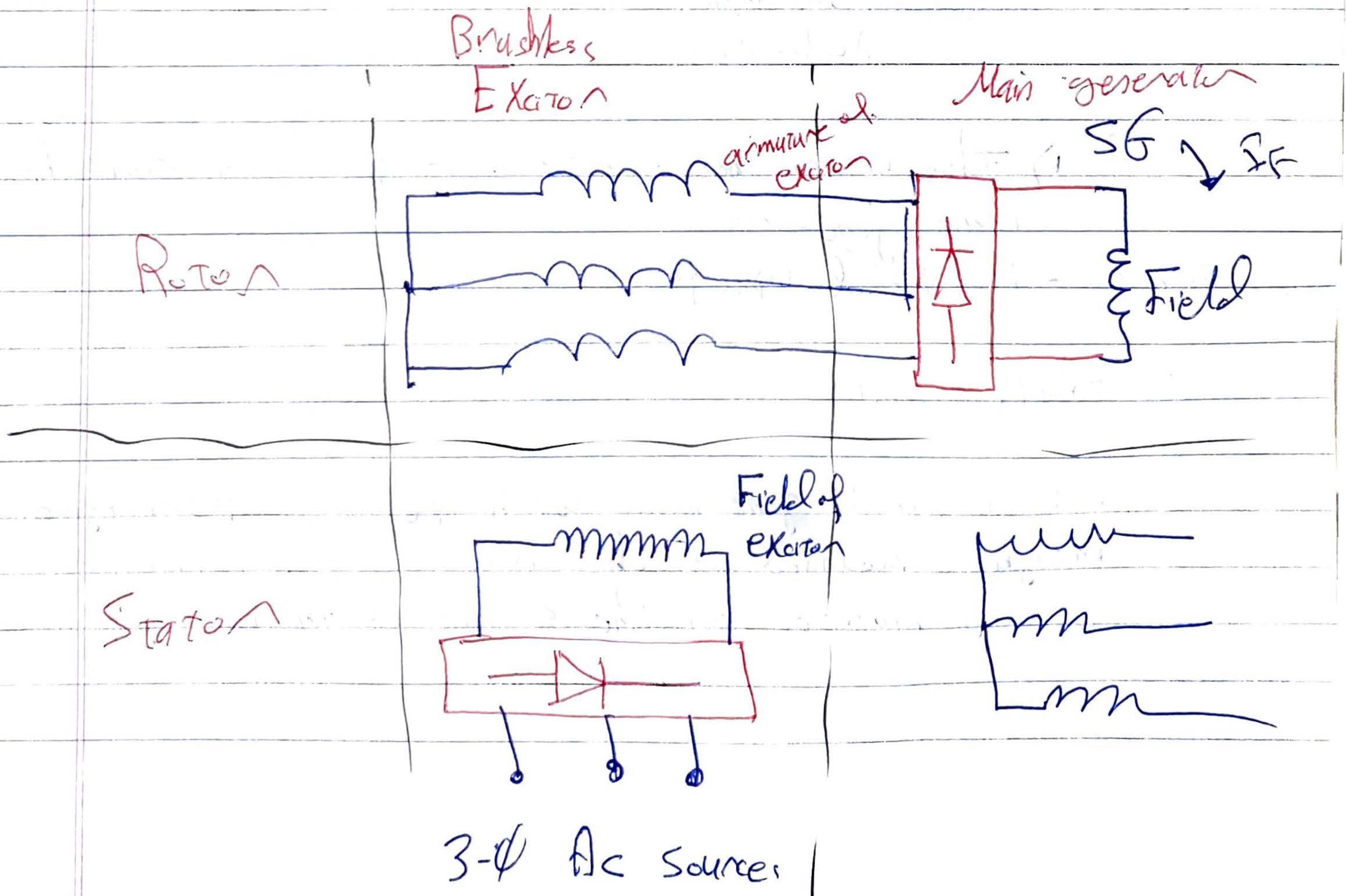
1) The brushes need regular maintenance.
2) The voltage drop across brushes may cause a power losses

② Brushless exciters

③ Pilot exciter

Brushless exciter: it's a small ac generator with it's field circuit mounted on the stator of main generator, and it's armature windings mounted on the rotor of main generator.

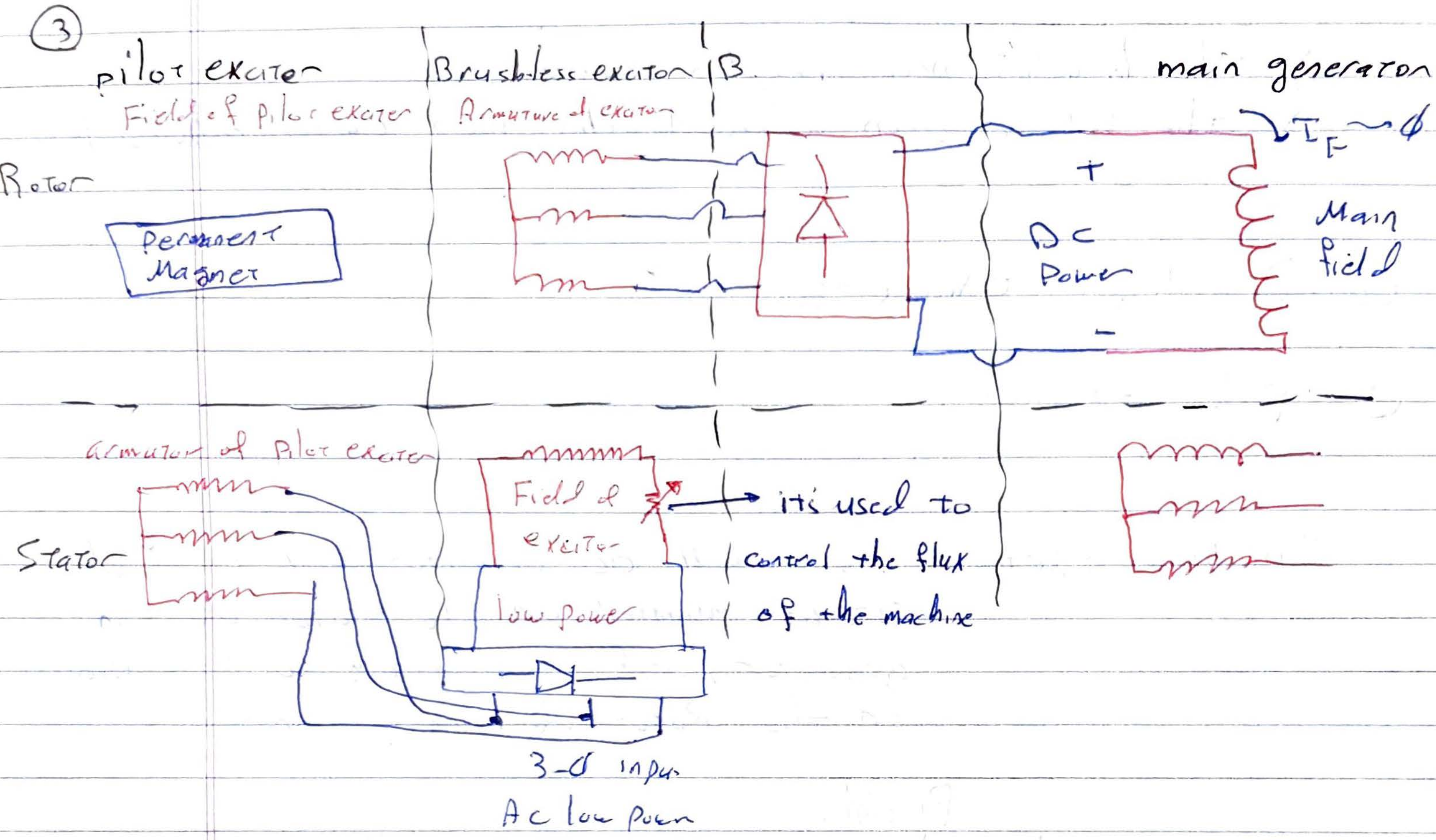
Don phone



② Brushless exciter

it's a small Ac generator with its field mounted on the stator and its armature mounted on the rotor.

③



②

Disadvantages: 1) This method needs a 3ϕ input power to run the main generator.

advantages: - No Need input power

③ pilot exciter

its a small generator with ~~parameter~~ permagnent magnet mounted on the rotor and its armuture circuit mounted on the stator of the main generator.

The mechanical speed of SG:

Synchronous → The mechanical speed is synchronized with the electric frequency.

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

n_m → Mechanical speed (rotor speed)

n_s → synchronous speed.

where P is the number of poles,
f_e is the electric frequency

$$n\,[\text{rpm}] = 60\, \underbrace{f\,[\text{Hz}]}_{\text{rev/sec.}}$$

$$n_m = \frac{2}{P} n_e \times \frac{60}{60} \quad \text{or} \quad \boxed{\omega_m = \frac{2}{P}\omega_e}$$

Internal or induced Voltage of SG:

The RMS value of L-N induced voltage, E_A, is given by

$$E_A = \frac{N_c \phi \overset{2\pi f_e}{\omega_e}}{\sqrt{2}} = \sqrt{2}\,\pi N_c \phi f_e$$

E_A → Armature

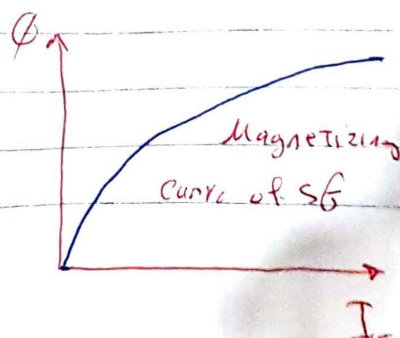
In general, the induced voltage is given by:

$$E_A = K\phi\omega_e$$

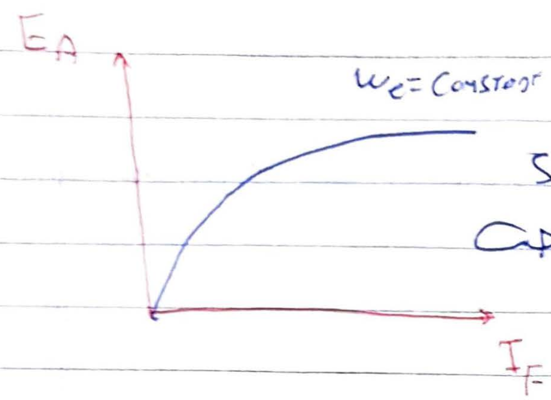
- ϕ → Flux of the machine
- ω_e → Speed of machine
- K → Constant representing the construction of the machine

Note: $\phi \propto I_F \Rightarrow \phi = C I_F$

C → constant



E_A → it's also called back emf voltage



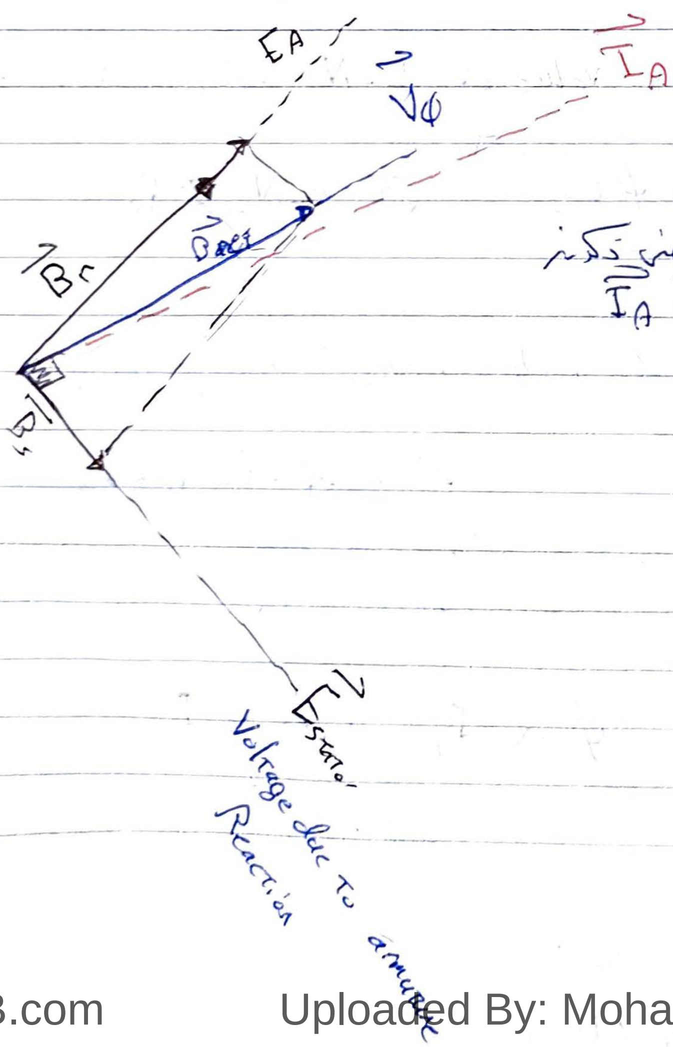
$E_A = K\phi w_e = K\phi' = c' I_F$

للفكرة: انا اهم طريقة نغير فيها الجهد SG
نغير ϕ اضافة لتغير السرعة من
العلاقة $E_A = K\phi w$

Equivalent circuit of SG

The terminal, V_ϕ is different from the internal voltage, E_A of SG due to the armature reaction and the self impedance of the stator windings

Armature Reaction: Distortion of air gap magnetic field due to the current flowing in the stator windings.



