EEE 322

Electromechanical Energy Conversion – II

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CHAPTER 2

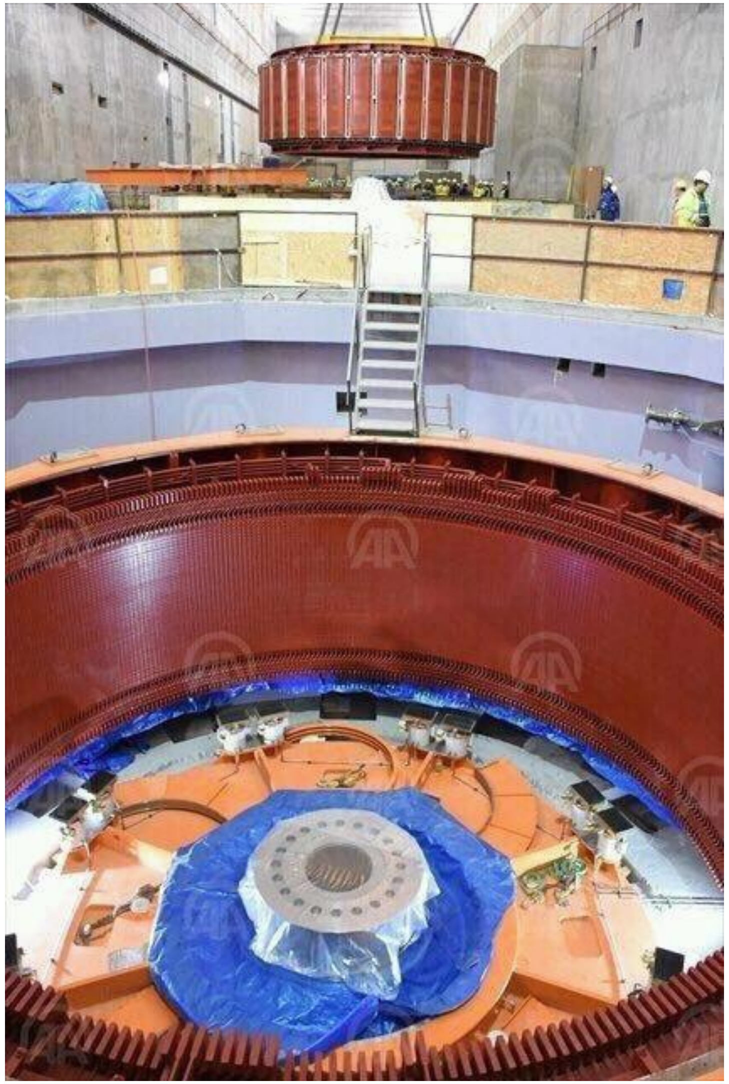
SYNCHRONOUS GENERATORS

Synchronous Generators

Synchronous generators (***alternators***) are synchronous machines used to convert mechanical power to AC electric power.

The rotor is being replaced inside the stator of a large synchronous generator in a hydro power plant

Synchronous Generators



The rotor is being replaced inside the stator of a large synchronous generator in a hydro power plant

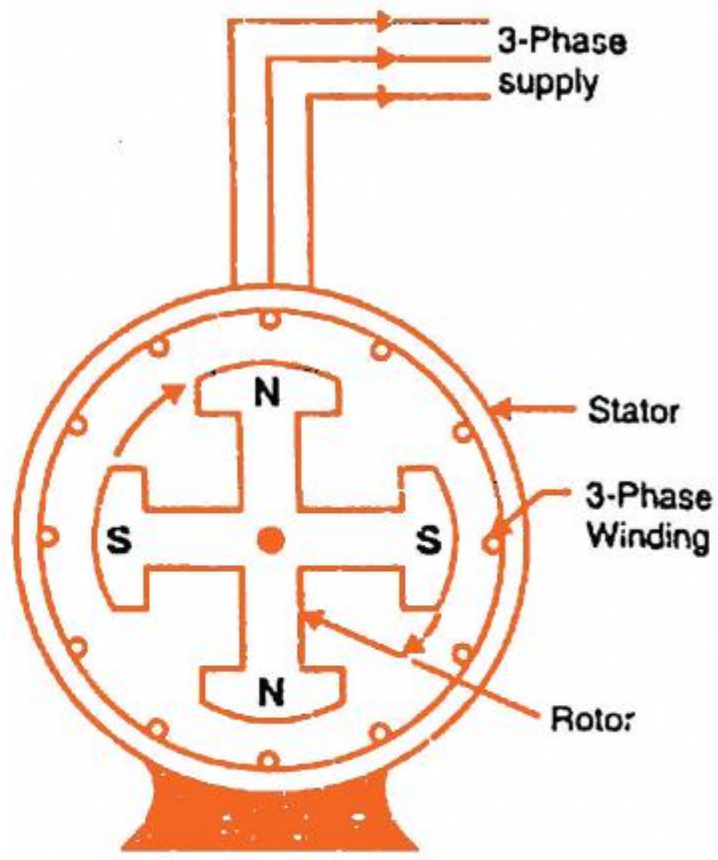
Operation principle of synchronous generator

- A **DC current** is applied to the **rotor winding** which produces a **rotor magnetic field**.
- The rotor of the generator is then **turned** by a **prime mover**, producing a **rotating magnetic field** within the machine.
- This **rotating magnetic field** induces a **three-phase set of voltages** at the stator windings of the generator.

Reference: https://www.youtube.com/watch?v=tiKH48EMgKE

Field winding *vs* armature winding

- *Two terms* commonly used to describe the windings on a synchronous machine: **field windings** and **armature windings**
- The "**field windings**" is the winding that produces the **main magnetic field** in the synchronous machine
- For **synchronous machines**, the **field windings** are on the **rotor**
- The "**armature windings**" is the winding where **the three-phase set of voltages** are induced
- For **synchronous machines**, the **armature windings** are on the **stator**



Reference: http://www.studyelectrical.com

Rotor types of synchronous generator

- There **two types of rotors** in synchronous generators and motors
  - ✓ Cylindrical rotor (*non-salient rotor*)
  - ✓ Salient-pole rotor

Cylindrical rotor

- **Cylindrical rotors** are generally designed for **high speed rotation,** such as in steam turbines
- Because of high rotor speed, the pole number can be kept small
- Pole number is generally **2** or **4**

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

If f_e =50 Hz;

↑ higher

$$120x50 = 6000 = n_m P$$

↓ lower

Rotor types of synchronous generator

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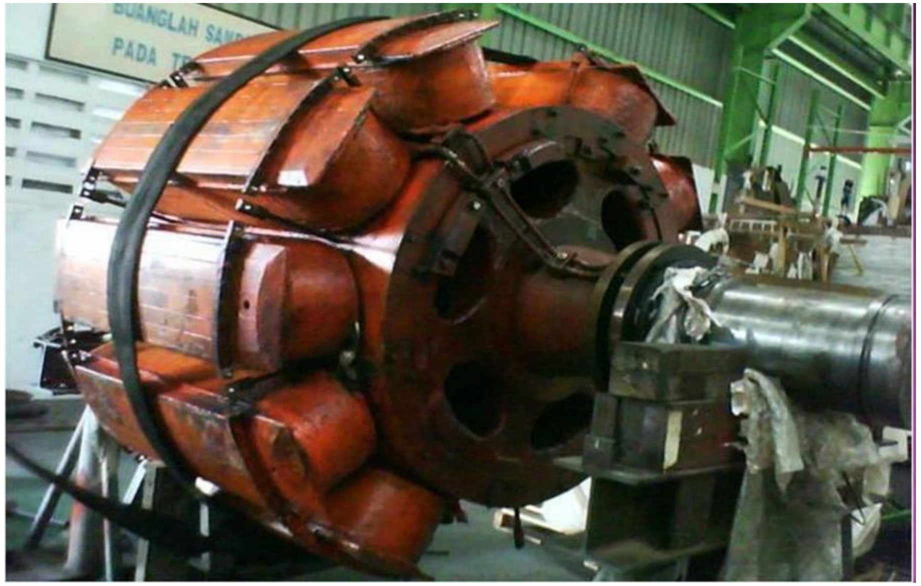
  - ✓ Cylindrical rotor (*non-salient rotor*)
  - ✓ Salient-pole rotor



Salient-pole rotor

- Salient-pole rotors are generally designed for **low speed rotation,** such as in hydro turbines
- Because of low rotor speed, the pole number should be increased
- Pole number is generally **4** or **more**

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

higher

If f_e =50 Hz;

