Synchronous Generators

The ALTERNATOR

* any heteropolar rotating machine with alternate North and South poles is inherenltny an altern-
-ator.

* voltage in the conductors alternates between 2polarities

Aternator
- Rotating armature type
  * suitable for small outputs
- rotating field / fixed armature
  * for larger voltages 6600 to 33,000 V

Speed of a Synchronous Generator

electrical frequency produced is locked in or synchronized with mechanical rate of rotation of the generator

rotor has an electromagnet,

rate of rotation is related to stator electrical frequency;

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

f_e : electrical freq
P : no of poles
n_s : synchronous speed

* Electrical power is generated @ 50 HZ or 60 HZ, so the generator must rotate at a fixed speed depending upon the poles in the machine

ex: 50 HZ Gen, 2 poles

→ $n_s = \frac{120 f_e}{P} = \frac{120 \times 50}{2} = 3000$ rpm

→ 4 poles

$n_s = \frac{120 \times 50}{4} = 1400$ rpm

The Internal Generated voltage of an AC Generator

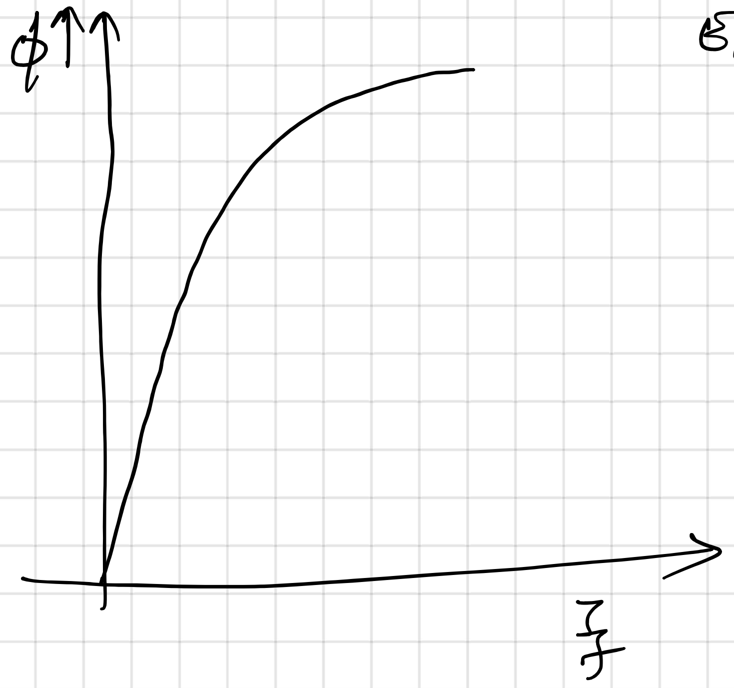
$$E_a = \sqrt{2}\pi N_c \phi f = \frac{2}{\sqrt{2}}\pi N_c \phi f = \frac{N_c}{\sqrt{2}}\phi\omega$$

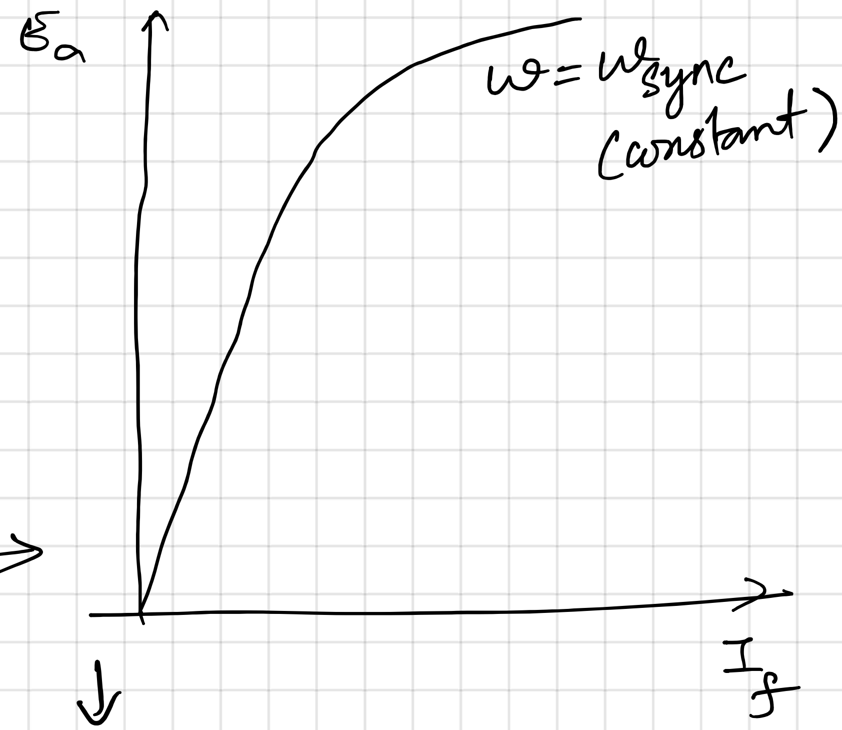
now, $E_a = k\phi\omega$

comparing the 2 equations we get electrical rad s^{-1}

$\boxed{k = N_c/\sqrt{2}}$ Electrical rad s^{-1}

now, $E_a \propto \phi$ but $\phi \propto I_f \Rightarrow E_a \propto \cancel{\phi}\, I_f$





this plot is called the magnetization curve or open circuit characteristics (OCC)

In mechanical degrees in mech rad/sec

$$E_a = \sqrt{2}\pi N_c \phi f = \sqrt{2}\pi N_c \phi \left(\frac{N_m P}{120}\right) = \frac{2}{\sqrt{2}}\pi N_c \phi \frac{N_m P}{120}$$

$$E_a = \frac{N_c P}{\sqrt{2}}\phi\omega_m \qquad E_a = k\phi\omega_m$$

$$\boxed{k = \frac{N_c P}{\sqrt{2}}} \rightarrow \text{mech rad } s^{-1}$$

Equivalent Circuit of a Synchronous Generator

* E_a is the voltage generated in one phase of the stator, but E_a is not the value that comes out of the terminal.

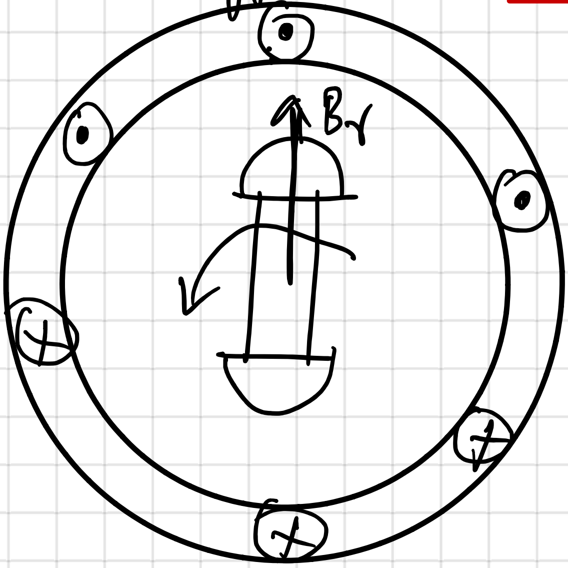
* $E_a = V_\phi$ only when the gen is in no load condition (ie) no armature current flowing in the generator

* factors that cause this difference:

  1) armature reaction [distortion of air gap magnetic field by current flowing in the stator] → largest one
  2) self-inductance of coil
  3) Resistance of the coil
  4) effect of salient pole rotor shapes

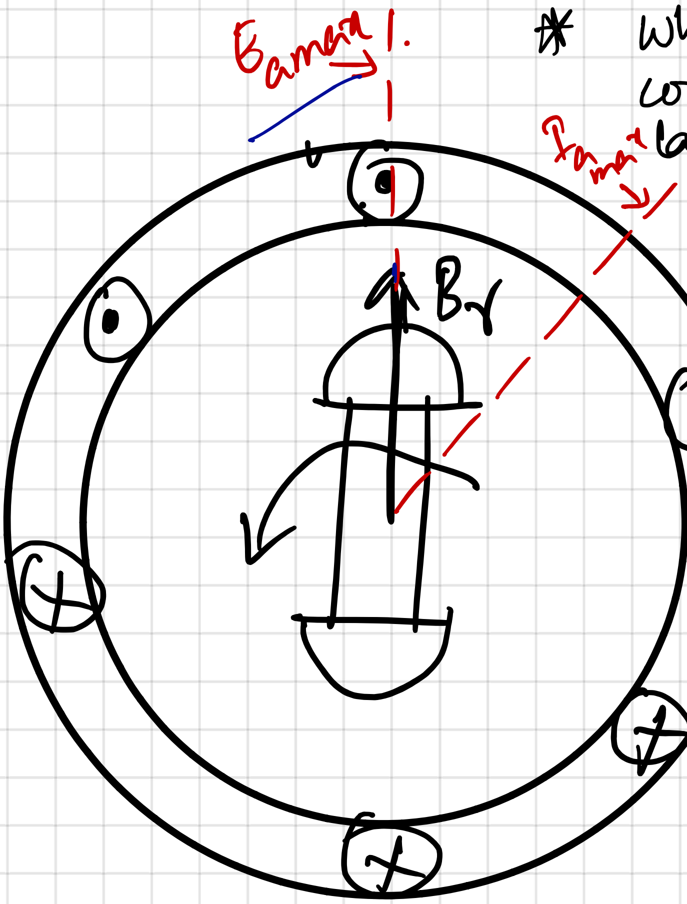
1) Armature Reaction:

When rotor is spun, E_a is induced and when E_a is induced, a current flows through the armature, this armature current produces its own magnetic field and distorts the original magnetic field, this effect is "ARMATURE REACTION".

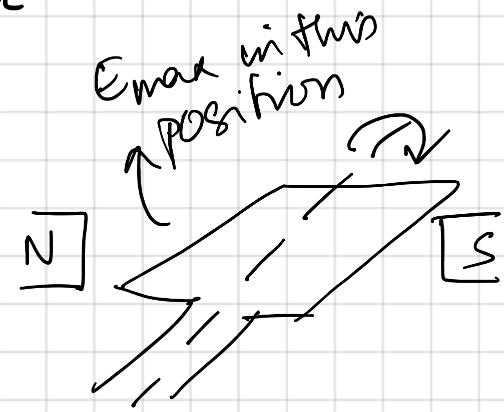


→ B_R produces internal generated voltage E_a whose peak coincides with the vector B_R

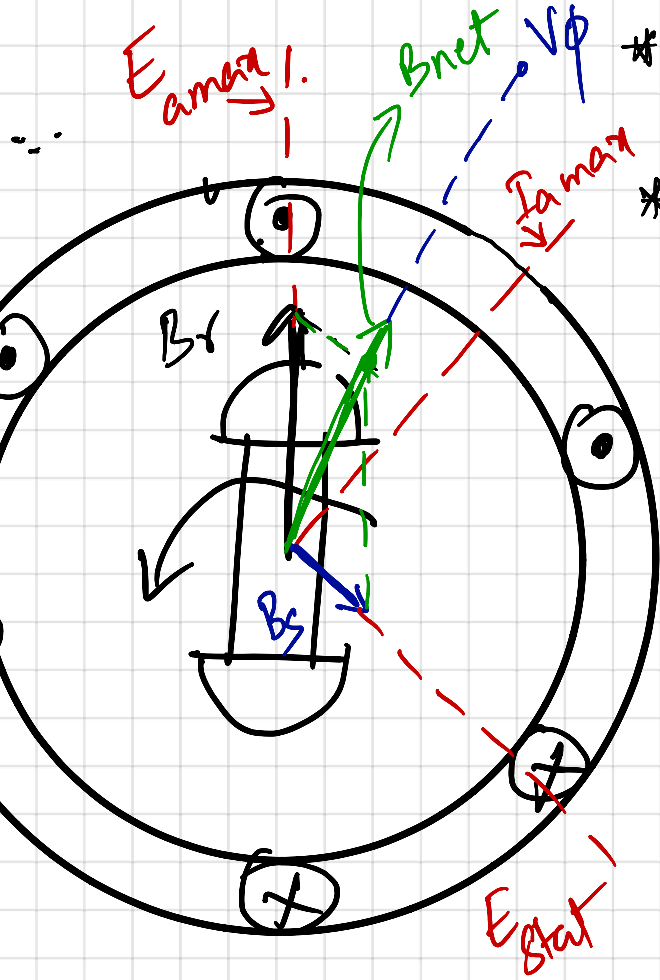
→ $E_a = V_\phi$



* when currents flows as load gets connected, assumed to be a lagging load, then I_{amax} lags E_{amax}



* Current in stator winding produces its own magnetic field B_s (dir given by right hand screw rule)



* B_s produces its own emf in the stator, E_{stat}

* ⇒ $\bar{V}_\phi = \bar{E}_a + \bar{E}_{stat}$

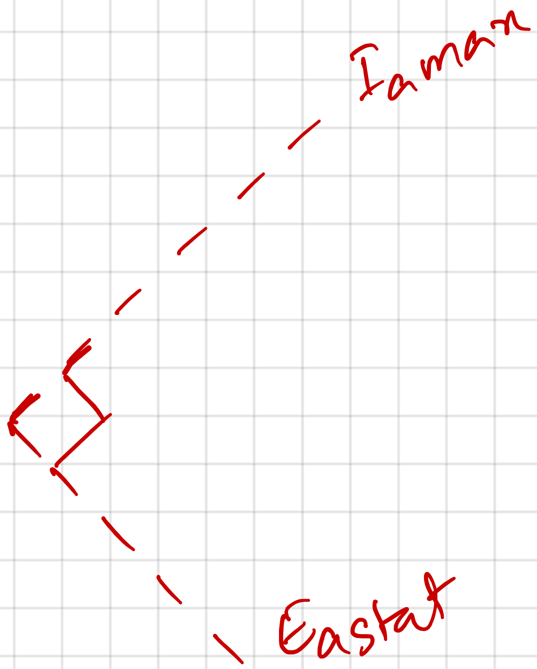
$\bar{B}_{net} = \bar{B}_r + \bar{B}_s$

$E_a \to B_R$

$E_{stat} \to B_s$

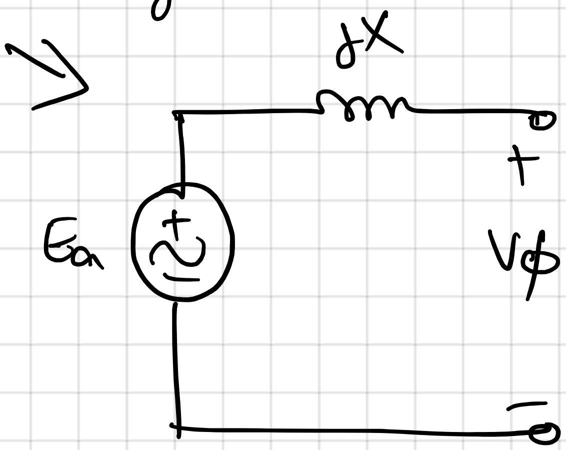
⇒ $V_\phi \to B_{net}$

MODELLING THE ARMATURE REACTION



$$E_{a\,stat} = -j \times X \times I_a$$

$\Rightarrow$ $V_\phi = E_a - jX I_a$



$\Rightarrow$ the E_{stat} can be modelled as an inductor in series with E_a

$\Rightarrow$ now including self inductance & arm-resistance

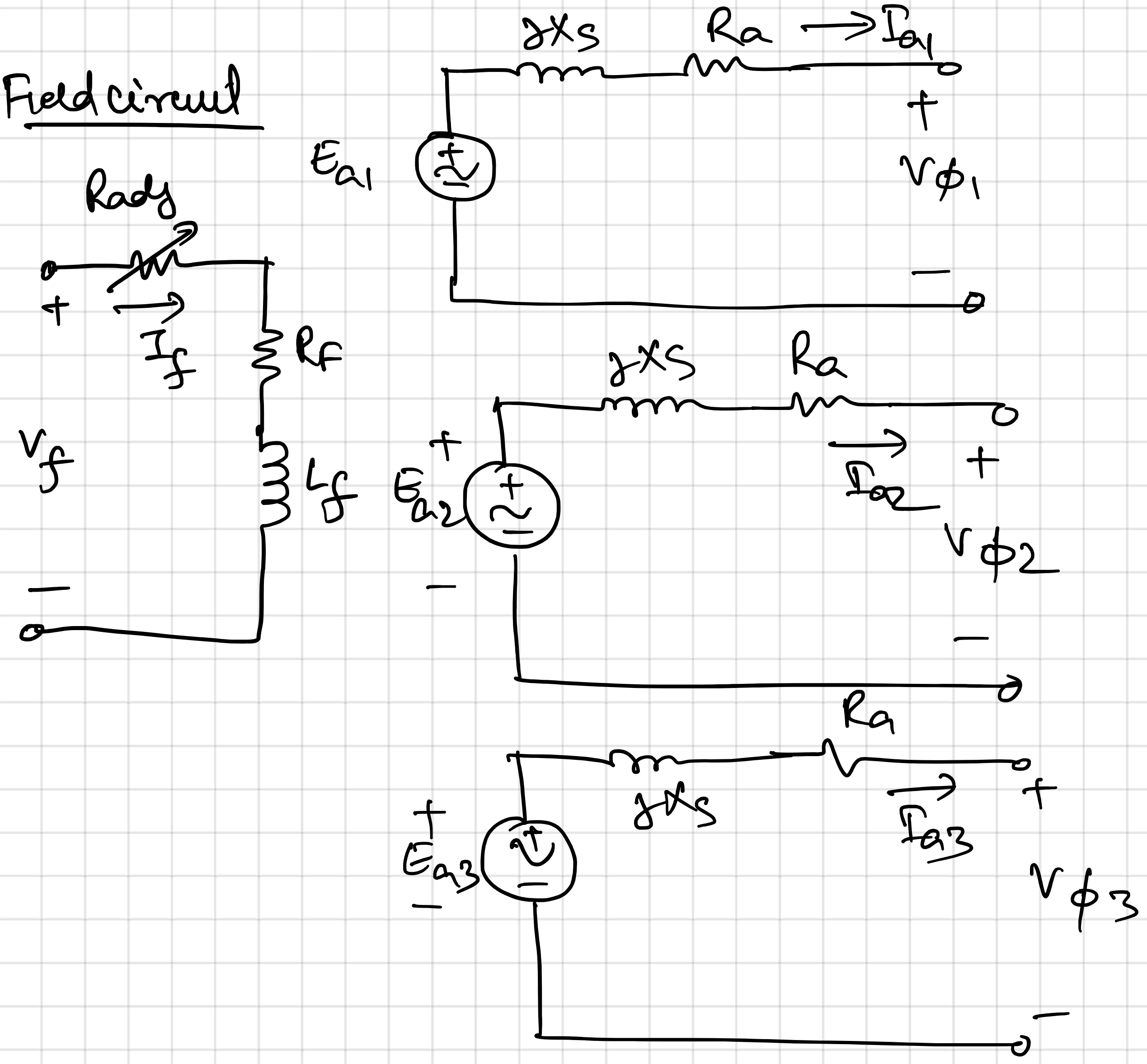
$\rightarrow$ $V_\phi = E_a - \underbrace{jXI_a}_{\text{arm-rea}} - jX_a I_a - I_a R_a$ ← arm-resis drop

↳ self inductance

now, if $X_s = X_a + X$ = Synchronous reactance

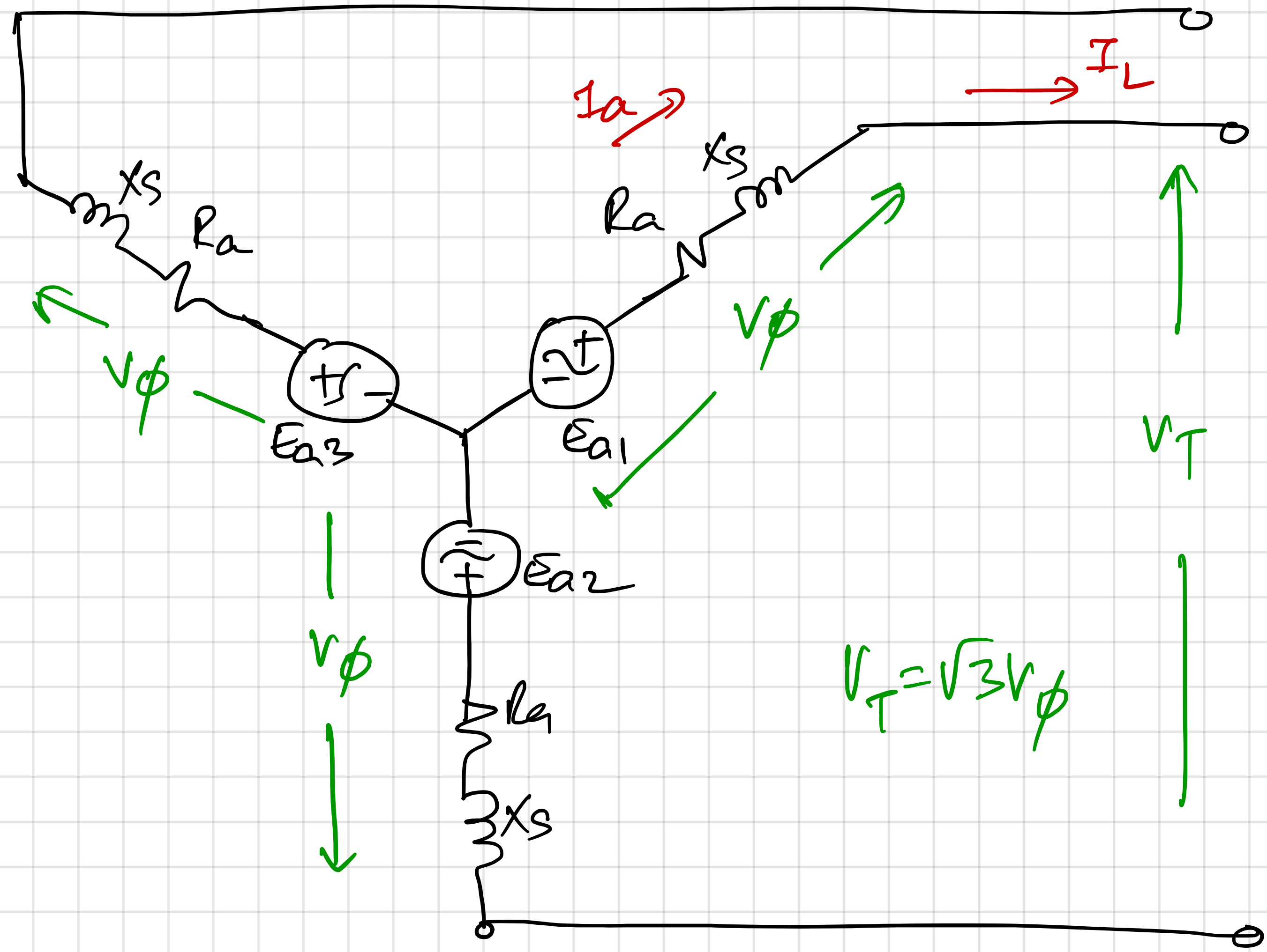
$$\boxed{V_\phi = E_a - jI_a(X_s) - I_aR_a}$$ ← this represent one phase

Field circuit

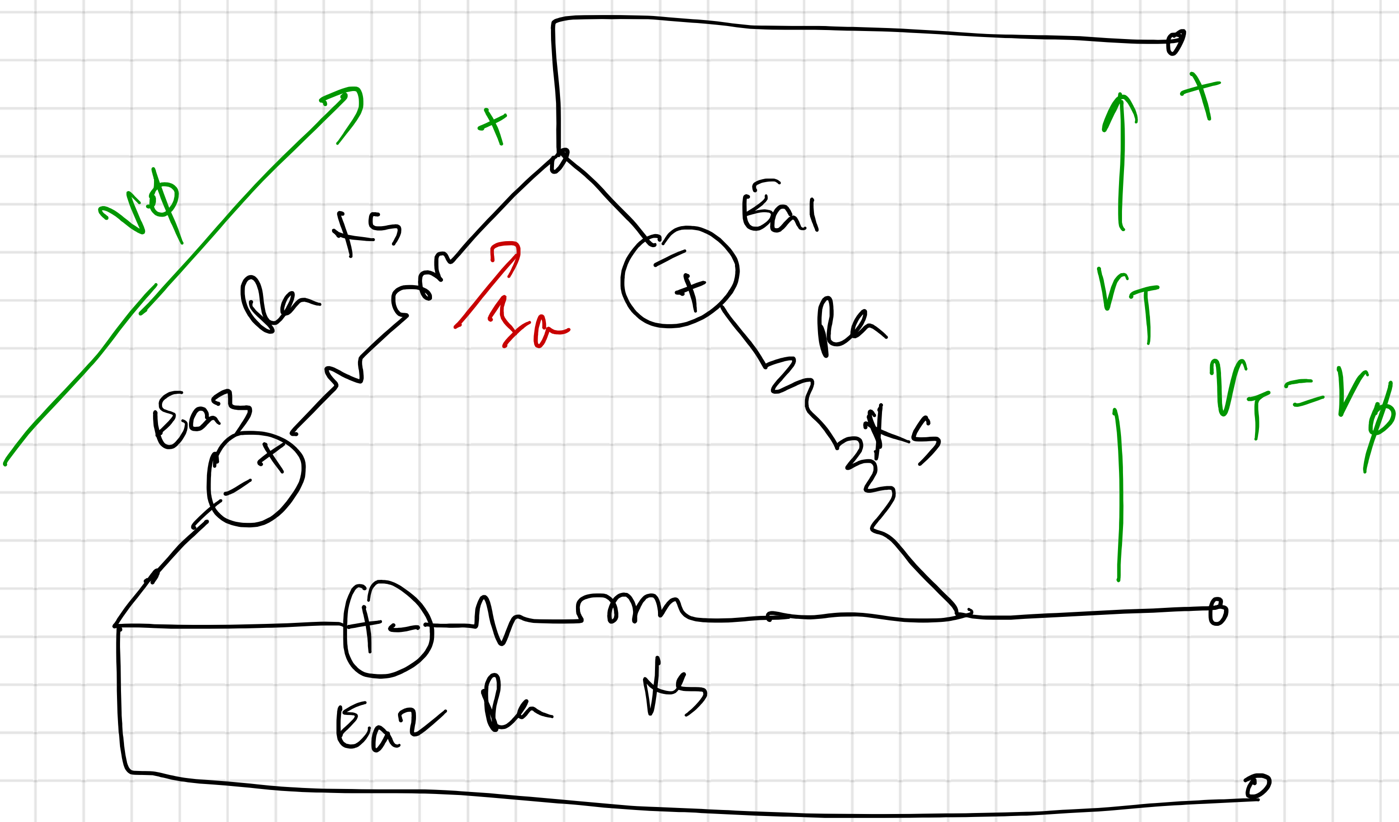


E_{a1}, E_{a2}, E_{a3} sep by 120° electrical

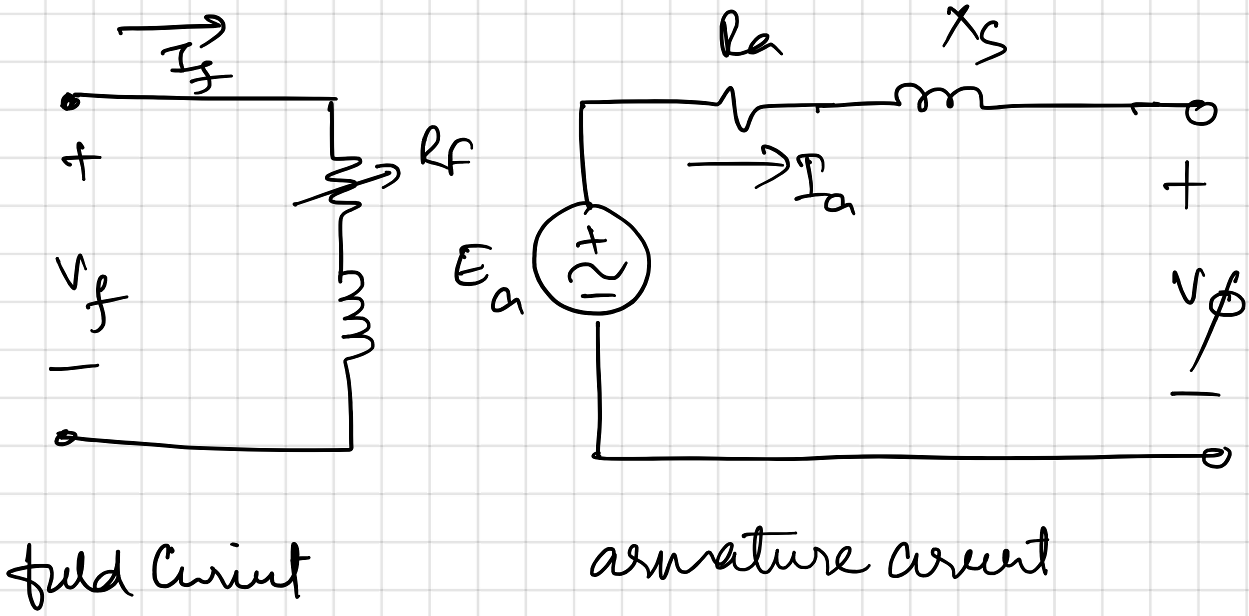
Star connection



Delta connection



Per phase Equivalent



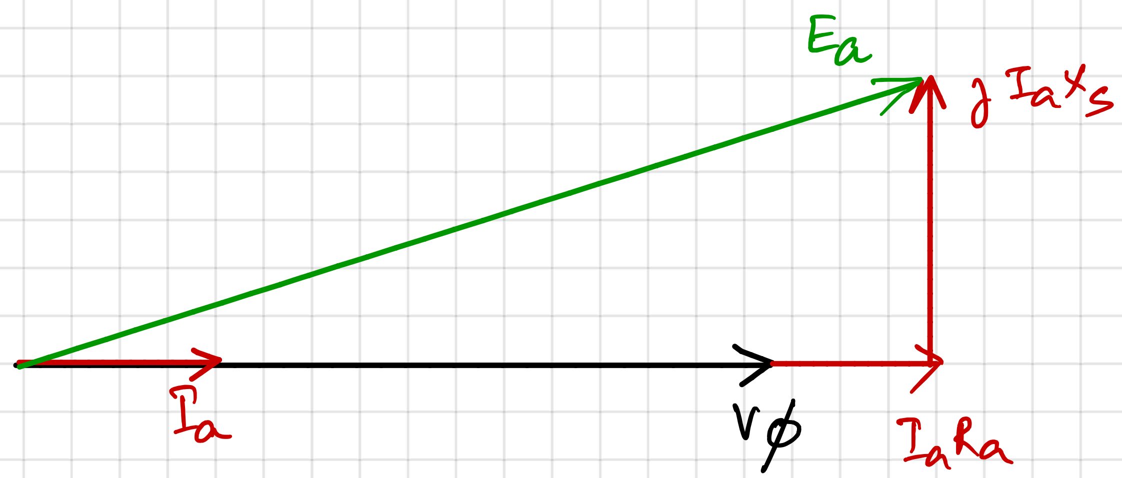
for per phase equivalent, the loads have to be balanced.