حسب قاعدة اليد اليمنى نكون I_A عمودي على B_s

$$\vec{V}_\phi = \vec{E}_A + \vec{E}_{stator}$$

$$\vec{E}_{stator} = -jX\vec{I}_A$$, where X: is the reaction of armature reaction.

$$\cancel{\vec{V}_\phi = \vec{E}_A}$$

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

we consider the self-impedance of the stator windings, the terminal phase voltage will be expressed as:

$$\vec{V}_\phi = \vec{E}_A - \underbrace{jX\vec{I}_A}_{\text{self reactance}} - jX_A\vec{I}_A - R_A\vec{I}_A$$

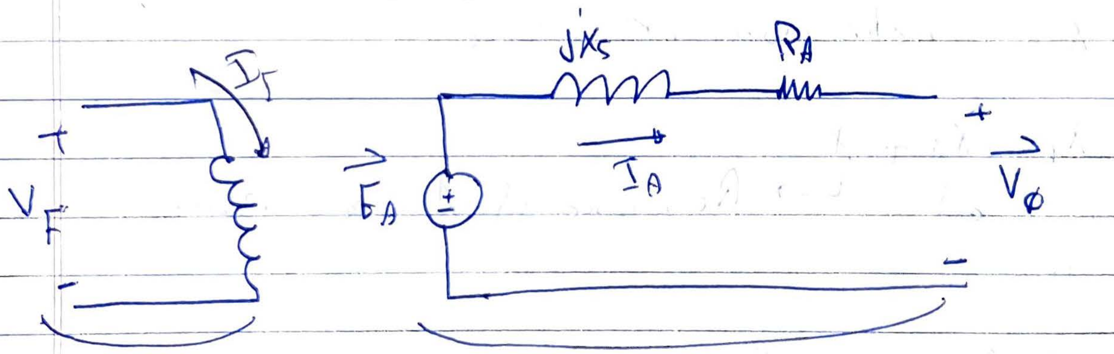
↳ self reactance of stator winding

$$\vec{V}_\phi = \vec{E}_A - j(X + X_A)\vec{I}_A - R_A\vec{I}_A$$

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

where $X_s = X + X_A$

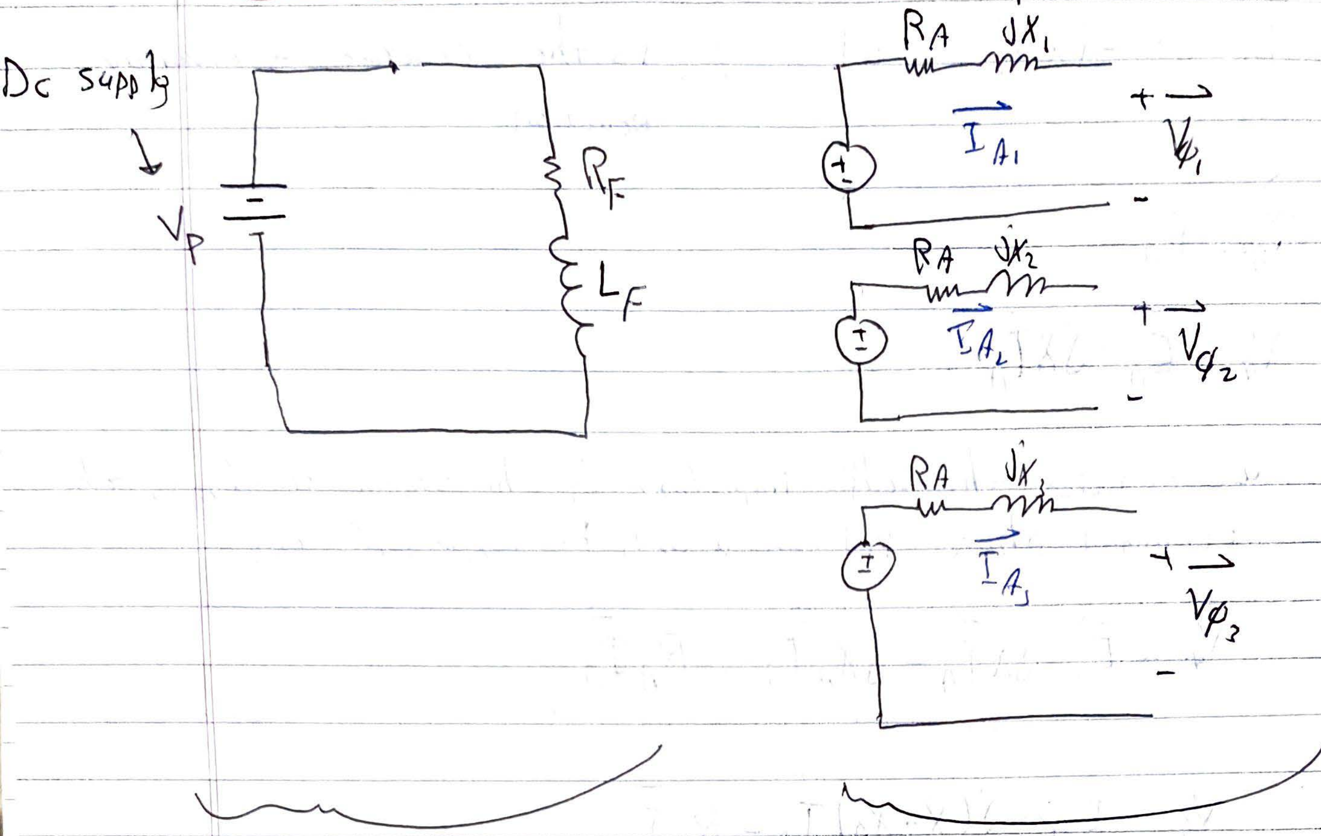
↳ synchronous reactance.



field circuit

pe-phase equivalent circuit.

The full equivalent circuit of 3ϕ SG



Field circuit "Rotor" — Armature circuit "Stator"

R_A : self-resistance of stator winding.

X_s : synchrounous reactance

$X_1 = X_A + X$

self reactance of stator winding ← X_A ; X → Reactance of Armature reaction

$$\left.\begin{matrix} B_R \\ B_S \end{matrix}\right\} \Rightarrow B_{net} \rightarrow V_\phi$$

Y - Connection

$V_L = \sqrt{3}\, V_\phi$

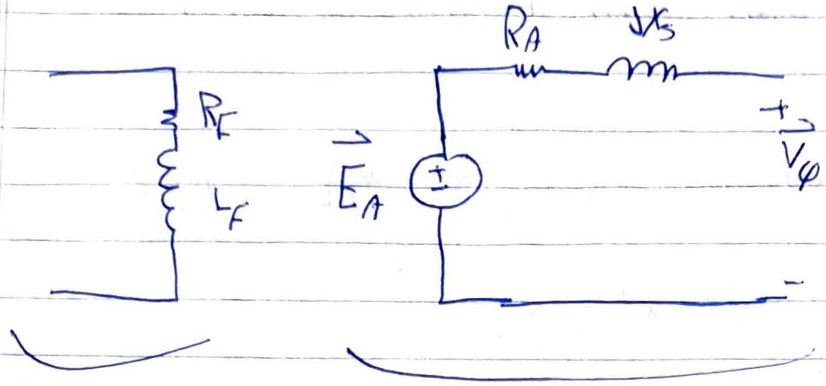
$\vec{I}_L = \vec{I}_\phi = \vec{I}_A$

Δ Connection

$V_L = V_\phi$

$I_L = \sqrt{3}\, I_\phi = \sqrt{3}\, I_A$

The per phase equivalent circuit and machine KVL equation



Field circuit

Armature per-phase equivalent circuit

E_A: Internal voltage
Induced voltage
or back emf voltage

$$\boxed{E_A = K\phi\omega}$$

Machine KVL equation:-

KVL in the armature per-phase equivalent circuit.

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

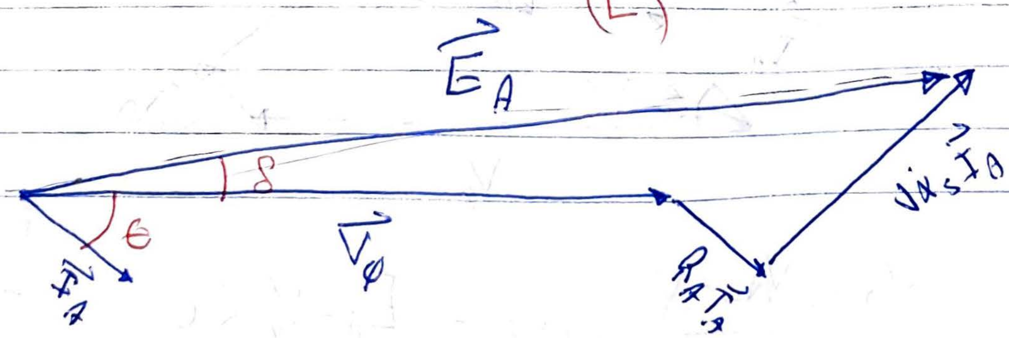
* phasor Diagram

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

* Assume that the Reference angle of $\vec{V}_\phi$ is zero

$$\Rightarrow \vec{V}_\phi = V_\phi \angle 0^\circ$$

1. Lagging PF operation $\Rightarrow$ The SG is connected to an inductive Load. (L)



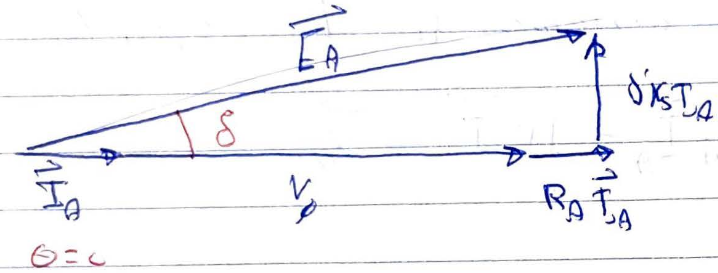
$V_\phi < E_A$

θ : pf angle
δ : Torque angle (angle between $\vec{V_\phi}$ + $\vec{E_A}$)

Voltage Regulation = $VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$

$VR = \frac{E_A - V_\phi}{V_\phi} \times 100\% > 0$

② Unity PF ⇒ The generator is connected to a resistive load (R)

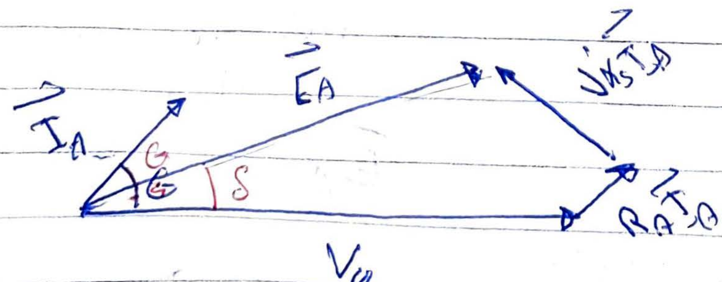


$V_\phi < E_A$

$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{E_A - V_\phi}{V_\phi} > 0$

$VR_{unity} < VR_{lagging}$

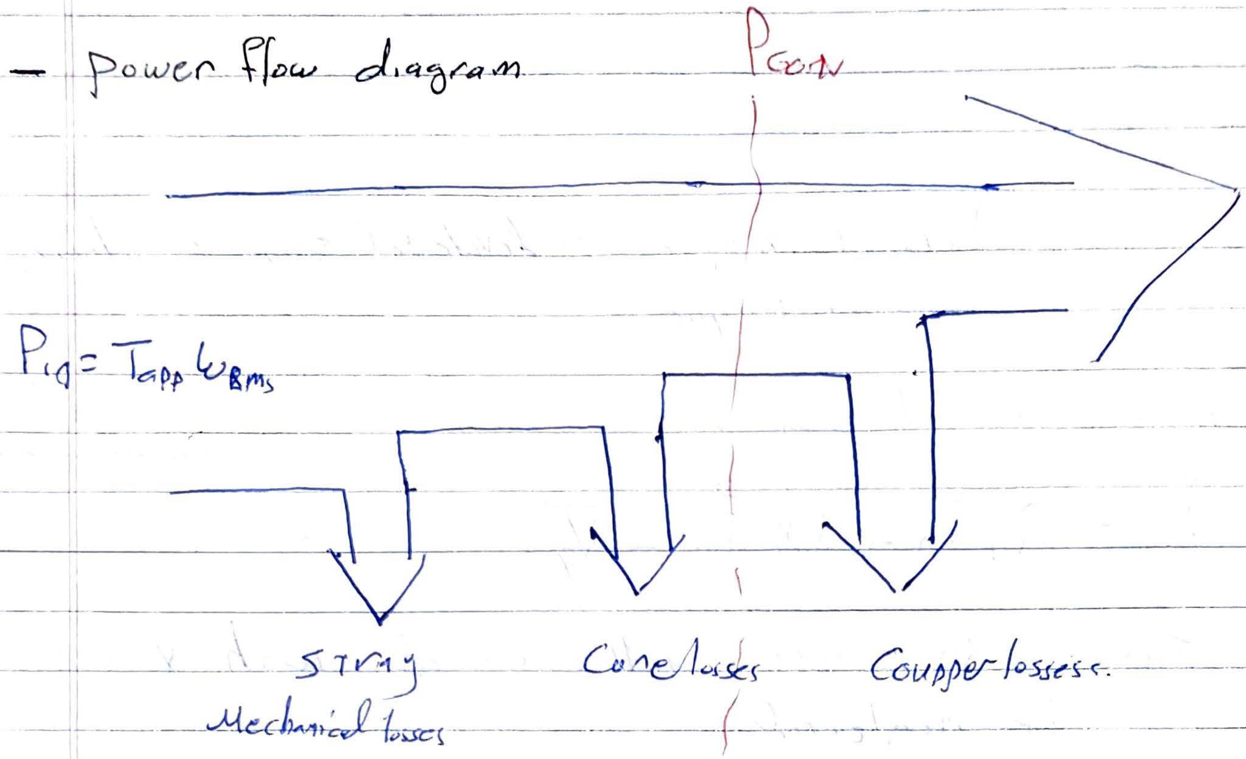
② Leading PF ⟶ The generator is connected to a capacitive load (C)



$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{E_A - V_\phi}{V_\phi} < 0$ [$V_\phi > E_A$]

Power and Torque equations.