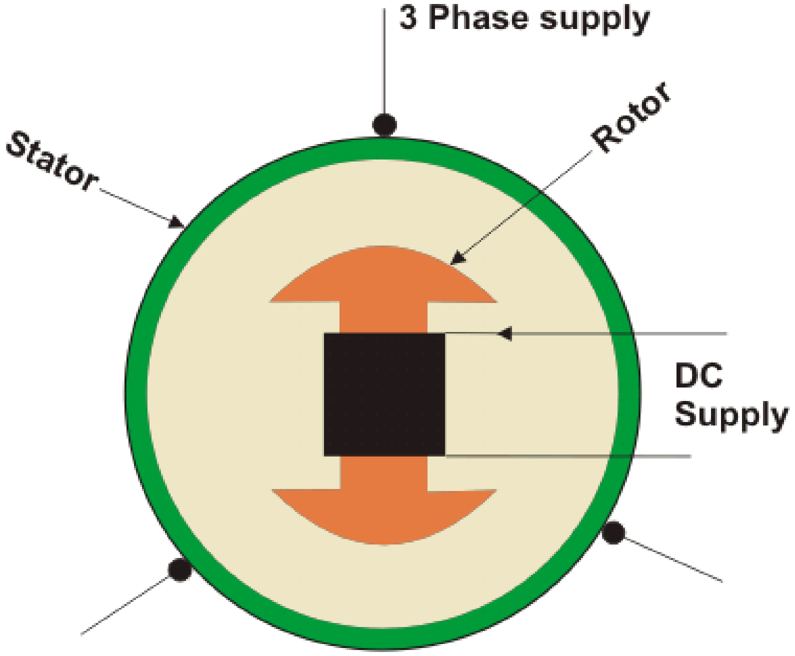
$$120x50 = 6000 = n_m P$$

lower

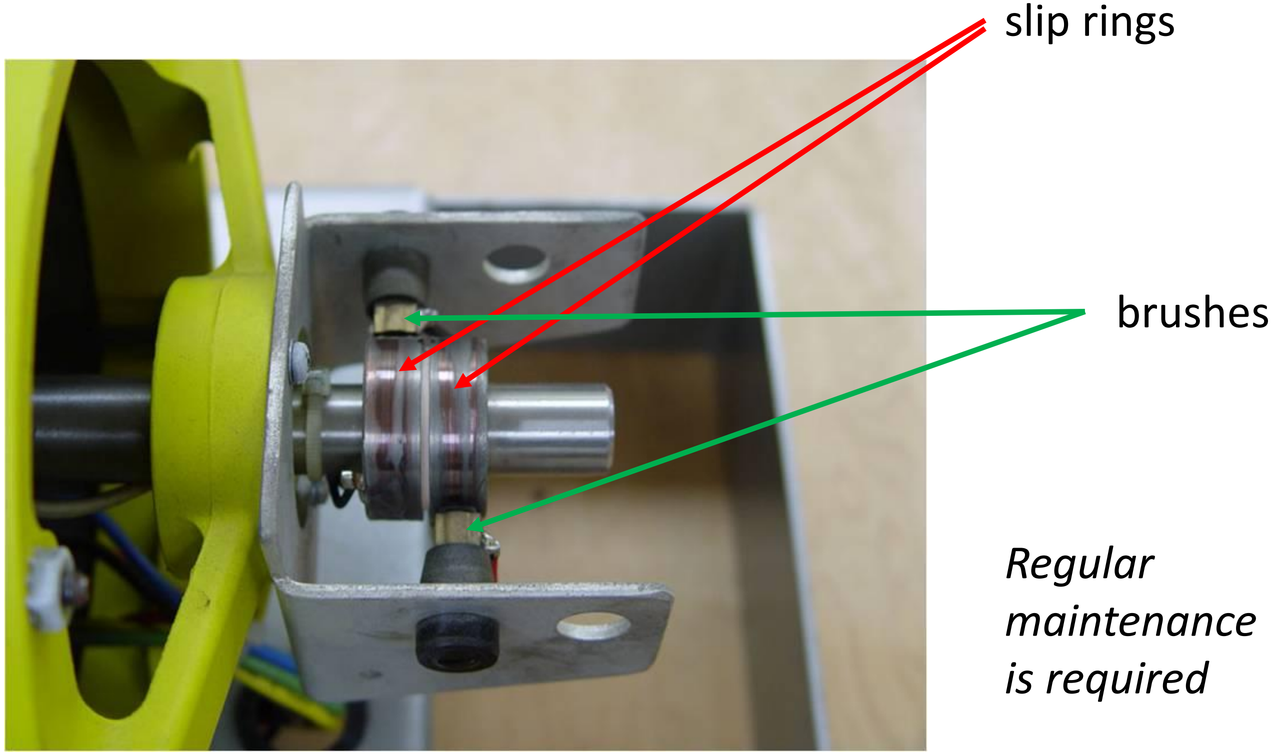
How DC current is supplied to rotor ?

- There are **two common approaches** to supplying DC current to the rotor (*field winding*)

First method: Supply the DC current from an **external DC source** to the rotor by means of *slip rings* and *brushes* ***(suitable for smaller generators)***



Reference: https://www.quora.com



Regular maintenance is required

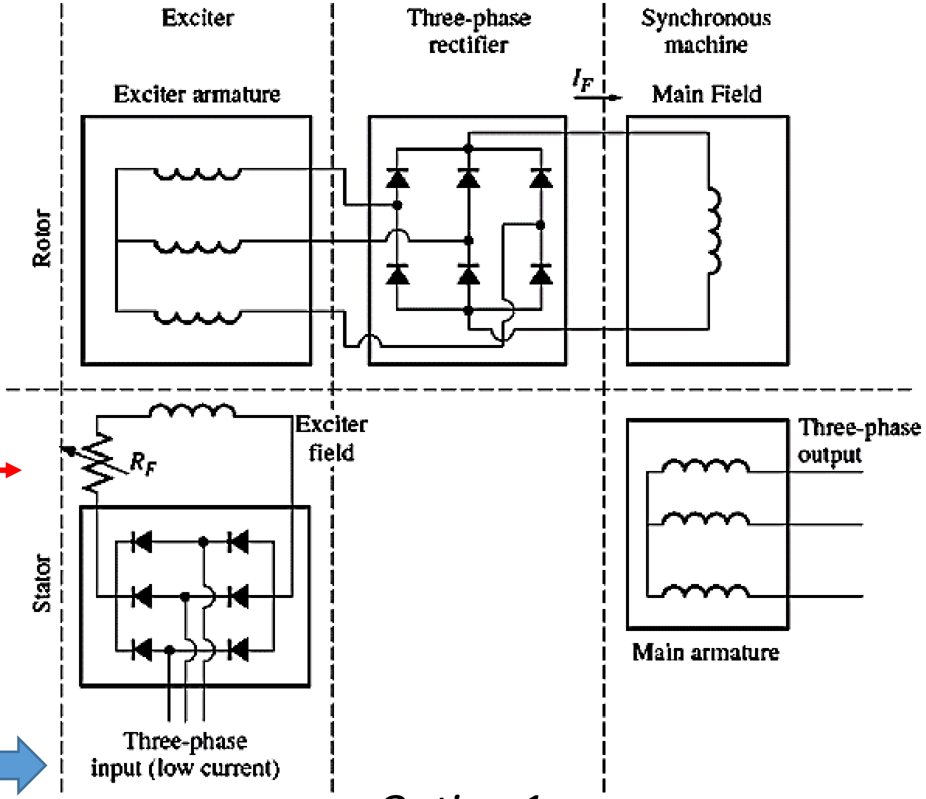
Reference: http://users.ece.utexas.edu/~kwasinski/EE394J10DGFa12.html

How DC current is supplied to rotor ?

- There are **two common approaches** to supplying DC current to the rotor (*field winding*)

Second method: Supply the DC current from a **special DC power source** mounted directly on the shaft of the synchronous generator (***Brushless exciter for larger generators***)

By adjusting **rheostat**, it is possible to adjust field current



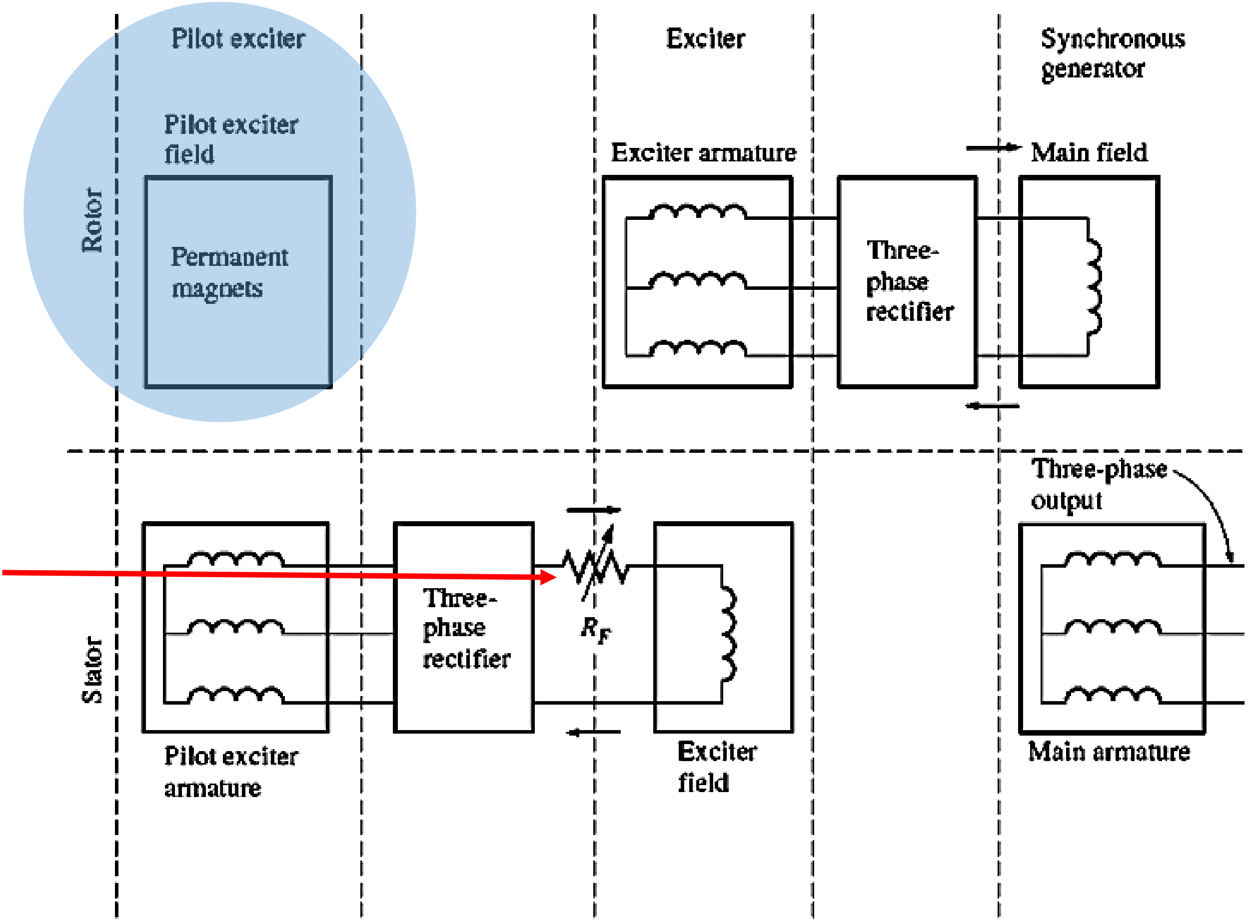
We need an external small three-phase current

Option 1

How DC current is supplied to rotor ?

No external current is needed !

By adjusting **rheostat**, it is possible to adjust field current



Option 2

Speed of rotation of a synchronous generator

- **Synchronous generators** are by definition ***synchronous***, meaning that the electrical frequency produced in the stator is ***locked*** or ***synchronized*** with the mechanical rate of rotation of the generator.
- In another words, the speed of rotating magnetic field and mechanical rate of rotation are **equal**
- However, **asynchronous generators** are by definition ***asynchronous***, meaning that there is **always a difference** between the speed of rotating magnetic field and mechanical rate of rotation of the generator.