Phasor Diagram of Synchronous Generator → upf / lagging / leading

* Gives us a relationship between various electrical quantities like (V_ϕ, E_a, jX_sI_a, I_aR_a etc)

* UNITY POWER FACTOR (o/p voltage and current in phase)

* V_ϕ & I_a are in phase
* I_aR_a & I_a are in phase
* jI_aX_s is leading I_a by 90° ("j" operator)
* $\boxed{\bar{E_a} = \bar{V_\phi} + \bar{I_a}R_a + j\bar{I_a}X_s}$

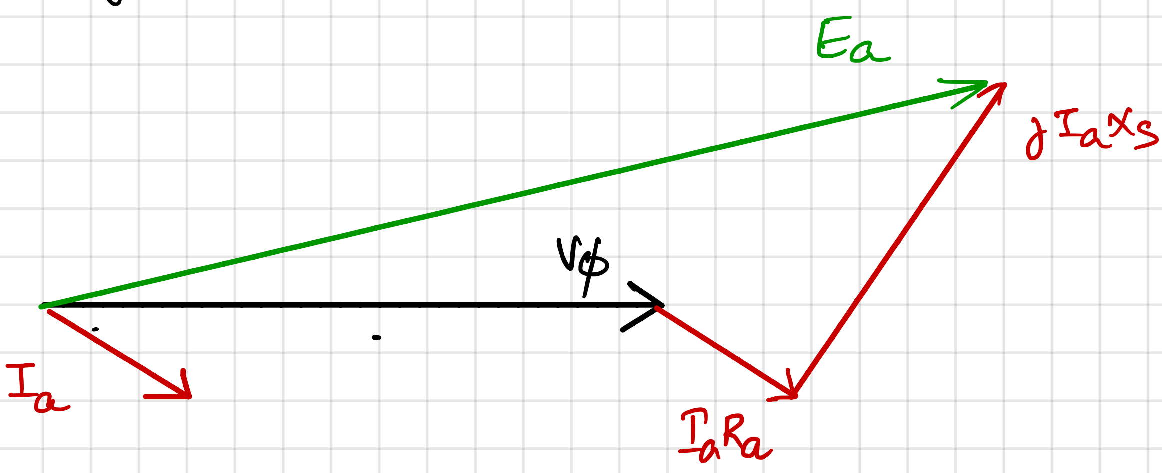


* LAGGING POWER FACTOR

* I_a lags V_ϕ by angle determined by power factor
* I_aR_a is in phase with I_a
* jI_aX_s is 90° leading I_a

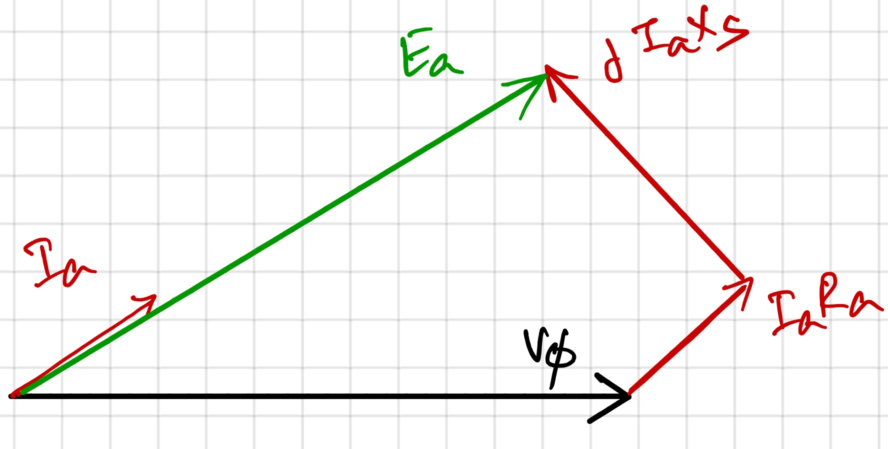
$$\boxed{\bar{E_a} = \bar{V_\phi} + \bar{I_aR_a} + \overline{jI_aX_s}}$$

Lagging loads



LEADING LOADS

* I_a leads V_ϕ by angle determined by power factor
* I_aR_a is in phase with I_a
* jI_aX_s in 90° leading I_aR_a
* $\boxed{E_a = V_\phi + I_aR_a + jI_aX_s}$

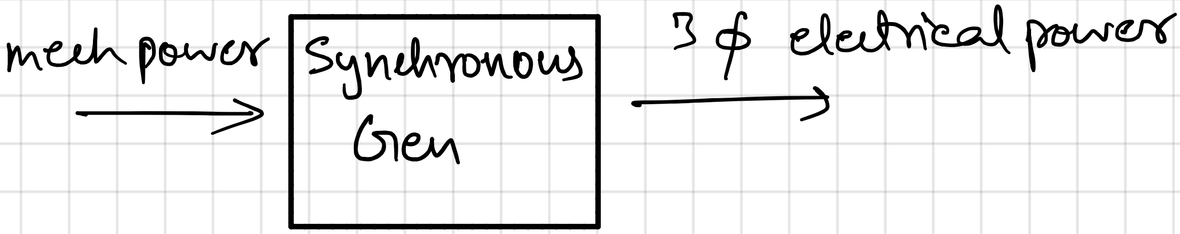


* Clearly for a given V_ϕ and I_a, the E_a required is higher for lagging load

$\Rightarrow$ field current supplied should be higher in lagging loads $\Big\} \Rightarrow E_a = K\phi\omega$ (constant: ω)

* Or for a given field current and load current, the V_ϕ for a lagging load will be less than V_ϕ for a leading load.

Power and Torque In Synchronous Generators

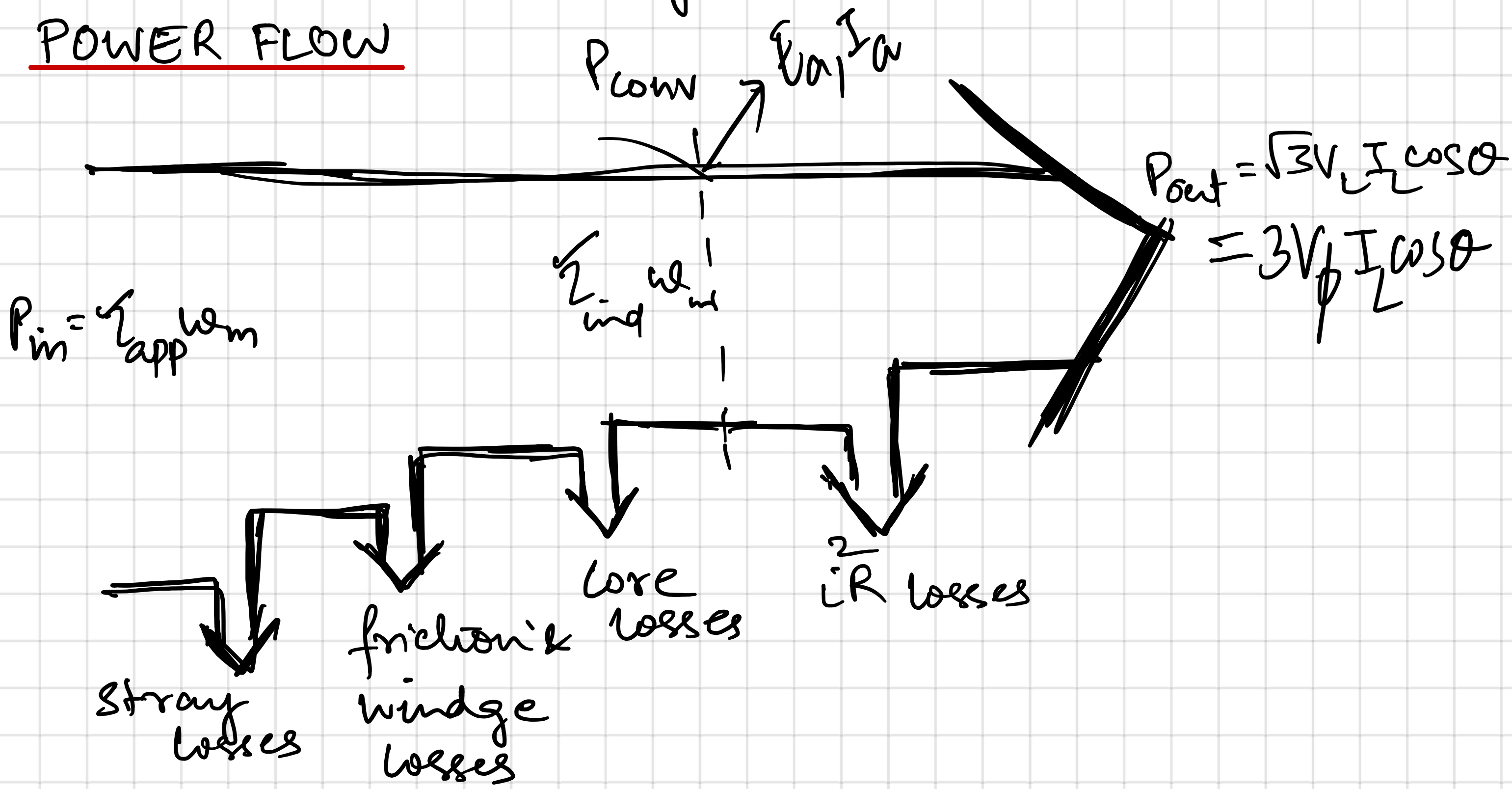


Source of mech power :-

primemover : diesel engine, a steam turbine, water turbine or similar devices

* prime mover must have constant speed irrespective of load demand, if not resulting power freq would change.

POWER FLOW



* $P_{in} = \tau_{app} \omega_m$ $\quad P_{conv} = \tau_{ind} \omega_m = 3 E_A I_A \cos\gamma$

γ : angle b/w E_a & I_a

* $P_{in} - P_{conv}$: stray losses + (no load losses)

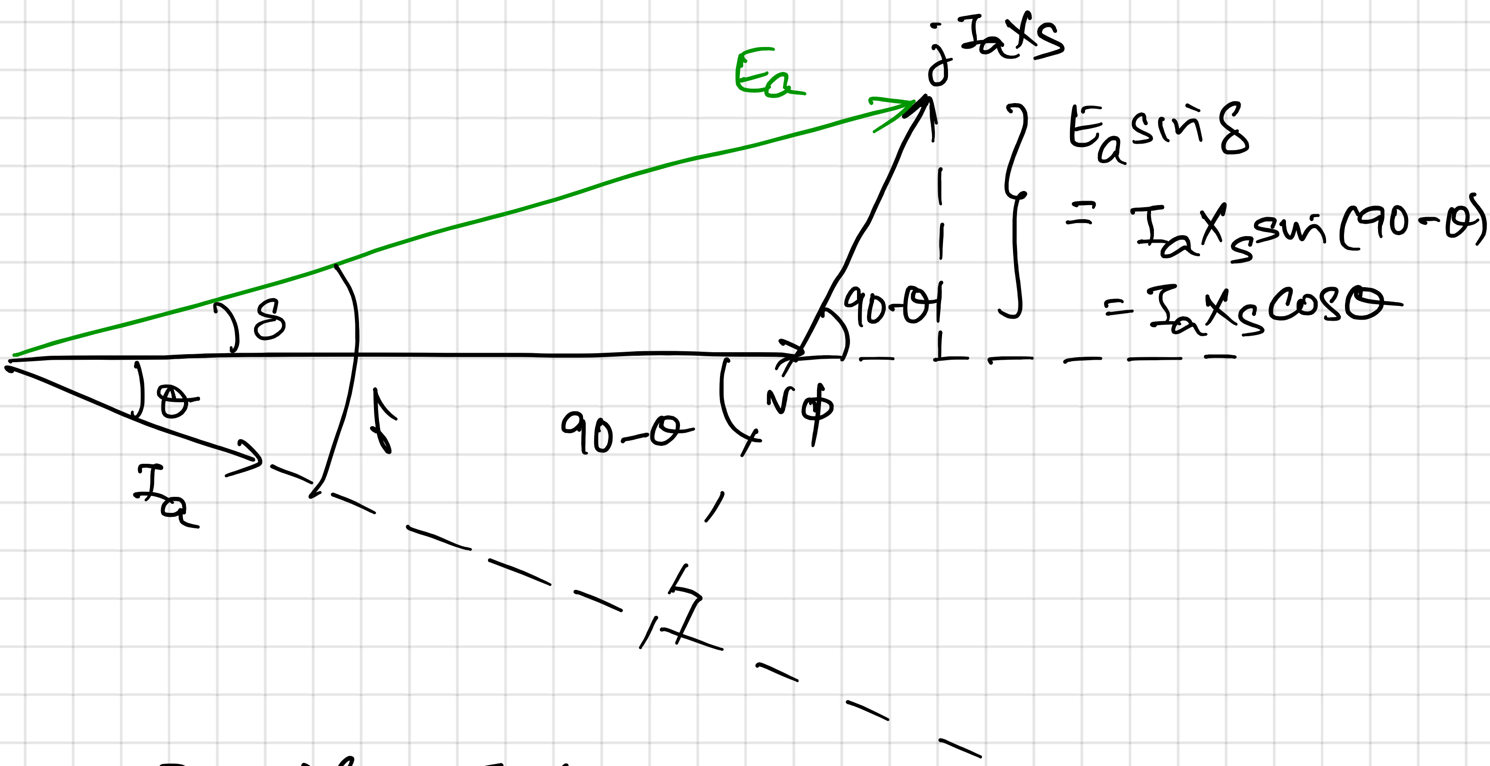
* Real electrical o/p power; $P_{out} = \sqrt{3} V_T I_L \cos\theta$

$$= 3 V_\phi \underline{I_a} \cos\theta$$

* Reactive Power, $Q_{out} = \sqrt{3} V_T I_L \sin\theta$

$$= 3 V_\phi \underline{I_a} \sin\theta$$

phasor diagram after neglecting R_a



$$\Rightarrow E_a \sin\delta = I_a X_s \cos\theta$$

$$I_a \cos\theta = \frac{E_a \sin\delta}{X_s}$$

$$\Rightarrow P = 3V_\phi \left(\frac{E_a \sin\delta}{X_s} \right) \Rightarrow \boxed{P = \frac{3 V_\phi E_a \sin\delta}{X_s}}$$

* In this equation as $R_a \approx 0 \Rightarrow P_{conv} = P_{out}$ bcz there is no electrical losses

$P = \frac{3 V_\phi E_a \sin\delta}{X_s}$ → power produced by Synchronous generator

⇒ power produced P depends on V_ϕ, E_a and δ

δ : torque angle

$P_{max} = @ \ \delta = 90°$ $P_{max} = \frac{3 V_\phi E_a}{X_s}$

P_{max} : static stability limit of Gen and usually real generators never come close to this limit and are usually full load torque angles are 15°–20° and full load.

$$P = \frac{3 V_\phi E_a \sin\delta}{X_s}$$

if V_ϕ = constant, then $P \propto \cancel{E}\ I_a \cos\theta$, $E_a \sin\delta$

& $Q \propto I_a \sin\theta$,

INDUCED TORQUE

$\tau_{ind} = k B_r \times B_s$

$\tau_{ind} = k B_r \times B_{net}$
$= k B_r B_{net} \sin\delta$

$\left\{ \begin{array}{l} B_r \rightarrow E_a \\ B_{net} \rightarrow V_\phi \end{array} \right.$

angle b/w E_a & $V_\phi = \delta$

⇒ " " B_r & $B_{net} = \delta$

$$P_{conv} = \tau_{ind}\,\omega_m = \frac{3V_\phi E_a \sin\delta}{X_s}$$

$$\Rightarrow \boxed{\tau_{ind} = \frac{3V_\phi E_a \sin\delta}{\omega_m X_s}}$$

↑ all the info in electrical quantities

* A 10,000 KVA, 3ϕ Y connected, 2pole, 60Hz, 13,800V, line-to-line turbo gen has air gap chara, arm winding resistance $R_a = 0.07\,\Omega/\text{phase}$, and arm. winding leakage reactance $= 1.9\,\Omega/\text{phase}$. arm mmf @ rated current = 155 ~~AT~~ equivalent field amperes. find I_f that produces rated terminal voltage when rated I_a flows @ 0.8pf

$$E_a \angle \delta = V_t \angle 0 + \cancel{j}\, I_a (R_a + jX_s)$$

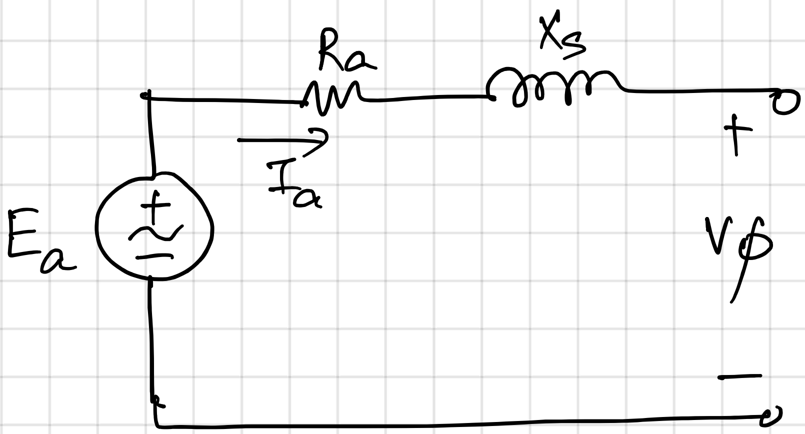
$$V_t = \frac{13,800}{\sqrt{3}} = 7967.4\text{V}$$

$$P = \sqrt{3}\, V_T I \cos\theta \rightarrow I_a = \frac{10,000 \times 10^3}{\cancel{\sqrt{3}}\, 13,800 \times 0.8}$$

$$= 418.4\text{A}$$

$$\Rightarrow E_a \angle \delta = 7967.4 \angle 0 + 418.4 \angle -36.8 (0.07 + j1.9)$$

MEASURING SYNCHRONOUS GENERATOR MODEL PARAMETERS



per phase equivalent

→ determining the equivalent circuit parameters.

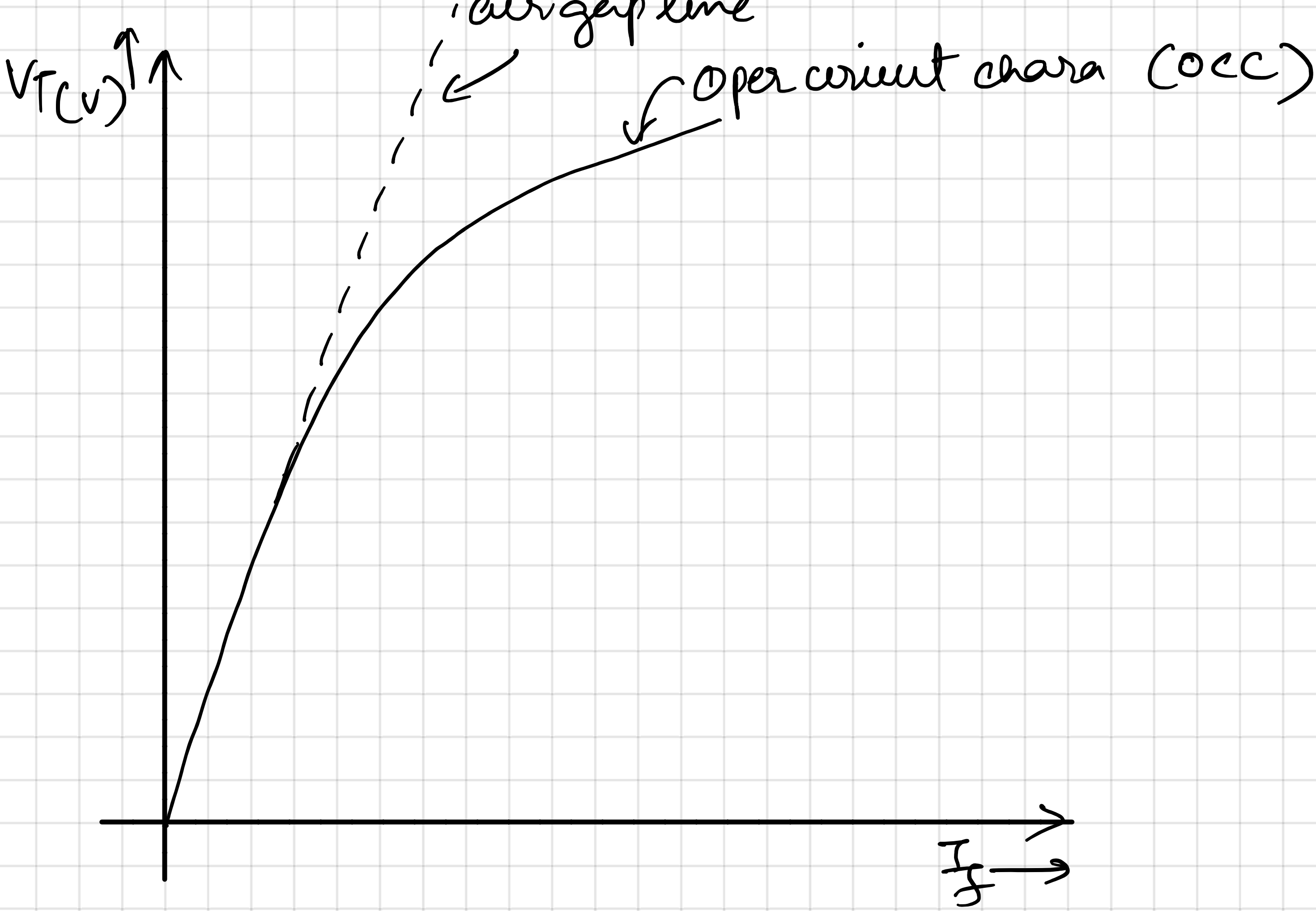
* relationship between field current and flux (and therefore b/w the field current and E_a)
* Synchronous reactance
* armature resistance

Steps :-

→ determining the OCC.

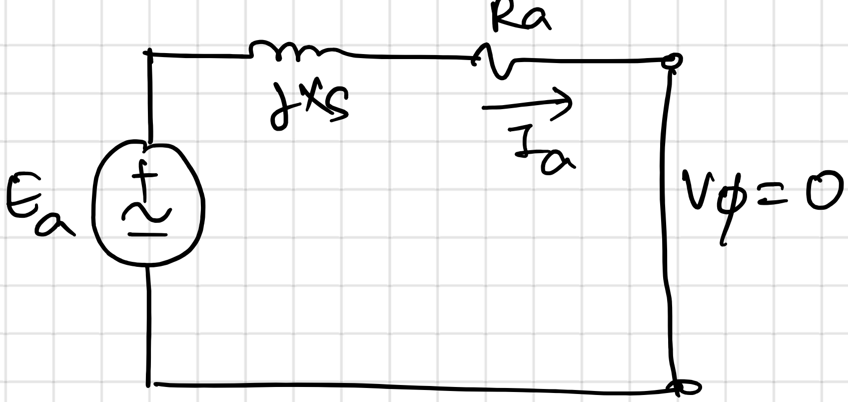
* generator turned at its rated speed and terminals are disconnected from loads and I_f is increased gradually and terminal voltage is measured at each step.
* no load ⇒ $E_a = V_\phi = V_T$
* this plot b/w E_a or V_T v/s I_f is called OCC (open circuit characteristics)
* we can find E_a for any given I_f

* linear portion of OCC → air gap line



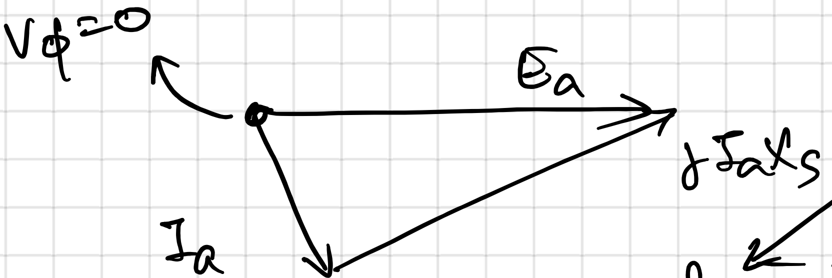
Short circuit characteristics (SCC)

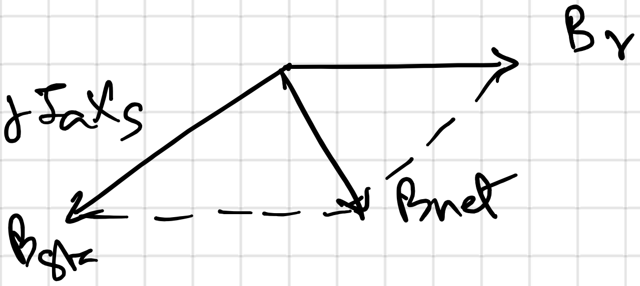
* I_a or I_L is measured with terminals short-circuited



$$I_a = \frac{E_a}{R_a + jX_s}$$

$$|I_a| = \frac{E_a}{\sqrt{R_a^2 + X_s^2}}$$





B_{net} is very small, so m/c is unsaturated and curve SCC is linear.