- power flow diagram



$P_{out} = 3 V_\phi I_\phi \cos\theta = \sqrt{3}\, V_L I_L \cos\theta$

$Q_{out} = 3 V_\phi I_\phi \sin\theta = \sqrt{3}\, V_L I_L \sin\theta$

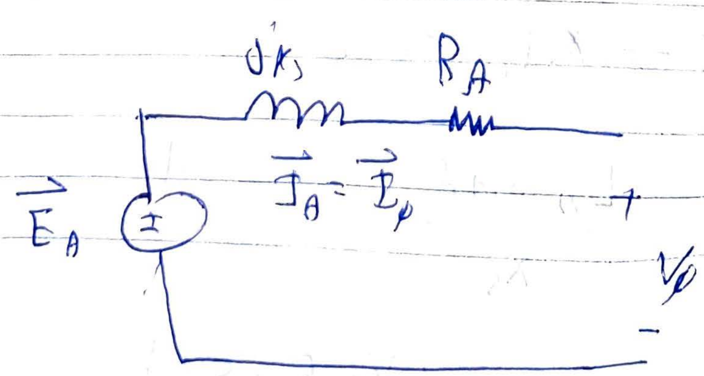
Y connection — Δ-Connections

$V_L = \sqrt{3}\, V_\phi$ — $V_L = V_\phi$

$I_L = I_\phi$ — $I_L = \sqrt{3}\, I_\phi$

T_{app}: Applied Torque

ω_{sync}: synchronous speed.



3-ϕ

$$P_{conv} = T_{ind}\,\omega_{ms} = 3 E_A I_A \cos\delta$$

power converted into electrical

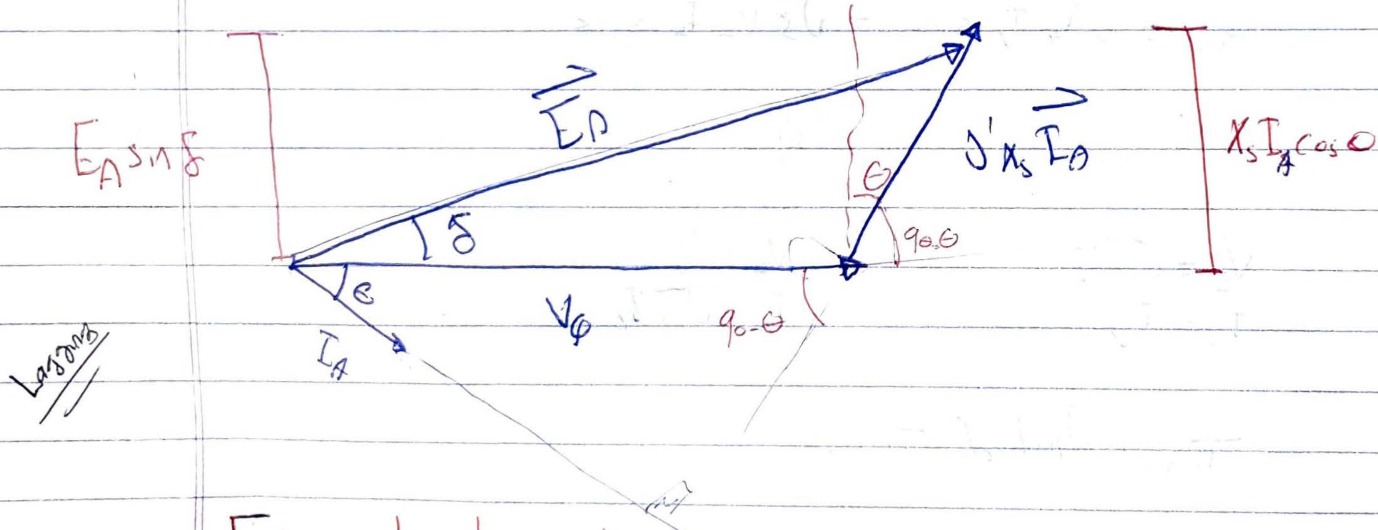
T_{ind} = Induced torque or developed torque or electro magnet torque

① Assume that the generator is connected to 3-ϕ inductive load

$$\vec{E_A} = R_A \vec{I_A} + jX_s \vec{I_A} + \vec{V_\phi}$$

Since R_A is very small compared with X_s its can be neglected.

$$\vec{E_A} = jX_s \vec{I_A} + \vec{V_\phi}$$



From the phasor diagram

$$E_A \sin\delta = X_s I_A \cos\theta$$

$$\left(\Rightarrow I_A \cos\theta = \frac{E_A \sin\delta}{X_s} \right) \times 3V_\phi$$

P_{conv} vs δ δ?

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

R_A is ignored

$$\Rightarrow P_{out} = 3V_\phi I_A \cos\theta = \frac{3V_\phi E_A}{X_s}\sin\delta = P_{conv}$$

$$P_{conv} = \tau_{ind}\,\omega_{ms} = \frac{3V_\phi E_A \sin\delta}{X_s}$$

Machine Rated δ

$\boxed{0 \le \delta \le 90}$

$$\boxed{\tau_{ind} = \frac{3V_\phi E_A}{X_s\,\omega_{ms}}\sin\delta}$$

$\delta \rightarrow$ Torque angle

The maximum output power is:

$(0 \le \delta \le 90)$

$$P_{max} = \frac{3V_\phi E_A}{X_s} \Rightarrow \sin\delta = 1 \Rightarrow \delta_{max} = 90^\circ$$

This is the steady state stability limit.

Effect of load changes on SG operation.

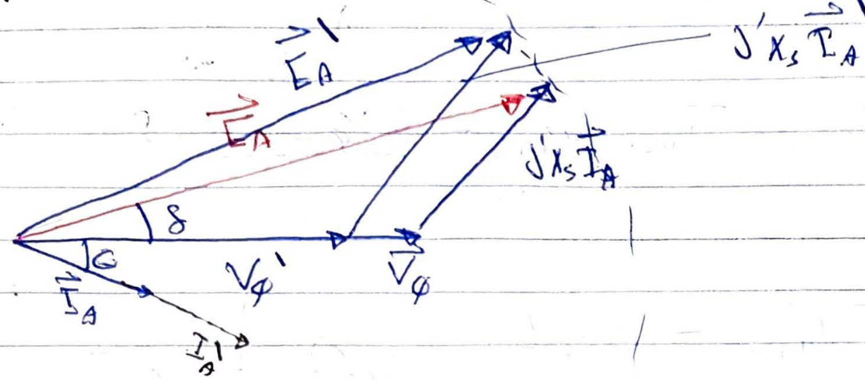
Assume that - SG is connected to a 3ϕ inductive load

- E_A = constant — Speed of primemover = constant, Machine flux = constant

- R_A is ignored

- load increases at the same PF angle.

① Lagging pF operation , $\vec{E}_A = \vec{V}_\phi + jX_s \vec{I}_A$

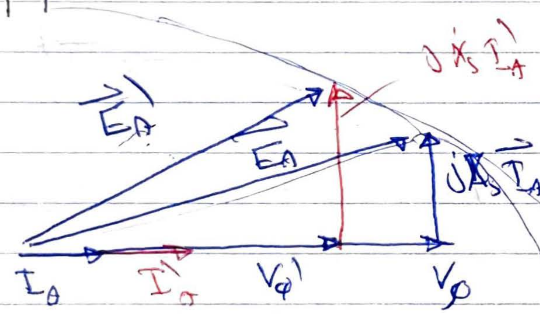


The phase voltage decreases as the load increases

AVR ⇔ Automatic voltage Regulator

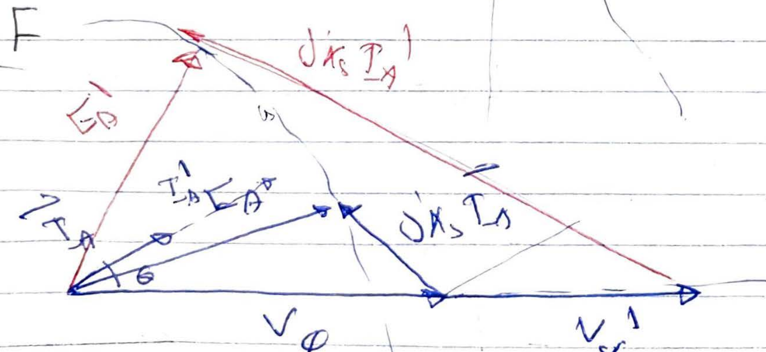
↳ its a closed loop controller to keep the phase voltage of generator constant.

② unity pF



V_ϕ decreases as the load increases.

③ leading pF



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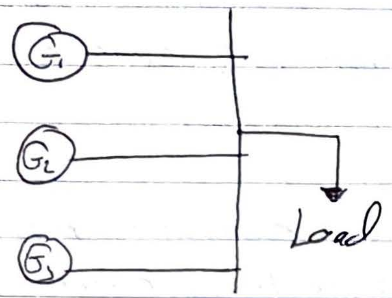
parallel operation of synchronous Generators

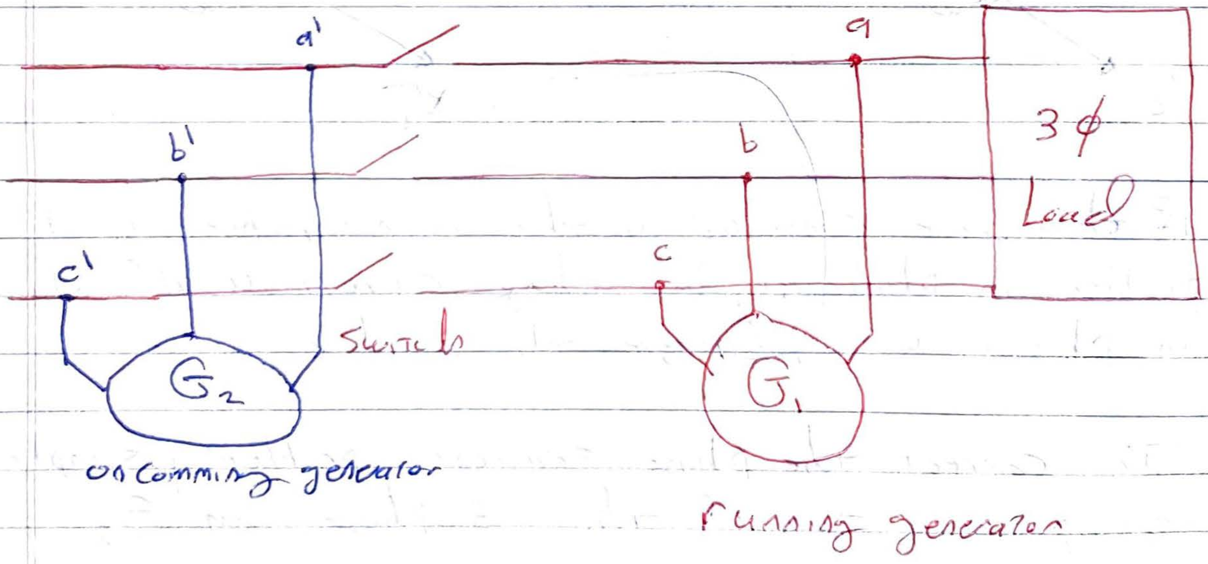
other than emergency generator, rarely there is a case where a single / isolated generator supplies a load.