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

f_e is the electrical frequency in the stator (Hz)

n_m is the mechanical speed of magnetic field rotation (rev/min or rpm)

n_m is also equals to the rotor speed of synchronous machines (also called "***synchronous speed***")

P is number of poles (always even number)

Internal generated voltage of a syn. generator

- In Chapter 1, we have seen that the magnitude of the induced voltage in a given stator phase is equal to:

$$E_A = \sqrt{2}\pi N_C \emptyset f$$

- Let's write this equation in more simpler form:

$$E_A = K\emptyset \mathrm{w}$$

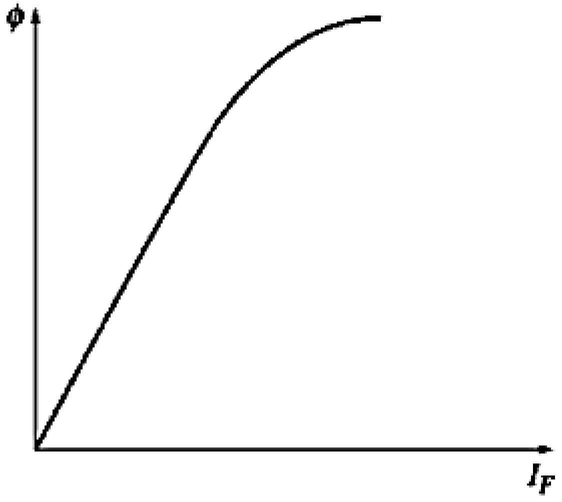
$$K = \frac{\sqrt{2}}{2} N_C$$ (*a constant related with the machine*)

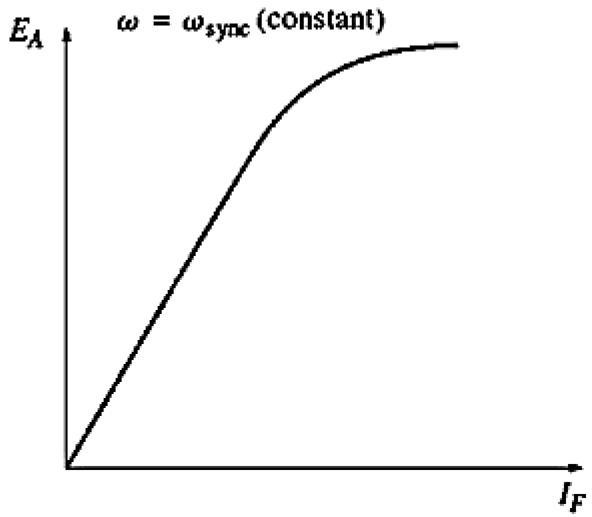
N_C is the number of conductors per phase

- The induced voltage E_A depends on;
  - Flux in the machine
  - Angular speed of rotor
  - A constant related with the machine

Internal generated voltage of a syn. generator

- The field circuit current I_F is related to the flux Ø
- E_A is directly proportional to the flux Ø (*if w is constant*)
- So E_A **must be related** to the field current I_F

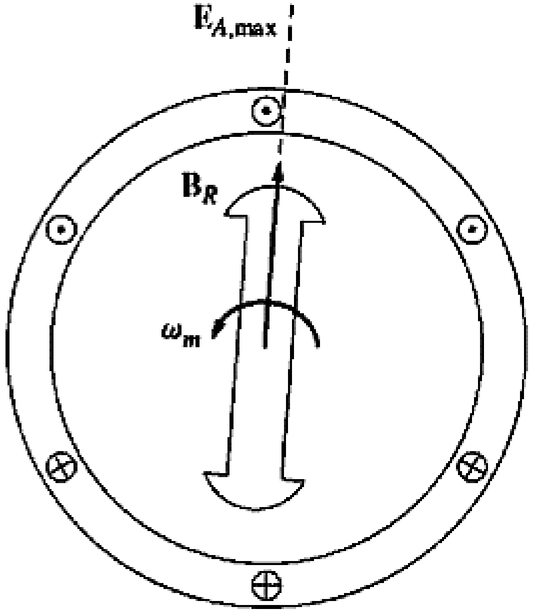




Magnetization curve (*open-circuit characteristic*) of the synchronous machine

Derivation of equivalent circuit of sync. gen.

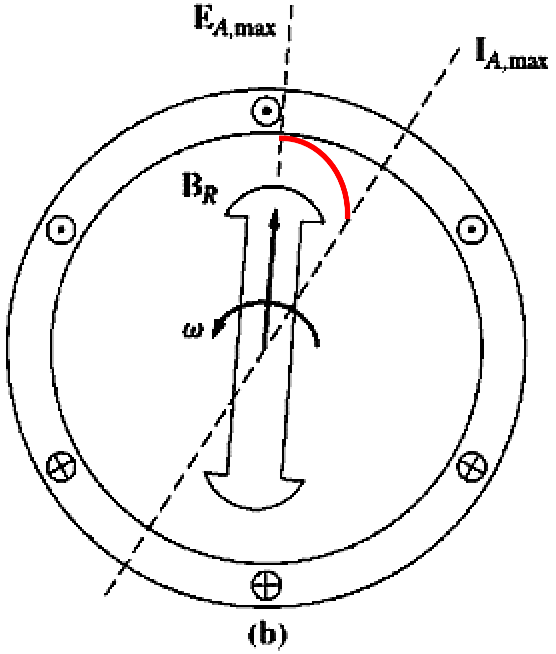
- The figure shows a **two-pole rotor** rotating inside a **three-phase stator**
- Now assume that there is **no load** connected to the stator
- The rotor magnetic field B_R produces an ***internal generated voltage*** **(**E_A**)**
- The peak value of E_A (E_{Amax}) coincides with the direction of B_R.
- With **no load** on the generator, there is **no armature current flow**
- E_A will be taken directly from the terminals of the generator
- In this case, phase voltage (V_Φ) is equal to E_A



(a)

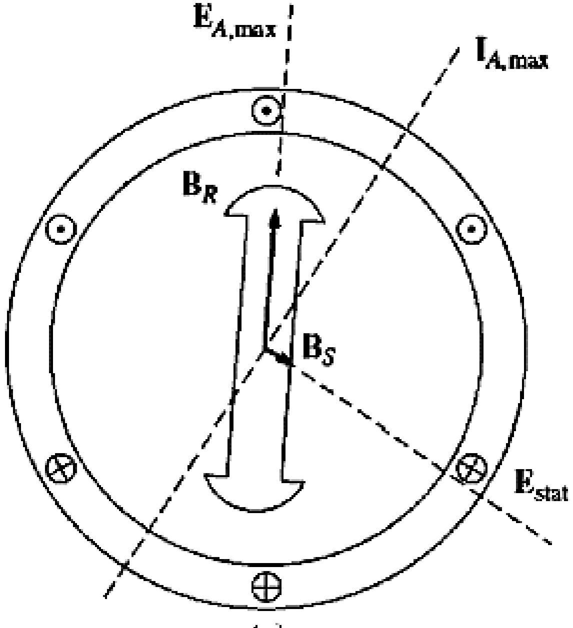
Derivation of equivalent circuit of sync. gen.

- Now suppose that the generator is connected to a **lagging load**
- Since the **load is lagging**, the peak current will occur at an angle **behind** the peak voltage



Derivation of equivalent circuit of sync. gen.

- The current flowing in the stator windings produces a magnetic field of its own
- This stator magnetic field is called (***B_S***)
- The direction of ***B_S*** is found by the right hand rule
- The stator magnetic field (***B_S***) induces a voltage on the stator, called "***armature reaction voltage***" (***E_{STAT}***)



(c)

Derivation of equivalent circuit of sync. gen.

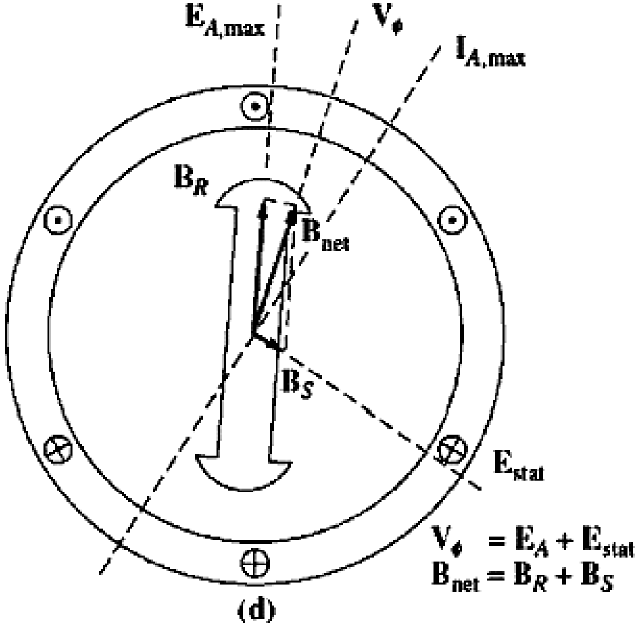
- With two voltages present in the stator windings, the phase voltage of the generator becomes the sum of the **internal generated voltage** (***E_A***) and the **armature reaction voltage** (***E_{STAT}***)

$$V_{\emptyset} = E_A + E_{STAT}$$

- On the other hand, the **net magnetic field** in the generator becomes the sum of the rotor and stator magnetic fields

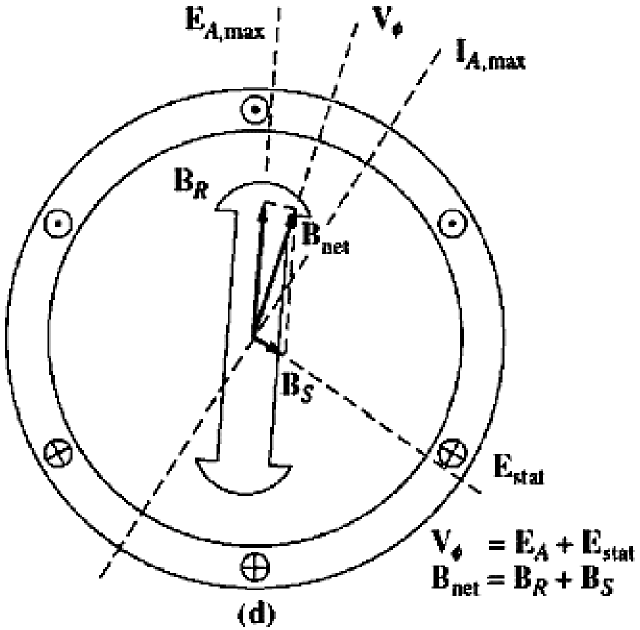
$$B_{net} = B_R + B_S$$

- Since the angles of ***B_R*** and ***E_A*** are the same
- and the angles of ***B_S*** and ***E_{STAT}*** are the same
- The angles of ***$V_{\emptyset}$*** and ***Bnet*** will be the same



Definition of armature reaction

- When a synchronous generator's rotor is spun (*rotated*), a voltage $\boldsymbol{E_A}$ is induced in stator windings
- If a load (*three phase*) is attached to the terminals of the generator, a three-phase current flows in stator windings
- This three-phase stator current produce a magnetic field ($\boldsymbol{B_S}$) of its own in the machine.
- The stator magnetic field ($\boldsymbol{B_S}$) distorts the original rotor magnetic field ($\boldsymbol{B_R}$)
- This distortion effect is called "**armature reaction**"



$$\left.\begin{aligned} B_S &= 0 \\ B_{net} &= B_R \\ B_{net} &= B_R + B_S \end{aligned}\right\}$$

(**without load**)

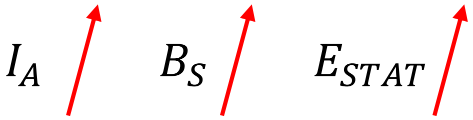
$$\left.\begin{aligned} B_{net} &\neq B_R \\ B_{net} &= B_R + B_S \end{aligned}\right\}$$

(**with load**) (**armature reaction**)

Modeling of armature reaction

- How can the effects of **armature reaction** on the phase voltage be **modeled** ?