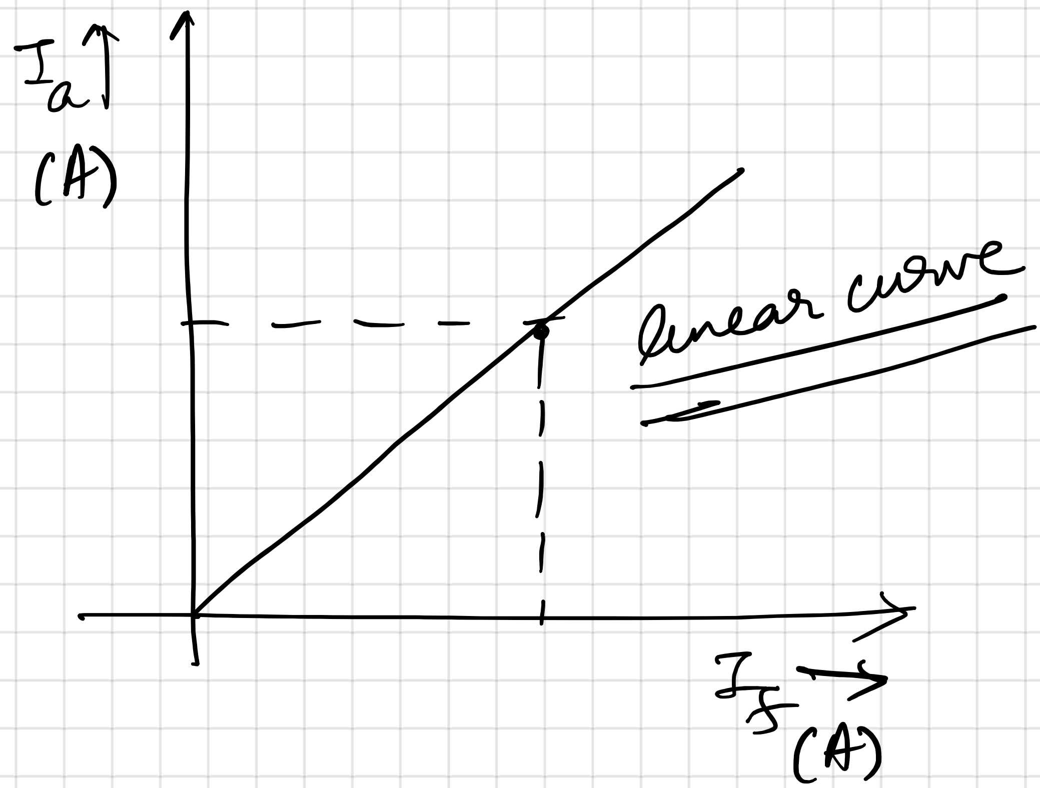
$$Z_s = \frac{E_a}{I_a} = \sqrt{R_a^2 + X_s^2}$$

and $X_s >>> R_a \rightarrow X_s \simeq \frac{E_a}{I_a} = \frac{V_{\phi oc}}{I_a}$

* If E_a and I_a is known X_s can be determined.

⇒ 1) Get internal gen v/g E_a from OCC for given I_f
2) Get short circuit current $I_{a,sc}$ @ that field current from SCC
3) find $X_s = E_a / I_{a,sc}$

now $E_a \rightarrow$ obtained by partially saturated core ~~and I_a~~
$I_a \rightarrow$ determined by unsaturated core



THE SHORT CIRCUIT RATIO

* Short circuit ratio is the ratio of the field current required for the rated voltage at open circuit to the field current required for the rated armature current at short circuit.

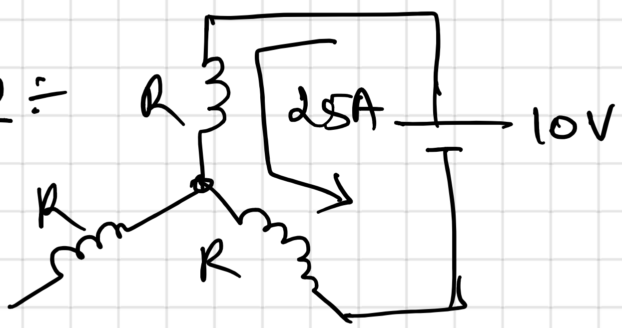
$$\boxed{SCR = \frac{I_f \text{ @ } V_{rated} \text{ at OC}}{I_f \text{ @ } I_{a,rated} \text{ at SC}}}$$

<u>Ex</u>: A 200 kVA, 480-V, 50 Hz, Y connected sync. generator with $I_{f\,rated}$ of 5 A were tested and following data is taken.

1. $V_{T,oc}$ @ rated I_f = 540 V
2. $I_{L,sc}$ @ rated I_f = 300 A
3. When dc voltage 10 V was applied across 2 terminal a current of 25 A was measured.

find R_a, X_s

<u>ans</u>:



$2R = 10/25 \rightarrow R = 0.2\Omega$

now, $I_{a,sc} = I_{L,sc} = 300\,A$

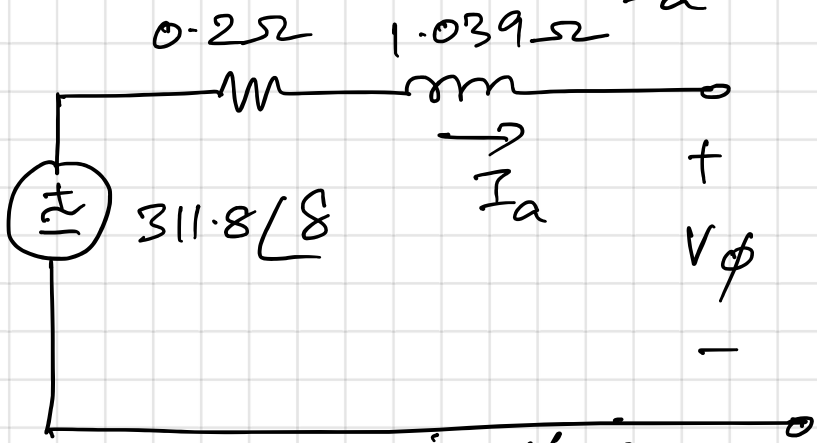
$$E_A \text{ (phase v/g)} = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} \approx 311.8\,V$$

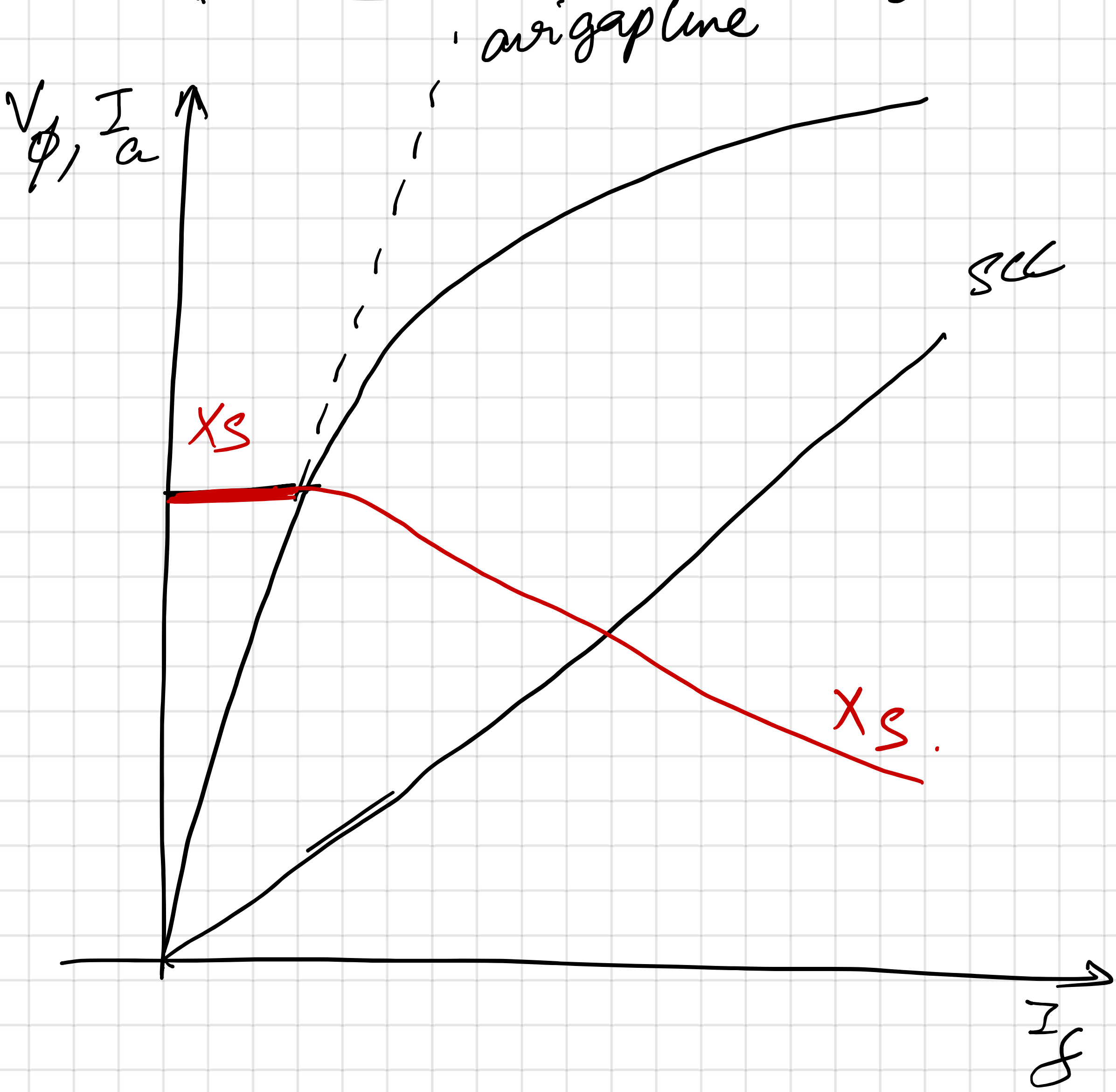
$$Z_s = \frac{E_A}{I_A} = \frac{311.8}{300} = 1.039\,\Omega$$

$$\sqrt{R_a^2 + X_s^2} = 1.039 \rightarrow \sqrt{(0.2)^2 + X_s^2} = 1.039\,\Omega$$

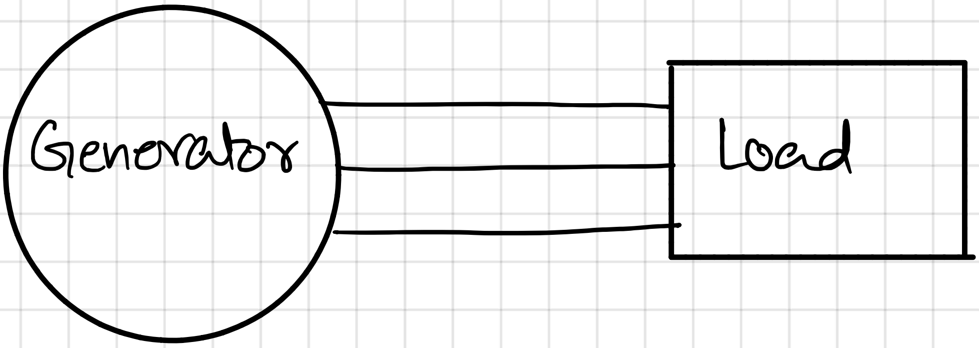
$$\Rightarrow \underline{X_s = 1.02\,\Omega}$$

approx value of $X_s \simeq \frac{E_a}{I_a} = 1.04\,\Omega$





The Synchronous Generator Operating alone



* Speed of generator is assumed to be constant.
* rotor flux is assumed to be constant.
* neglect value of R_a

Effect of load changes on Synchronous Generator

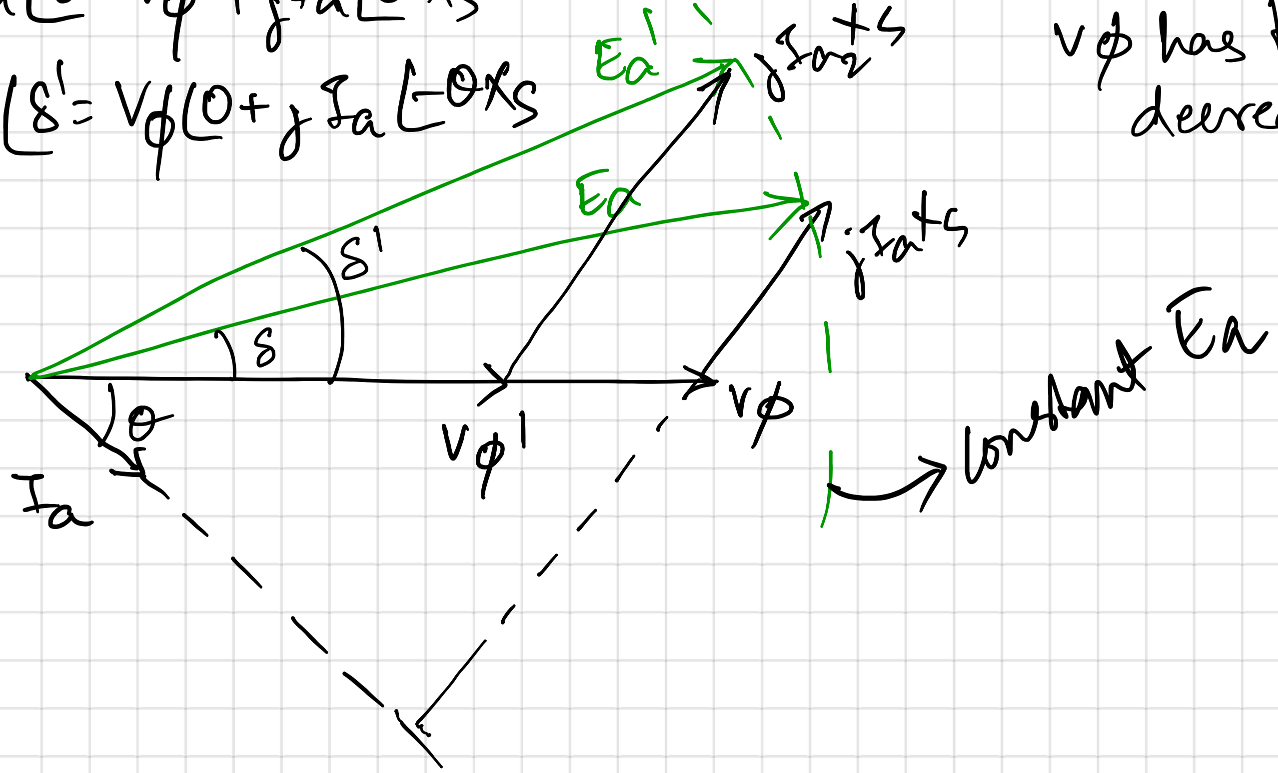
$I_L \uparrow \Rightarrow I_a \uparrow \Rightarrow jI_aX_s \uparrow$

* however $E_a = K\phi\omega$ = constant as ϕ & ω = constant

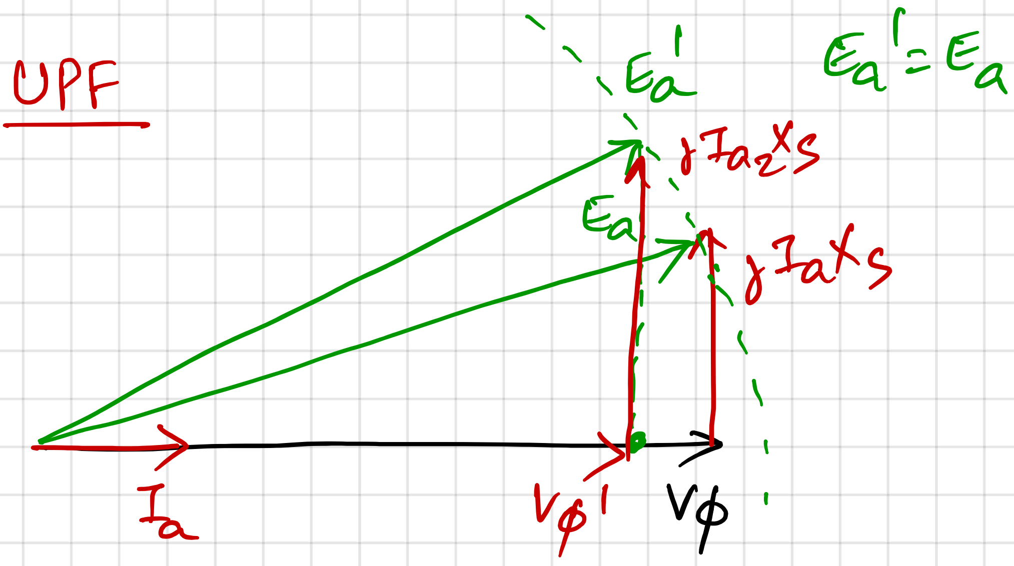
$E_a = V_\phi + jI_aX_s \Rightarrow$ if $I_a \uparrow \rightarrow$ to keep E_a constant V_ϕ has to decrease.

$E_a \angle\delta = V_\phi + jI_a\angle\theta X_s$

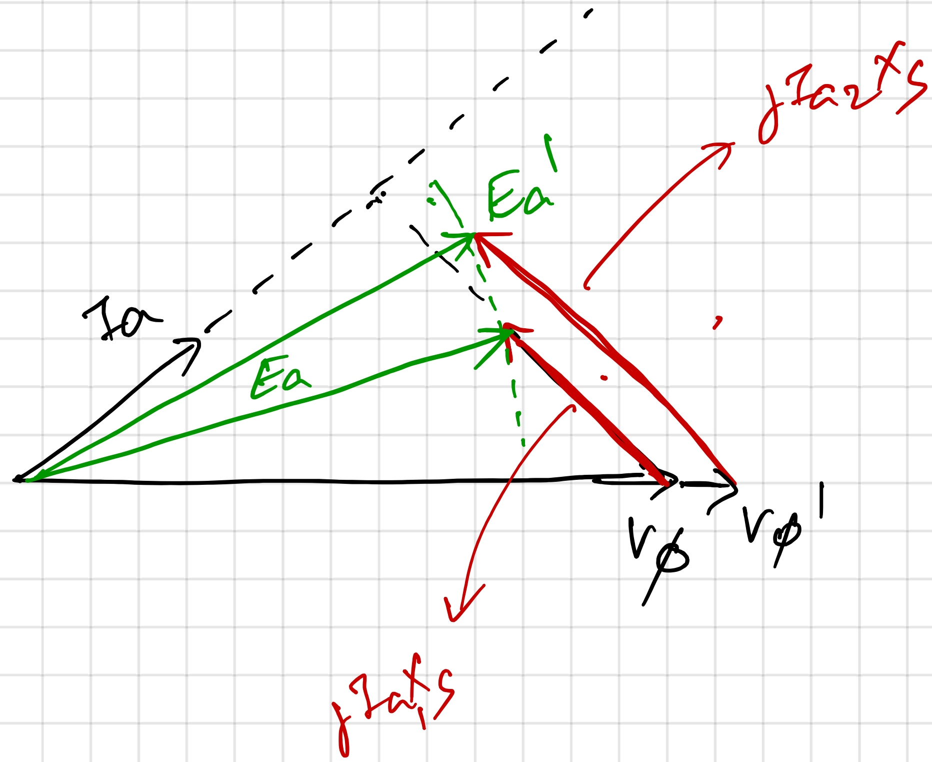
$E_a \angle\delta' = V_\phi \angle 0 + jI_a \angle{-\theta} X_s$



UPF



Leading



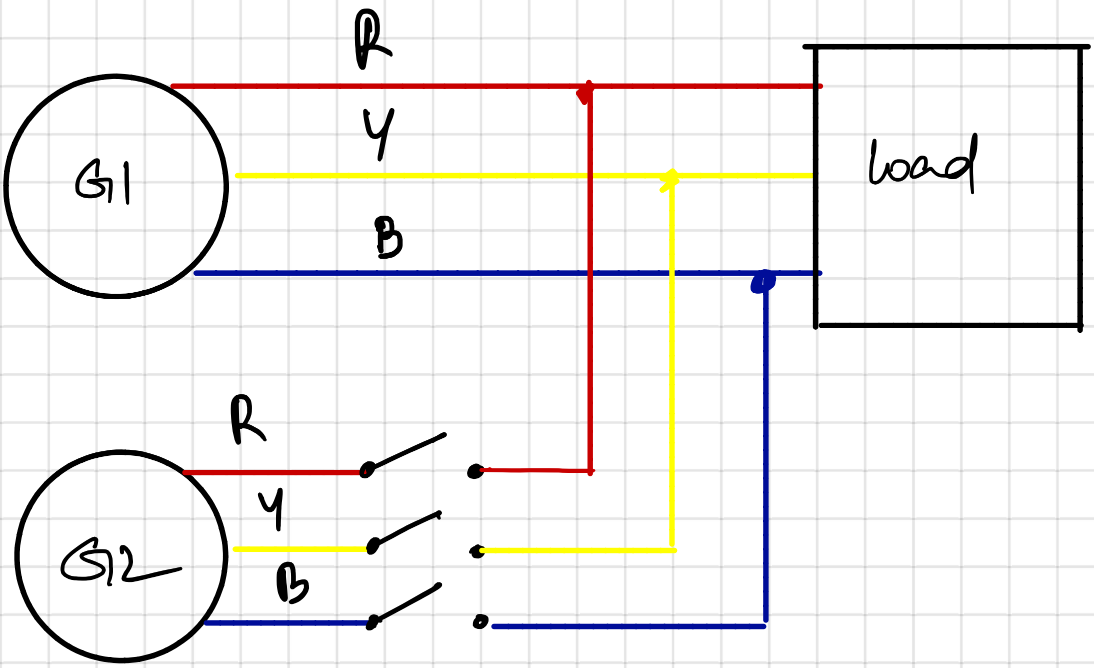
1. Lagging loads ($+\theta$) $V_\phi \downarrow$ with $I_a \uparrow$
2. UPF $V_\phi \downarrow$ slightly with $I_a \uparrow$
3. Leading loads ($-\theta$) $V_\phi \uparrow$ with $I_a \uparrow$

Parallel Operation of Ac Generator

* Isolated generators operating are very rare

Adv :

1. Several generators can supply a bigger load than one machine by itself
2. Increased reliability of the power system, since failure of one generator doesn't affect the system as a whole
3. Allows one or more generators to be removed for shutdown or preventive maintenance.
4. If only one generator is used and it is not operating at near full load, it is relatively inefficient

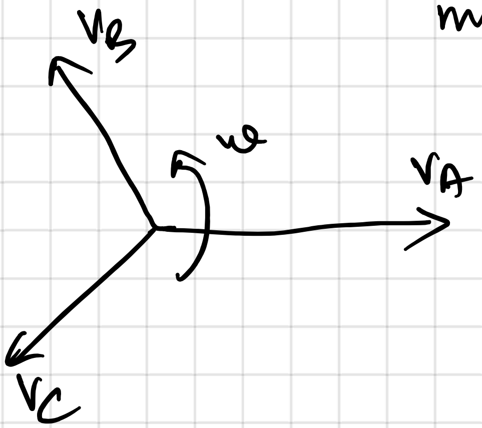


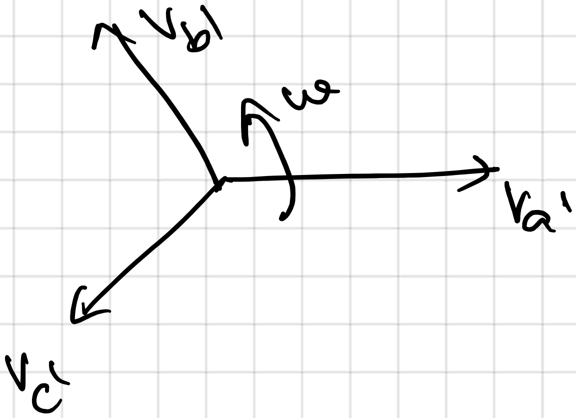
CONDITIONS REQUIRED FOR PARALLELING

1. The rms line voltage of the generators must be equal.
2. The generators must have same phase sequence.
3. The phase angles of two "a" phases must be equal
4. Frequency of the incoming generator must be slightly higher than frequency of the running system

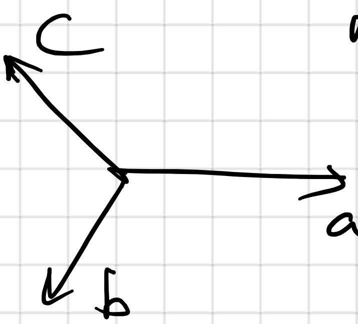
Condition 1 & 3 * for voltages to be equal, rms magnitude should be also same.

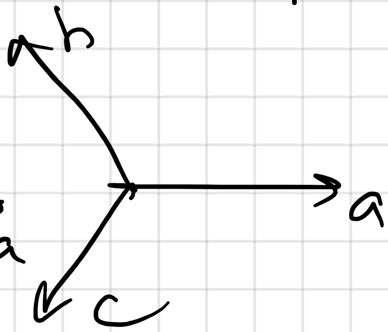
* Voltages a & a' must be same and angles must also be same.





Condition 2 : ensures that the generators peak at the same time. If phase sequence was diff. the generators would peak at diff times





* phase a has no problem.
* phase b & c will have huge circulating currents.

* If the frequencies are not same, heavy transients will occur till generators operate at the same frequency.

The incomer generator freq should be slightly diff as compared to the already existing generator, this is so that the phase would shift gradually and we get an exact point @ which paralleling can be done

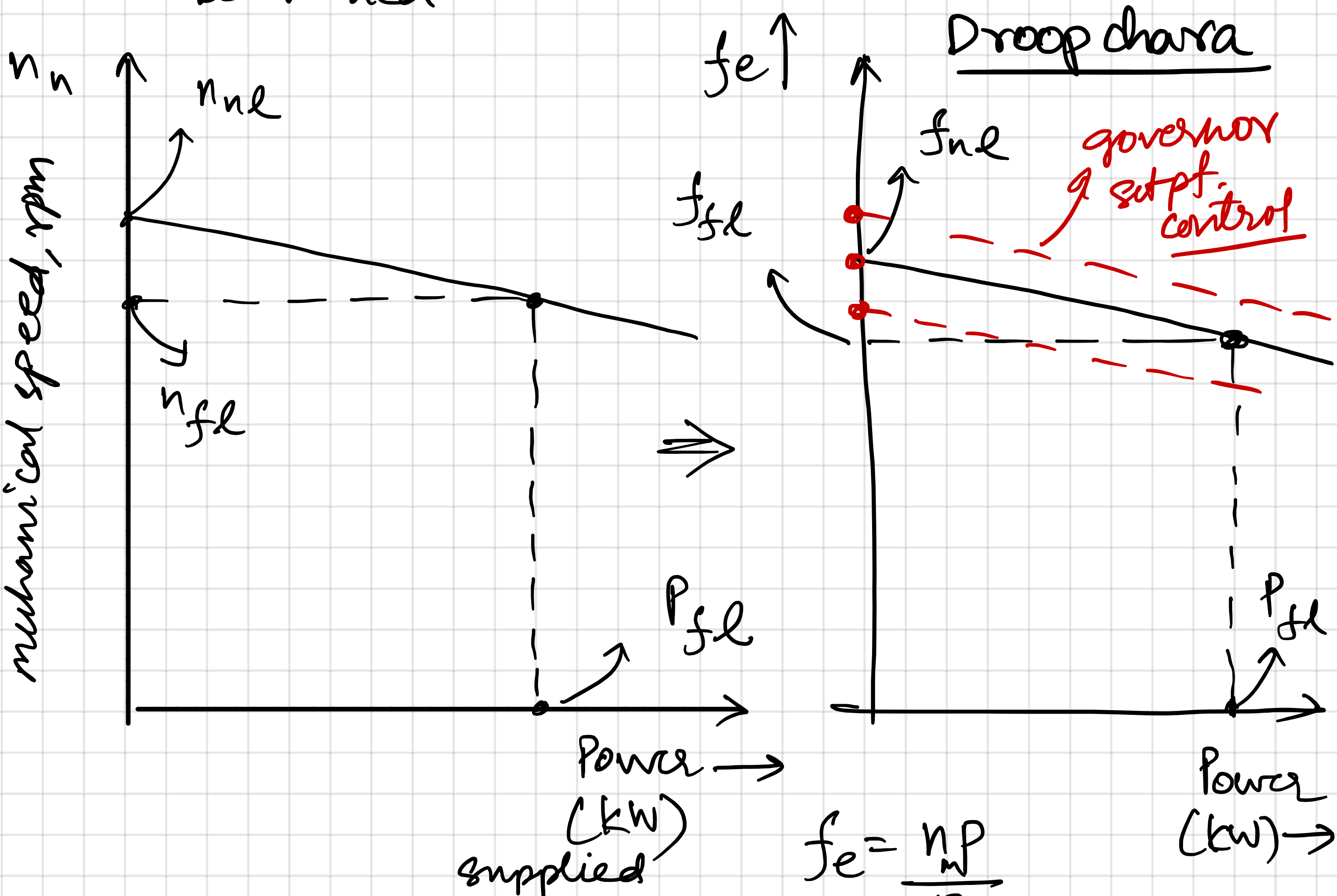
Freq Power & Voltage - Reactive Power chara of a Synchronous Generator.

* all primemovers have similar behaviour (ie) as power drawn from them increases, their speed drops, this variation is usually non-linear, but is made linear by using a suitable speed governing arrangement.