Major advantages

1) supplies a larger load
2) high reliability of power system
3) Allows one or more generator to be removed for shutdown & preventive maintenance
4) if only one generator is used, and it's non running of full-load, it's a very inefficient process.

Conditions required for paralleling



1) The generator must have the same Rms line Voltage

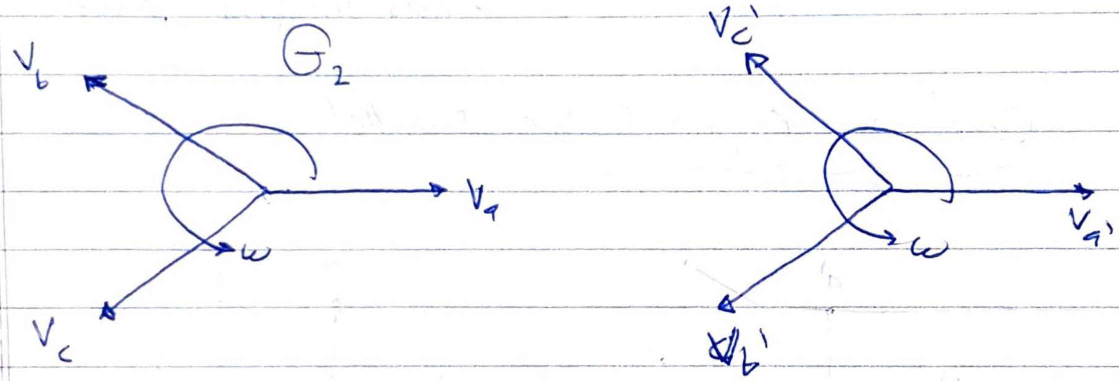
2) The generator must have the same phase sequence.

3) The phase angle of two "a" phases, "b" phases or "c" phases must be the same

4) The frequency of the oncoming generator must be slightly higher than the frequency of running generator

Point ① → The RMS line voltages of the two generators must be the same to avoid any huge circulating current flowing the phases and damaging the generator.

Point ② → Assume the generators have an opposite phase sequence.

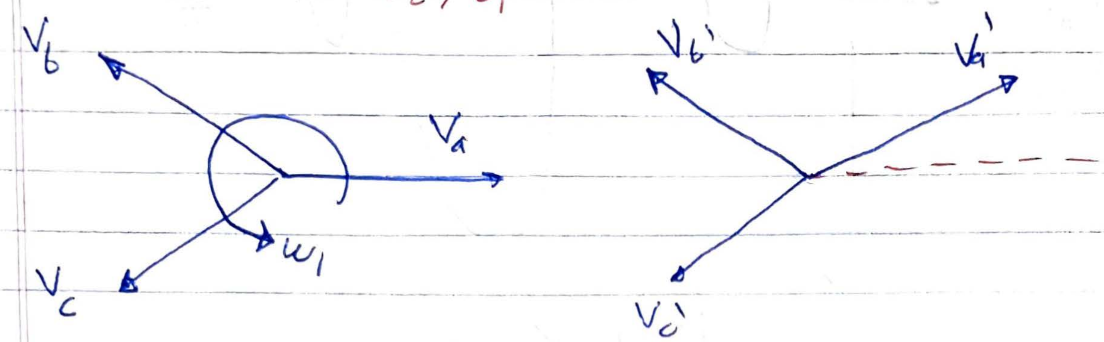


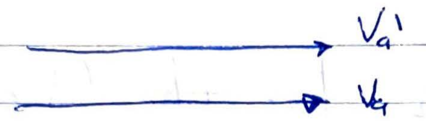
⊛ if they were connected in this manner, there would no problem in phases (a), but a huge current would flow in phases b & c, damaging the machine.

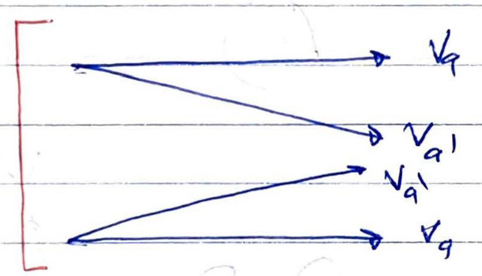
Solution → To correct the phase sequence problem, simply swap any two of the 3 phases on G_2

Point 3&4 → Assume that the frequency of G_1 is $\omega_1 = 2\pi f_1$, and the frequency of G_2 is $\omega_2 = 2\pi f_2$

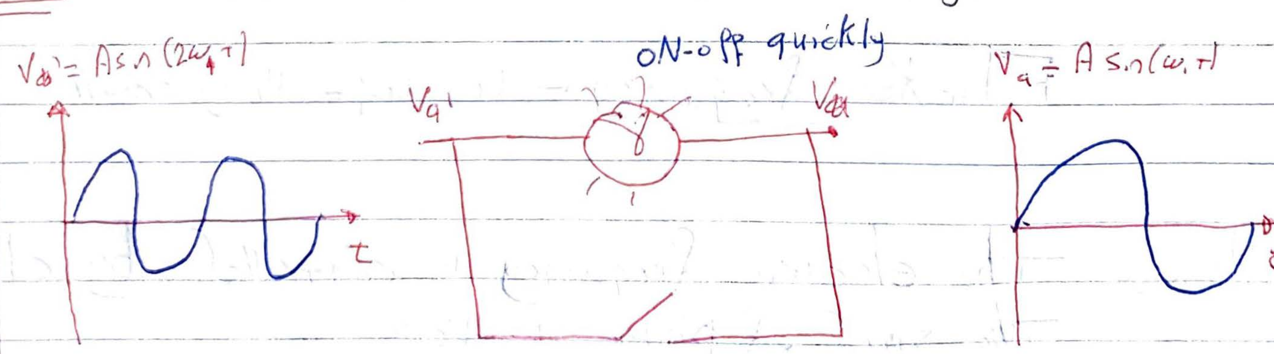
Assume that $\omega_2 > \omega_1$







Case 1 $\omega_1 \neq \omega_2$, but the difference is high



$PD = V_a - V_a'$

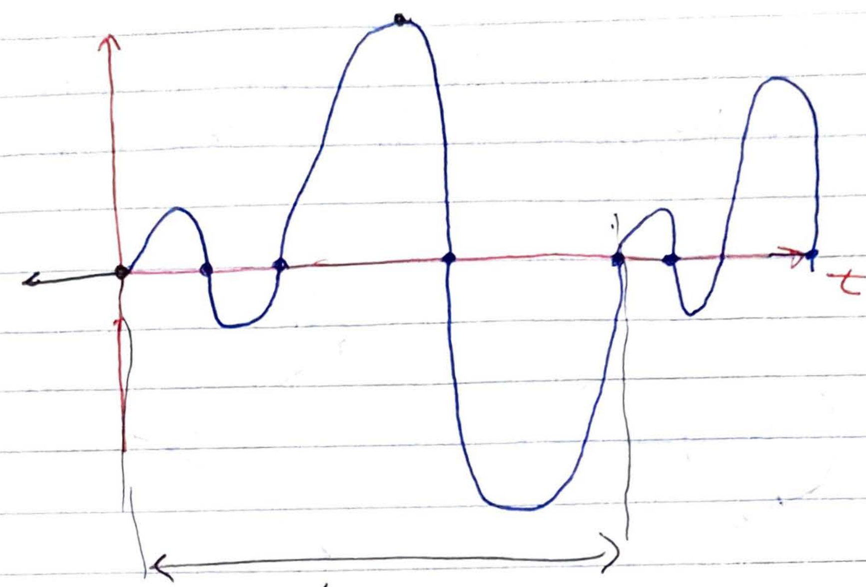
* Potential difference

Flicker $= \omega_2 - \omega_1$

frequency $= \omega$

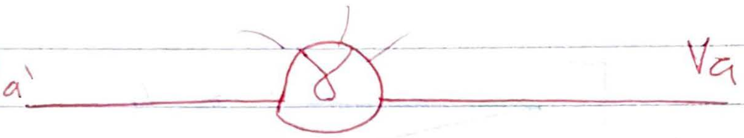
120 out-of phase

$V_a = V_a'$
inphase



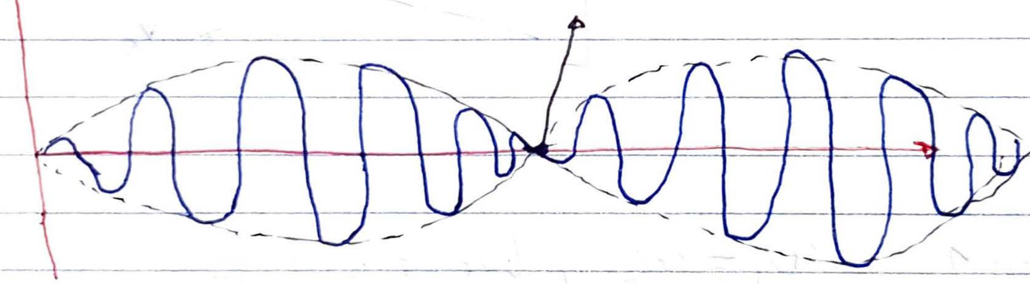
1/ flicker frequency

<u>Case 2</u> $\omega_1 \neq \omega_2$, but the difference is very small



$PD = V_a - V_a'$

$V_a' = V_a$ "In-phase"



Flicker frequency = $\omega_2 - \omega_1$ = Very small

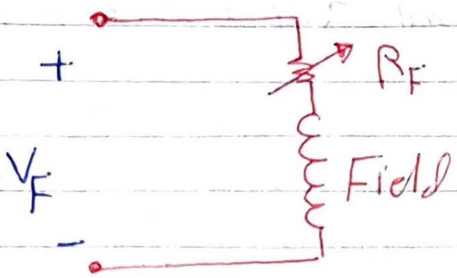
Notes: The electric frequency is controlled by changing the speed of prime mover

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

$n_m \uparrow \Rightarrow f_e \uparrow$

$n_m \downarrow \Rightarrow f_e \downarrow$

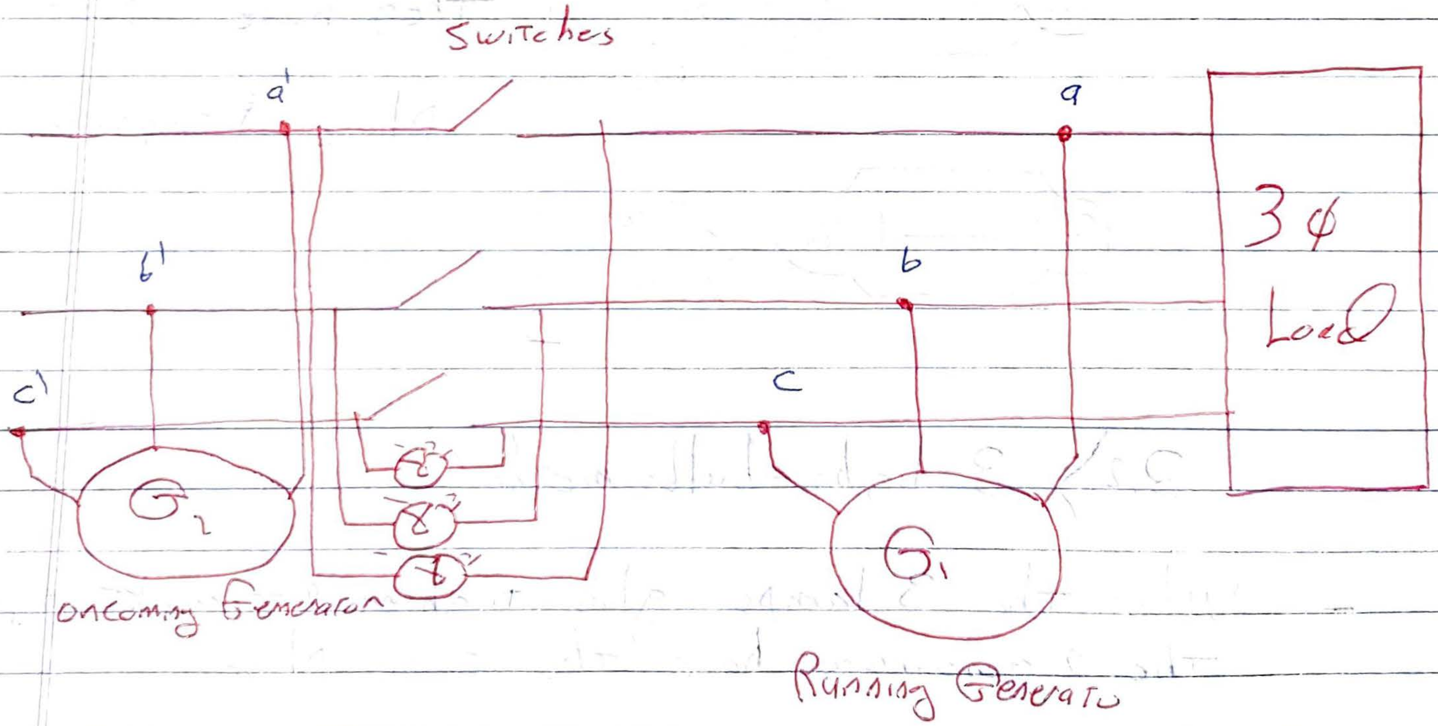
Note: The terminal voltage is controlled by changing the field current.