- First; the voltage $\boldsymbol{E_{STAT}}$ lies at an **angle of 90° behind** the armature current $\boldsymbol{I_A}$
- Second; the voltage $\boldsymbol{E_{STAT}}$ is directly proportional to the armature current $\boldsymbol{I_A}$



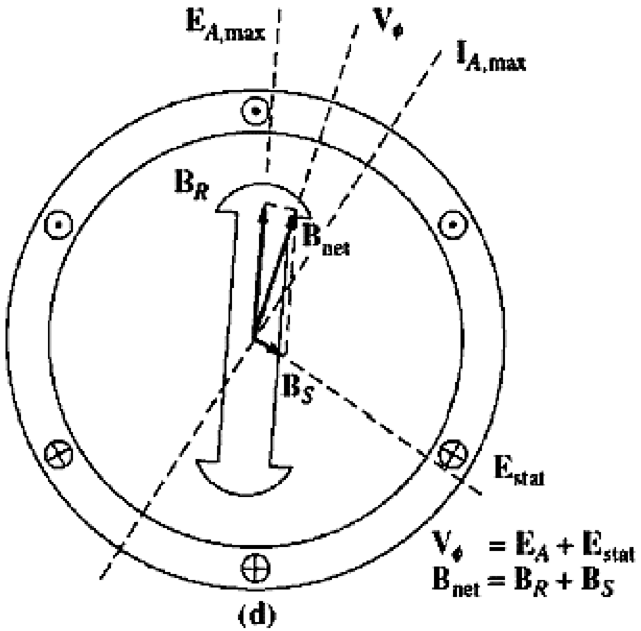
- If $\boldsymbol{X}$ is a constant of proportionality (**reactor**), then the **armature reaction voltage** $\boldsymbol{E_{STAT}}$ can be expressed as:

$E_{STAT} = -jXI_A$ ➡ (**-j** means that $\boldsymbol{E_{STAT}}$ **lags** $\boldsymbol{I_A}$ by **90°**)

- Since;

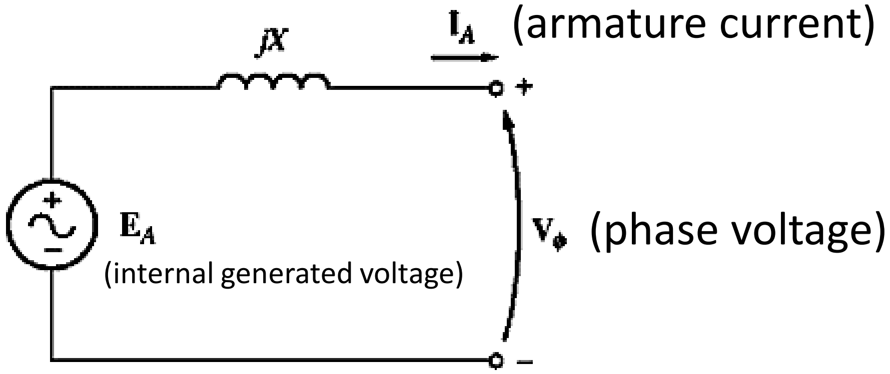
$$V_\emptyset = E_A + E_{STAT}$$

$$\boxed{V_\emptyset = E_A - jXI_A}$$



Modeling of armature reaction

$$V_{\emptyset} = E_A - jXI_A$$



- In addition to armature reaction, the **stator coils** have a **self-inductance (*L_A*)** and a **resistance (*R_A*)**
- These parameters can also be used in the mathematical model for more accurate calculations:
- If;

$X_A = 2\pi f L_A$ **(armature self-reactance)**

R_A **(armature resistance)**

$$\boxed{V_{\emptyset} = E_A - jXI_A - jX_AI_A - R_AI_A}$$

Modeling of armature reaction

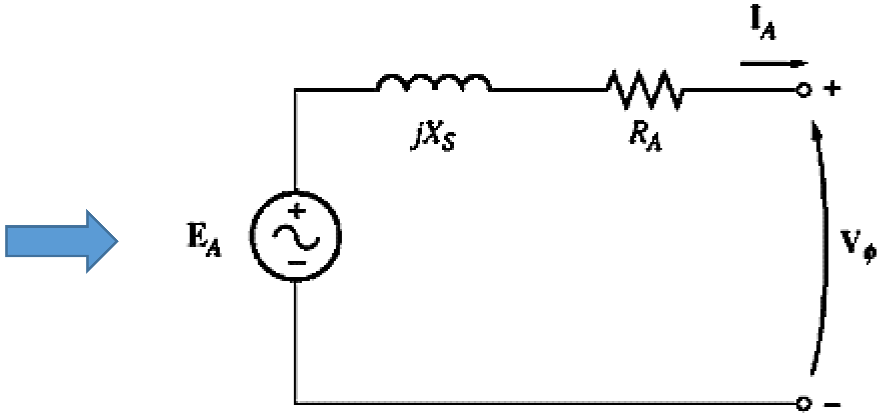
$$V_{\emptyset} = E_A - jXI_A - jX_AI_A - R_AI_A$$

- If we join these two reactances in the last equation:

$X_S = X + X_A$ **(synchronous reactance)**

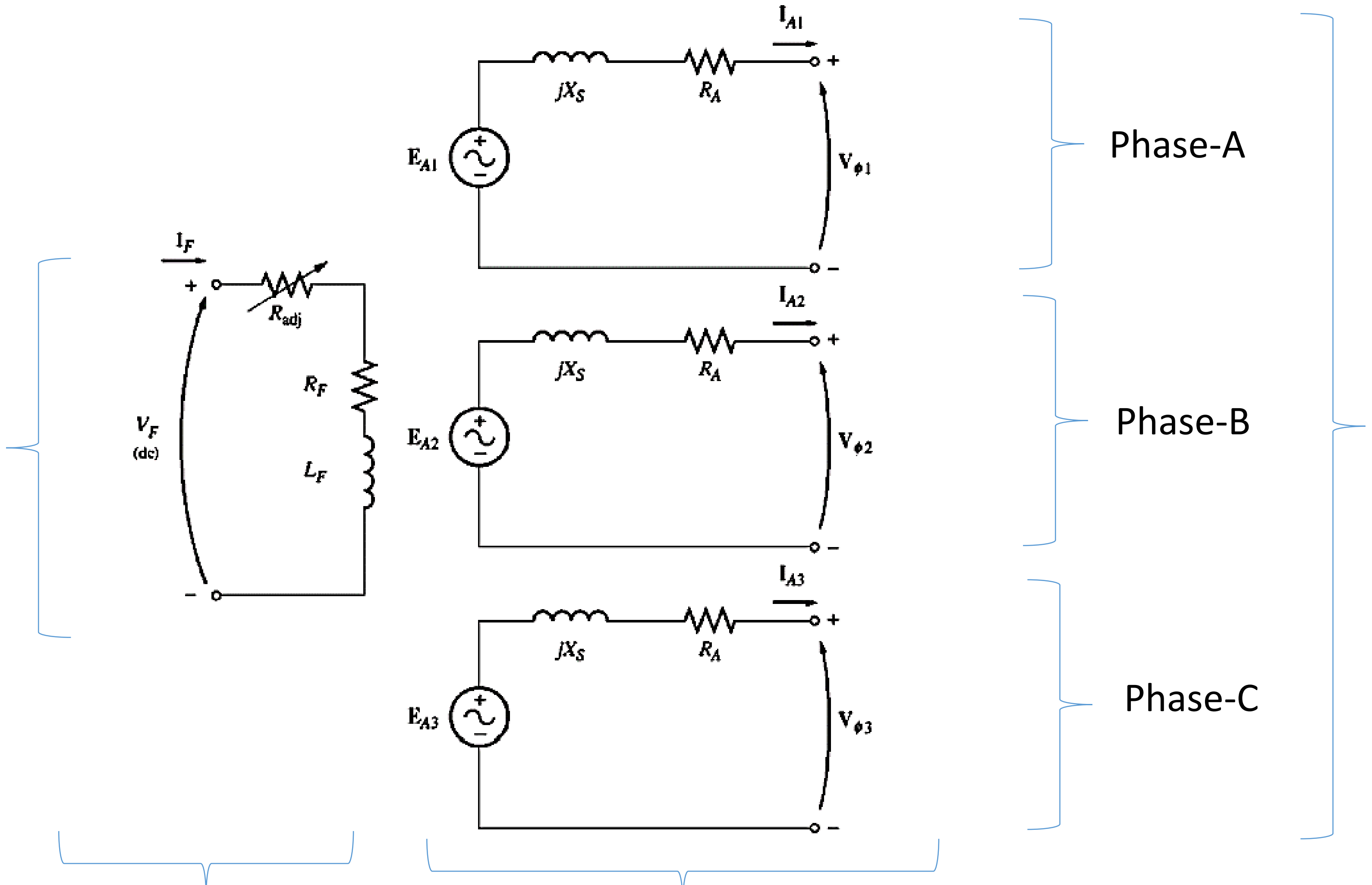
- The final form of the voltage equation for the stator is obtained as:

$$\boxed{V_{\emptyset} = E_A - jX_SI_A - R_AI_A}$$



Per-phase equivalent circuit of stator

Full equivalent circuit of synchronous generator



Field circuit

Phase-A

Phase-B

Phase-C

Three-phase output

Rotor side

Stator side (armature windings)