* Speed droop, $SD = \dfrac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$

  → usually 2-4%

* usually there is a setpoint where the no load speed can be varied



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

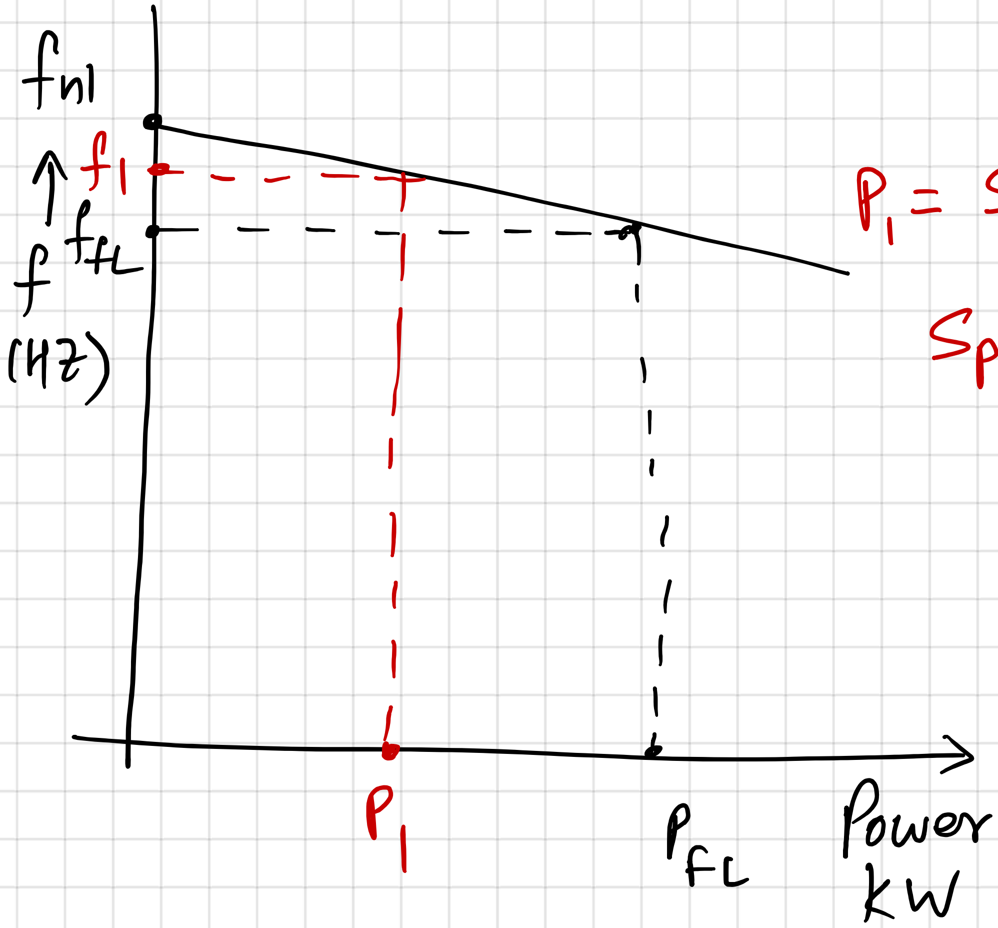
now,

$$\frac{f_{nl} - f_{fl}}{P_{fl} - 0} = \text{slope } (Hz/kW)$$

$$\rightarrow \quad P_{FL} = \frac{1}{\text{slope}(Hz/kW)} (f_{nL} - f_{FL})$$

$$\boxed{P_{FL} = S_p (f_{nL} - f_{fL})}$$

$S_p = kW/Hz$ or MW/Hz



$$P_1 = S_p (f_{nl} - f_1)$$

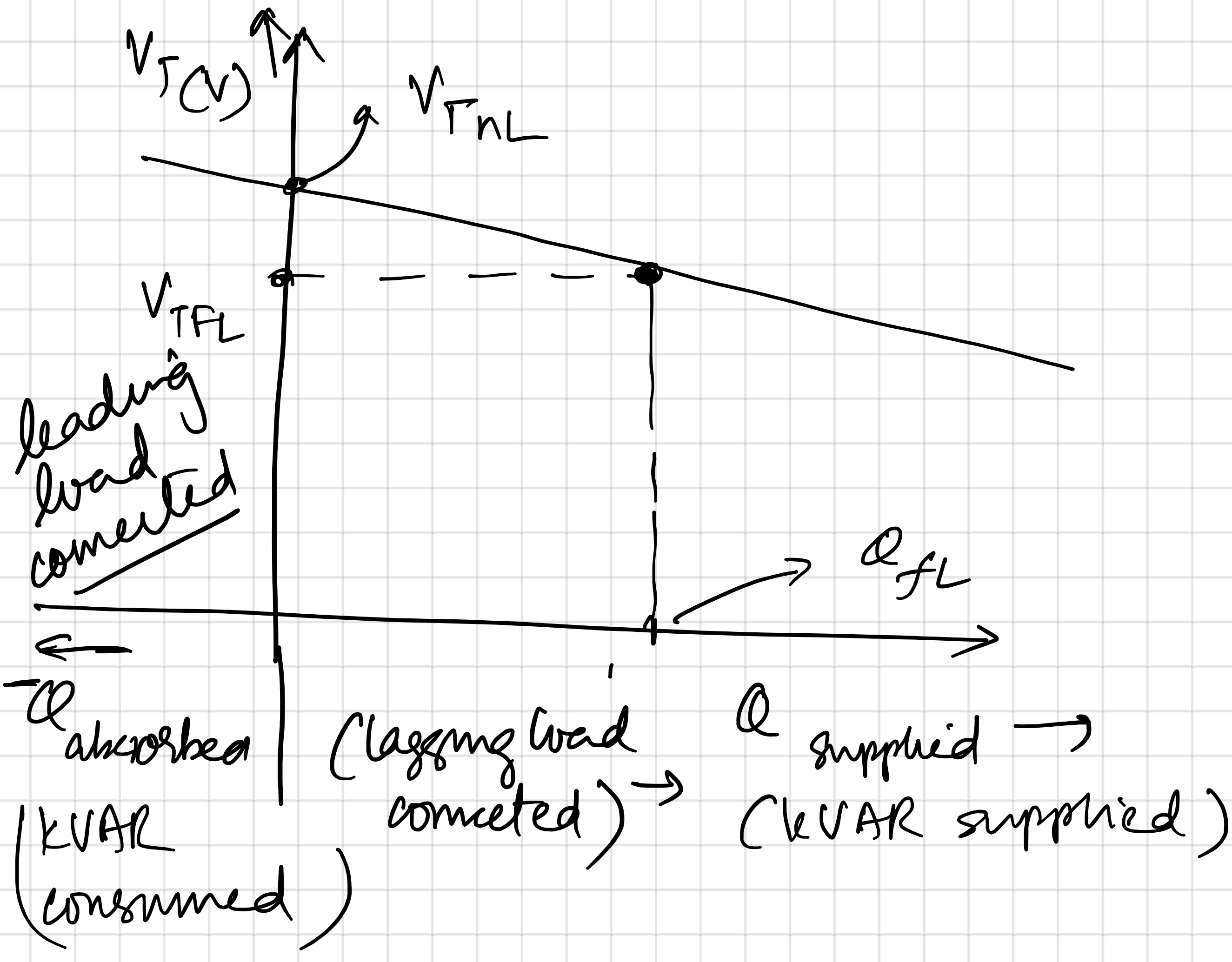
$S_p \rightarrow kW/Hz$ or MW/Hz

* In generator esp when as lagging load ↑ ⇒ V_T ↓
(ie) when a lagging load consumes more reactive power (or) when a gen supplied more reactive power V_T ↓

* Voltage regulators help to maintain this drop linear by changing the voltage regulator setpoint we can move the curve up or down based on requirement

* when generator operates alone :- P & Q are set by ↓
  governor set point → decides freq of operation
  field current → decides V_T

Reactive Power, Q & V_T



Recap :

→ when the freq between two waveform ~~are and~~ ~~only~~ differ ~~slightly~~, the. then flicker freq $= f_2 - f_1$

⇒ when freq are close, flicker freq is less

flicker freq ↑ → turn ON, turn OFF ~~high~~ rate is high

flicker freq ↓ → turn ON, turn OFF rate is low.

Synchronising Procedure.

1. Adjust the speed of the "oncoming" Generator, G_2 to match that of the speed of G_1

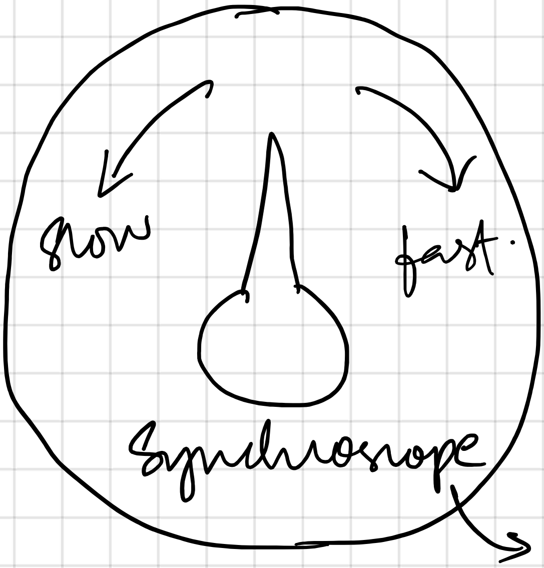
2. Using the voltmeters, the field currents of the oncoming generator should be adjusted such that the terminal voltage G_2 is equal to the line voltage of the running system.

3. Phase sequence of the oncoming generator must be compared to the phase sequence of the running system (using say a small Induction motor it can be verified if both the oncomer and the running system have the same phase sequence)

4. ↳ 3 lamp method : if all the 3 lamps get dark and bright togeather they have the same sequence, if they glow in succession they have opp. phase sequence.

4. frequency of oncoming generator is adjusted. slightly higher then the running system,
   - → the phases will change with respect to each other very slowly making it easier for us to identity when they are exactly in phase
   - → In the 3 lamps when the lamps go off the phase difference is zero, and paralleling can be performed.

→ not very accurate, so we used a "synchroscope".



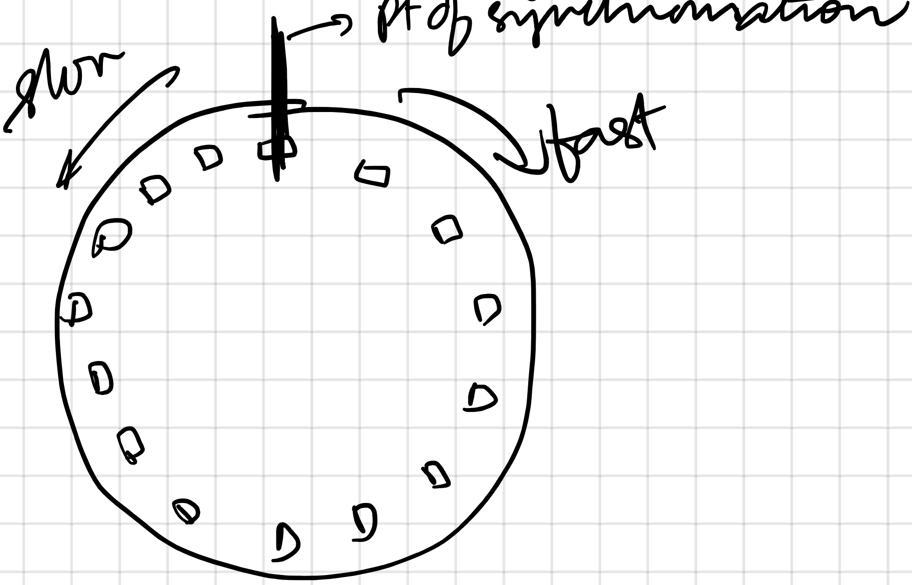
fast: the incomer is faster than the line

slow, the incomer is slower than line.

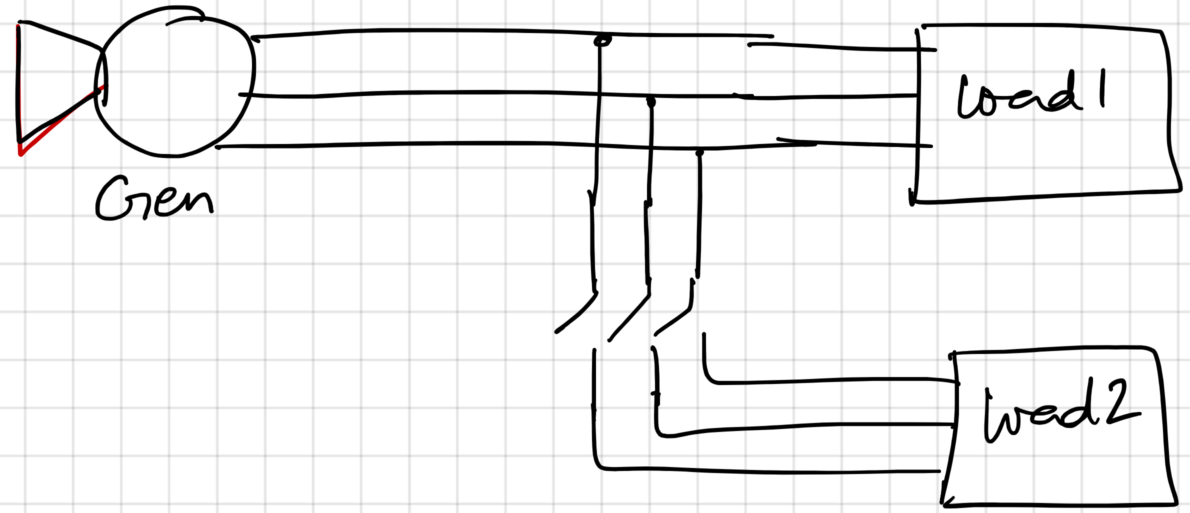
gives only info about phase and not phase sequence

~~and exactly~~

when the synchroscope needle is at vertical position synchronising switch can be pressed.



e)



* Gen supplies a load 1. A second load 2 is to be connected in parallel to first one.
* Gen has no load freq of 61 Hz and $S_p = 1\,MW/Hz$
* load 1 consumes real power of 1000 kW @ 0.8 pf lag
* load 2 consumes real power of 800 kW @ 0.707 pf lag

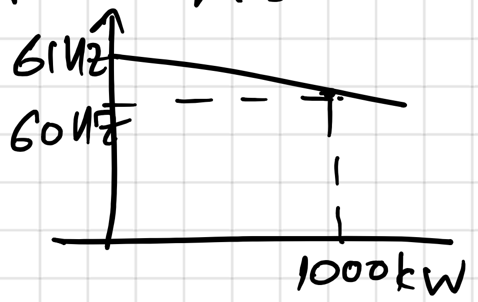
a) Before switch is closed what is op. freq of system

$$P_1 = S_p(f_{nl} - f_1)$$

$$1000 = 1000\,(61 - f_1)$$

$$\rightarrow 1 = 61 - f_1 \rightarrow f_1 = 60\,Hz$$

$S_p = 1\,MW/Hz = 1000\,kW/Hz$



b) after load 2 is connected what is op. freq of system.

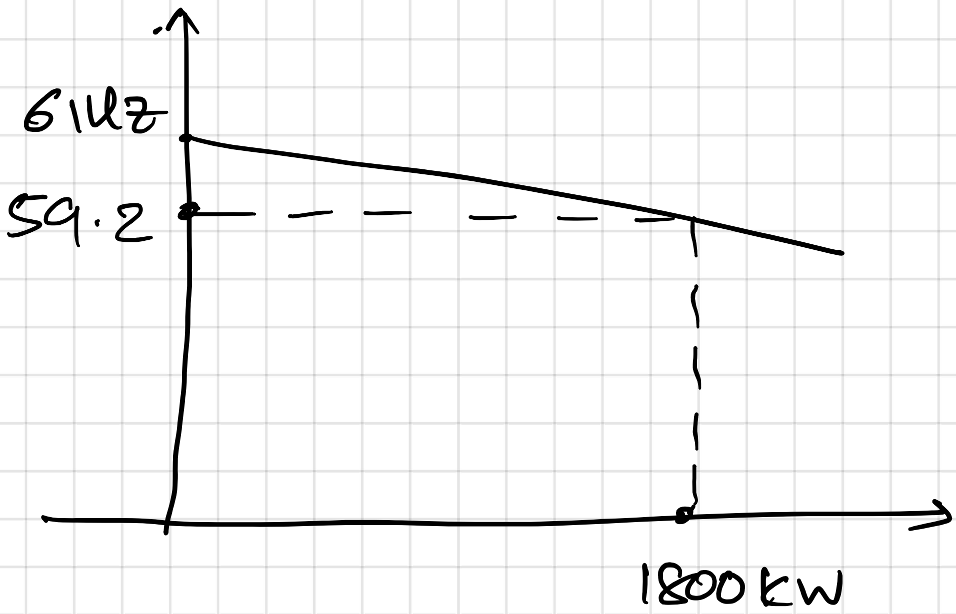
$$P = P_1 + P_2 = 1000 + 800 = 1800$$

$$1800 = S_p(f_{nl} - f)$$

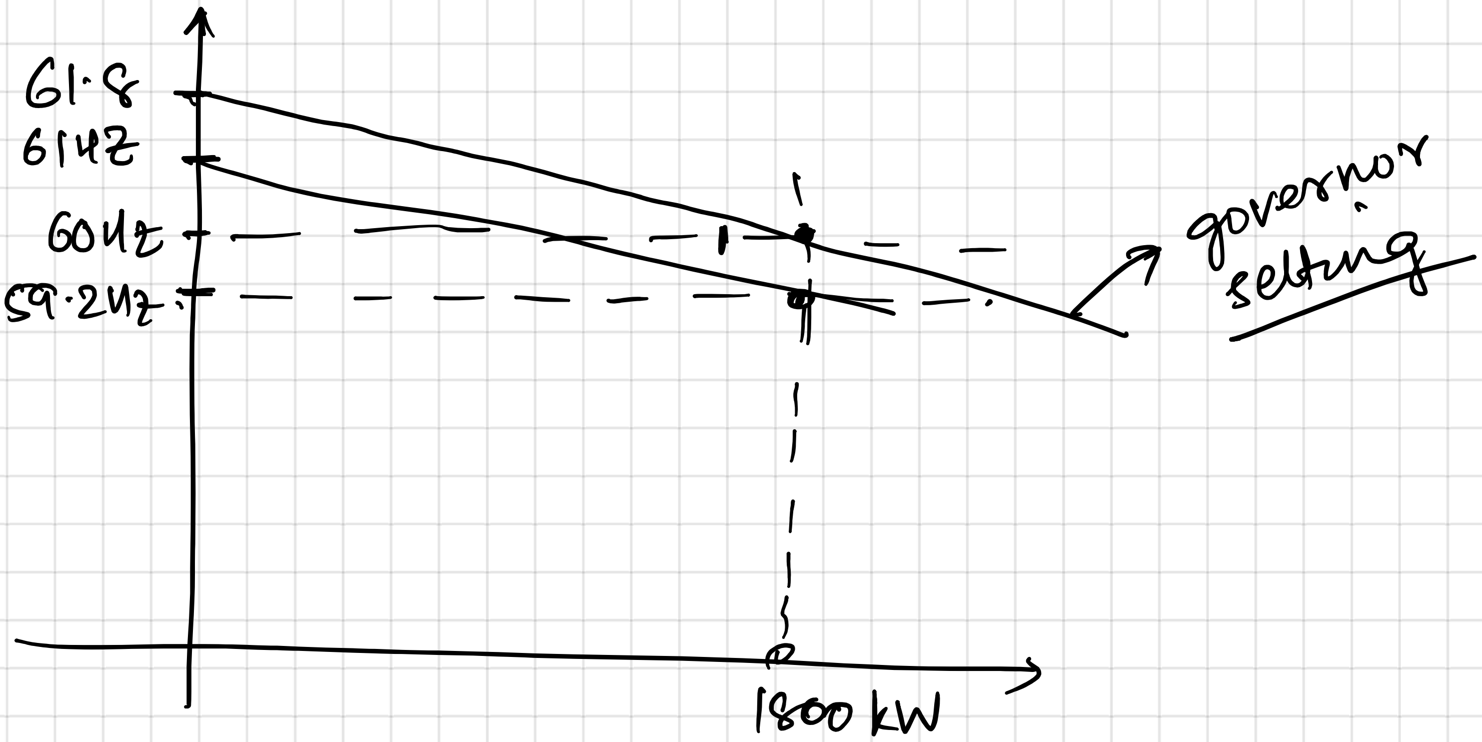
$$1800 = 1000\,(61 - f)$$

$$\rightarrow f = 61 - 1.8 = 59.2\,Hz$$

c) after load 2 is connected what action can operator take to make system operate @ 60Hz



→ 0.8 Hz has to be increased ⇒ the operator should adjust the governor so that the no load freq increases by 0.8 (ie) 61+0.8
= 61.8Hz



Operation of Generators in Parallel with Large Power Systems (Simple explanation)

→ infinite bus is so powerful that it imposes its own voltage and frequency upon any apparatus that is connected to its terminals

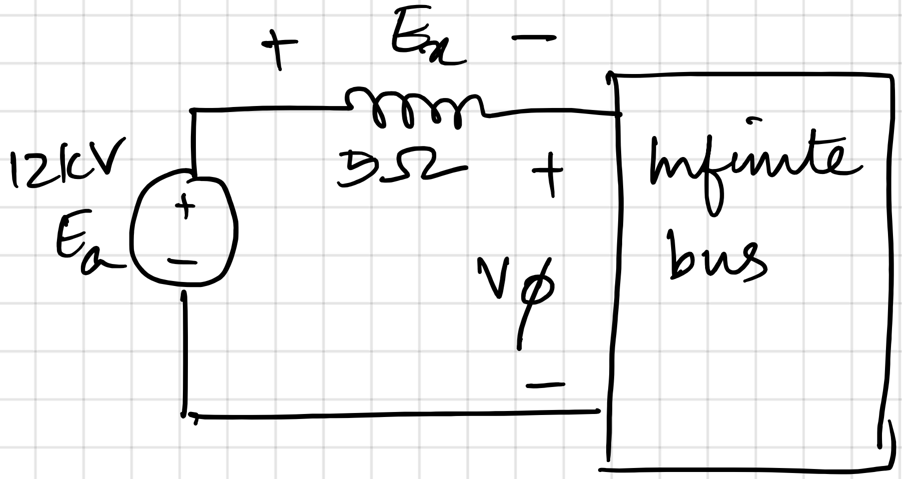
→ it is impossible to specify the nature of load (small/large or ind/capacitive) connected at generator terminals

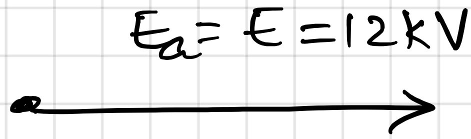
→ What determines how much power is delivered?

* Voltage and freq : constant
* variable :- 1. field excitation
  2. mechanical torque exerted by turbine

→ Effect of Variation of I_f

* just after synchronisation E_a is almost in phase with the terminal voltage V_ϕ
* $\Rightarrow E_x = jI_aX_s \simeq 0 \Rightarrow I_a = 0 \Rightarrow P = 0$
  * generator is said to be floating in the line



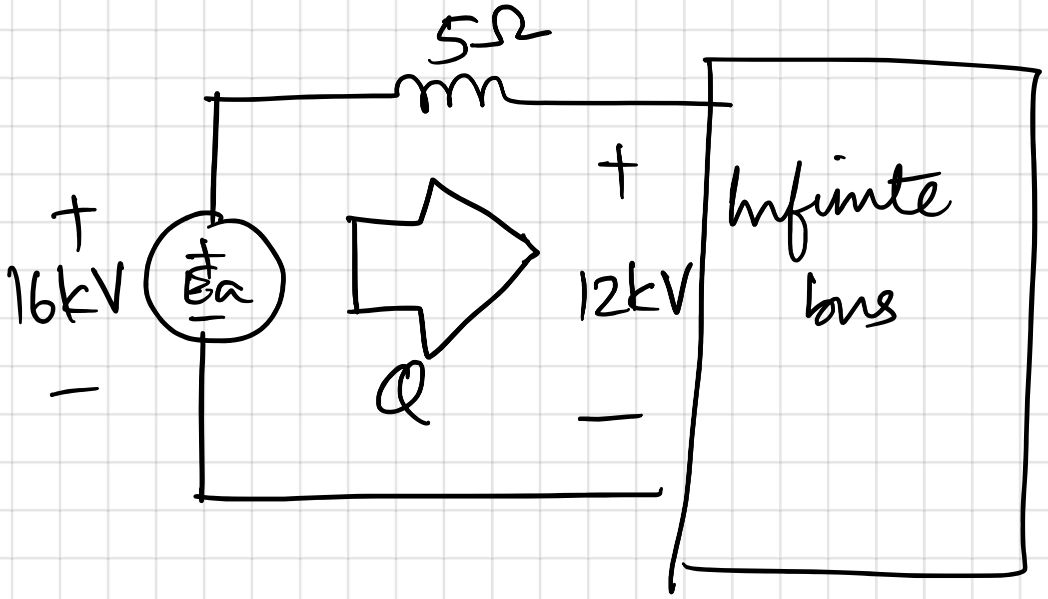


$P=0 \Rightarrow EV\cancel{X_s}\sin\delta=0 \Rightarrow \delta=0$

* If we increase I_f, voltage $E_a\uparrow = K\phi\uparrow\omega$

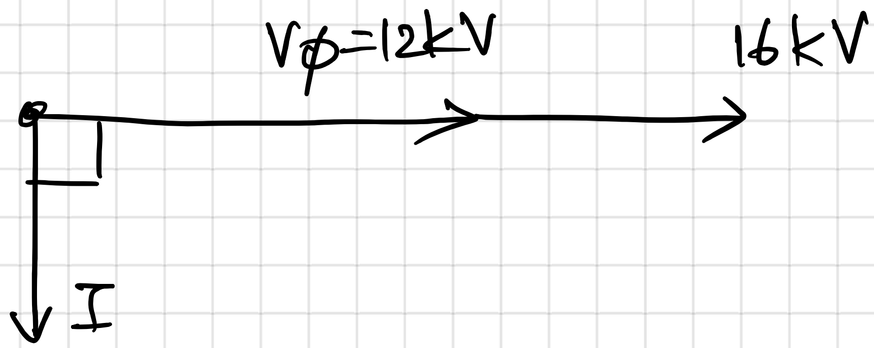
→ $E_x = E_a - V_\phi$ and $I_a = E_a - V_\phi / X_s$

and I_a lags E_x by 90°



$I_a = \frac{16kV - 12kV}{5\Omega}$

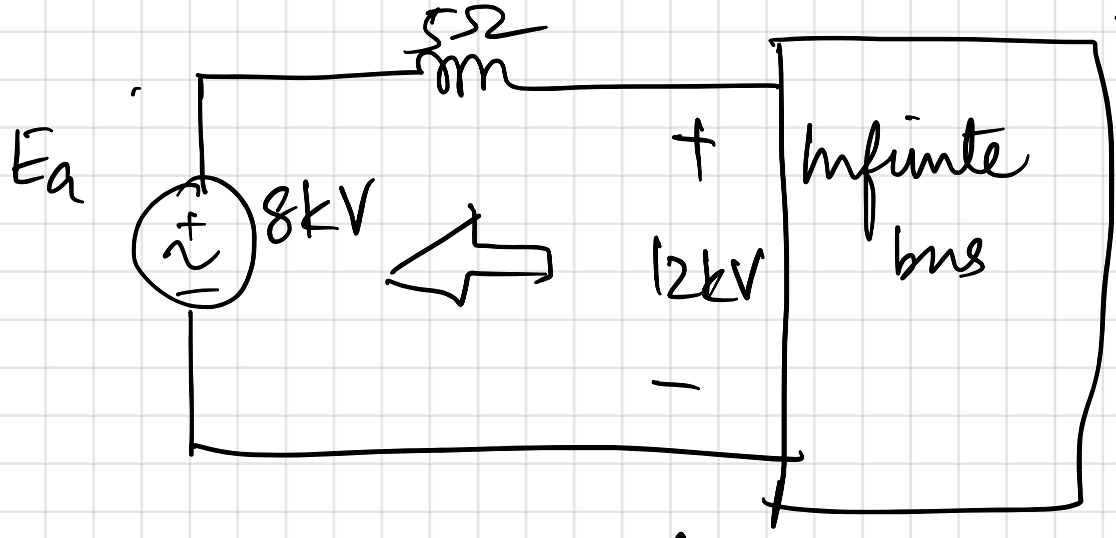
$I_a = 800A$

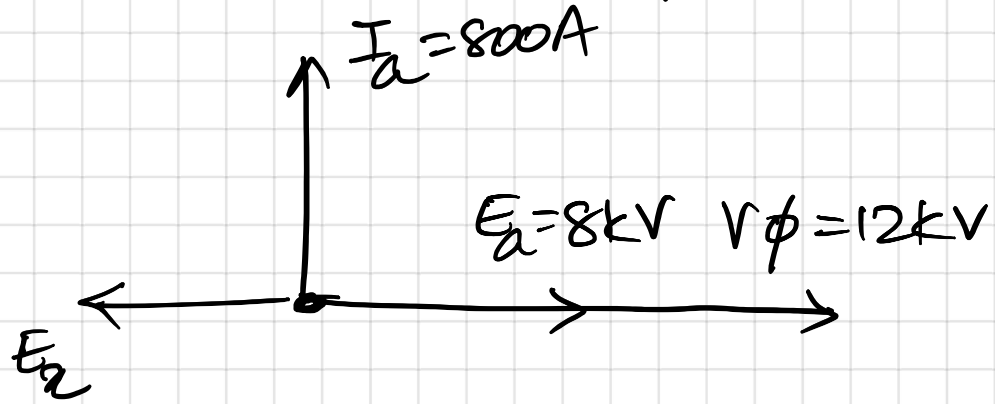


⇒ as far generator is concerned, the infinite bus looks like an inductive load and since an inductive load consumes reactive power, the generator supplies reactive power to the system

* If and bcz of the high reactive nature, the active power is very small.