$$R_F \uparrow \Rightarrow \left(I_F = \frac{V_F}{R_F}\right)\downarrow \Rightarrow \phi \downarrow \Rightarrow E_A \downarrow \Rightarrow V_\phi \downarrow$$

$$R_F \downarrow \Rightarrow I_F \uparrow \Rightarrow \phi \uparrow \Rightarrow E_A \uparrow \Rightarrow V_\phi \uparrow$$

⊛ procedure of synchronizing



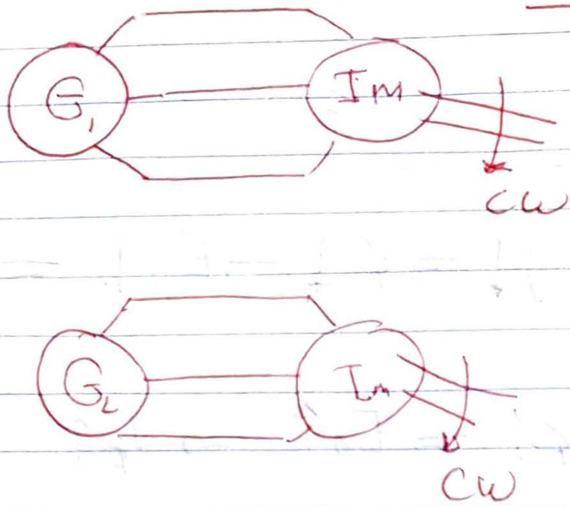
1) Adjust the speed of G_2 to match that of G_1

2) Using Voltmeters, adjust I_F of G_2 to make the (V_T) terminal voltage of G_2 equals the terminal rms voltage of G_1

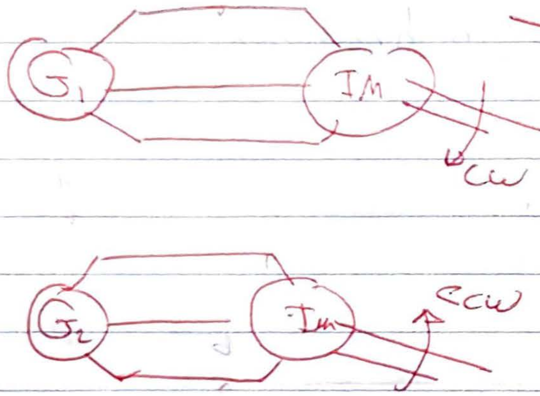
V_T: Terminal Voltage

3) phase - sequence

3.1) small 3-ϕ induction motor method.



They have the same phase sequence.



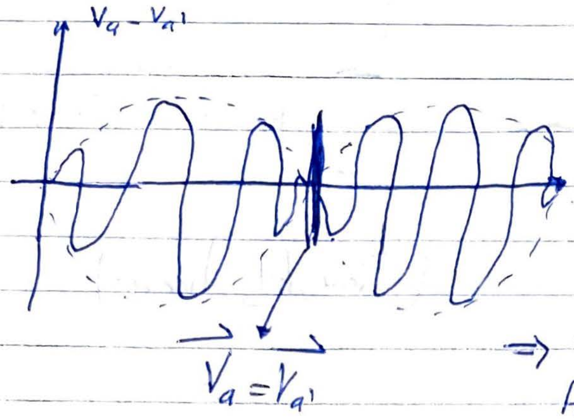
They have oppsite phase & sequence

3.2) 3 light-bulbs method.

- When the 3 lamps glow toghter & turn off togther The 2 generators have the same phases

- When the 3 lamps glow in succession sequence, then the 2 generator have oppsite phase sequence.

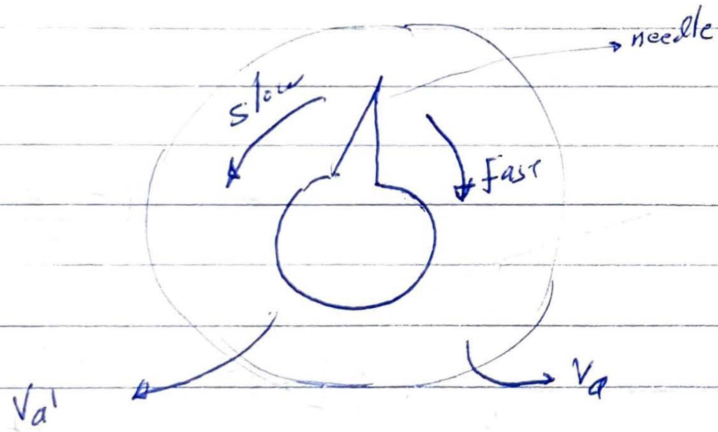
4) Frequency of G_2 is slightly higher than the frequency of G_1.



when the 3 lamps go out $\vec{V_a}$ & $\vec{V_{a'}}$ are in phase, and paralleling can be done.

⇒ This method is not very accurate. A better method should be used (synchroscope).

$\boxed{\text{synchroscope}}$: Device that gives an indication about the phase shift between V_a & $V_{a'}$



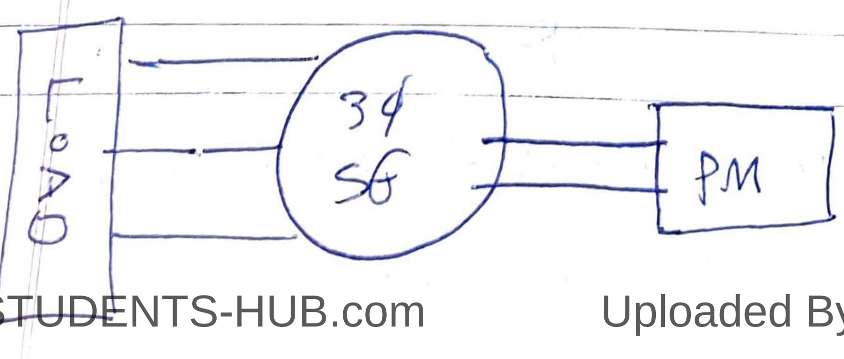
$f_2 > f_1 \Rightarrow$ CW Rotation (Fast)

$f_2 < f_1 \Rightarrow$ CCW Rotation (slow)

when the needle is in the vertical position, V_a is in phase with $V_{a'}$ and paralleling can be done.

f-P Q-V

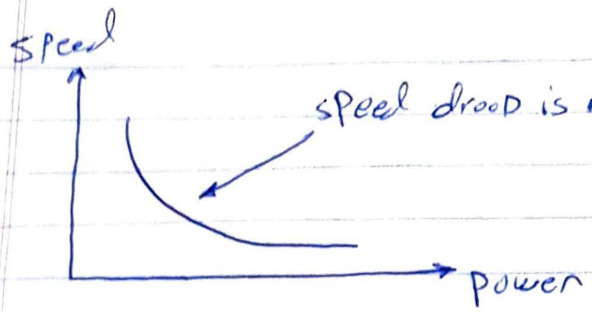
Frequency-power and voltage-reactive power characteristics of generator.



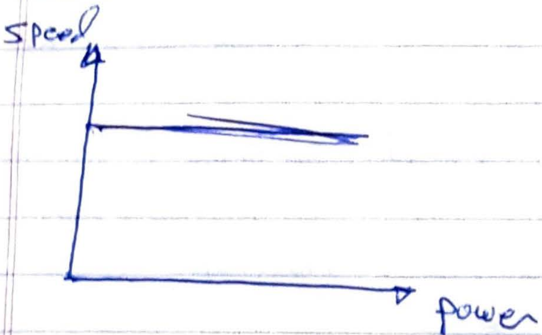
wind Turbine

water Turbine

Diesel engine



governor mechanism makes the speed droop linear

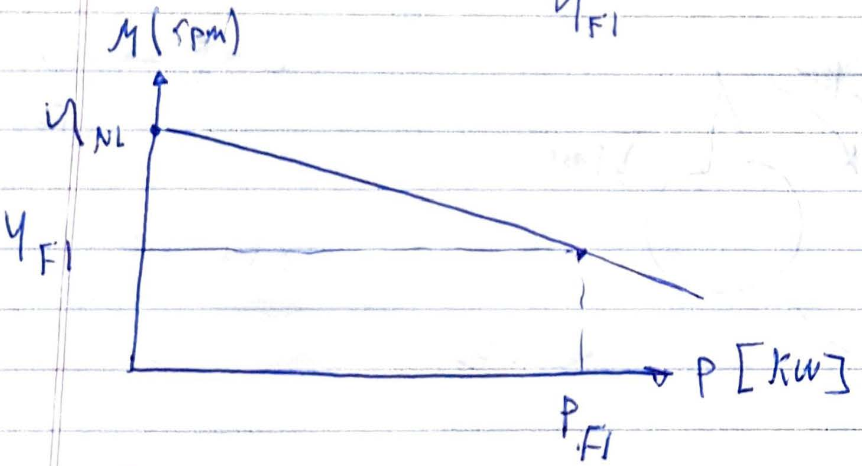


(Roughly linear)

No load speed

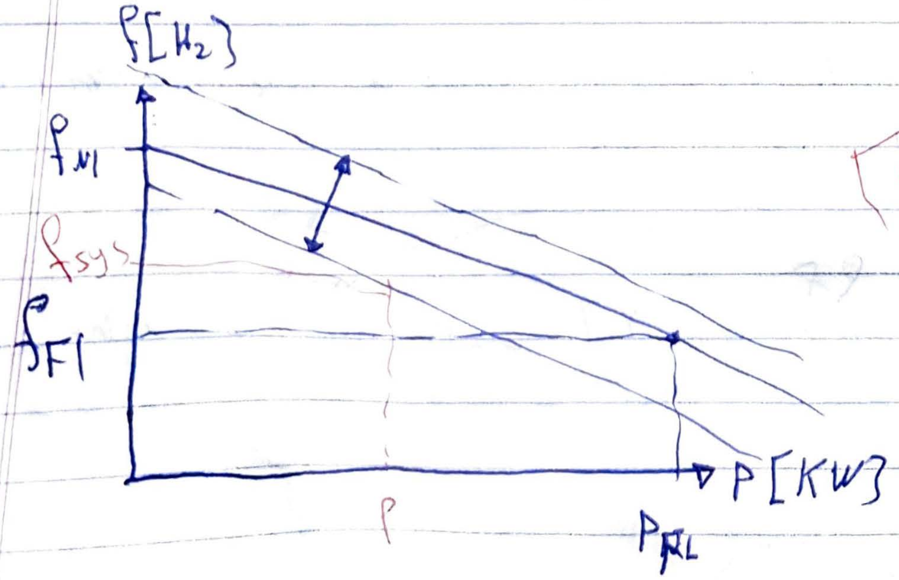
Full load speed

$$\boxed{\text{Speed Droop}} = SD = \frac{n_{NL} - n_{Fl}}{n_{Fl}} \times 100\%$$



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

$$f = \frac{nP}{120}$$



Speed governer

By adjusting the setpoint of the speed governor, we can increase or decrease the no load speed.

$$\text{slop} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{f_{FI} - f_{NL}}{P_{FI}} \quad [Hz/KW]$$

$$P_{FI} = \frac{1}{\text{slop}}\left[f_{FI} - f_{NL}\right] = \frac{-1}{\text{slop}}\left[f_{NL} - f_{FI}\right]$$

In general, $\boxed{P = S_P\left[f_{NL} - f_{sys}\right]}$ → system frequency

where S_P is the power slop [KW/Hz].