Full equivalent circuit of synchronous generator

- The stator windings of the generator can be connected as **wye (Y)**:

$$|E_{A1}| = |E_{A2}| = |E_{A3}| = E_A$$

$$|V_{\emptyset 1}| = |V_{\emptyset 2}| = |V_{\emptyset 3}| = V_{\emptyset}$$

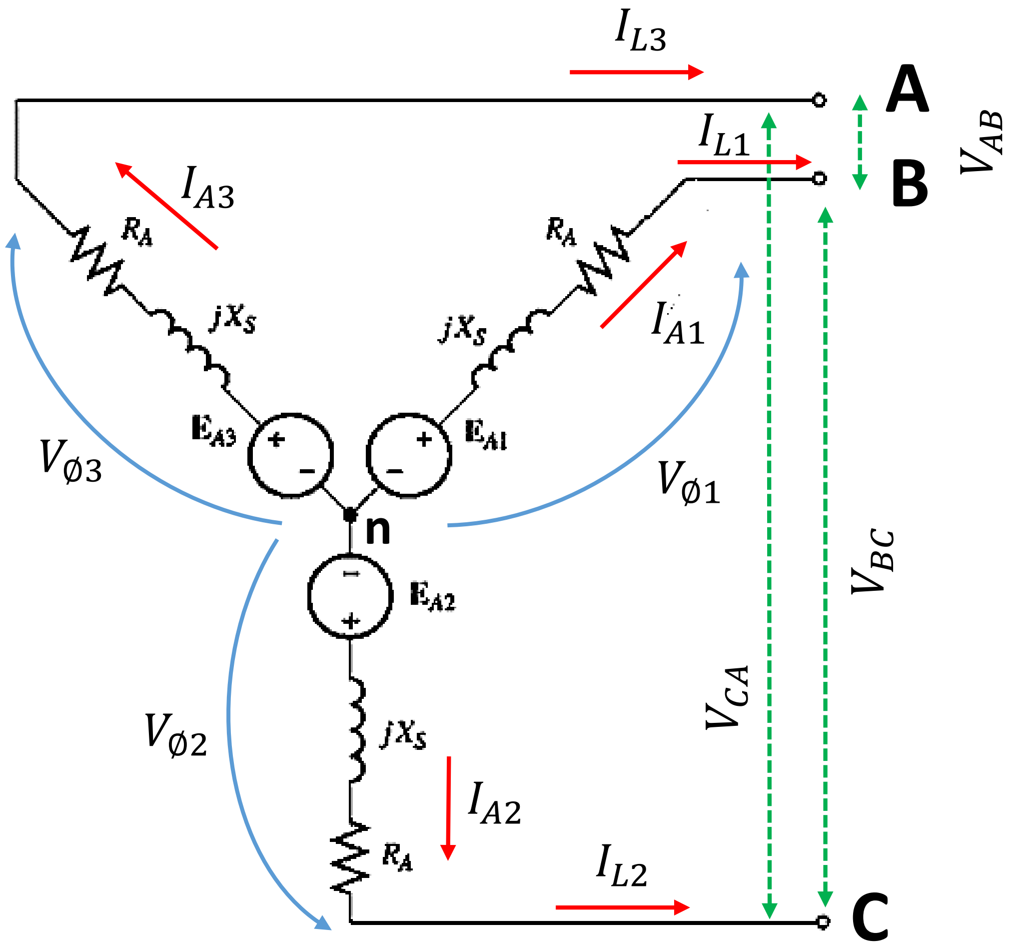
$$|V_{AB}| = |V_{BC}| = |V_{CA}| = V_{LL}$$

$$|I_{A1}| = |I_{A2}| = |I_{A3}| = I_A$$

$$|I_{L1}| = |I_{L2}| = |I_{L3}| = I_L$$

$$\boxed{\begin{aligned} V_{LL} &= \sqrt{3}.V_{\emptyset} \\ I_L &= I_A \end{aligned}}$$

Line-to-line voltage (V_{LL}) = line voltage = terminal voltage (V_T)



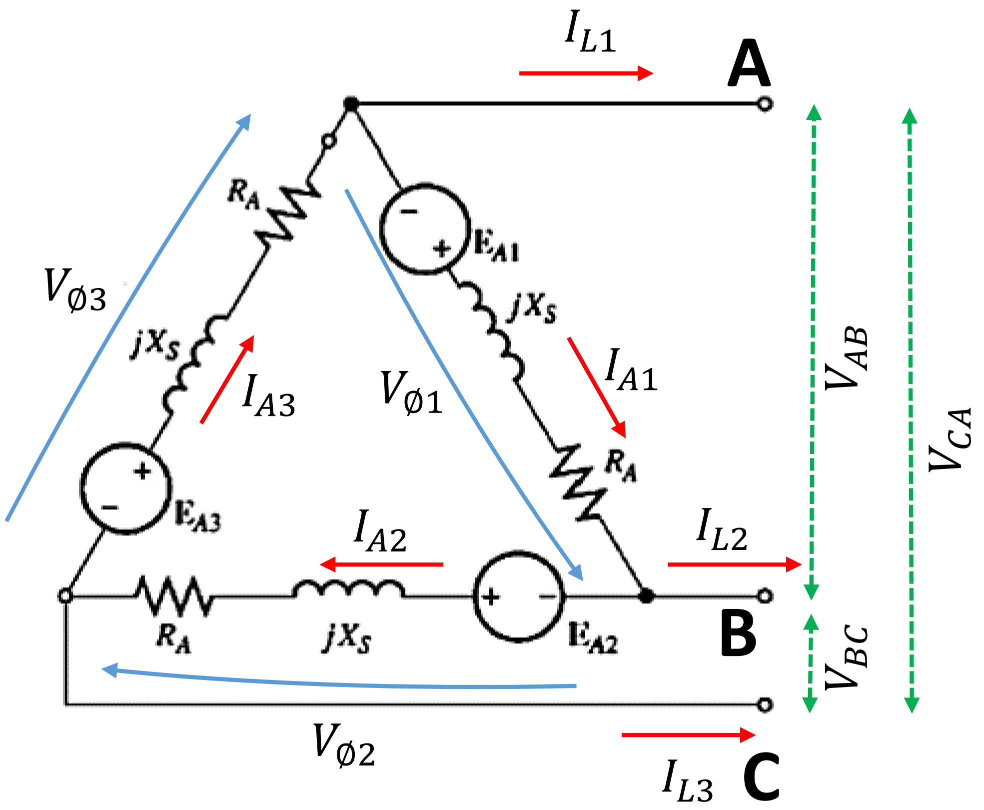
Equivalent circuit of stator connected in Y

Full equivalent circuit of synchronous generator

- The stator windings of the synchronous generator can be connected as **delta (Δ)**:

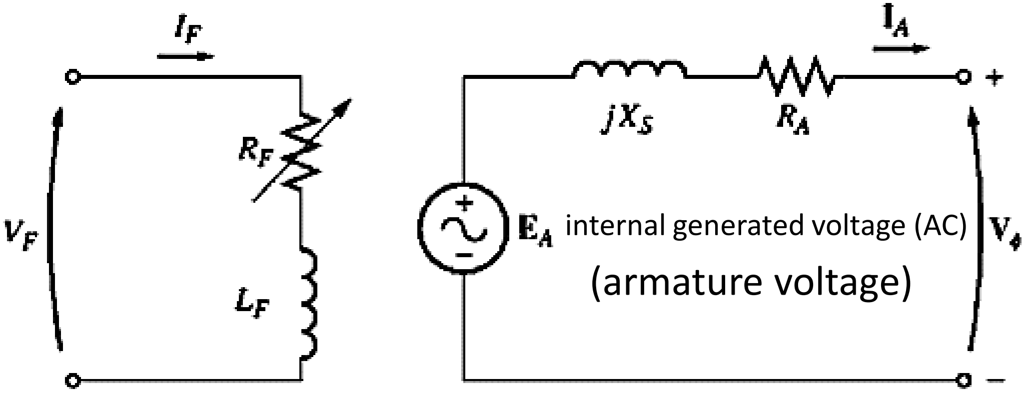
$$\left.\begin{aligned} |E_{A1}| &= |E_{A2}| = |E_{A3}| = E_A \\ |V_{\emptyset 1}| &= |V_{\emptyset 2}| = |V_{\emptyset 3}| = V_\emptyset \\ |V_{AB}| &= |V_{BC}| = |V_{CA}| = V_{LL} \\ |I_{A1}| &= |I_{A2}| = |I_{A3}| = I_A \\ |I_{L1}| &= |I_{L2}| = |I_{L3}| = I_L \end{aligned}\right\} \boxed{\begin{aligned} V_{LL} &= V_\emptyset \\ I_L &= \sqrt{3}.I_A \end{aligned}}$$

Line-to-line voltage (***V_{LL}***) = line voltage = terminal voltage (***V_T***)



Equivalent circuit of stator connected in Δ

Per-phase equivalent circuit of sync. gen.



Field current (DC)

Armature current (AC)

DC voltage source for field circuit

internal generated voltage (AC)

(armature voltage)

Phase voltage (AC)

Rotor side

Stator side (armature windings)

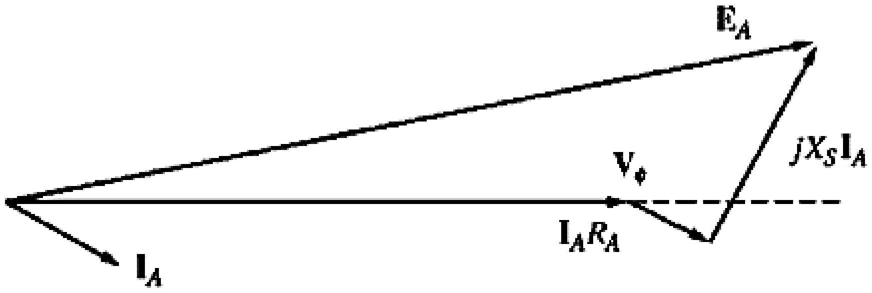
Field circuit

NOTE: By changing $\boldsymbol{R_F}$, we can control the magnitude of $\boldsymbol{E_A}$

$R_F \downarrow$ $I_F \uparrow$ $\uparrow |E_A|$

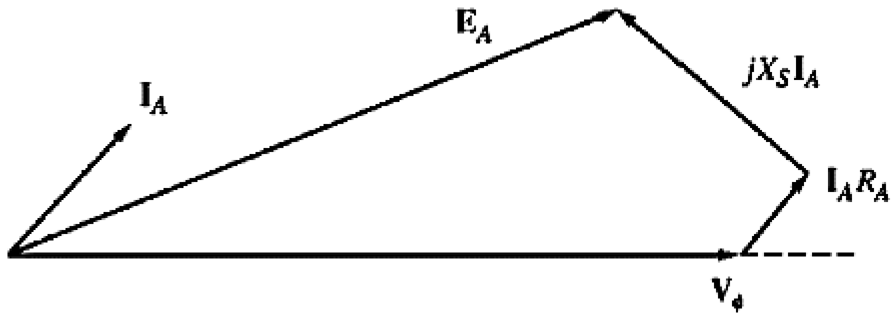
$R_F \uparrow$ $I_F \downarrow$ $\downarrow |E_A|$