* If we decrease excitation, $E_R = E_a - V$ is -ve and I_a lags E_R ⇒ the generator see, the infinite bus like a capacitor and so it takes in reactive power from the system.

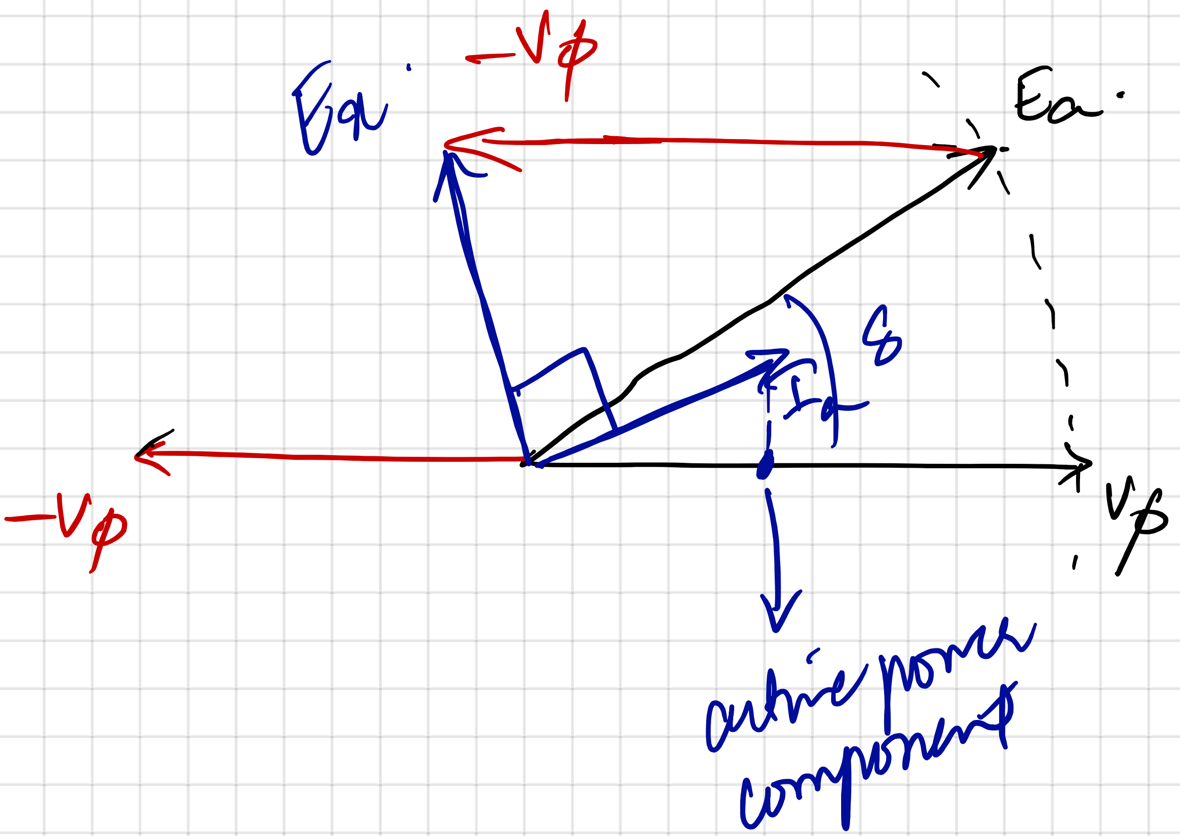




* as excitation increases reactive power supplied ↑
* as excitation decreases reactive power supplied ↓

Effect of Varying Mechanical Torque

* E_a and V_ϕ are in phase @ pt of synchronisa-tion
* If we open steam valve, rotor accelerates and E_a attains max. value faster than V_ϕ
  * $P_{in} = \tau_{app}\,\omega_m$ $\quad P_{in}\uparrow \; P_G\uparrow \Rightarrow \delta\uparrow$
* E_a and V_ϕ have same value but are now sep by an angle δ
* $\overline{E_R} = \overline{E_a} - \overline{V_\phi}$



Operation of Gen. in parallel with other gene of same size

Single Gen operated alone:

* real power (P) and reactive power (Q) supplied by Generator were fixed, constrained to be be equal to Power demanded by load

* freq varied by adj. governor setpoints.
* Terminal voltage varied by adj field current

Gen operated in parallel with Infinite bus

* freq and V_T constrained to be constant by infinite bus

* real power (P) → varied by adj governor set points

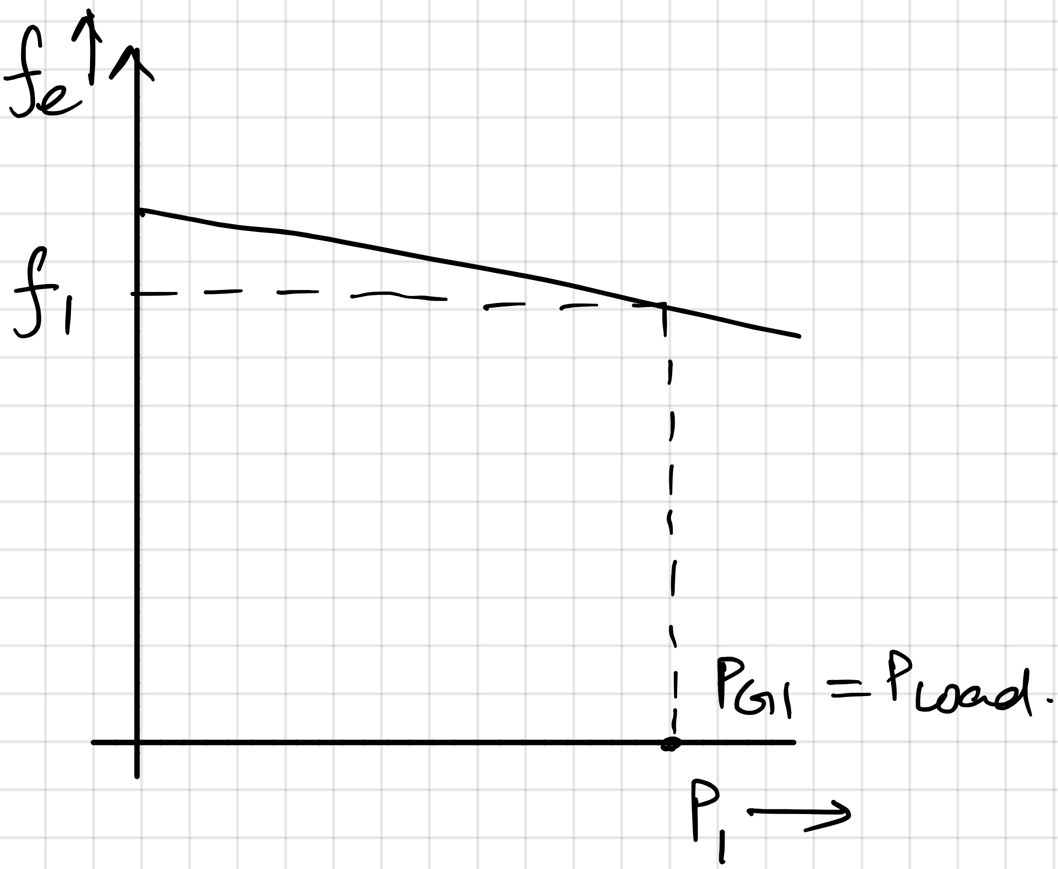
* reactive power (Q) → varied by adj excitation

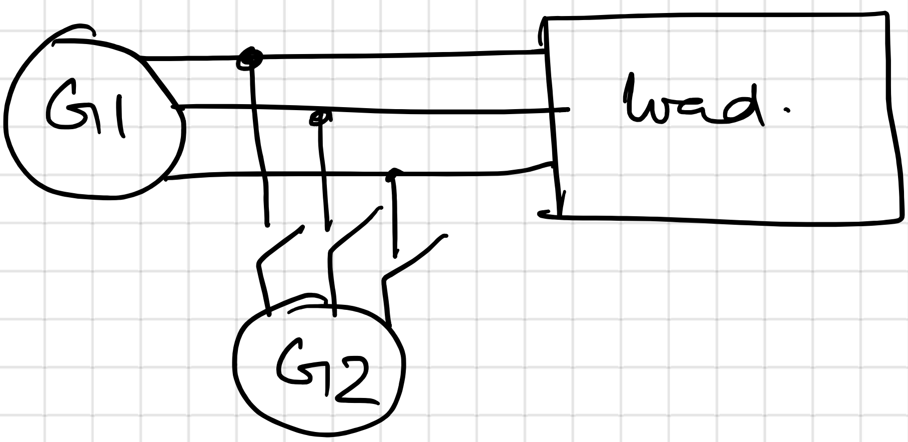
- What happens when a gen. is connected in parallel with another generator, similar to its rating?
- Effect of adj governor set points, excitation.

* constraint : The sum of real and reactive powers supplied by the 2 generators must equal to the P & Q demanded by load

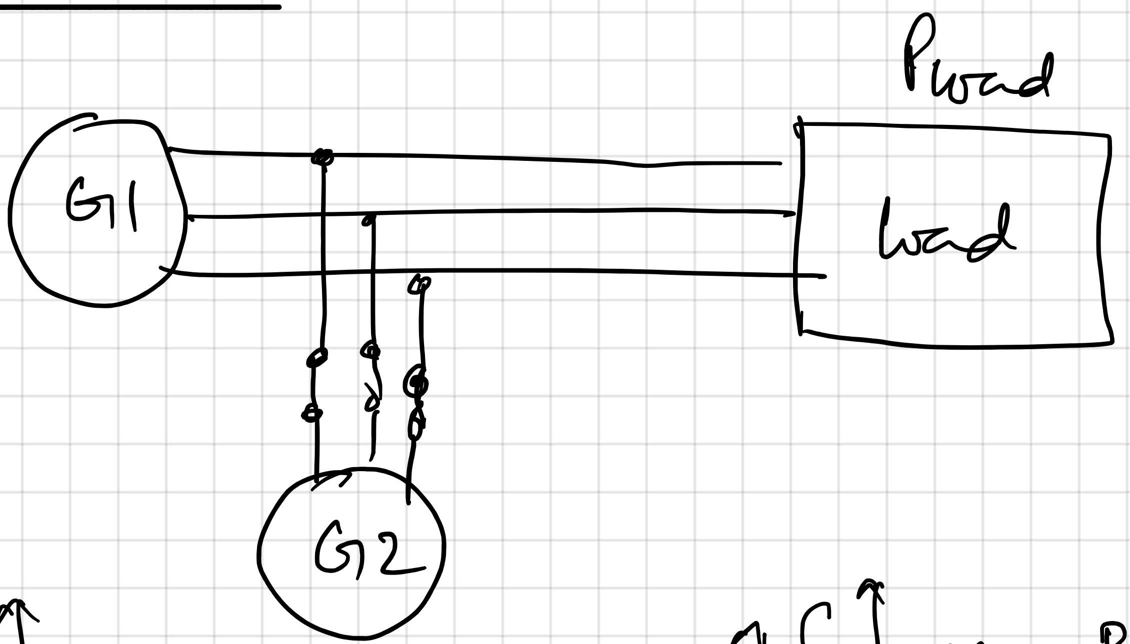
* freq and V_T are not constrained to be constant

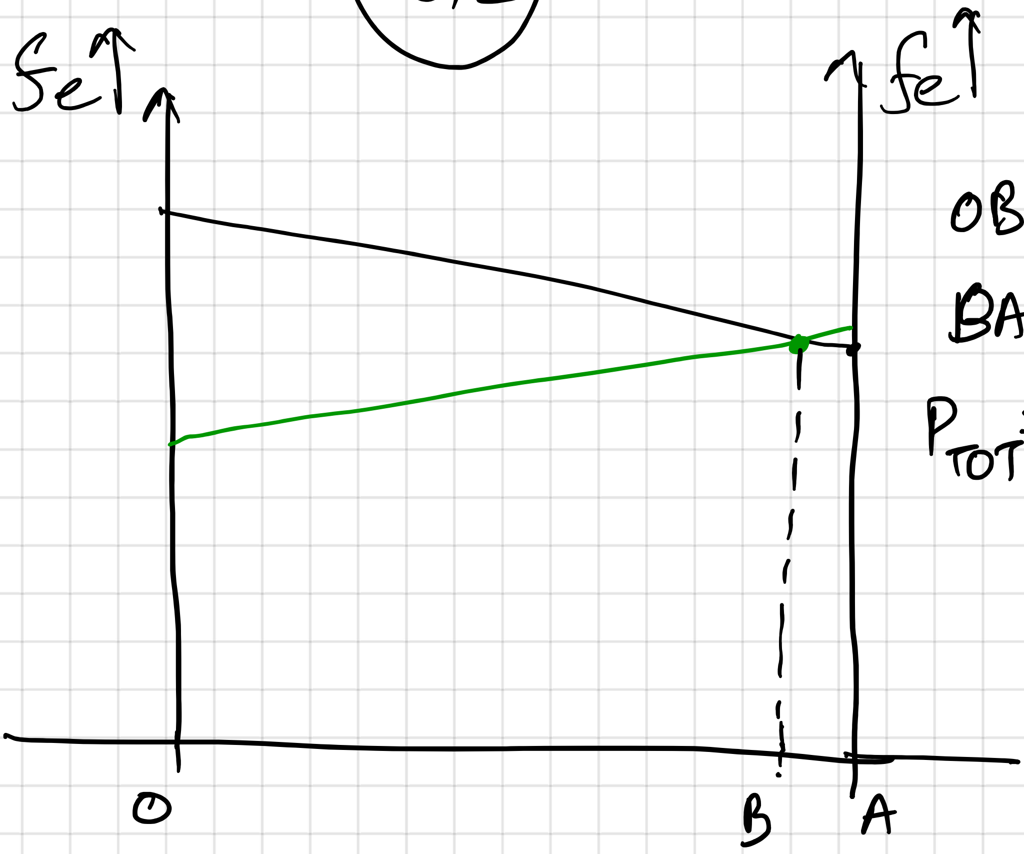
Generator op alone (house diagram)





Gen G_2 parallel with Gen G_1 in supplying the same load





$OA = P_{load}$

$OB = P_{G1}$

$BA = P_{G2}$

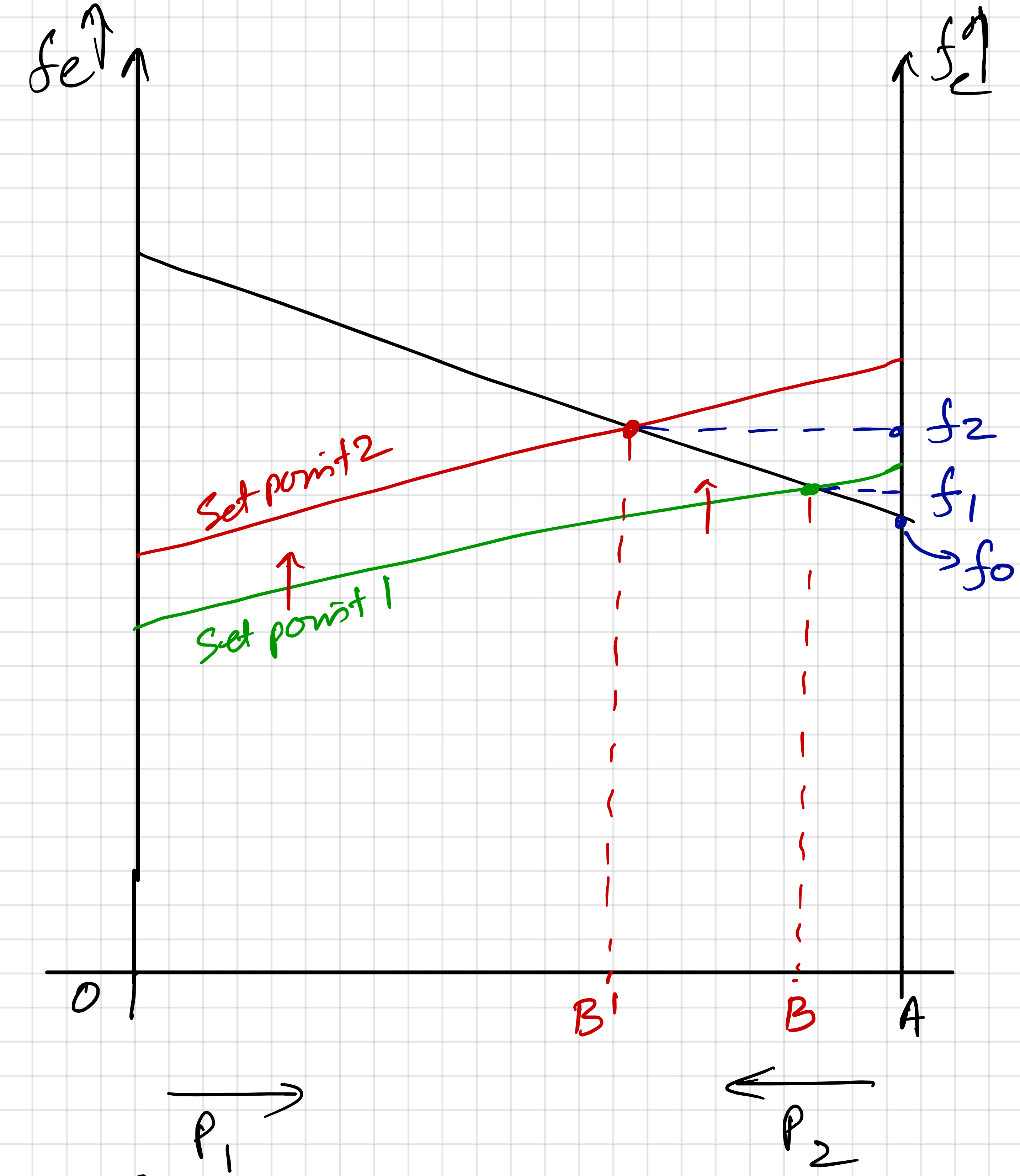
$P_{TOT} = P_{load} = P_{G1} + P_{G2}$

$P_{G1} \longrightarrow$

$\longleftarrow P_2$

(just after paralleling)

* when governor set points are increased for G_2



OA = Total load power

$OB = P_{G_1}$ @ set point 1 ; $BA : P_{G_2}$ @ set point 1

$OB' = P_{G_1}'$ @ set point 2 ; $B'A = P_{G_2}'$ @ set point 2

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

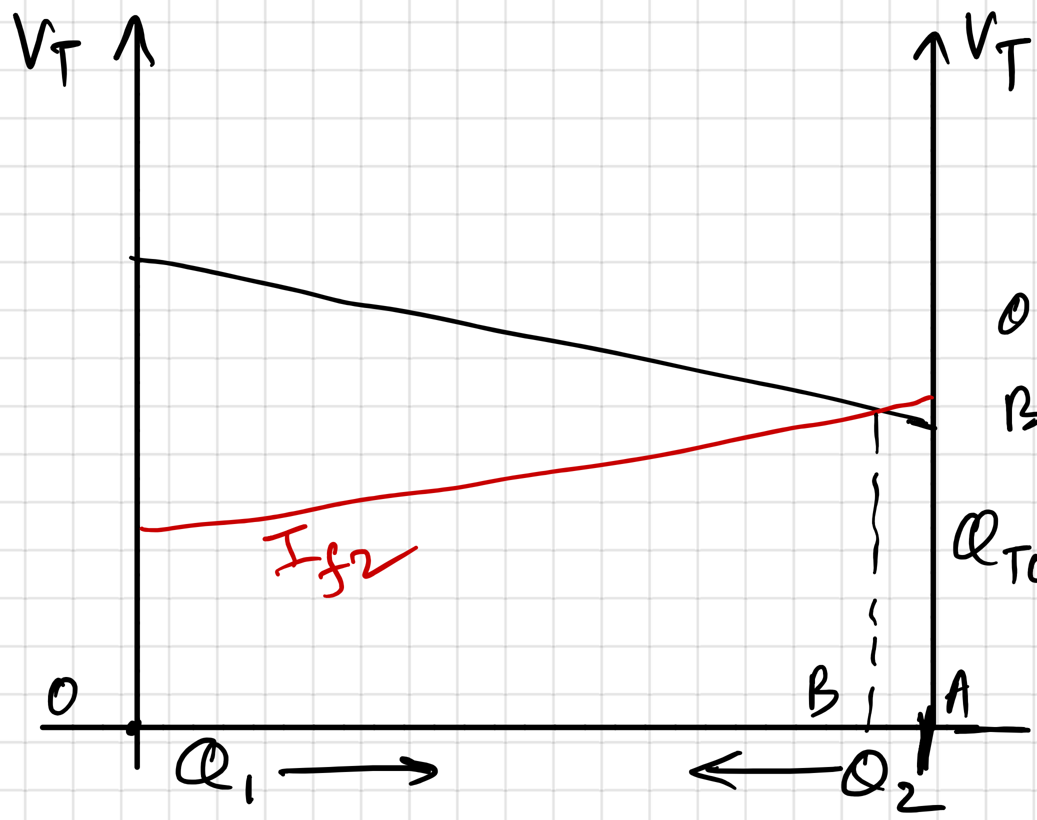
clearly $P_{G1}' < P_{G1}$ & $P_{G2}' > P_{G2}$

$$f_2 > f_1 > f_0$$

$\Rightarrow$ when 2 Gen are operating togeather, an increase in governor set points in one of them :

1) increases System freq
2) increases power supplied by that Gen, while reducing power supplied by other one.

* When excitation is increased for G_2

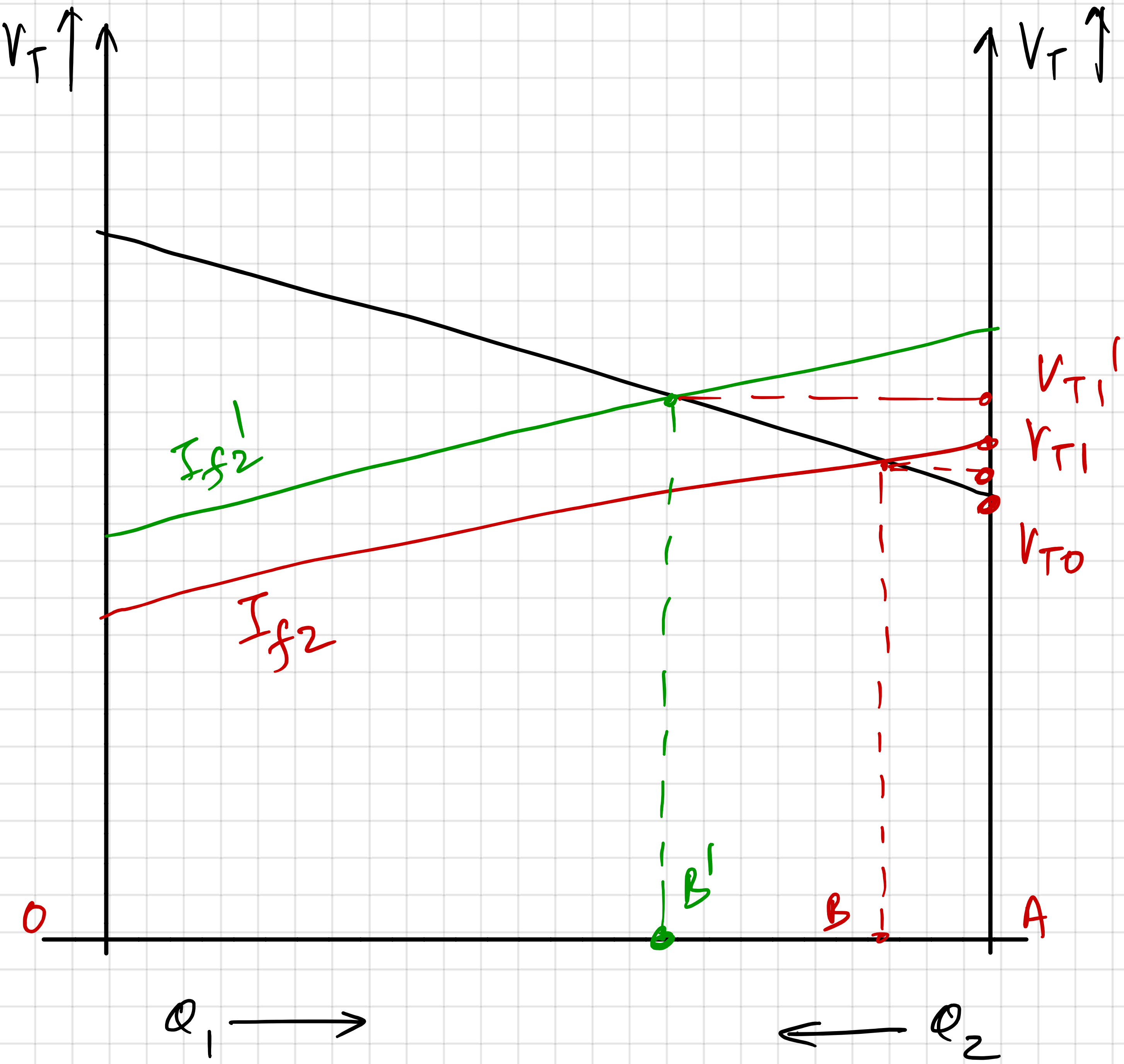


OA = KVAR dem of load

$OB = Q_{G1} @ I_{f2}$

$BA = Q_{G2} @ I_{f2}$

$Q_{TOTAL} = Q_{G1} + Q_{G2}$



$OA = Q_{LOAD} = Q_{TOTAL}$

$OB = Q_{G1}$ @ I_{f2} ; $BA = Q_{G2}$ @ I_{f2}

$OB' = Q_{G1}'$ @ I_{f2}' $B'A = Q_{G2}'$ @ I_{f2}

$Q_{TOTAL} = Q_{G1}' + Q_{G2}'$

$Q_{G1}' < Q_{G1}$ & $Q_{G2}' > Q_{G2}$

$V_{T1}' > V_{T1} > V_{T0}$

⇒ When 2 Generators are operating together and field current G_2 is increased:

1. System terminal voltage is increased
2. Reactive power Q supplied by that Gen is increased, while reactive power supplied by other Gen is decreased

Num : Gen G_1 and Gen G_2 supply a load.

$G_1 \rightarrow$ no load freq : 61.5 Hz and $S_{p1} = 1 MW/Hz$

$G_2 \rightarrow$ " " " : 61.0 Hz and $S_{p2} = 1 MW/Hz$

both gen supply a real power = 2.5 MW @ 0.8 pf lag

a) find freq of the system and power supplied by each gen.

$$P_1 = S_{p1}(f_{nl_1} - f_{sys}) \;\&\; P_2 = S_{p2}(f_{nl_2} - f_{sys})$$

$$P_{load} = P_1 + P_2 = 2.5 MW$$

$$\rightarrow 2.5 = P_1 + P_2 = S_{p1}(61.5 - f_{sys}) + S_{p2}(60 - f_{sys})$$

$$2.5 = 1(61.5 - f_{sys}) + 1(60 - f_{sys})$$

$$\rightarrow f_{sys} = \frac{122.5 - 2.5}{2} = 60 Hz$$

and $P_1 = S_{p1}(f_{nl_1} - f_{sys}) = 1(61.5 - 60)$

$= 1.5 MW$

$$P_2 = 2.5 - P_1 = S_{p2}(f_{nl_2} - f_{sys})$$

$= 2.5 - 1.5$

$= 1 MW$

$1(60 - 60)$

$1 MW$

b) load is increased by 1 MW, The new freq = ?