$S_P = \frac{(P)_{max}}{f_{NL} - f_{FI}}$

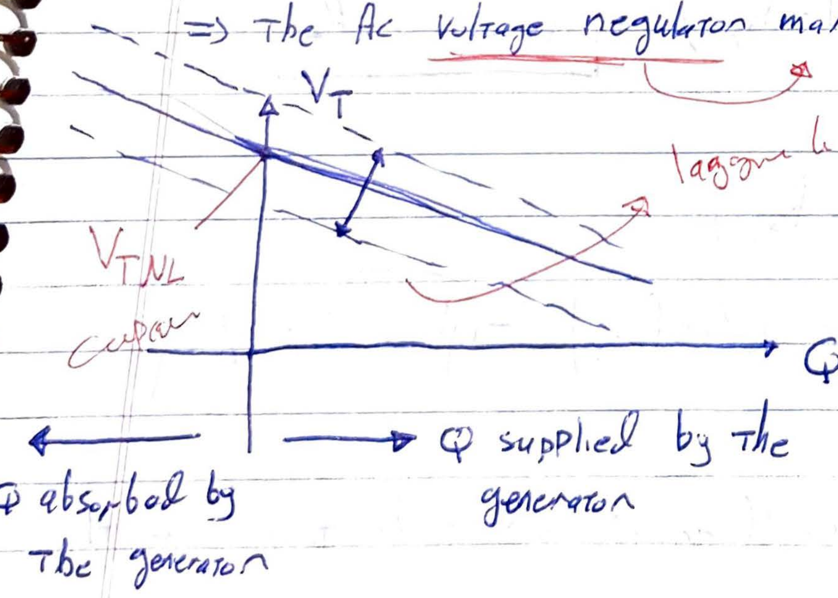
Voltage - Reactive power characterstic

lagging Load ↑ ⟹ The load absorbs more Q

⟹ the generator supplies more Q ⟹ V_T ↓

⟹ The characterstics is non-linear

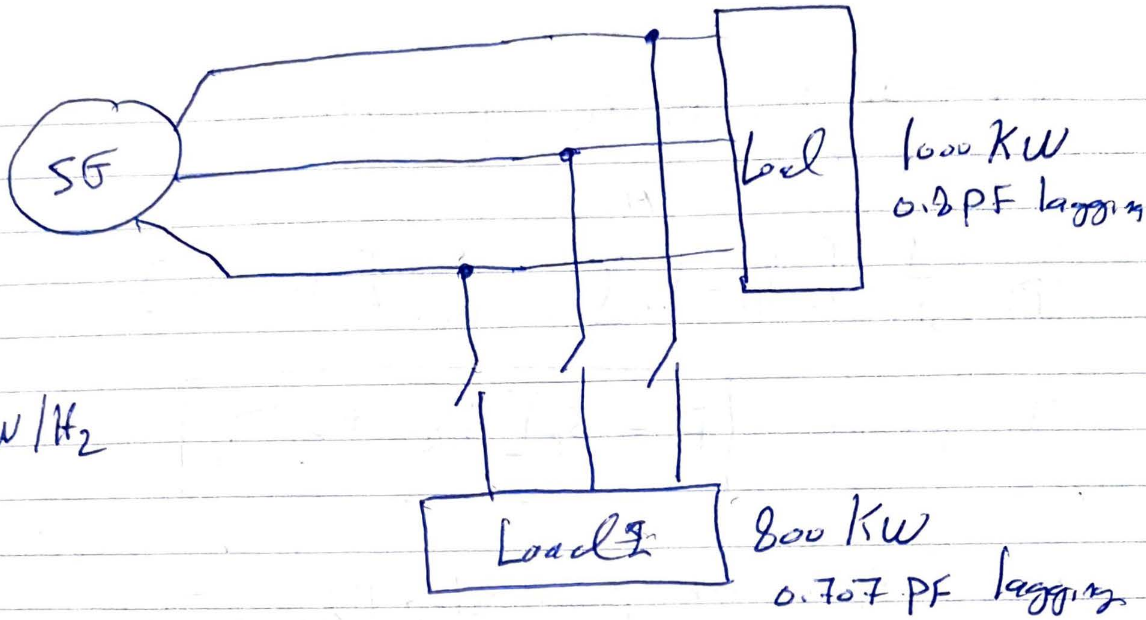
⟹ The Ac voltage regulator makes it linear.



Ac Voltage Regulator

By adjusting the set points of the Ac voltage regulator we can increase or decrease the no load Terminal voltage

Example



$f_{NL} = 61\ Hz$

$S_P = 1\ MW/Hz$

a) before the switch is closed, what is the operating frequency of the system

b) After, load 2 is connected, what is the operating frequency of the system

Solution

a) $P = S_P(f_{NL} - f_{sys})$

$1000 = 1000\,(61 - f_{sys}) \Rightarrow \boxed{f_{sys} = 60\ Hz}$

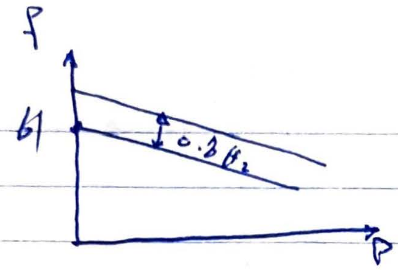
b) $P = S_P(f_{NL} - f_{sys})$

$1000 + 800 = 1000\,(61 - f_{sys}) \Rightarrow \boxed{f_{sys} = 59.2\ Hz}$

c) what action could an operator take to restore the system frequency.

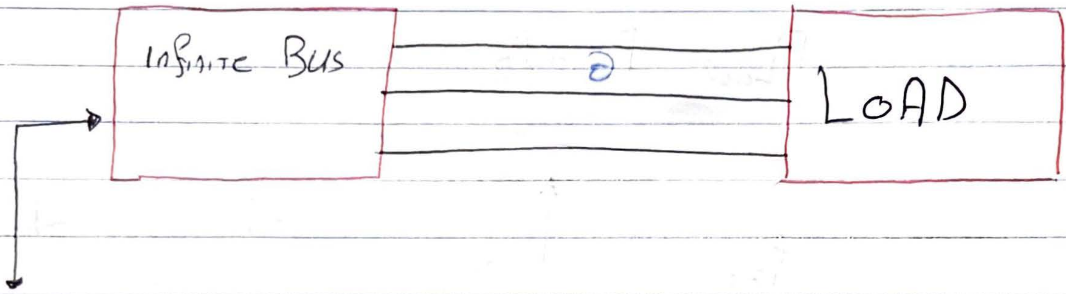
$P = S_P(f_{NL} - f_{sys})$

$1000 + 800 = 1000\,(f_{NL} - 60) \rightarrow \boxed{f_{NL} = 61.8}$

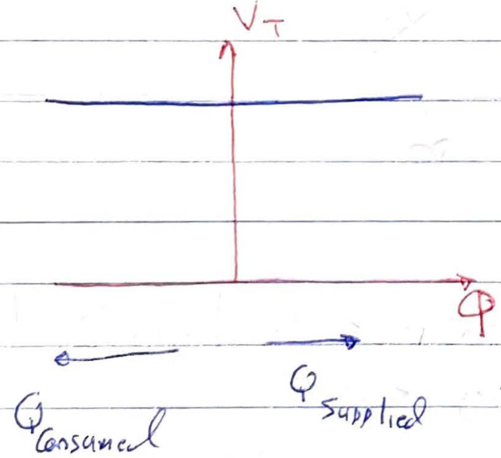


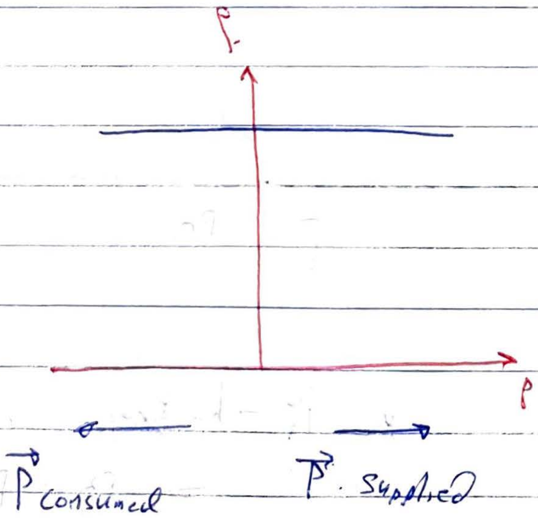
⊛ Parallel operation of Generators with large power system.

Infinite Bus: it's a large power system that its voltage and frequency do not vary regardless of How much power are down from or supplied do it.

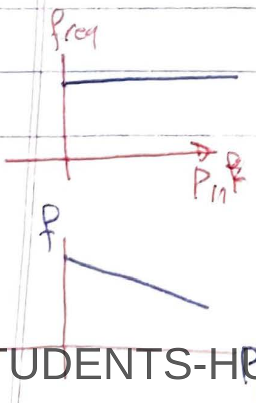


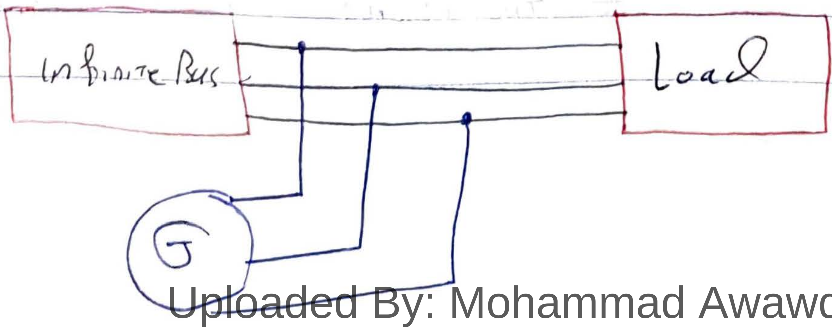
high number of parallel connected generators in power station

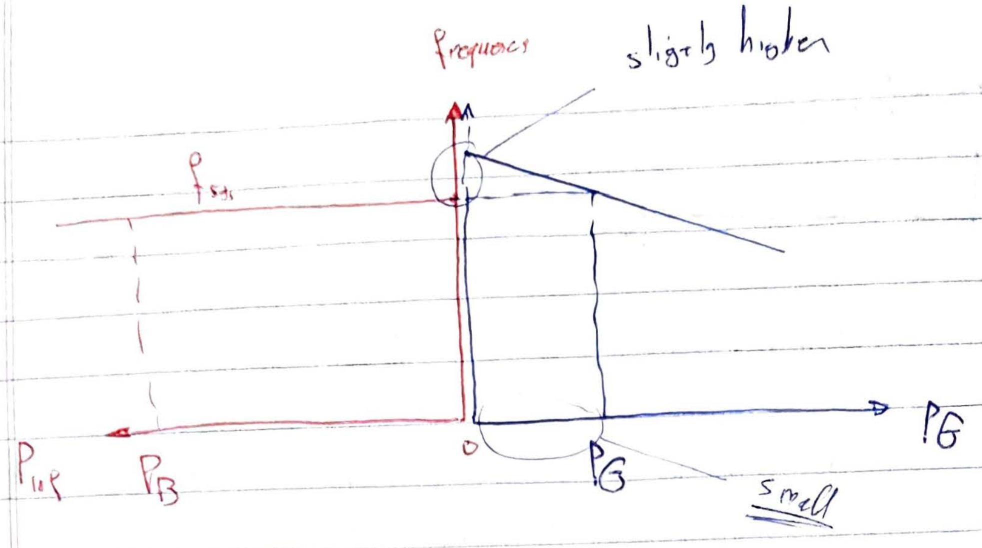




⊛ Parallel operation



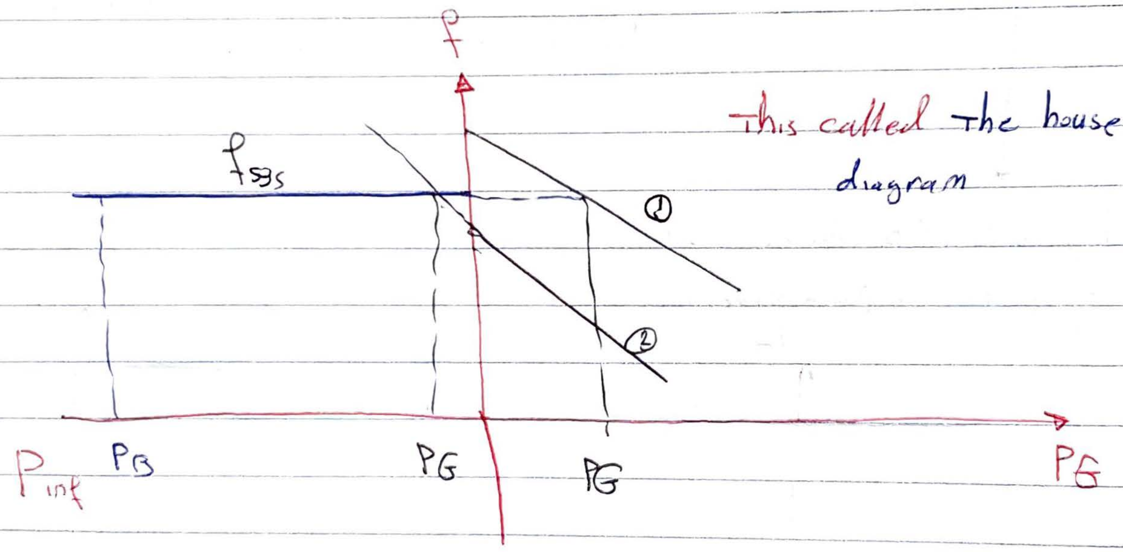




P_B: power supplied by infinite Bus

P_G: power ~~by~~ supplied by the generator.