Phasor diagram of a synchronous generator

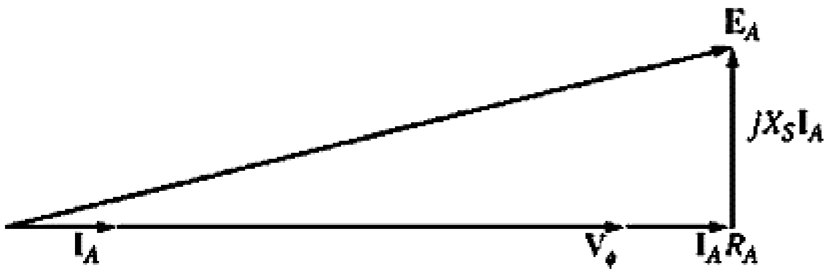


Syn. generator is supplying a **lagging power factor load** (*inductive load*)

(the most common case)



Syn. generator is supplying a **leading power factor load** (*capacitive load*)

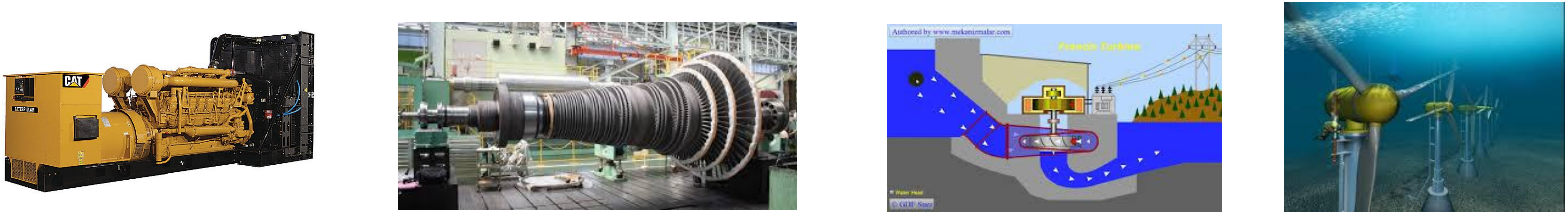


Syn. generator is supplying a **unity power factor load** (*purely resistive load*)

Power and torque in synchronous generators

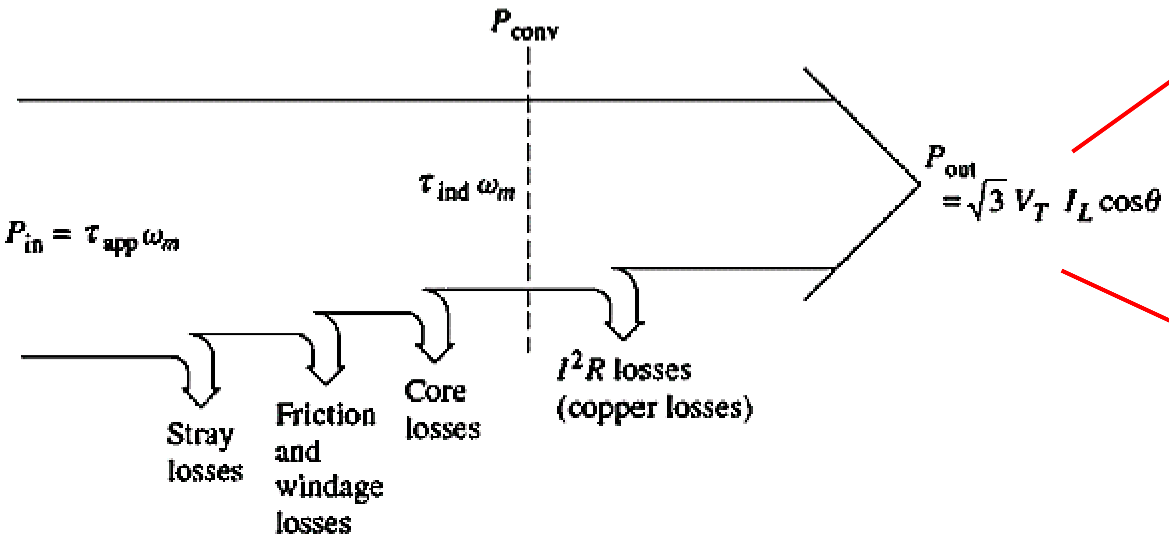
- A **synchronous generator** is a **synchronous machine** used as a **generator**
- **Synchronous generator** converts **mechanical power** into **three-phase electrical power**
- The **prime mover** is the source of **mechanical power**
- The prime mover can be a "***diesel engine***", "***steam turbine***", "***water turbine***", or any suitable system
- **<u>The rule is that:</u>** The prime mover **speed must be kept constant** in order to generate a **constant frequency of electrical power**

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



Different types of prime mover

Power-flow diagram of a synchronous generator



Y-connected stator

$$\left.\begin{aligned} V_T &= \sqrt{3}.V_\emptyset \\ I_L &= I_A \end{aligned}\right\}$$

$$P_{out} = \sqrt{3}.\sqrt{3}.V_\emptyset.I_A.cos\theta$$

$$\boxed{P_{out} = 3.V_\emptyset.I_A.cos\theta}$$

Δ-connected stator

$$\left.\begin{aligned} V_T &= V_\emptyset \\ I_L &= \sqrt{3}.I_A \end{aligned}\right\}$$

$$P_{out} = \sqrt{3}.V_\emptyset.\sqrt{3}.I_A.\cos\theta$$

$$\boxed{P_{out} = 3.V_\emptyset.I_A.cos\theta}$$

Power-flow diagram of a synchronous generator

$$P_{out} = \sqrt{3}.V_{\emptyset}.\sqrt{3}.I_A$$

$$P_{out} = 3.V_{\emptyset}.I_A.cos\theta$$

Three-phase output active (*real*) power of the synchronous generator

The unit is: W or kW or MW

$$Q_{out} = \sqrt{3}V_T.I_L.sin\theta$$

$$Q_{out} = 3.V_{\emptyset}.I_A.sin\theta$$

Three-phase output reactive power of the synchronous generator

The unit is: VAR or kVAR or MVAR

Y or Δ connected stator

$$S_{out} = P_{out} + jQ_{out}$$

Three-phase output complex power of the synchronous generator

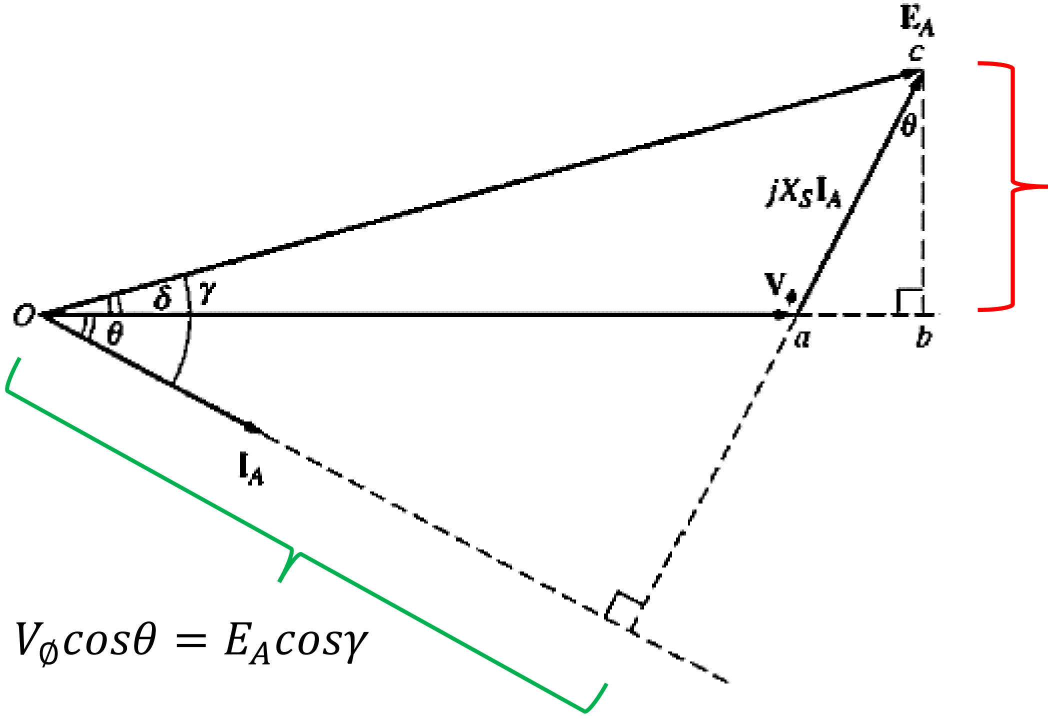
$$|S_{out}| = \sqrt{P_{out}{}^2 + Q_{out}{}^2}$$

Three-phase output apparent power of the synchronous generator

The unit is: VA or kVA or MVA

Power-flow diagram of a synchronous generator

- Generally **synchronous reactance** is much greater than **armature resistance** ($X_S \gg R_A$)
- Hence $R_A$can be ignored in most of the calculations (*but this is not always a rule !*)
- By geometric properties the following two equations can be written if $\boldsymbol{R_A}$ is ignored:



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

$$V_\emptyset cos\theta = E_A cos\gamma$$

Phasor diagram of sync. gen if $\boldsymbol{R_A}$ is ignored

Power-flow diagram of a synchronous generator

- Three practical equations for the synchronous generator can be obtained by the following derivations:
- At first;

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

$$I_A cos\theta = \frac{E_A sin\delta}{X_S}$$

- And since;

$$P_{out} = 3. V_{\emptyset}. I_A. cos\theta$$

$$\boxed{P_{out} = 3V_{\emptyset} \frac{E_A sin\delta}{X_S}}$$ (if ***R***

(if $\boldsymbol{R_A}$ is ignored)