$P_{load} = 2.5 + 1 = 3.5 \text{ MW}$

$\rightarrow 3.5 = 1(f_{nl,1} - f_{sys}) + 1(f_{nl,2} - f_{sys})$

$3.5 = 1(61.5 - f_{sys}) + 1(61 - f_{sys})$

$\rightarrow f_{sys} = \dfrac{122.5 - 3.5}{2} = 59.5 \text{ Hz}$

$P_1 = S_{P1}(f_{nl,1} - f_{sys}) = 1(61.5 - 59.5) = 2 \text{ MW}$

$P_2 = P_L - P_1 = 3.5 - 2 = 1.5 \text{ MW}$

$P_2 = S_{P2}(f_{nl,2} - f_{sys}) = 1(61.0 - 59.5) = 1.5 \text{ MW}$

c) If no load governor setpoints of G_2 is increased by 0.5 Hz, the new system freq = ?

$\Rightarrow f_{nl,2} = 61 + 0.5 = 61.5 \text{ Hz}$

$P_{load} = P_1 + P_2 = S_{P1}(f_{nl,1} - f_{sys}) + S_{P2}(f_{nl,2} - f_{sys})$

$3.5 = 1(61.5 - f_{sys}) + 1(61.5 - f_{sys})$

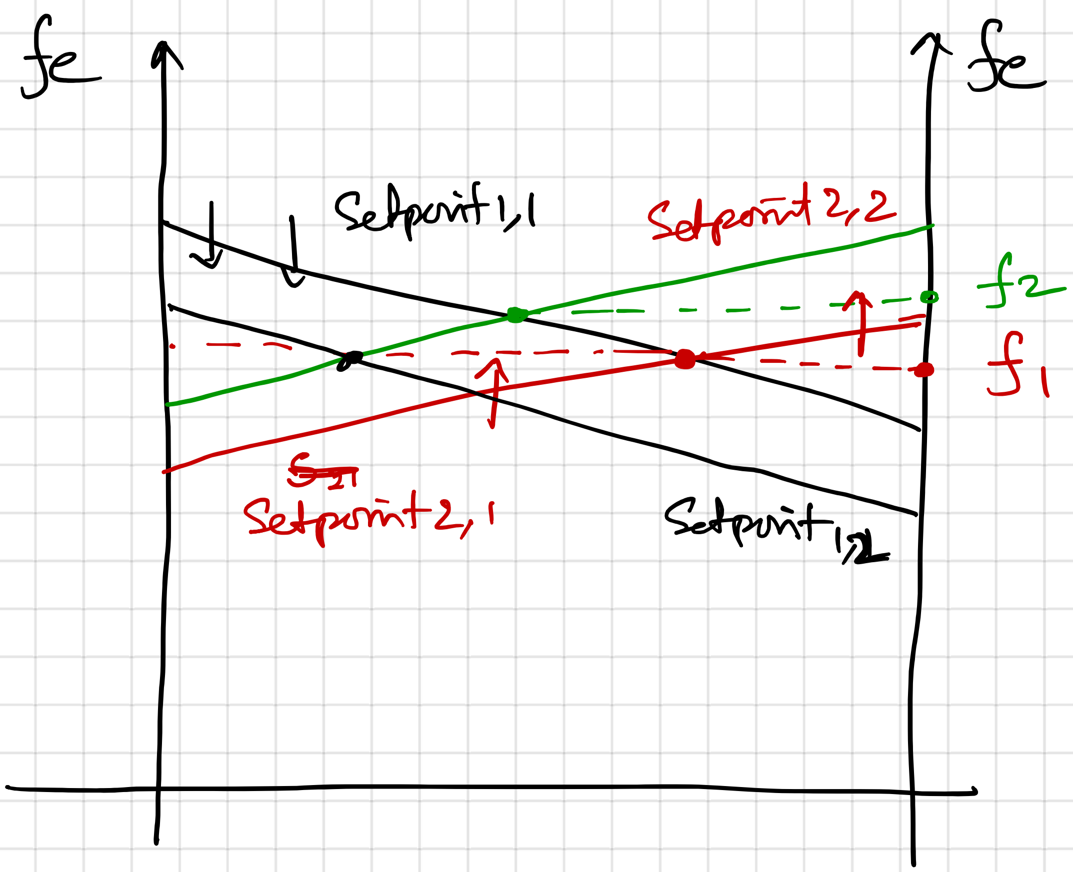
$\rightarrow f_{sys} = \dfrac{123 - 3.5}{2} = 59.75 \text{ Hz}.$

$P_1 = S_{P1}(f_{nl,1} - f_{sys}) = 1(61.5 - 59.75) = 1.75 \text{ MW}$

$P_2 = 3.5 - 1.75 = 3.75 \text{ MW}$

POWER SHARING ADJUSTED INDEPENDENT OF SYSTEM FREQUENCY

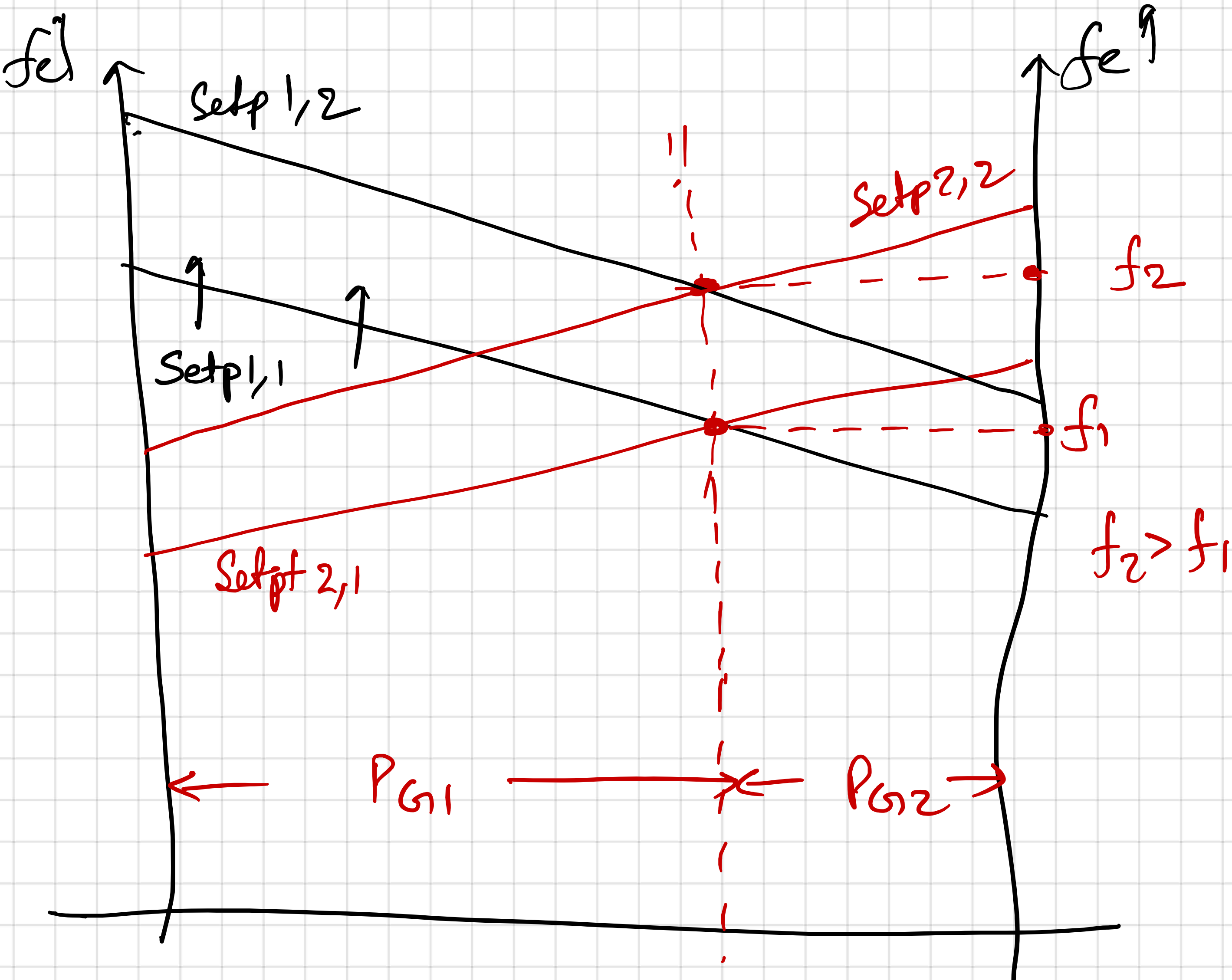
* Increasing governor setpoints in one generator increases machine's power and system freq.
* decreasing governor setpoints in other gen. decreases the machines power and system frequency
* ⇒ To adjust power sharing without changing frequency increase governor setpoints on one gen and simultaneously decrease governor setpoints on other generator



$f_2 > f_1$

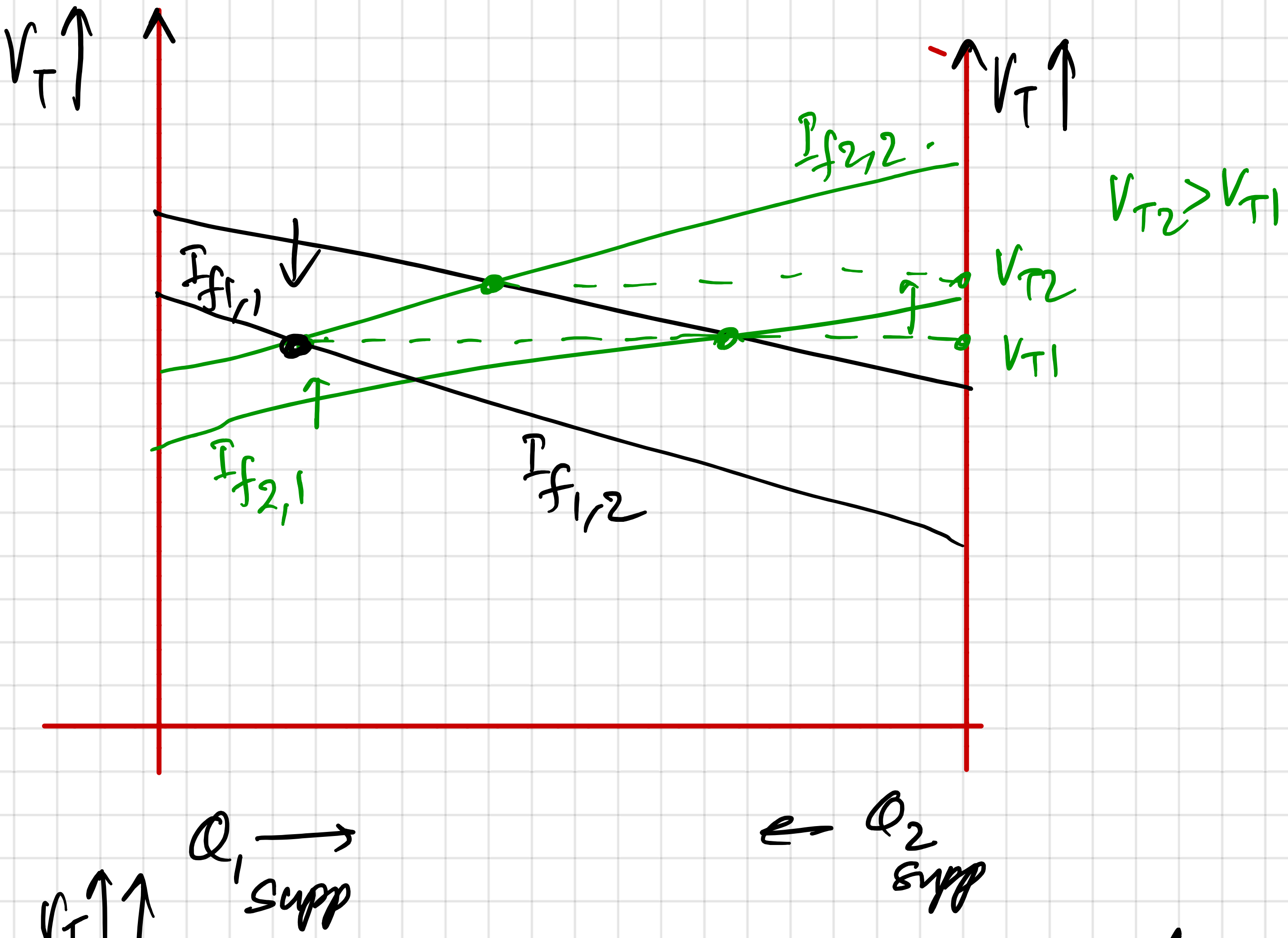
ADJUSTING FREQ WITHOUT CHANGING POWER SHARING

* Simultaneously increase or decrease the governor set-points of both generators.

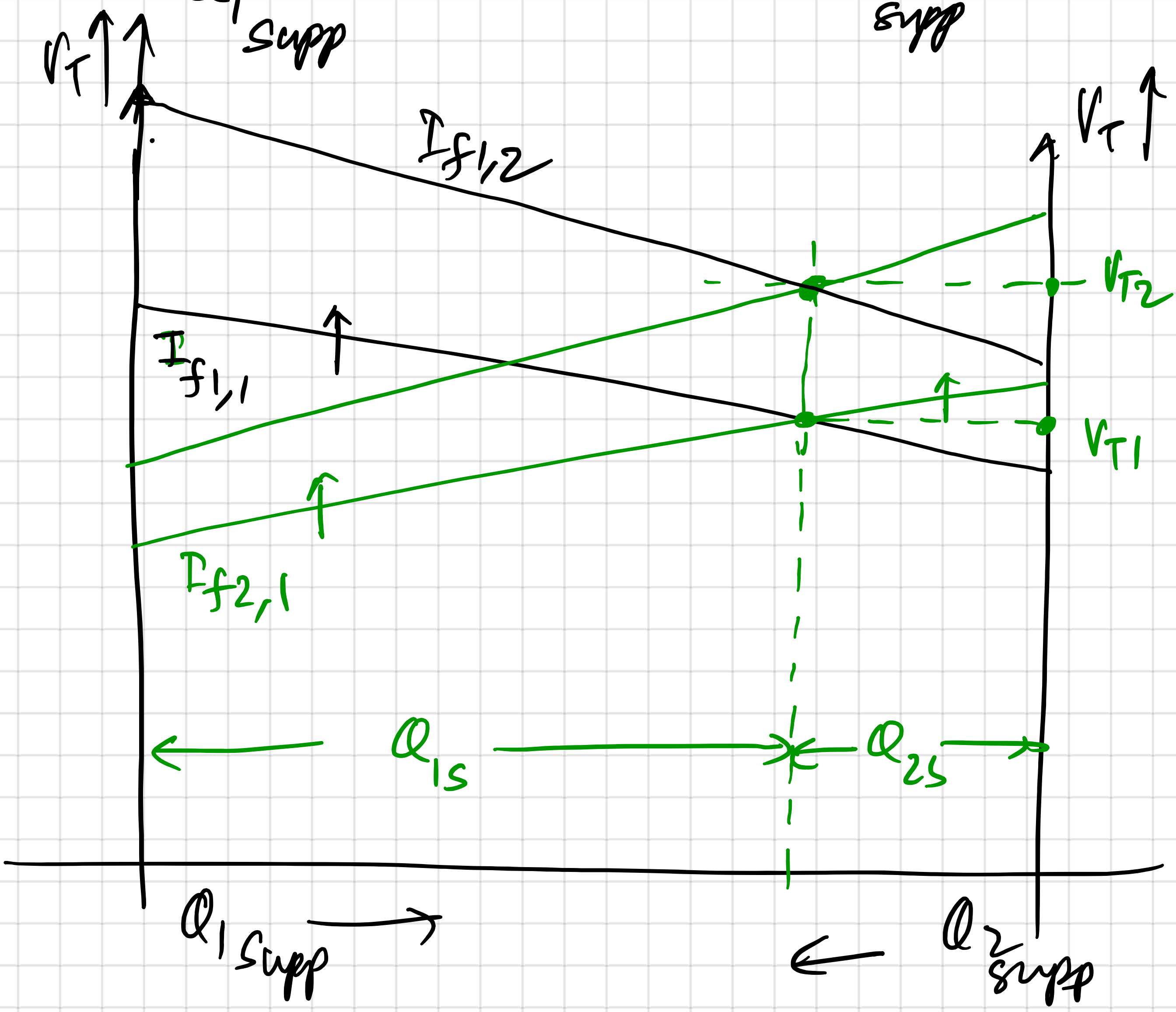


Reactive Power : To adjust reactive power sharing indep of ~~freq~~ V_T, increase I_f in one gen and decrease I_f in other

To adjust V_T, with same power sharing increase or decrease I_f ~~with~~ simultaneously on both Gen



V_T
V_T
$I_{f2,2}$
$V_{T2} > V_{T1}$
$I_{f1,1}$
V_{T2}
V_{T1}
$I_{f2,1}$
$I_{f1,2}$
$Q_{1\,supp}$
$Q_{2\,supp}$



V_T
V_T
$I_{f1,2}$
V_{T2}
$I_{f1,1}$
V_{T1}
$I_{f2,1}$
Q_{1S}
Q_{2S}
$Q_{1\,supp}$
$Q_{2\,supp}$

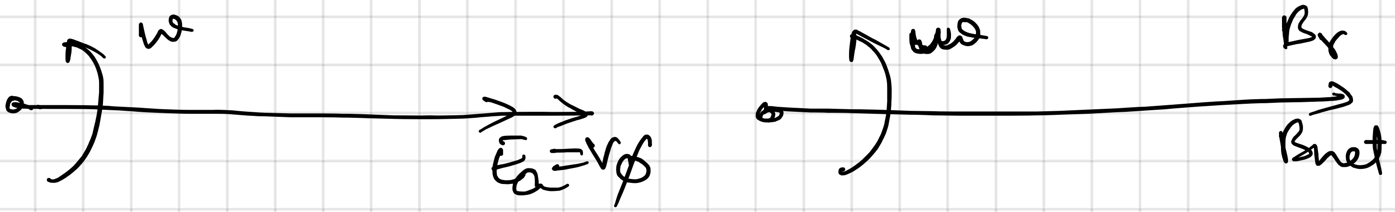
Synchronous Generator Transients

→ When shaft torque / output load on a generator changes suddenly there is a transient lasting for sometime before the generator comes back to its steady state

→ ex: when a generator will paralleled with an infinite bus, it runs faster because of its higher gen. freq, however steadies down to a lower speed to match the system freq

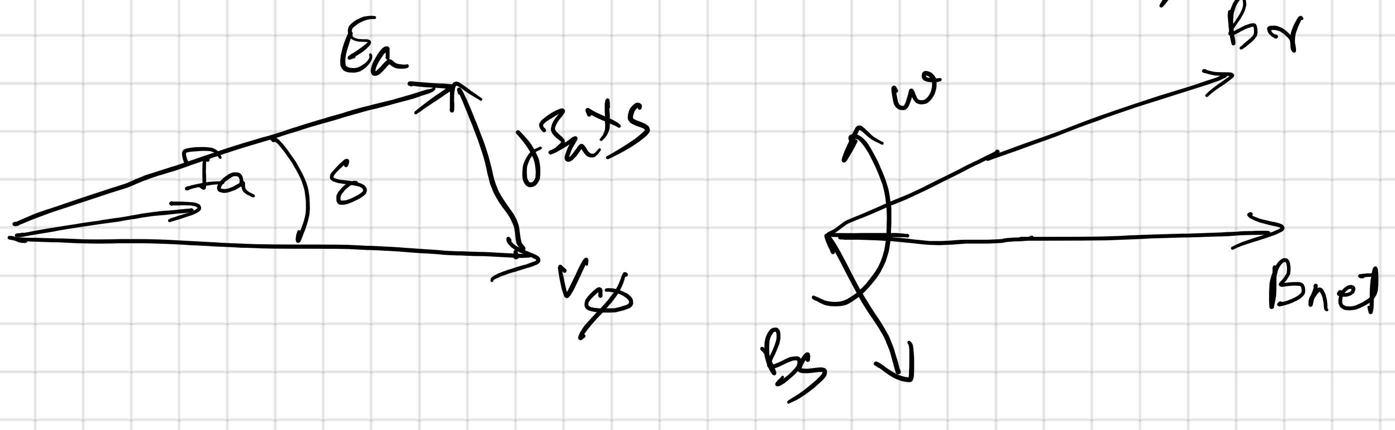
@ t → just before paralleling,

→ Gen is at no load and $E_a = V_\phi \Rightarrow B_r = B_{net}$

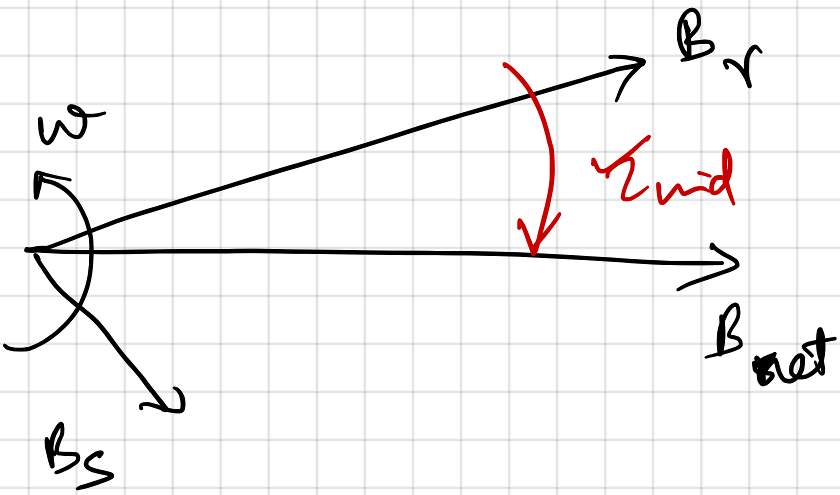


@ t=0, when paralleling switch has been closed,

* stator currents start to flow
* gen's rotor is turning faster than system speed, so E_a starts to lead V_ϕ



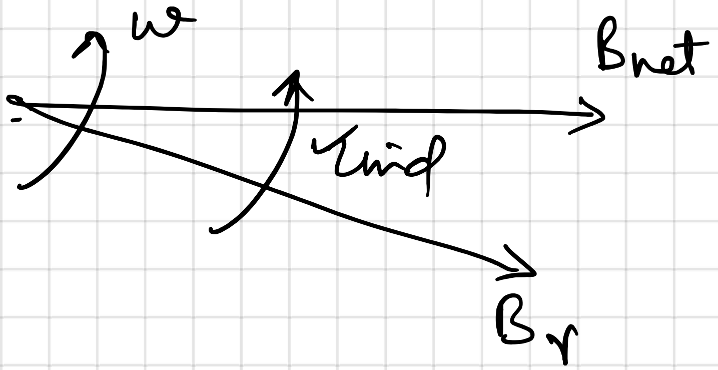
$\tau_{ind} = k B_r \times B_{net}$ dir of τ_{ind} = dir $B_r \times B_{net}$



* τ_{ind} opposes the direction of motion and increases with increase in phase angle b/w B_r & B_{net} or E_a and V_ϕ

* This opp. torque slows down the generator and it finally returns at synchronous speed with the rest of the power system.

* If gen is running @ a lower speed. E_a would lag V_ϕ and B_r would lag B_{net}



* τ_{ind} in the case aids direction of rotation and speed builds up till it reaches the sync. speed

Transient Stability

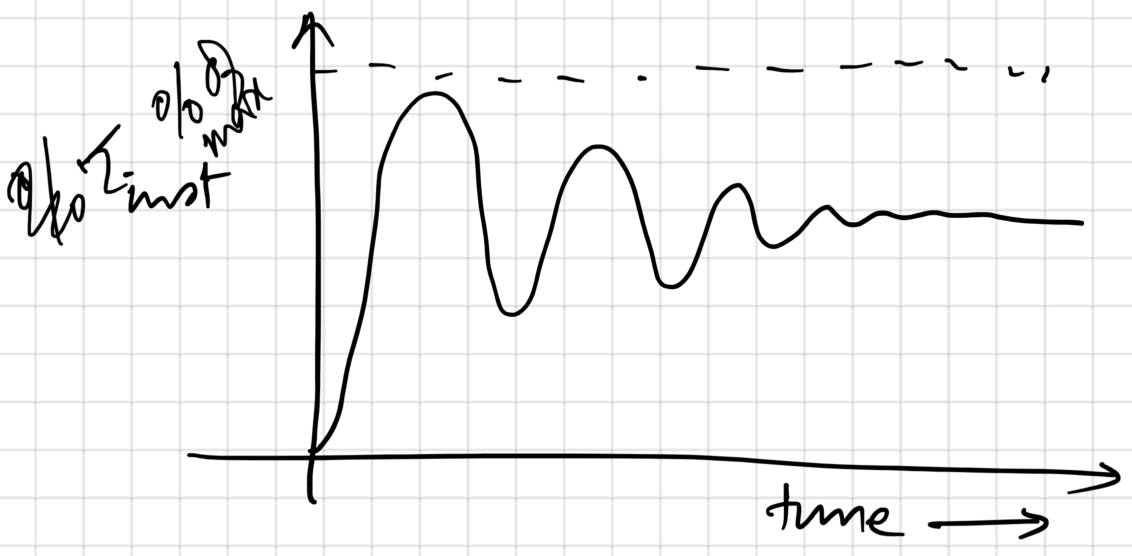
static stability limit = Max power that can be supplied by a Generator

$$P_{max} = \frac{3 E_a V_\phi}{X_s}$$

$$\tau_{ind \, @ \, max P} = \frac{3 E_a V_\phi}{\omega X_s}$$

→ however max load that can be supplied is limited by "Dynamic Stability limit".

→ If the τ_{app} is suddenly increased $\tau_{ind} \uparrow$ and increases till $\tau_{ind} = \tau_{app}$, but the rotor has inertia due to which it can overshoot and this decay via a "damped oscillation."



and any point if this instantaneous torque τ_{mot} becomes greater than τ_{max}, the generator can become unstable

* Size of oscillation depends on how suddenly the additional torque is applied

⇒ * If the torque is added gradually then we can make the m/c reach its stability limit (static)

* If suddenly added, the gen may be only stable @ a much lower limit

* for abrupt changes, the dynamic stability can be half of that of static stability limit.

SYNCHRONOUS GENERATOR RATINGS

Rating: Basic limits to speed and power from a synchronous generator

* purpose is to protect the generator from improper operation.

Typical ratings:- voltage, frequency, speed, apparent power (KVA), power factor, field current & service factor.

1. **Frequency**:- depends on the power system to which the generator is connected.

   * Commonly used: 50 Hz (Europe, asia), 60 Hz (U.S), 400 Hz (spl. control applications)

   * relation between freq and speed:- $f_e = \frac{n_m P}{120}$
     * If freq is fixed, for a given set of poles there is only one speed of rotation possible

2. **Voltage**:- $E_a = K\phi\omega \Rightarrow$ voltage depend on: 1. ϕ
   2. ω
   3. Construction of m/c

Limits to voltage: 1) for given speed and frame

$E_a \propto \omega \Rightarrow$ as $\phi \uparrow$ $E_a \uparrow$, but there is a limit to increase in flux which is set by the rotor field winding and so I_f is limited and so ϕ is limited and so E_a (voltage is also limited)

* breakdown value of insulation of winding
  → normal operating voltage should not approach breakdown ~~to~~ very easily.