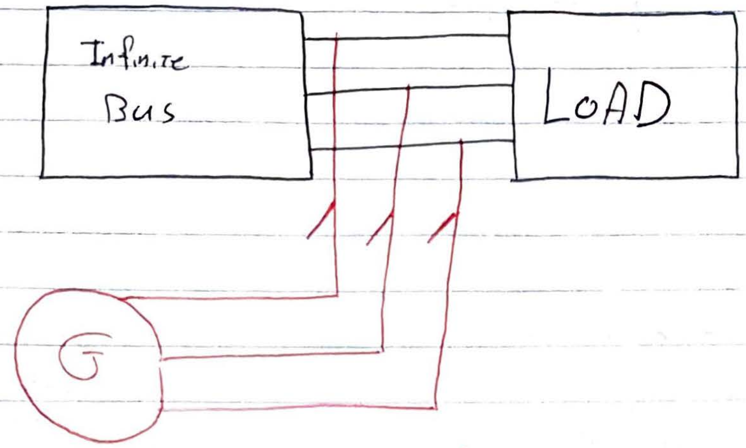
$$P_{Load} = P_G + P_B$$

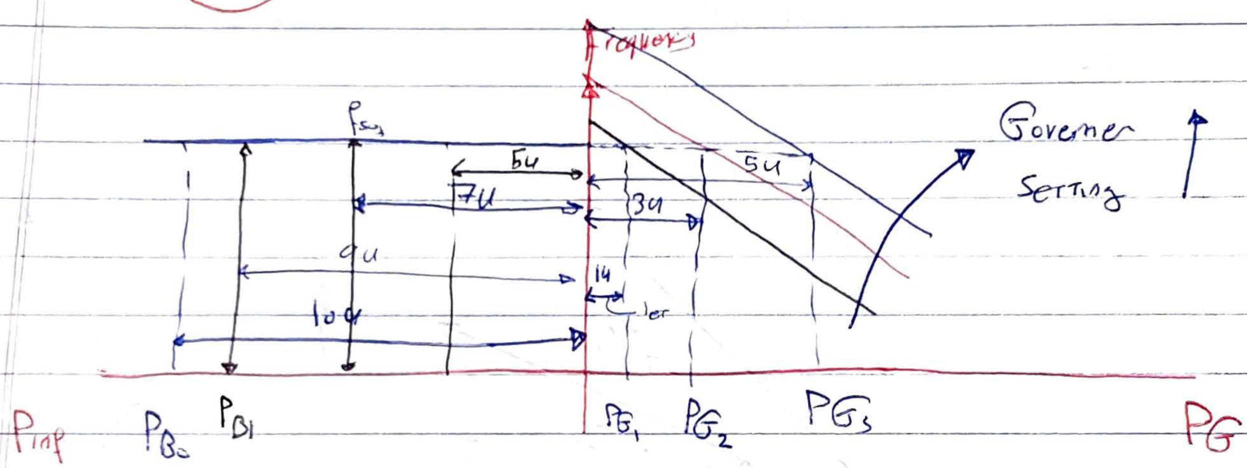


* if the frequency of the generator is slightly higer ① than f_{sys} ⇒ P_G is positive and very small
  ⇒ The machine acts as a generator.

* if the frequency of generator is slightly lower ② than f_{sys} ⇒ P_G is negative & very small
  ⇒ The machine acts as Motor.

* Increasing of governer setting





Before synchronizing: $P_{B_0} = 104$, $P_{G_0} = 0 \Rightarrow P_{Load} = P_{B_0} + P_{G_0} = 104$

After synchronizing: $P_{B_1} = 94$, $P_{G_1} = 14 \Rightarrow P_{Load} = P_{B_1} + P_{G_1} = 104$

Governer setting $\uparrow$: $P_G \uparrow$ & $P_B \downarrow \Rightarrow P_{G_2} = 34 > P_{G_1}$ & $P_{B_2} = 74 < P_{B_1}$

$$\Rightarrow P_{Load} = P_{G_1} + P_{B_2} = 104$$

Governer setting $\uparrow\uparrow \Rightarrow P_G \uparrow\uparrow$ & $P_B \downarrow\downarrow \Rightarrow P_{G_3} = 54$ & $P_{B_3} = 54 \Rightarrow$

$$P_{load} = P_{G_3} + P_{B_3} = 104$$

Phasor Diagram

$$P_G = \frac{3 V_\phi E_A}{X_s} \sin\delta \Rightarrow P_G \propto E_A \sin\delta$$

V_ϕ : constant

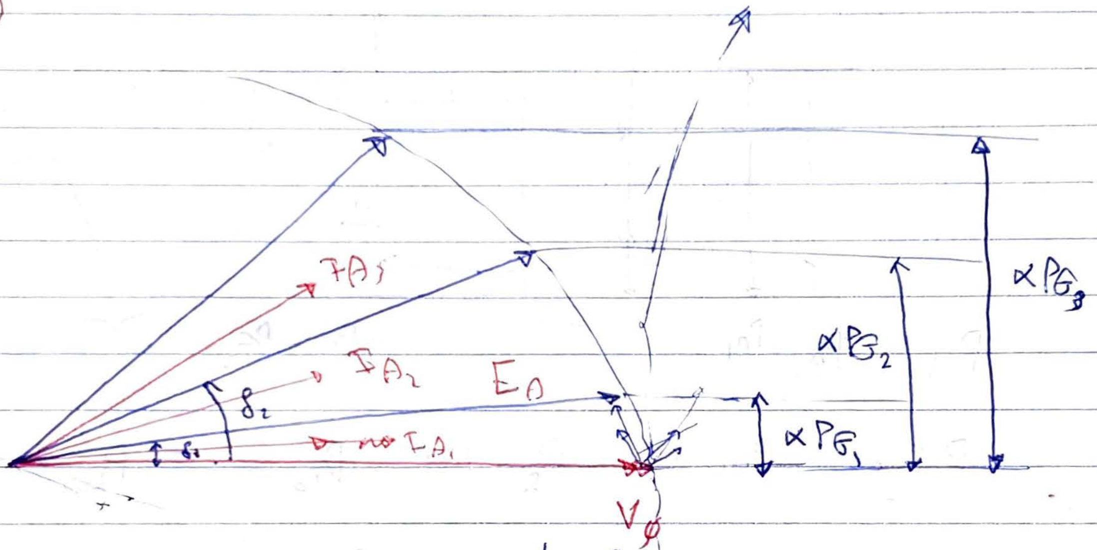
X_s : constant

$E_A = K\phi\omega$ = constant

ϕ → Constant (I_F = constant)

ω → Constant (Infinite Bus)

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



The generator is operating at leading PF → see loads as (C)

⇒ The generator supplies a negative reactive power or it consume reactive power from the infinite bus.

Ⓐ How can the generator be adjusted to supply reactive power?
" by field current adjustment "

المشكلة بلش G أصدر Q
مش قادر بالعكس بعمل

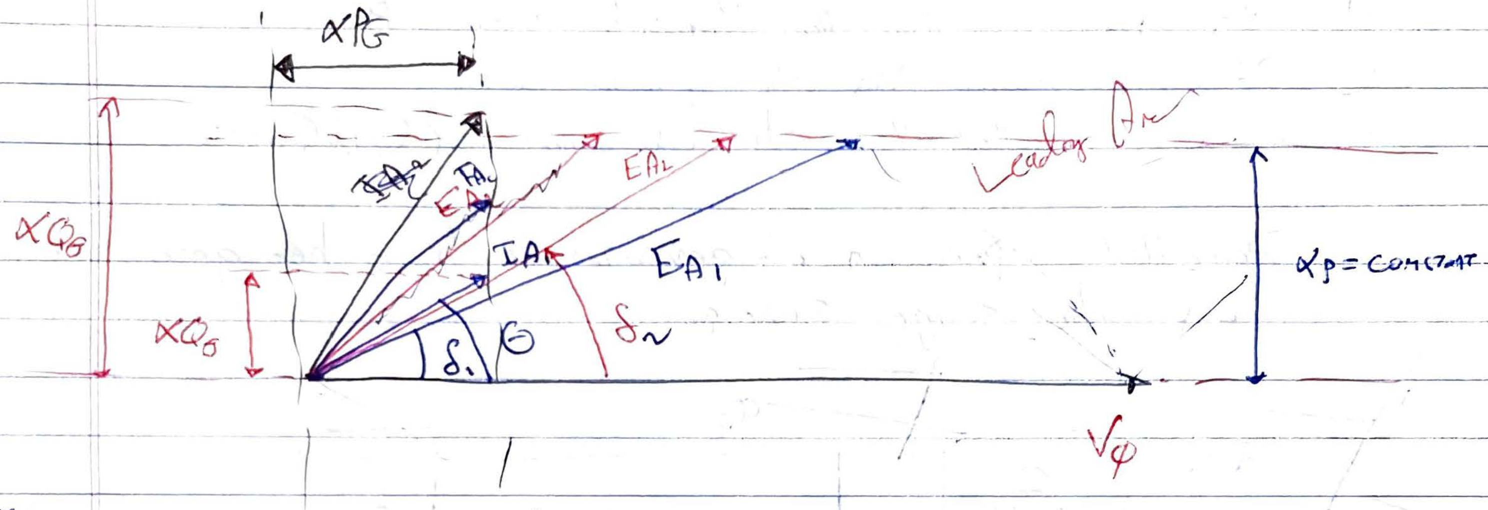
Adjustment of Reactive power:

" changing the excitation " field current "

$$P_G = \frac{3 V_\phi E_A}{X_s} \sin\delta = 3 V_\phi I_A \cos\theta = \text{Constant}$$ " by the user "

V_ϕ = Constant " Infinite Bus "
X_s = Constant " Infinite Bus "

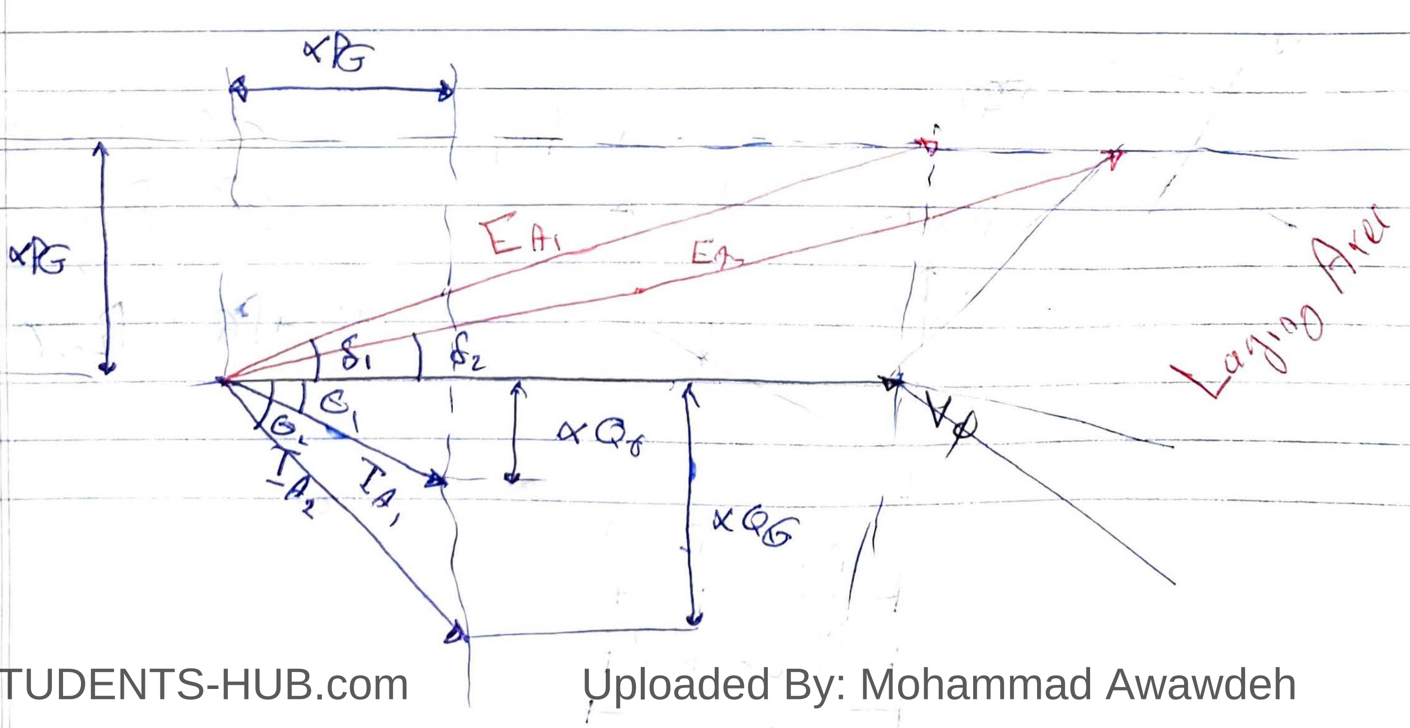
Since P_G is constant $\Rightarrow$ $E_A \sin\delta$ = constant
$I_A \cos\theta$ = constant.



" The Generators absorbed Reactive power " underexcitation process "

$I_F \downarrow \Rightarrow Q_G \uparrow$, absorbed   Leading Area

⊛ هنا كلما الحمل I_F تزداد كمية ال Q اللي بتمتصها ال Infinite Bus



② changing the excitation (field current)

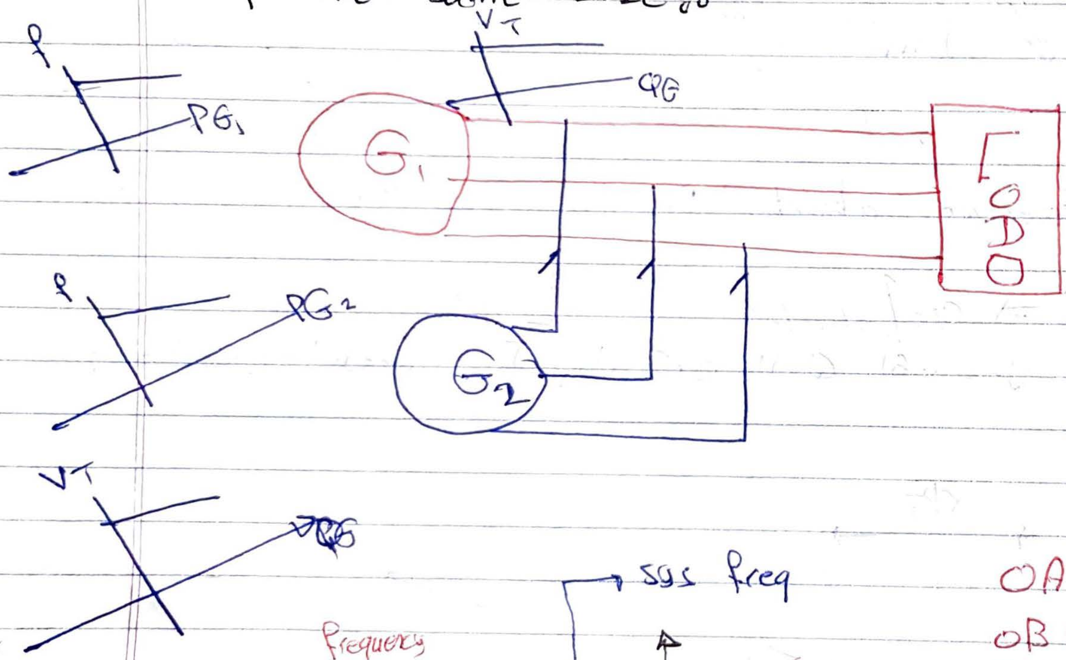
$I_F \uparrow \Rightarrow Q_G \uparrow$ supplied

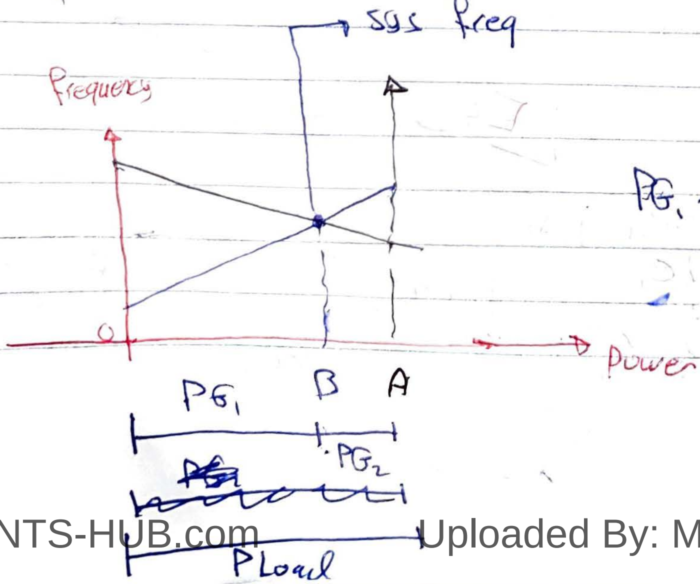
Lagging Area: The generator supplies reactive power "over-excitation"

Conclusion:

① V_T & f_{sys} are controlled via the infinite Bus.
② P_G is controlled via the governor setting.
③ Q_G is controlled via the excitation. (field current)

Parallel operation of generator with other generators of the same size:

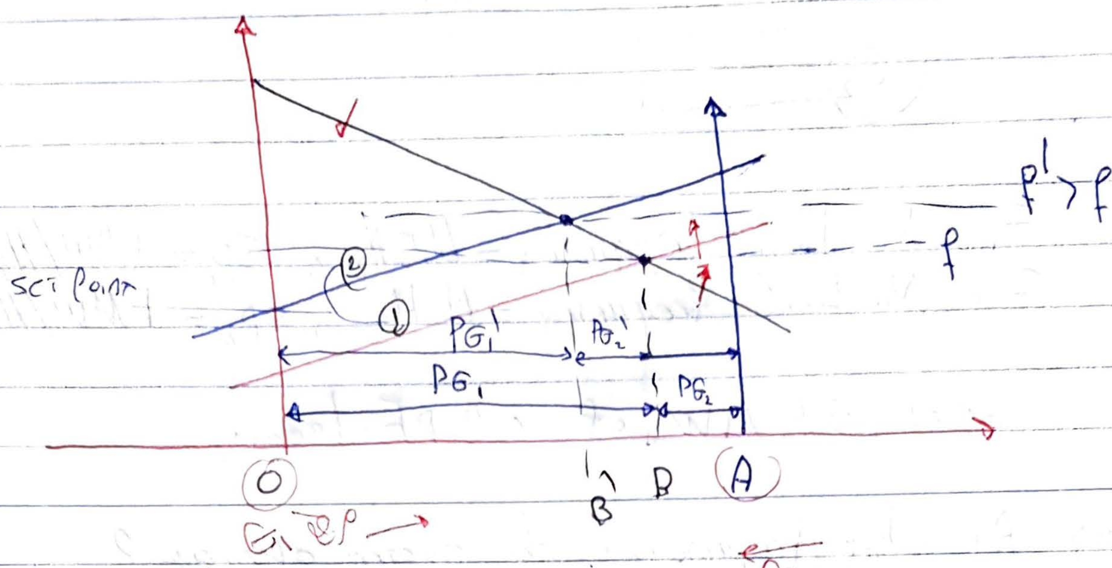




OA : P_{Load}
OB : P_{G1}
BA : P_{G2}

$P_{G1} + P_{G2} = P_{Load}$

changing the governer setting:

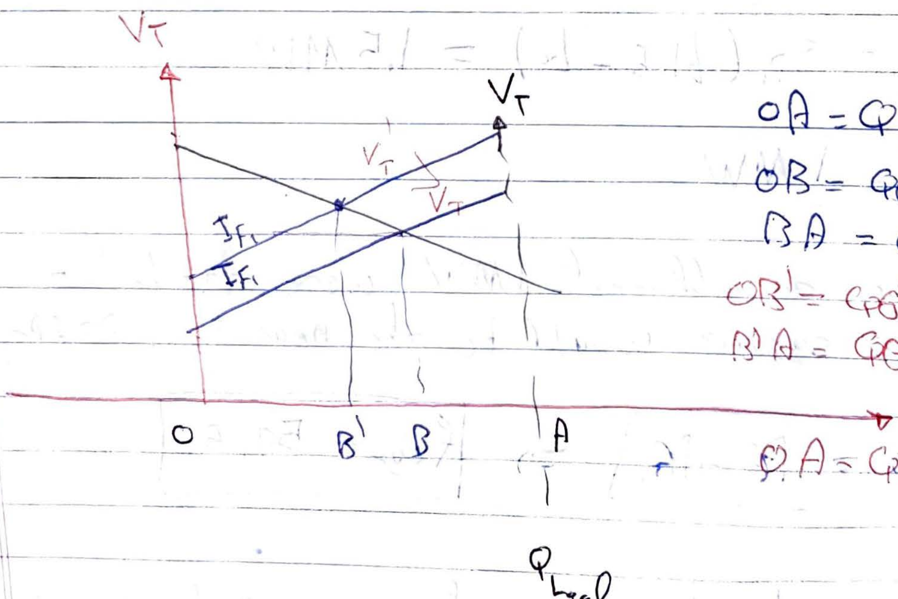


$OB' = PG_1'$ at ①
$B'A = PG_2'$ @ ②
$OA = P_{Load}$

$OB = PG_1$ @ set point ①
$BA = PG_2$ @ set point ①

Governer setting of $G_2 \uparrow$
$f_{sys} \uparrow$ $PG_1 \downarrow$, $PG_2 \downarrow$
$PG_1 + PG_2 = P_{Load}$

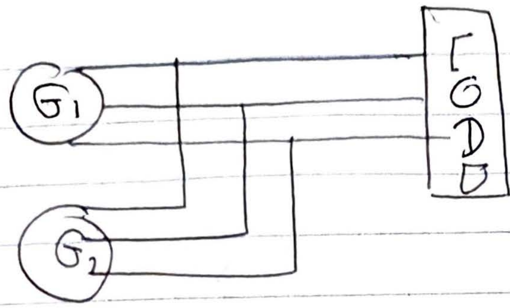
changing the excitation of



$OA = Q_{Load}$
$OB = QG_1$
$BA = QG_2$
$OB' = QG_1'$ @ I_{F_2}
$B'A = QG_2'$ @ I_{F_1}
$OA = Q_{Load} = QG_1' + QG_2'$

G_2 $\left(\begin{matrix} I_F \\ \text{of Generator} \end{matrix} \right) \uparrow \Rightarrow V_T \uparrow \rightarrow QG_1 \downarrow + QG_2 \updownarrow$

Example



G_1: No load frequency $= 61.5\ Hz$, $SP_1 = 1\ MW/Hz$
G_2: No Load frequency $= 61\ Hz$, $SP_2 = 1\ MW/Hz$

Load 2.5 MW of 0.8 PF lagging

a) At what frequency is the system operating?

$$P_{G_1} = SP_1 (f_{NL_1} - f_{sys})$$
$$P_{G_2} = SP_2 (f_{NL_2} - f_{sys})$$
$$P_{G_1} + P_{G_2} = 2.5 \Rightarrow \boxed{f_{sys} = 60\ Hz}$$

b) How much power is supplied by $G_1 + G_2$?

$$P_{G_1} = SP_1 (61.5 - 60) = 1.5\ MW$$

$$P_{G_2} = 1\ MW$$

c) Suppose an additional 1MW were attached to this power system would be the new f_{sys}, P_{G_1} & P_{G_2}?

$$\boxed{3.5 = P_{G_1} + P_{G_2}} \Rightarrow \boxed{f_{sys} = 59.5}$$

d) what will the system frequency and Generator Powers be if ~~Ge~~ the governer setting of G_2 is increased by half Hz?

$f_{NL_1} = 61.5 \quad f_{NL_2} = 61.5$

$P_{G_1} + P_{G_2} = 3.5 \Rightarrow \boxed{f_{sys} = 59.57}$

$P_{G_1} = 1.75\ MW$
$P_{G_2} = 1.75\ MW$

Example: A 480V, 50 Hz, Y-connected, 6 poles SG has $X_s = 1\Omega$ it's full load current is 60 A at 0.8 PF lagging friction & winding losses = 1.5 KW
core losses = 1 KW

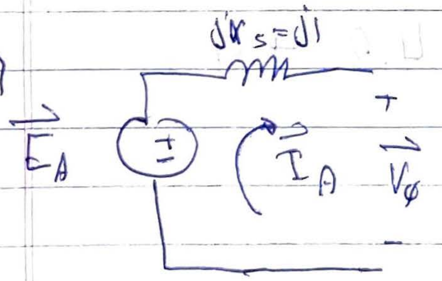
The field current has been adjusted so that $V_T = 480\ V$ at no load.

a) what is the speed of rotation of this generator?
b) what is the terminal voltage of the generator at full-load
c) what is the efficiency under full-load condition?

a) $\omega_m = \frac{2}{P}\omega_e = \frac{2}{6}(2\pi(50)) \Rightarrow \omega_m = \frac{1000\pi}{30}$ rad/sec

$= 1000$ rpm

b)



$\vec{I}_A = 60 \angle -\cos^{-1}(0.8)$

36.87

$\vec{E}_A = (jX_s I_A + \vec{V}_\phi) \Rightarrow \sqrt{\frac{1}{3}}\, 480 \angle \delta = V_\phi + j1(60 \angle -\cos^{-1}(0.8))$

$\sqrt{\frac{1}{3}}(480) =$

$j1(60\cos(36.87) - j60\ \sin(36.87)$

$= V_\phi + 60 \sin(36.27°) + j60 \cos(36.27)$

$\sqrt{\frac{2}{3}}\, 480 = \sqrt{(V_\phi + 60\sin(36.27))^2 + (60\cos(36.27))^2}$

$V_\phi = 236.8$ V RMS

$V_T = \sqrt{3}\,(236.2) = 410$ V

c) $P_{out} = \sqrt{3}\; V_T\, I_A\, PF$

$P_{out} = 34.1$ KW

$P_{in} = 34.1 + 1 + 1.5 = 36.6$ Kw

$\eta = \frac{34.1}{36.6} = 93.2\%$

d) find T_{app}?

$T_{app} = \frac{P_{in}}{\omega} = 291$ N

Homework Problems 4.6, 4.7, 4.8, 4.9