* Operating a generator rated @ one frequency with another freq

→ 60Hz Gen to be operated in 50Hz

now $E_a = K\phi\omega$ ϕ is limited by a max value

$$\rightarrow \quad \frac{E_a}{\omega} = \text{constant} = \phi_m \qquad \frac{E_a}{\omega} \propto \frac{E_a}{f}$$

$$\rightarrow \quad \frac{E_{a1}}{f_1} = \frac{E_{a2}}{f_2} \Rightarrow E_{a2} = \frac{f_2}{f_1}(E_{a1})$$

$$= \frac{50}{60} E_{a1}$$

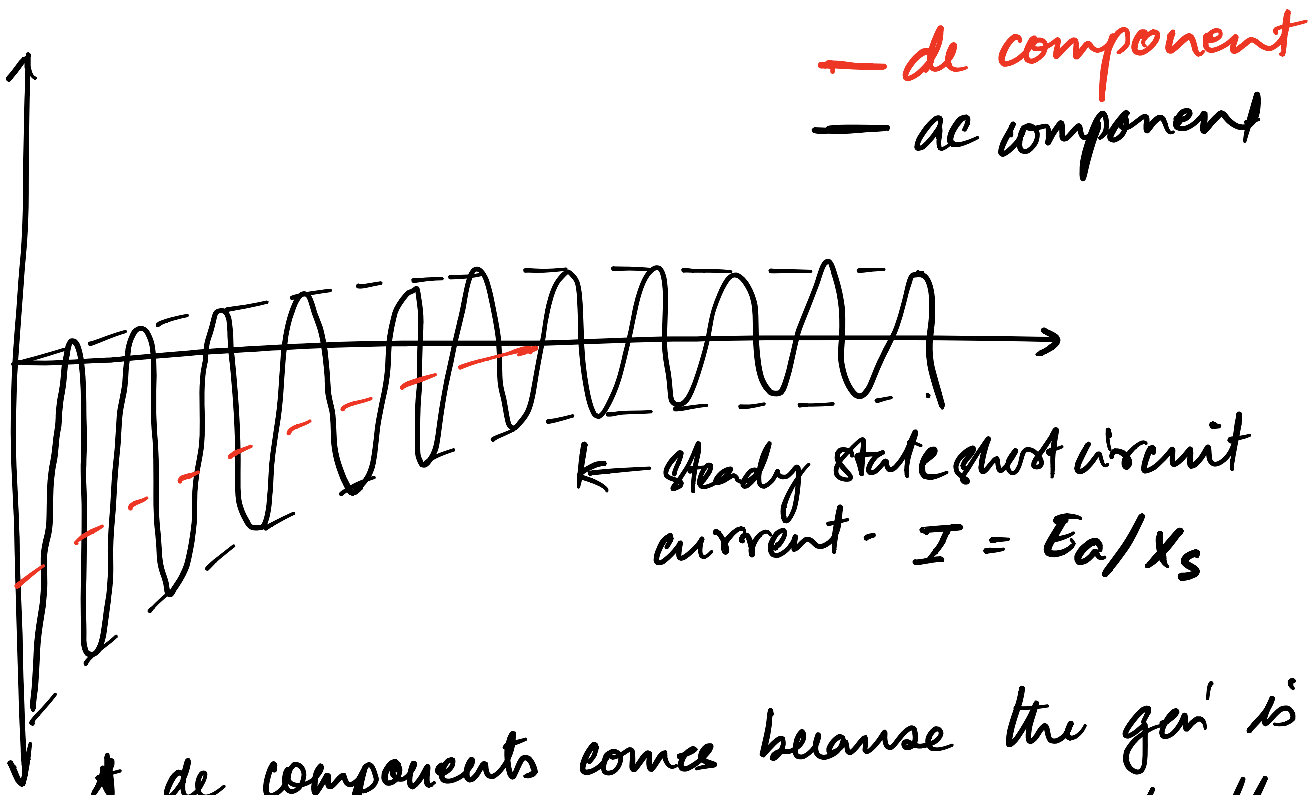
to operate the generator @ lower frequency the voltage should be derated by a factor of (50/60) and vice versa for a 50Hz gen to be operated @ 60Hz

Short Circuit Transients

* most severe condition on a Gen → shorting out three terminals

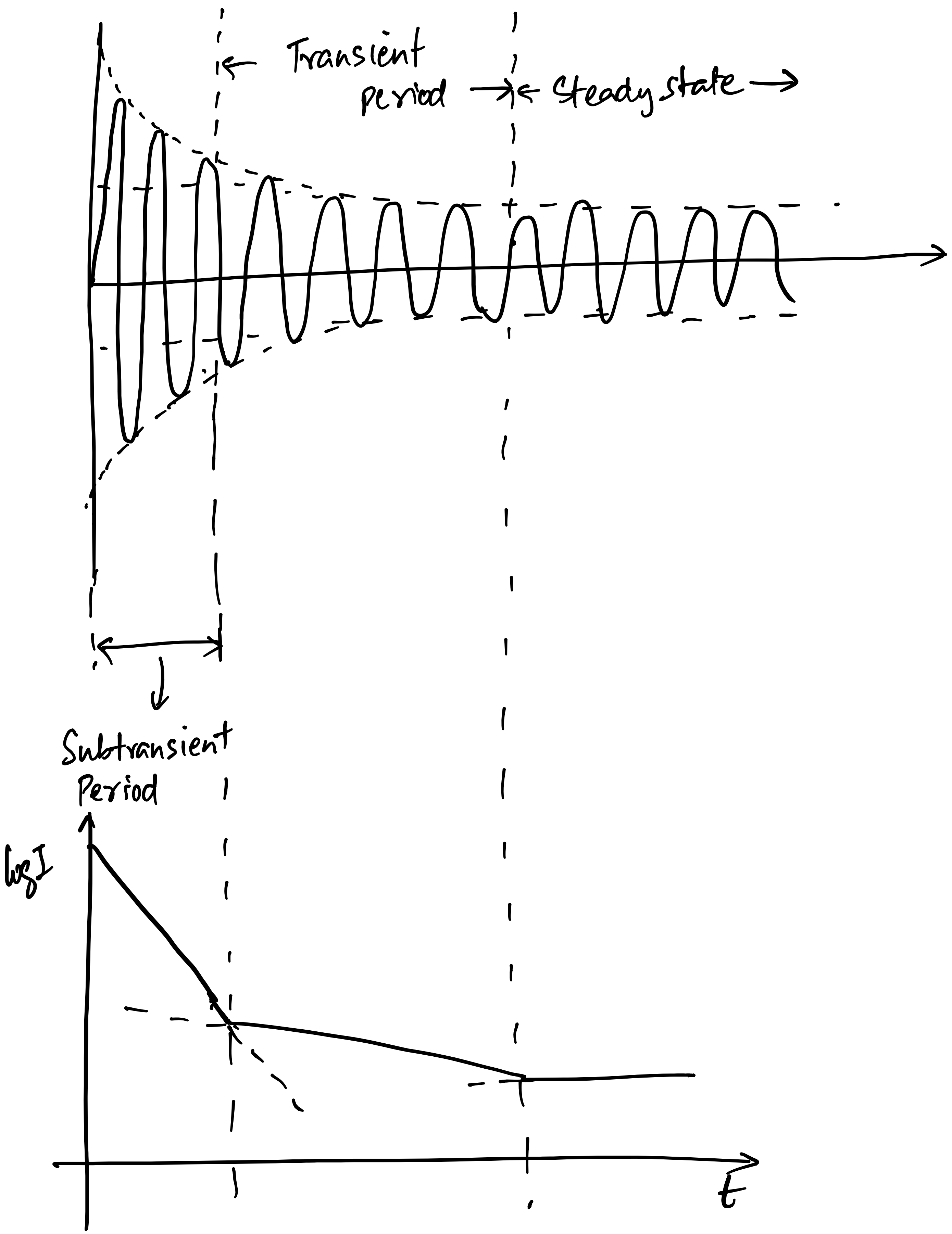
* this condition is called a "fault".

* Current flowing for one phase



* dc components comes because the gen is like an inductor and current before fault = current after fault and so the sum of ac and dc components maintains that relation.

AC symmetrical component



- Sub-Transient Current (I'') : * Due to Damper windings
  * ~~high~~ low time constant.
  * value $\simeq$ 10 times of steady state fault current

- Transient Current (I') : * caused by a DC component of current induced in the field windings
  * high time constant
  * value is $\simeq$ 5 times steady state fault current.

- Steady state fault current : $I_{ss} = \frac{E_a}{X_s} = \frac{\text{fundamental Comp of } E_a}{X_s}$

$$\Rightarrow I(t) = I'' + I' + I_{ss}$$
$$= (I'' - I')e^{-t/T''} + (I' - I_{ss})e^{-t/T'} + I_{ss}$$

and $X'' = \frac{E_a}{I''}$ (Sub transient reactance)

$X' = \frac{E_a}{I_a'}$ = (Transient reactance)

Q) 100 MVA, 13.5 kV, Y connected, 3ϕ 60 Hz Syn. Gen. operated @ rated voltage and no load when a 3ϕ fault occurs.

$X_s = 1.0$, $X' = 0.25$, $X'' = 0.12$.

$T' = 1.10$ $T'' = 0.04s$

→ Initial dc component averages 50% of initial ac component.

a) What is ac component of the current right after fault.

$$\rightarrow I_{L\,base} = \frac{S_{base}}{\sqrt{3}\,V_{L\,base}} = \frac{100\text{ MVA}}{\sqrt{3} \times 13.8\text{ kV}} \cong \cancel{4184A}\ 4277A$$

$$I''_{pu} = \frac{E_a}{X''} = \frac{1.0}{0.12} = 8.33 \Rightarrow I'' = 8.33 \times 4184 = 35627.4A$$

$$I'_{pu} = \frac{E_a}{X'} = \frac{1.0}{0.25} = 4.0 \Rightarrow I' = 4.0 \times 4184 = 17108A$$

$$I_{ss} = \frac{E_a}{X_S} = \frac{1.0}{1.0} = 1\,pu \rightarrow I_{ss} = 4277A$$

⇒ Initial ac component = 35627.4A

b) total current @ beginning of fault.

$$I_{total} = I'' + \underset{(dc)}{0.5I''} = 1.5I'' = 1.5 \times 35627.4A$$

$$= 53441.1\,A$$

c) ~~a~~ ac component after 2 cycles and 5sec

$$I(t) = (I'' - I')e^{-t/0.04} + (I' - I)e^{-t/1.1} + 4184$$

$$2\text{ cycles} = t = 2 \times \frac{1}{60} = \frac{1}{30}$$

$$I(t) = 18116\,e^{-t/0.04} + 12552\,e^{-t/1.1} + 4184$$

$I(1/30) =$

Literary rate

67% (Bad.)

Alex John

Factors that determine the power limits of a machine :

* Mechanical Torque on shaft
* Heating of the machine's windings

* Usually the machines shaft are strong to handle steady state torques much higher than ~~the~~ what the machine is rated for.
* So practical limits are usually set by the heating in the windings of the machine

Windings → Armature w/g's, Field w/g's } both have to be protected from overheating

now, Apparent Power, $S = 3V_\phi I_a$

⇒ the maximum allowable armature current $I_{a_{max}}$, sets the maximum apparent power rating of the gen.

(i.e) $$\boxed{\begin{aligned} S_{max} &= 3 V_\phi I_{a_{max}} \\ &= \sqrt{3} V_L I_{L\,max} \end{aligned}}$$ [V_ϕ : rated voltage of m/c]

Heating effect of stator Cu loss, $P_{SCL} = 3 I_a^2 R_a$

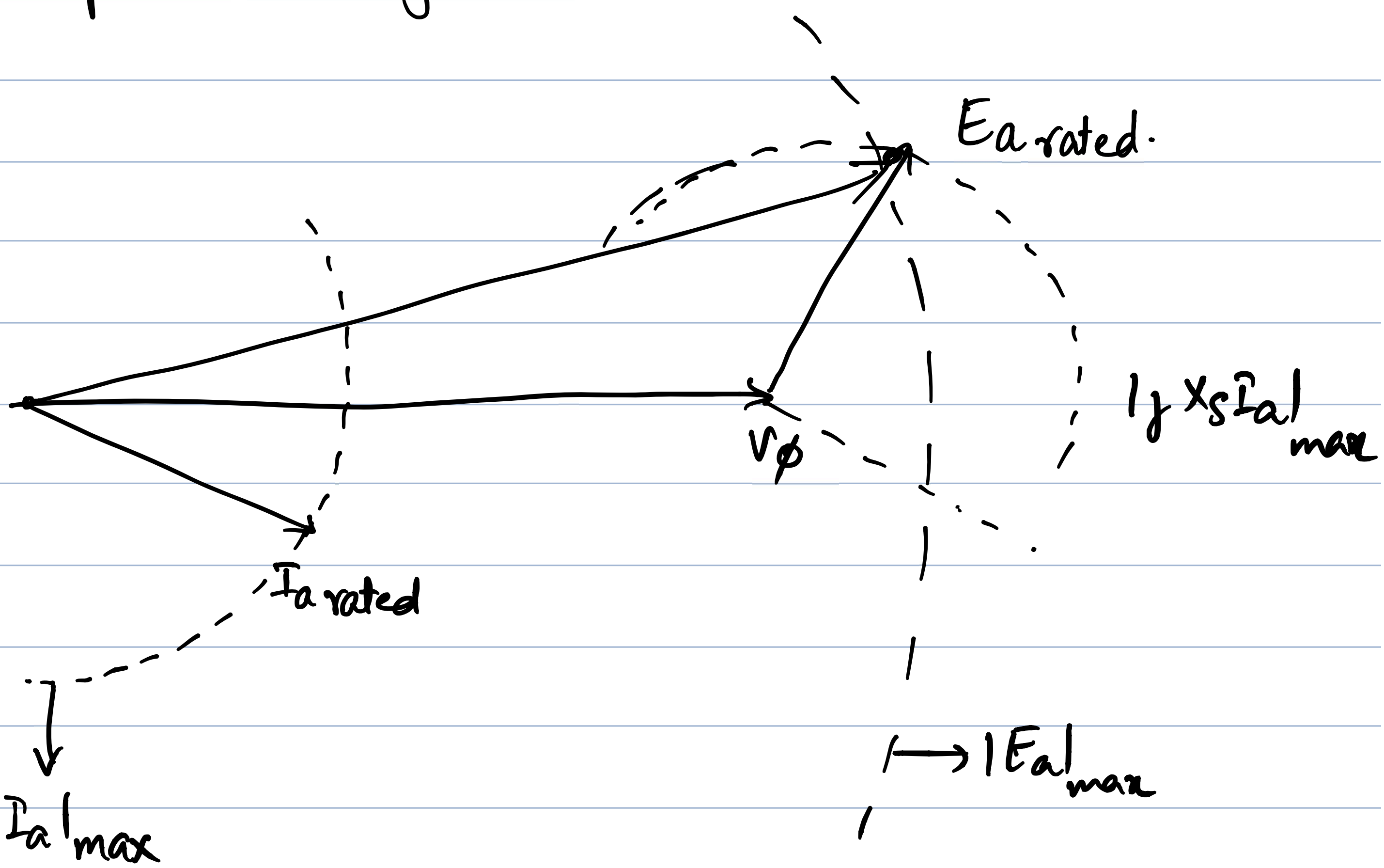
↓

both these heating effects are independent of the power factor of the machine, and because power factor is irrelevent to arm. heating the rating of the machine is in KVA and not kW

Heating effect of rotor cu loss $P_{RCL} = I_f^2 R_f$

because I_f is limited and so ϕ is limited $\Rightarrow$
$E_a = k\phi\omega$ limits are set by rotor current

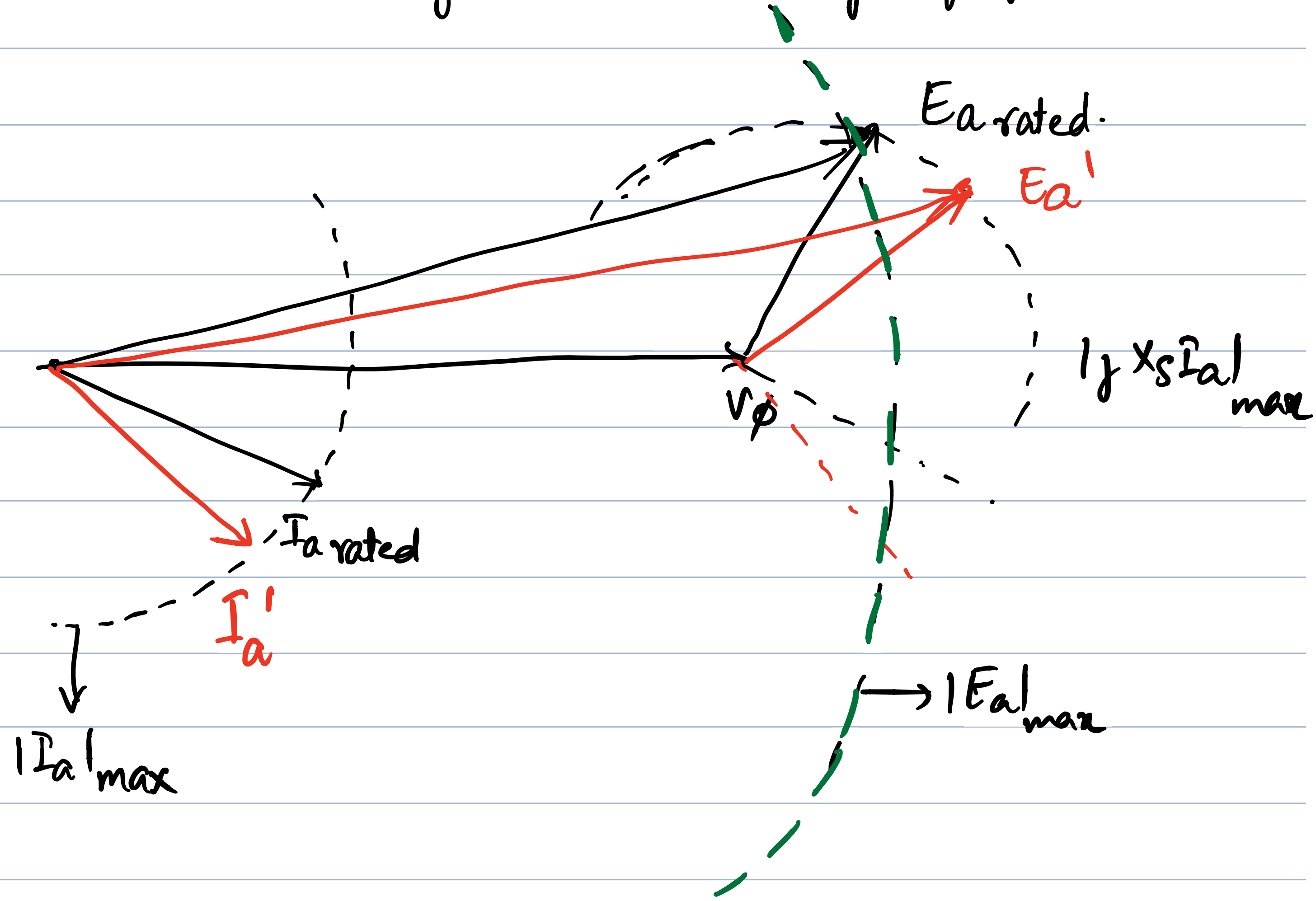
Acceptable Power factor @ rated KVA :-



* current can assume many angles staying in the same value $|I_a|_{max}$.

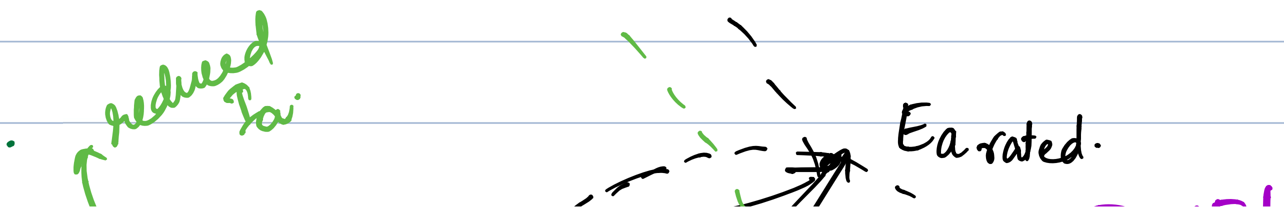
* @ a lower power factor, we can see the value of $|E_a| > |E_a|_{max}$ and this means an increase

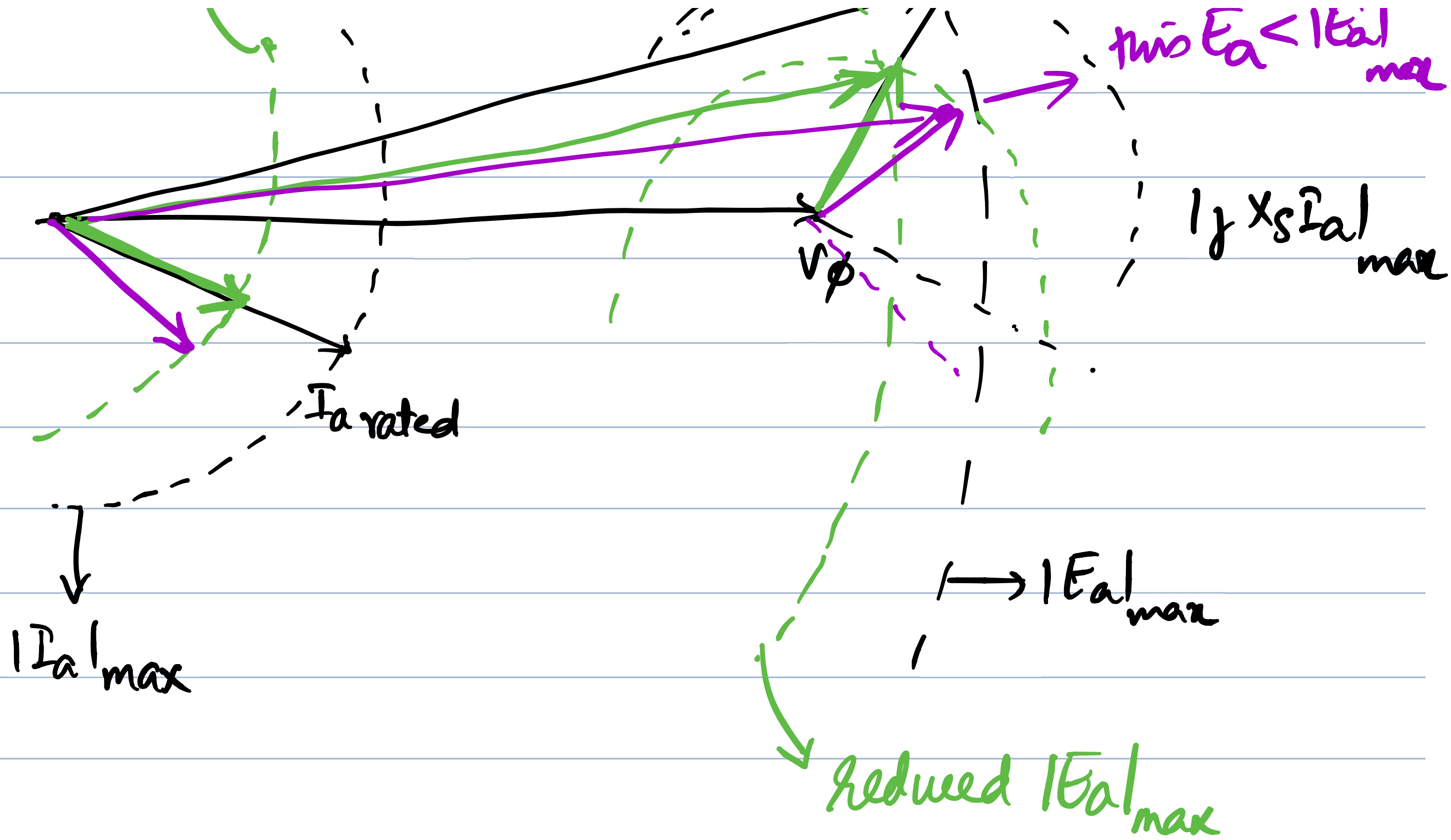
in flux and thereby I_f more than its rated value and may cause burning of field winding -



* the angle of I_a that requires max value of E_a - while V_ϕ is @ rated value gives the rated power factor of the generator.

* It is possible to operate the generator @ a lower power factor, only only be cutting down the KVA supplied by the gen

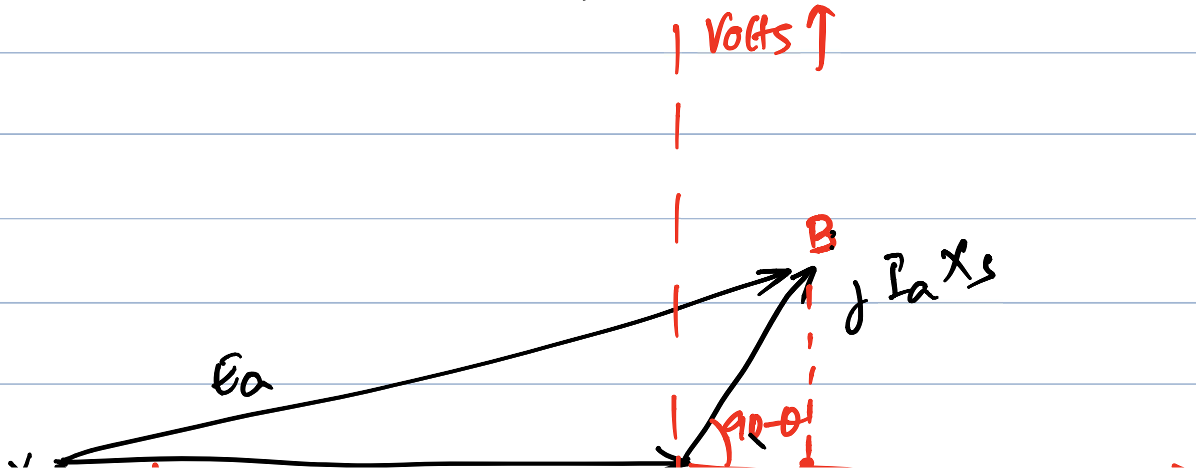


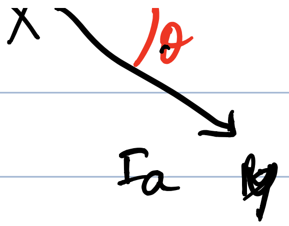


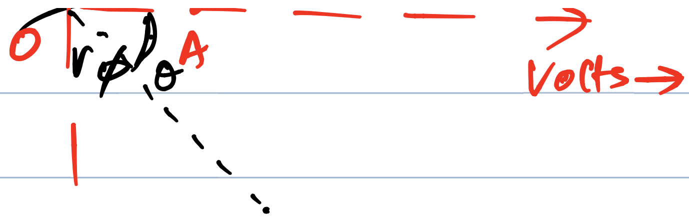
SYNCHRONOUS GENERATOR CAPABILITY CURVES

* representation of the stator (arm) and rotor (field) heating limits and any other limits of a sync. gen graphically → Capability Curves

* It is a complex plot of $S = P + jQ$ and is derived from phasor diagram of the Synchronous Generator







$OA = |I_a X_s| \cos(90-\theta) = I_a X_s \sin\theta$ (x axis)

$AB = |I_a X_s| \sin(90-\theta) = I_a X_s \cos\theta$ (y axis)

Active Power, $P = 3 V_\phi I_a \cos\theta$ ⇒ AB can be converted into P with suitable Caliberation factor

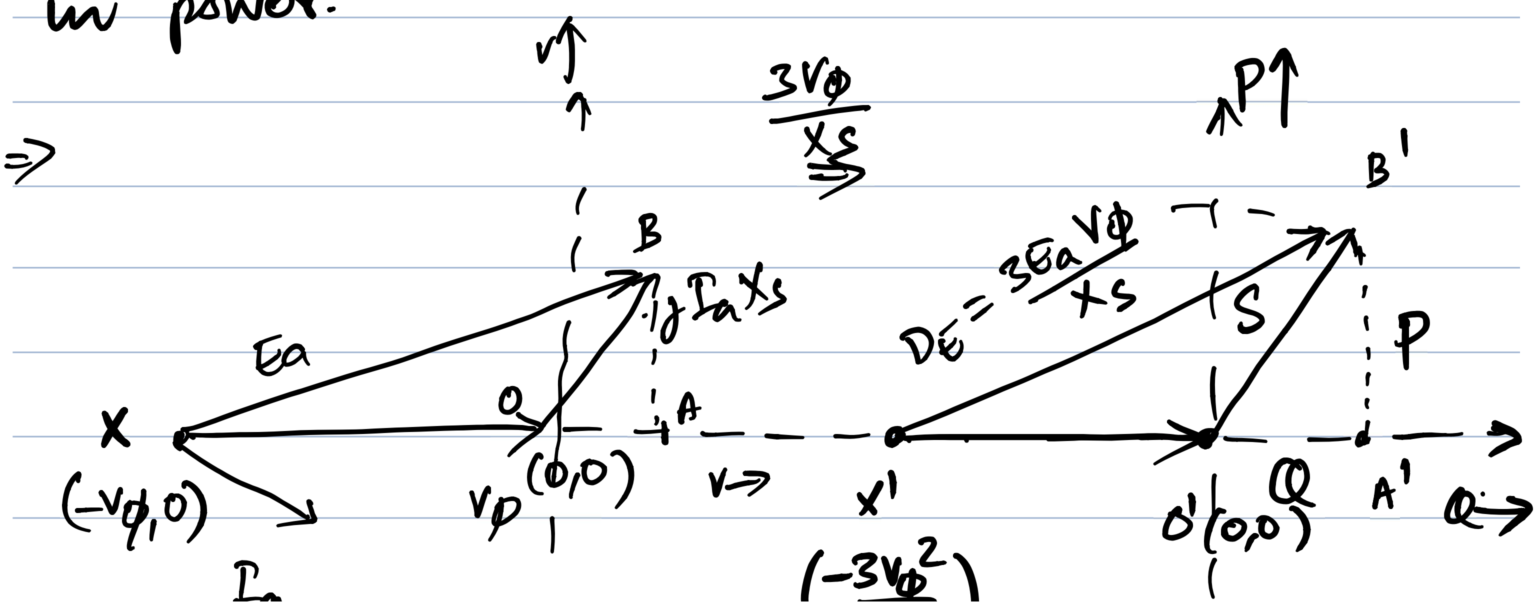
now, $AB_V = I_a X_s \cos\theta \times \dfrac{3V_\phi}{X_s}$

→ this converts $AB_V \rightarrow AB''_P = 3 V_\phi I_a \cos\theta$

$OA_V = I_a X_s \sin\theta \times \dfrac{3V_\phi}{X_s} \rightarrow OA''_Q = 3 V_\phi I_a \sin\theta$

⇒ Caliberation factor = $\dfrac{3V_\phi}{X_s}$ can be added to each element to make it a corresponding quantity in power.

⇒



$I_a \qquad \left(\frac{\quad}{X_s} \right)$

$O'A' = Q = 3V_\phi I_a \sin\theta$

$A'B' = P = 3V_\phi I_a \cos\theta$

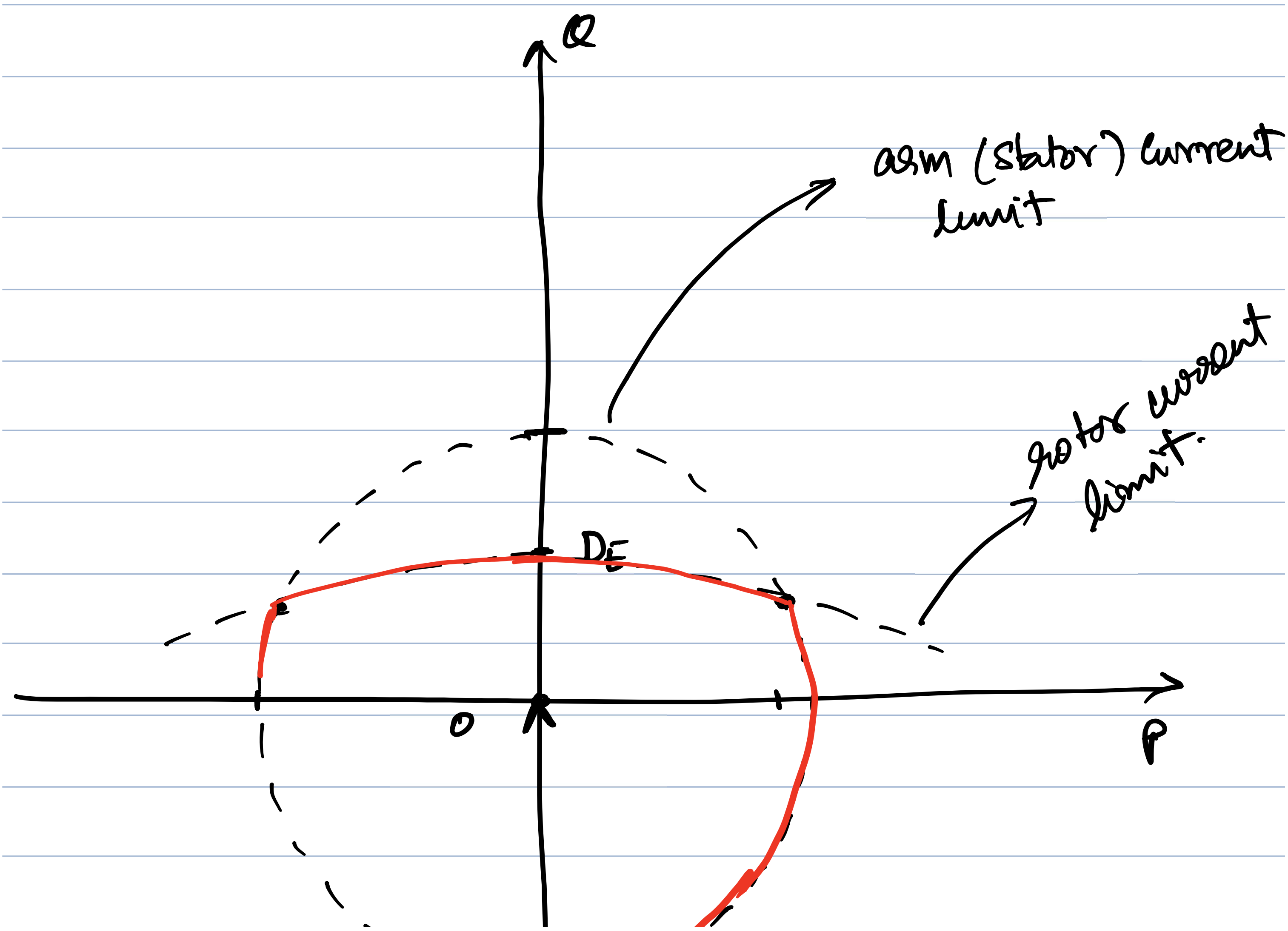
$$X(-V_\phi, 0) \xrightarrow{3V_\phi/X_s} X'\left(-\frac{3V_\phi^2}{X_s}, 0\right)$$

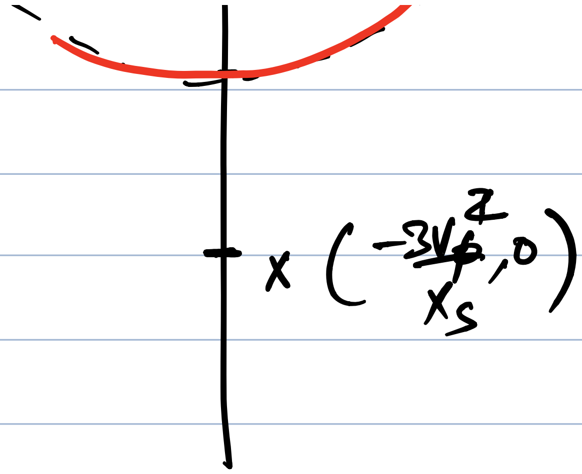
$$OA(I_a X_s \sin\theta) \xrightarrow{3V_\phi/X_s} 3V_\phi I_a \sin\theta = O'A' \quad (Q)$$

$$AB(I_a X_s \cos\theta) \xrightarrow{3V_\phi/X_s} 3V_\phi I_a \cos\theta = A'B' \quad (P)$$

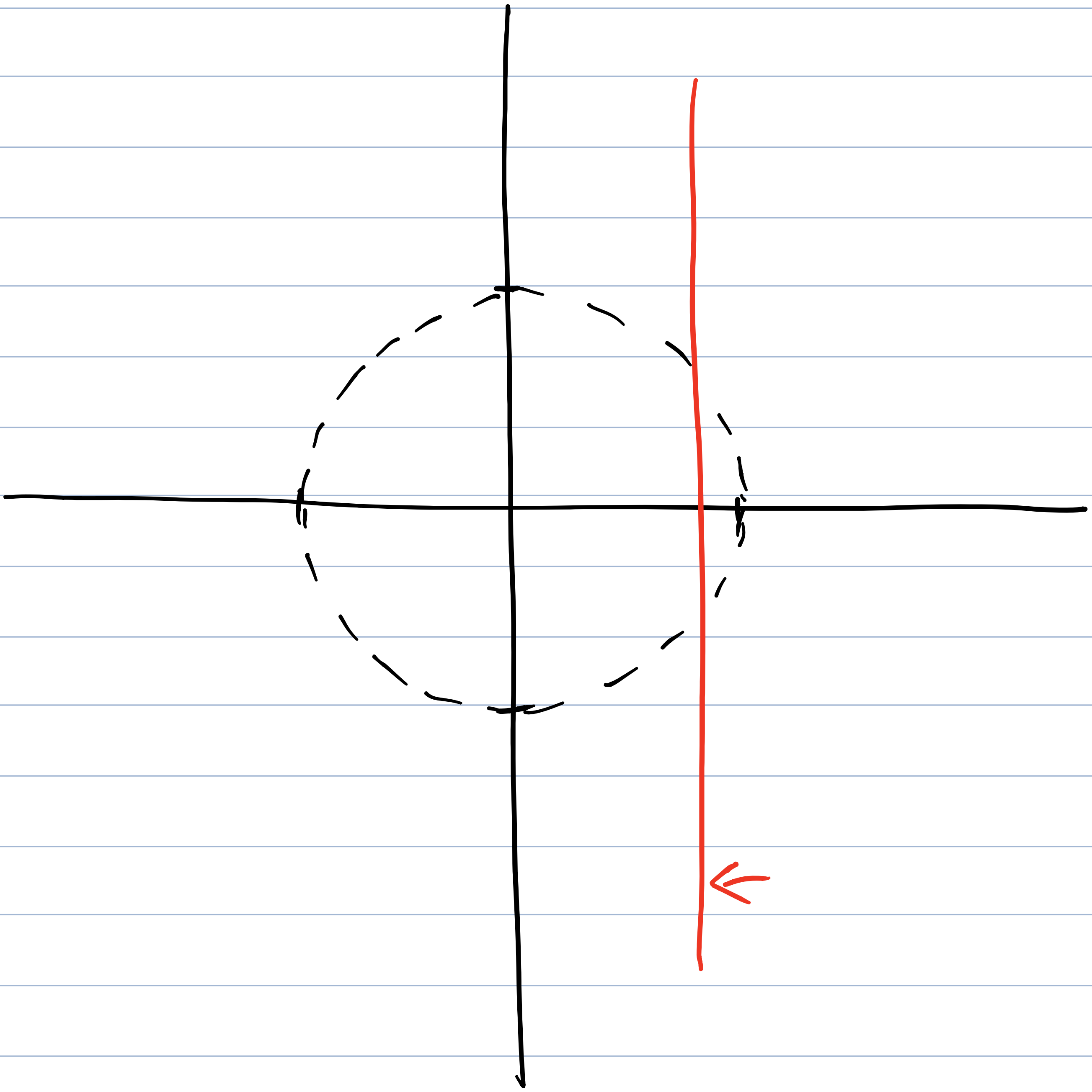
$$E_a \xrightarrow{3V_\phi/X_s} 3E_a V_\phi / X_s$$

$$OB'(I_a X_s) \xrightarrow{3V_\phi/X_s} O'B' = 3V_\phi I_a \quad (S)$$

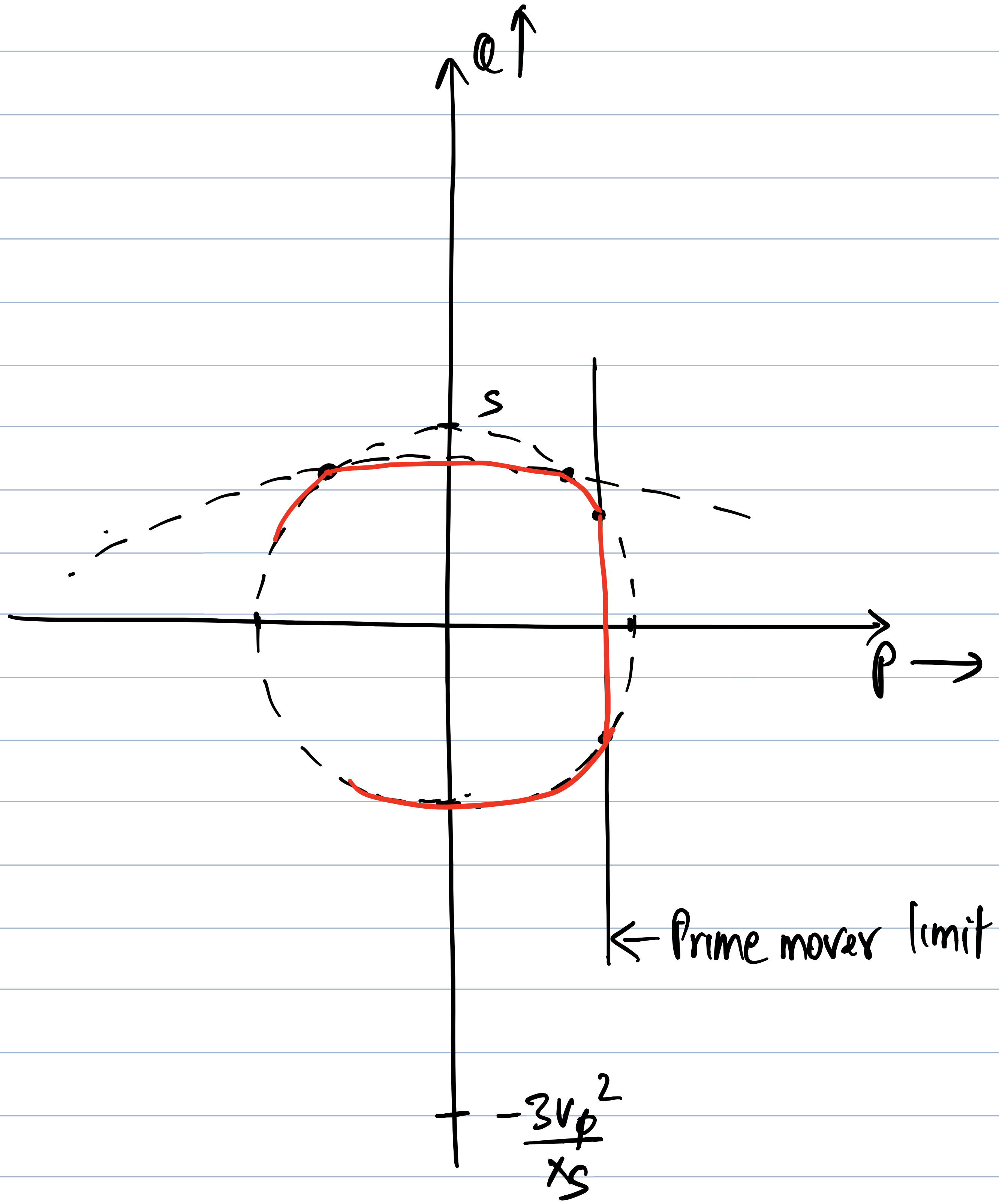




Generator Capability Curve

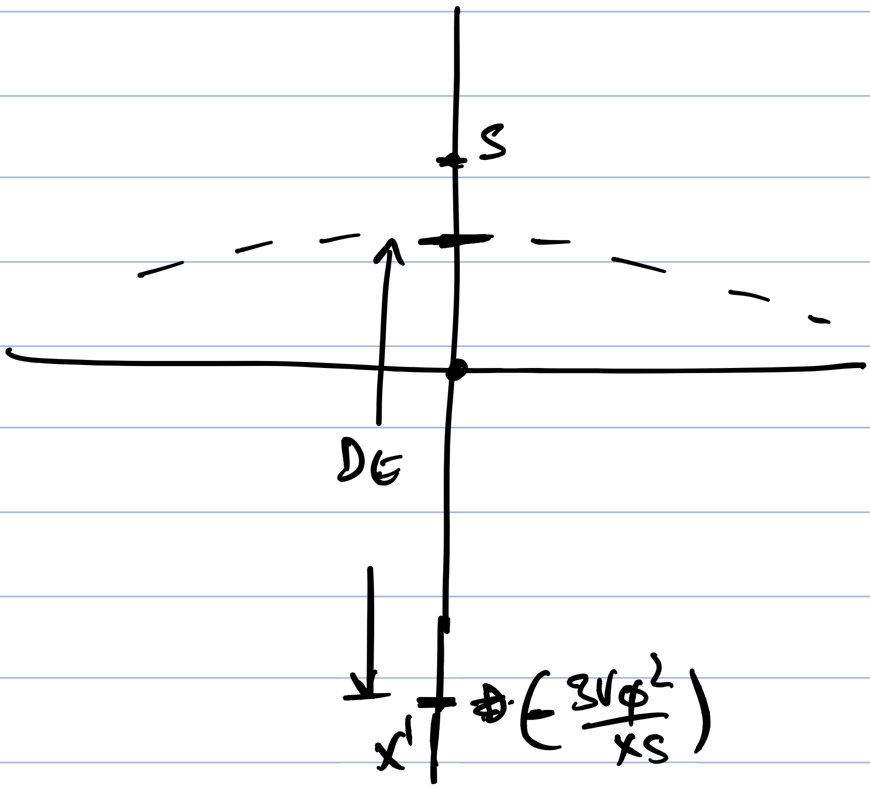


→ Adding a Prime mover limit



Q. A 480V, 50Hz, Y connected, 6 pole synchronous Gen is rated @ 50 KVA at 0.8 pf lag. $X_S = 1.0\Omega$ /phase. Assume Gen is connected to steam turbine capable of supply 45 kW, $P_{F\&W} = 1.5\,kW$, $P_{co} = 1.0\,kW$.

a) sketch Capability curve



* Gen is star connected $\Rightarrow V_\phi = \frac{V_L}{\sqrt{3}} = \frac{480}{\sqrt{3}} = 277\,V$

$\Rightarrow X'$ point is @ $-\frac{3 \times 277^2}{1} = -230\,kVAR$

* $D_E = \frac{3 V_\phi E_a}{X_S}$

$$E_a\angle\delta = V_\phi\angle 0 + jI_a\angle\bar{\theta}\, X_s$$

$$= 277\angle 0 + j\, I_a\angle -\theta \times 1$$

$$I_{a,max} = \frac{S_{rated}}{3V_\phi} = \frac{50\times 10^3}{3\times 277} = 60A$$

$$E_a\angle\delta = 277\angle 0 + j(60\angle -36.87)(1)$$

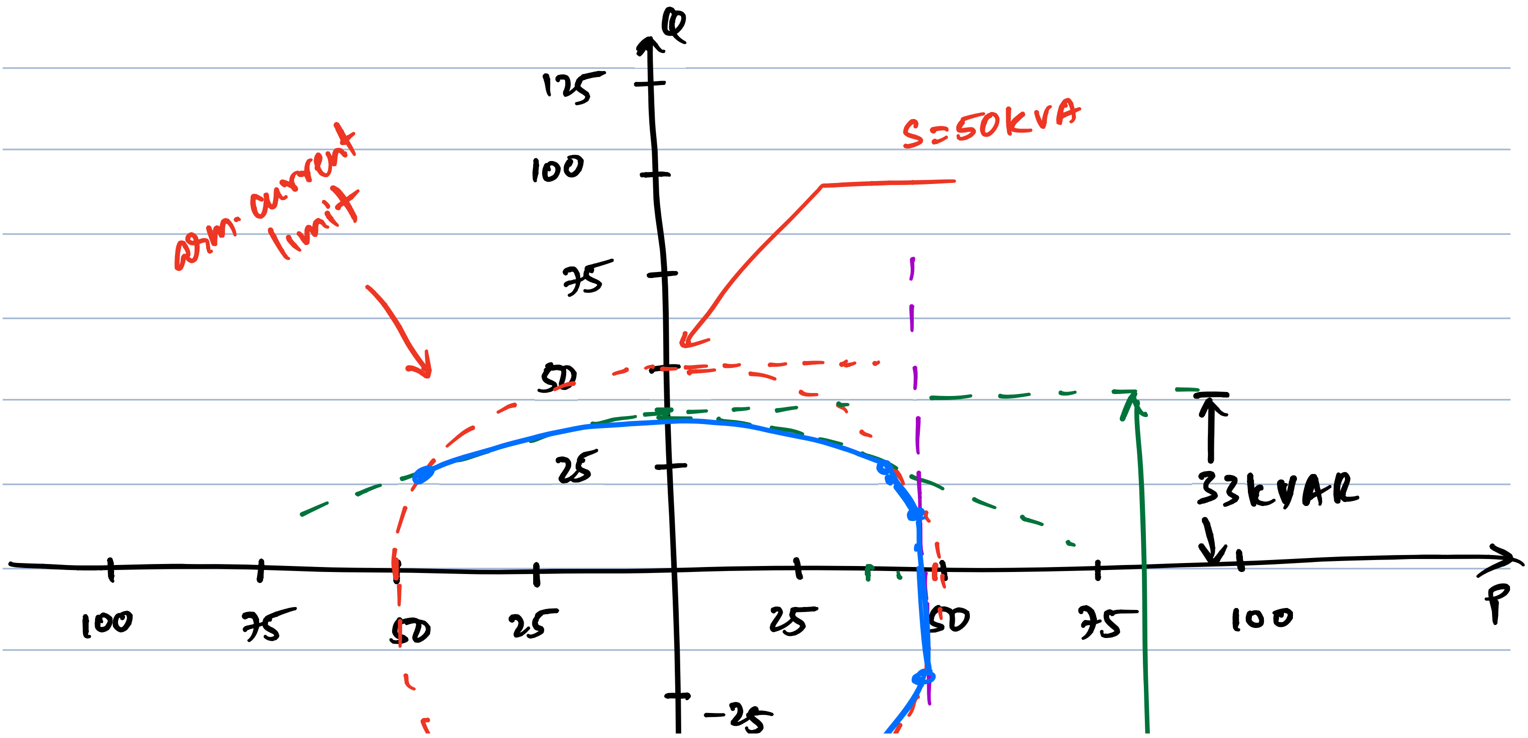
$$E_a\angle\delta = 317\angle 8.7^\circ\ V$$

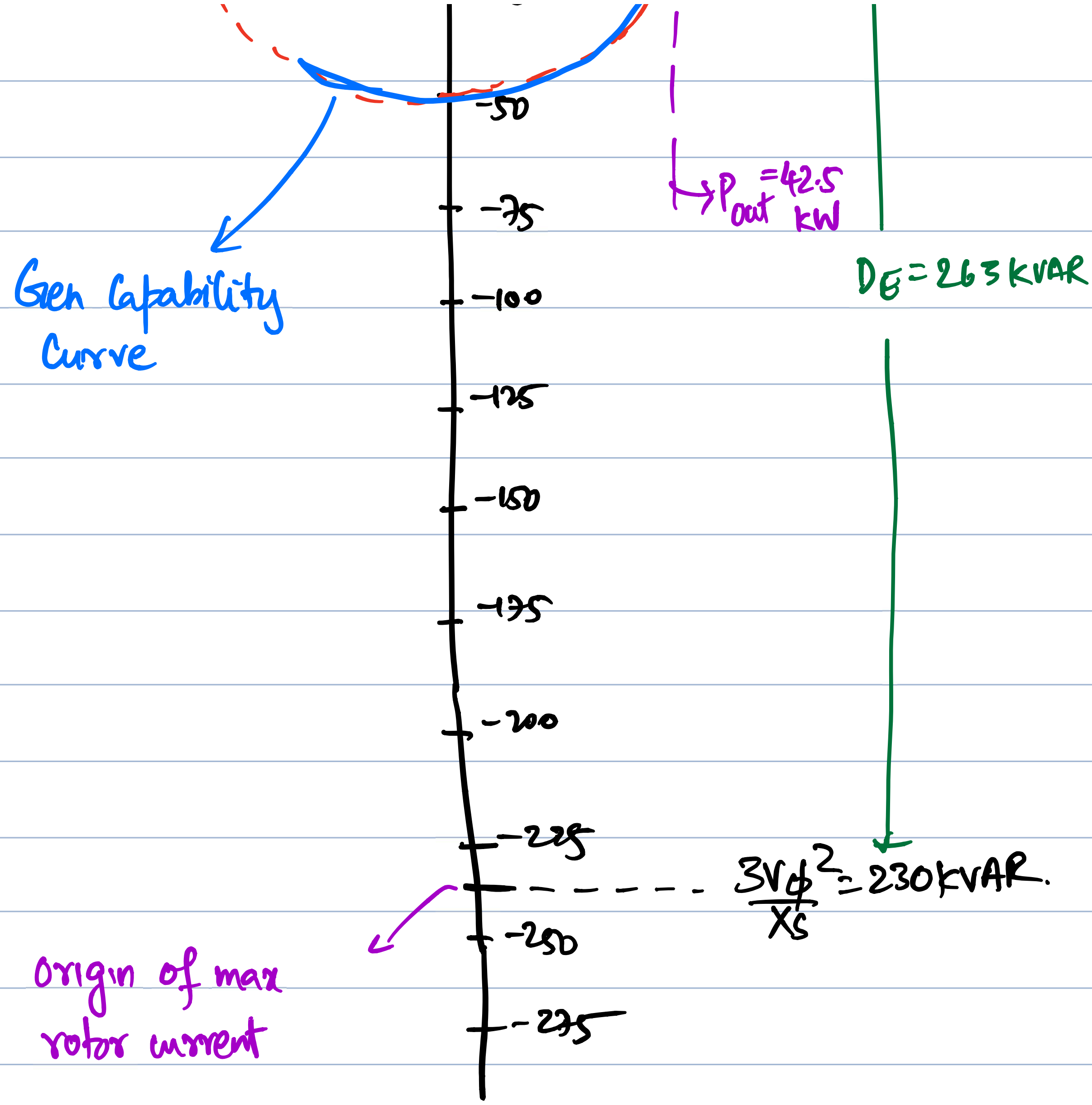
$$\rightarrow D_E = \frac{3E_aV_\phi}{X_s} = \frac{3\times 317\times 277}{1} = 263\text{ KVAR}$$

* max power i/p = 45kW

$$P_{out} = P_{in} - \cancel{P_{cu}}^{0} - P_{F\&W} - P_{co}$$

$$= 45 - 1.5 - 1.0 = 42.5\text{kW}$$





b) Can this gen supply 56A @ 0.7pf lag

→ rated pf = 0.8pf (lag), however the current is less than the rated value of 60A

$P = 3V_\phi I_a \cos\phi = 3 \times 277 \times 56 \times 0.7 = 32.6$ kW

$Q = 3V_\phi I_a \sin\phi = 3 \times 277 \times 56 \times 0.714 = 33.2$ kVAR

but this is outside the gen cap. curve in field current limit

$S_{@56A} = 3 \times 277 \times 56 = 46.54$ kVA

$\Rightarrow \quad Q = \sqrt{S^2 - P^2} = \sqrt{46.54^2 - 32.6^2} = 33.2$ kVAR.

c) maximum reactive power that can be produced.

max reactive power is when active power = 0.

@ $P = 0$; $Q = 33$ kVAR (from the cap curve)

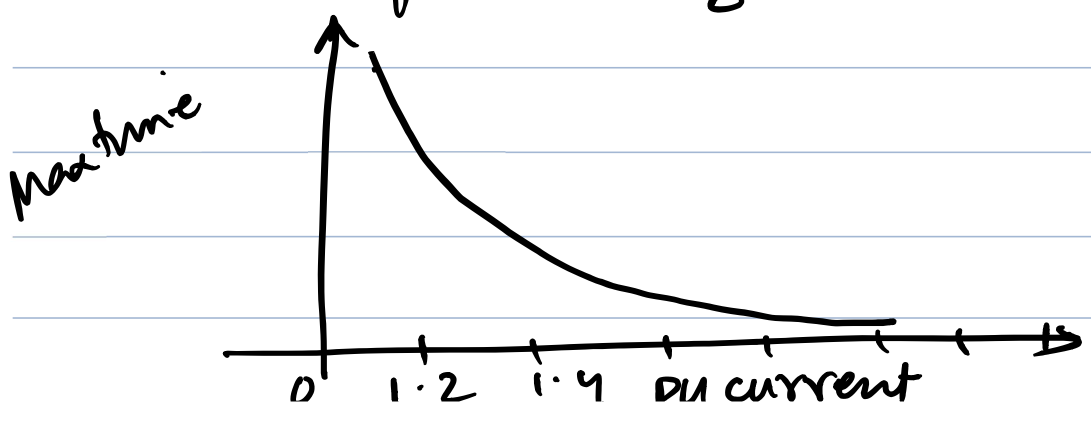
d) If the gen is supplying 30kW of real power, what is max. amount of reactive power that can be supplied

→ Graphically = 31.5 kVAR

SHORT-TIME OPERATION

* the heating limits usually occurs at a point much less than the maximum power that the generator is magnetically & mechanically able to supply
    * a gen maybe able to supply 300% of its rated power for a while (until the windings burn off)
    * this ability is used to supply momentary power surges & transients.

* also a generator can supply powers exceeding its rated value for longer time, as long as winding doesnt get time to heat up much.
    * a 1MW gen can supply 1.5MW for sometim provided the excess load is removed before winding overheats



maximum temp rise that a gen. can withstand depends on "Insulation Class" of the winding.

IC → A, B, F, & H

↓ ↓ ↓ ↓

60 80 105 125°C above ambient temperature

* higher the IC' greater the power that can be drawn from a gen without overheating the windings

* 10°C ↑ above rated → avg life ↓ by 1/2

so sync. gen should not be overloaded unless absolutely necessary.

Service factor :-

- Before installation, there is only an approximate estimate of the load.

$$SF = \frac{\text{actual max. power}}{\text{name plate rating}}$$

so if SF = 1.15 then a generator can supply upto 115% of the rated name plate rating

SF provides a a margin of error in case the loads were improperly estimated.