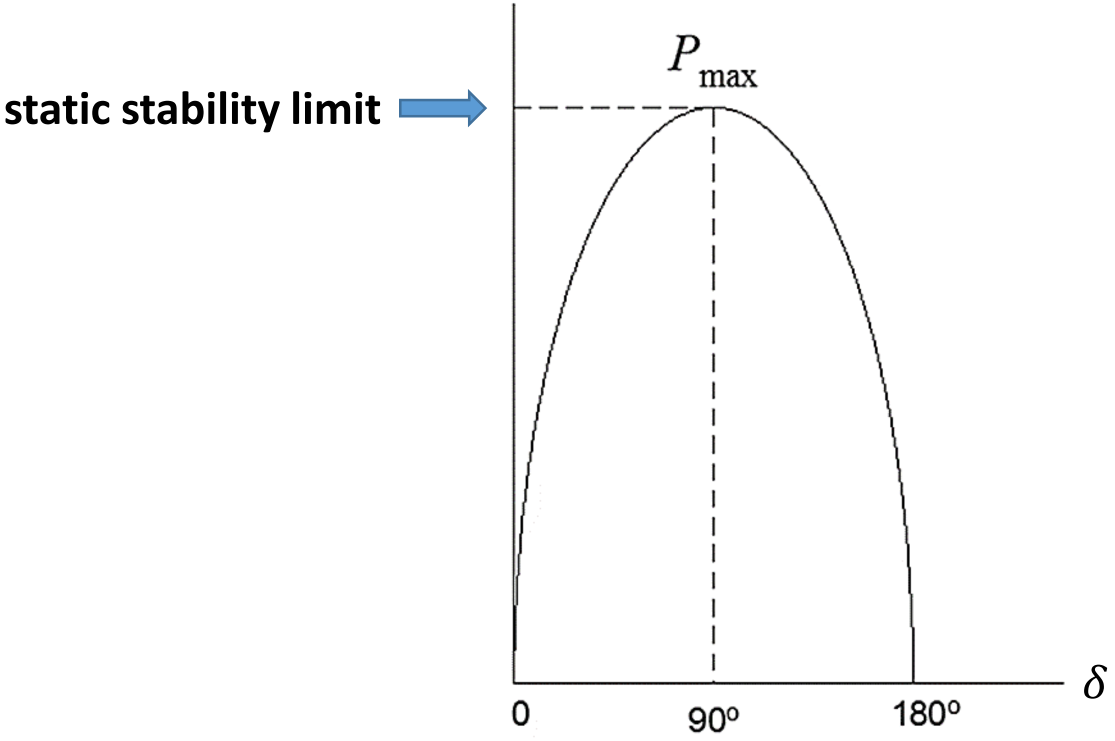
Power-flow diagram of a synchronous generator

- **Torque (power) angle** δ is increased by increasing driving torque
- **Maximum real power output** from a synchronous generator is attained **when δ = 90º**
- **If δ > 90º**, real power output suddenly drops to zero and **the machine losses synchronism**
- **$P_{out(max)}$** is called “**steady-state stability limit**” of the synchronous generator
- Generally, synchronous generators are operated with a **small torque angle** δ **(15°$\leq \boldsymbol{\delta} \leq \mathbf{20}$°)**

$$P_{out} = 3V_{\emptyset}\frac{E_A sin\delta}{X_S}$$ (if $\boldsymbol{R_A}$ is ignored)

$$P_{out(max)} = \frac{3V_{\emptyset}E_A}{X_S}$$ (when $\delta = 90°$)

Real power output and **output electrical frequency** are controlled by **generator governor** that controls input mechanical power



Power-flow diagram of a synchronous generator

- Secondly;
- When ***R***R_A is ignored, this means that **converted power** becomes equal to **output real power**

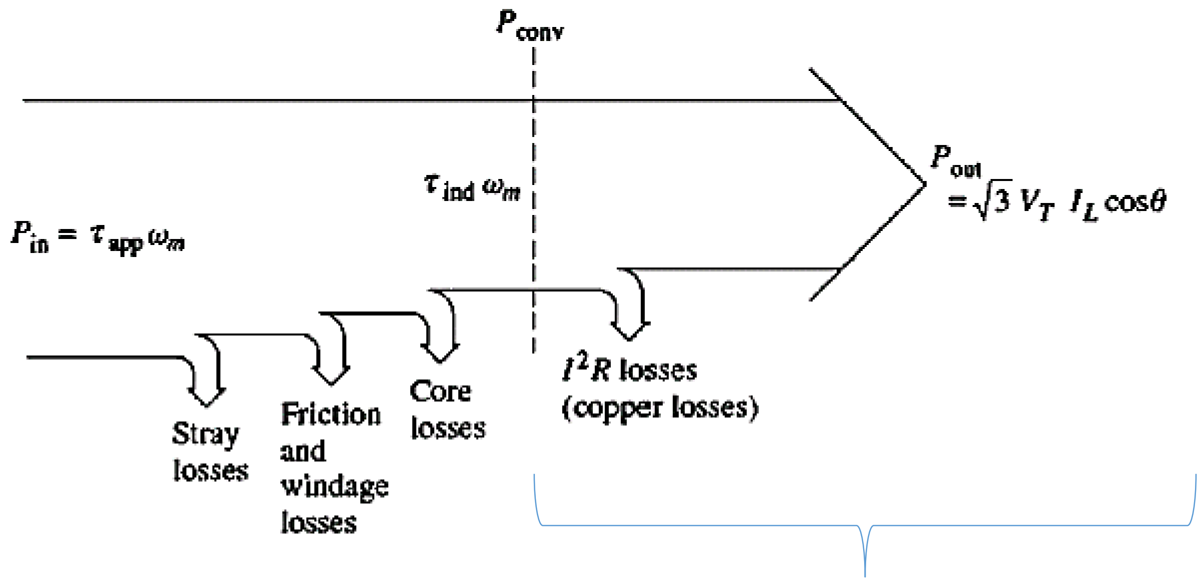
$$P_{conv} \cong P_{out}$$

- Since;

$$\left.\begin{aligned} P_{out} &= 3.V_{\emptyset}.I_A.cos\theta \\ V_{\emptyset}cos\theta &= E_A cos\gamma \end{aligned}\right\} P_{out} = 3.I_A.E_A cos\gamma$$

$$\tau_{ind} w_m \cong 3.I_A.E_A cos\gamma$$

$$\boxed{\tau_{ind} \cong 3.I_A.\frac{E_A cos\gamma}{w_m}}$$



$$P_{conv} \cong P_{out}$$

(If ***R***R_A *is ignored)*

Power-flow diagram of a synchronous generator

- Thirdly;
- Since;

$$P_{conv} \cong P_{out}$$

$$P_{out} = 3V_{\emptyset}\frac{E_A sin\delta}{X_S}$$

$$\tau_{ind} w_m \cong 3V_{\emptyset}\frac{E_A sin\delta}{X_S}$$

$$\boxed{\tau_{ind} = 3V_{\emptyset}\frac{E_A sin\delta}{w_m X_S}}$$

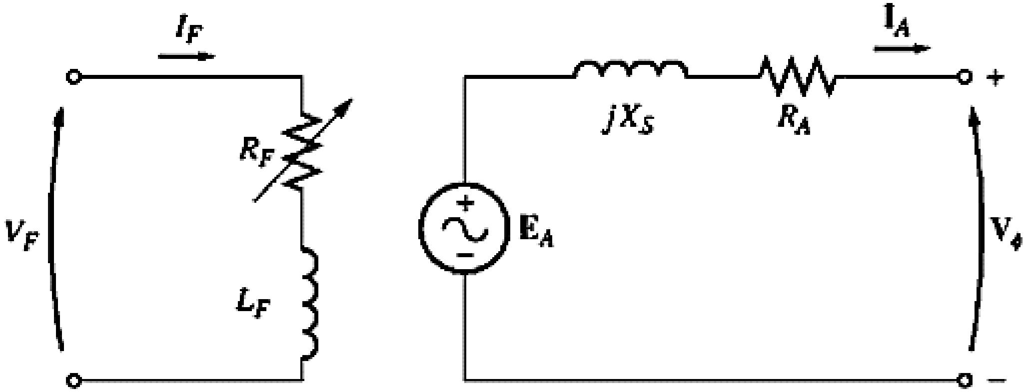
(if $\boldsymbol{R_A}$ is ignored)

Measuring sync. gen. model parameters

- The equivalent circuit of a synchronous generator that has been derived contains **three quantities** that must be determined in order to completely describe the behavior of a real synchronous generator:

1) The relationship between field current $\boldsymbol{I_F}$ and flux Ø (or between $\boldsymbol{I_F}$ and armature voltage $\boldsymbol{E_A}$)
2) Synchronous reactance, $\boldsymbol{X_S}$
3) Armature resistance, $\boldsymbol{R_A}$

- Different tests are applied to determine these quantities



Measuring sync. gen. model parameters

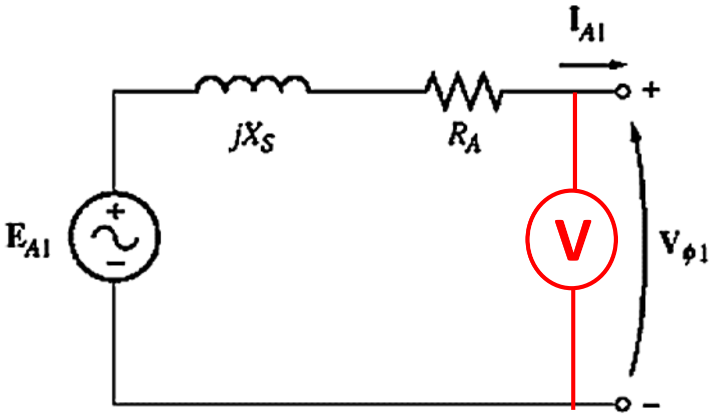
- The **first** test is «***open-circuit test***» on the synchronous generator
- The steps of this test can be listed as:
    - ➢ The **terminals of the stator** are **open circuited**
    - ➢ A voltmeter is connected through the terminals of the stator
    - ➢ The **field current** is set to **zero**
    - ➢ The generator is turned at the **rated speed** with the prime mover (for example an AC/DC motor)
    - ➢ The field current is **gradually increased in steps** and the **terminal voltage** is **measured** at each step
    - ➢ Since the stator is *open-circuited*, **armature voltage E_A** can be measured from stator terminals:

❑ İf stator is **Y-connected**:

$$V_{T(OC)} = \sqrt{3}.E_A \rightarrow E_A = \frac{V_{T(OC)}}{\sqrt{3}}$$

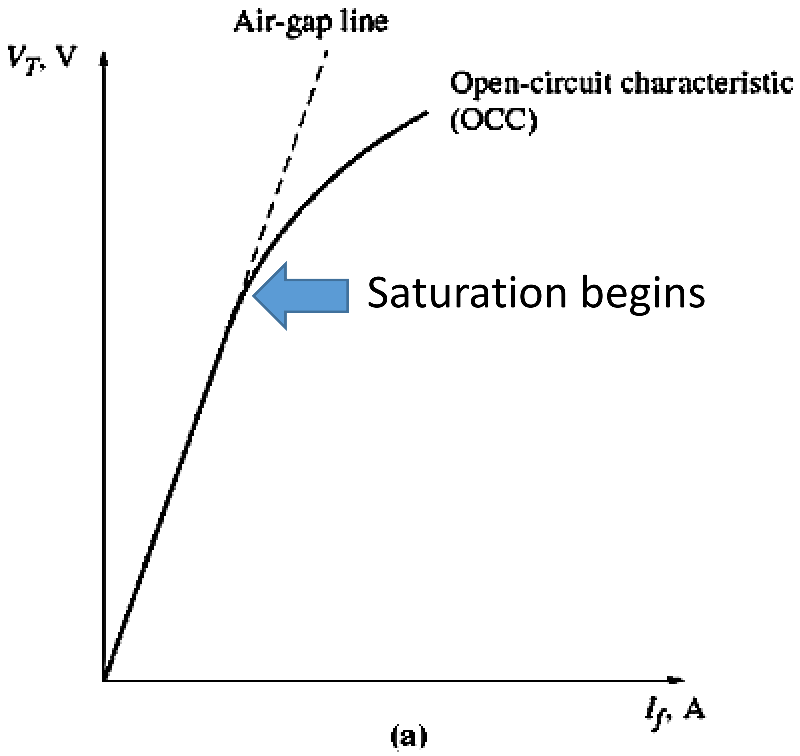
❑ İf stator is **Δ-connected**:

$$V_{T(OC)} = E_A$$



- ➢ The measured points are plotted to obtain **open-circuit characteristics**

Measuring sync. gen. model parameters



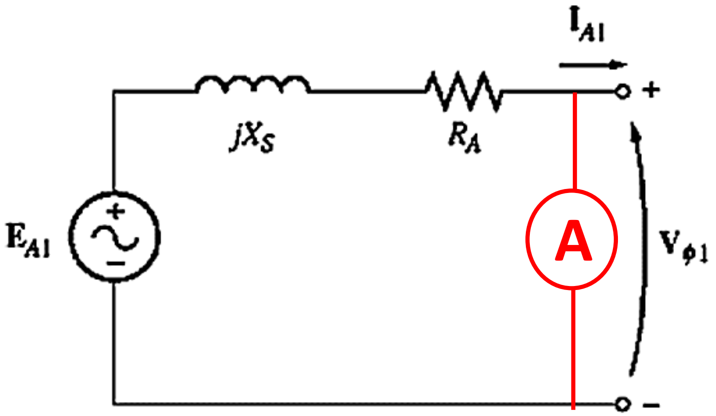
The **open-circuit characteristic** (*OCC*) of a three-phase synchronous generator

- With OCC, we can find the magnitude of $\boldsymbol{E_A}$ for any given field current $\boldsymbol{I_F}$
- Initially, the curve is almost perfectly **linear**, until some **saturation** is observed at high field currents
- When the iron finally saturates, the reluctance of the iron increases dramatically, and the flux increases much more slowly with an increase in magnetomotive force
- The linear portion of OCC is called «**air-gap line»**

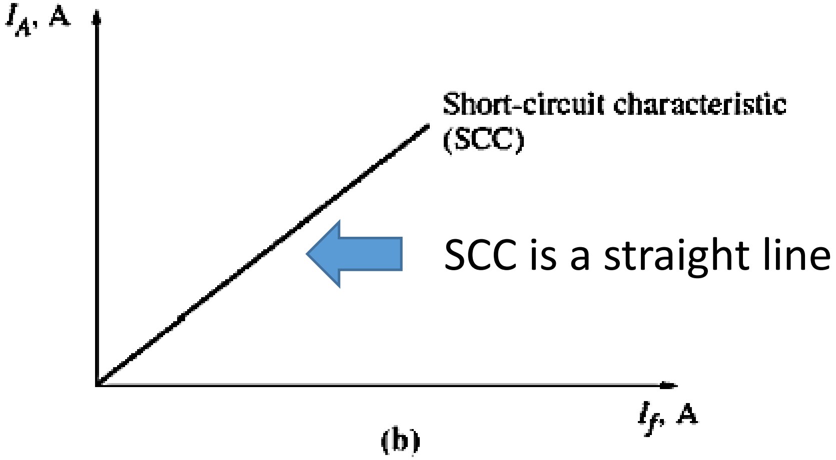
Measuring sync. gen. model parameters

- The **second** test is «***short-circuit test***» on the synchronous generator
- The steps of this test can be listed as:

  - The **terminals of the stator** are **short-circuited using an *ammeter***
  - **The field current** is set to **zero**
  - The generator is turned at the **rated speed** with the prime mover (for example an AC/DC motor)
  - The field current is **gradually increased in steps** and the **short-circuit armature current** (or *line current*) (*ammeter reading*) is mesaured
  - The measured points are plotted to obtain **short-circuit characteristics**



Measuring sync. gen. model parameters



SCC is a straight line

The **short-circuit characteristic** (*SCC*) of a three-phase synchronous generator

Measuring sync. gen. model parameters

- **An important question:** *Why is SCC a straight line*?
- Since;

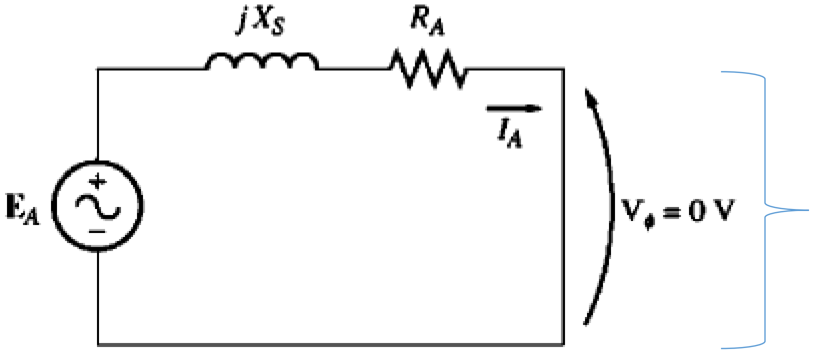
$V_{\emptyset} = E_A + E_{STAT} = 0$ (*Short-circuit*)

$E_A = -E_{STAT}$

- Since $\boldsymbol{B_R}$ is related with $\boldsymbol{E_A}$ and,
- $\boldsymbol{B_S}$ is related with $\boldsymbol{E_{STAT}}$
- $\boldsymbol{B_R}$ and $\boldsymbol{B_s}$ will **cancel** each other
- So there will be **no magnetic field** in the machine and hence **no saturation is observed**
- Because of this reason, **SCC of a synchronous generator is a straight line**

Measuring sync. gen. model parameters

- Let’s join the results of these two tests (*open-circuit and short-circuit tests*) to find X_S:



Short-circuit

$$I_A = \frac{E_A}{R_A + jX_S} \Rightarrow |I_A| = \frac{|E_A|}{\underbrace{\sqrt{{R_A}^2 + {X_S}^2}}_{|Z_S|\ \text{(synchronous impedance)}}}$$

(The magnitude of armature current)

Measuring sync. gen. model parameters

- Since;

$$|Z_S| = \sqrt{{R_A}^2 + {X_S}^2}$$

- And generally;

$$X_S \gg R_A$$

$$|Z_S| \cong X_S$$

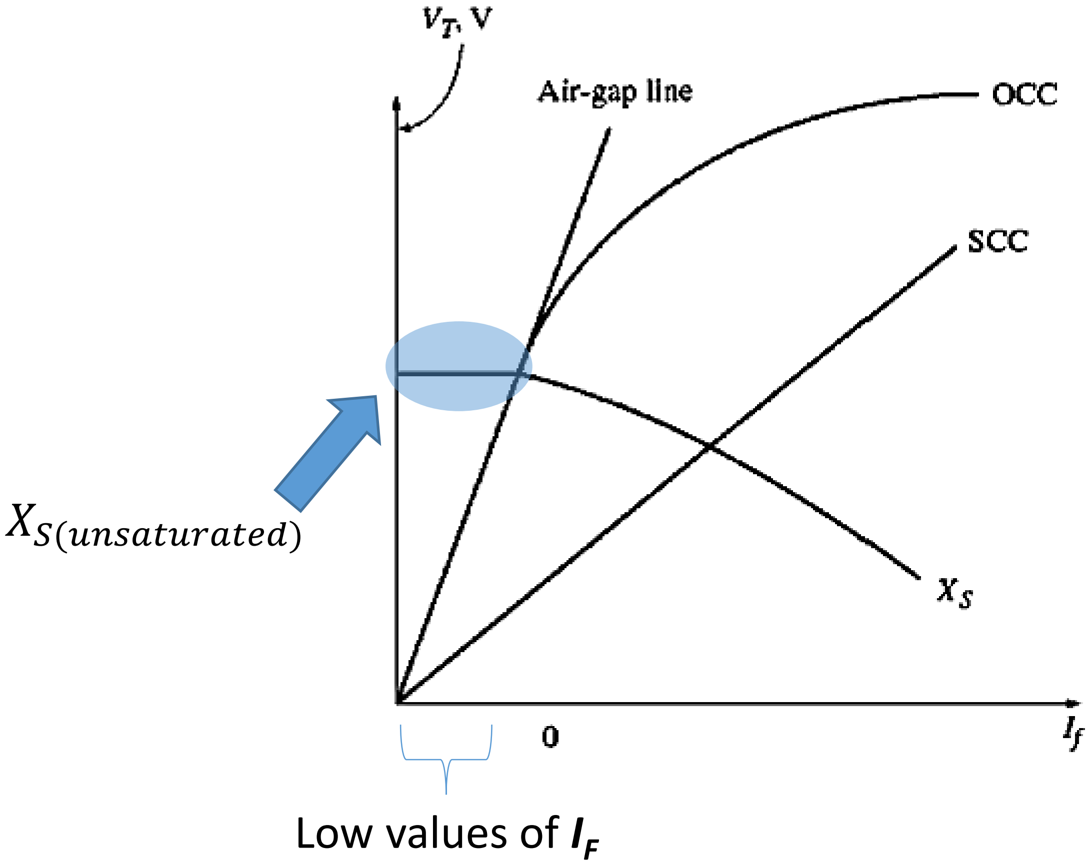
$$X_S \cong \frac{|E_A|}{|I_A|} = \frac{\left|V_{\emptyset(OC)}\right|}{|I_A|}$$

- Therefore, an approximate method for determining the synchronous reactance ***Xs*** at a given field current is

1) Get the internal generated voltage $\boldsymbol{E_A}$ from **OCC** at that field current
2) Get the short-circuit current $\boldsymbol{I_{A,SC}}$ from **SCC** at that field current
3) Find **Xs** by applying the below equation.

Measuring sync. gen. model parameters

- But with this method we can only find the **approximated value** of **Xs** in **unsaturated region**
- We have to use **low field current values** to find the value of **Xs** in **unsaturated region**

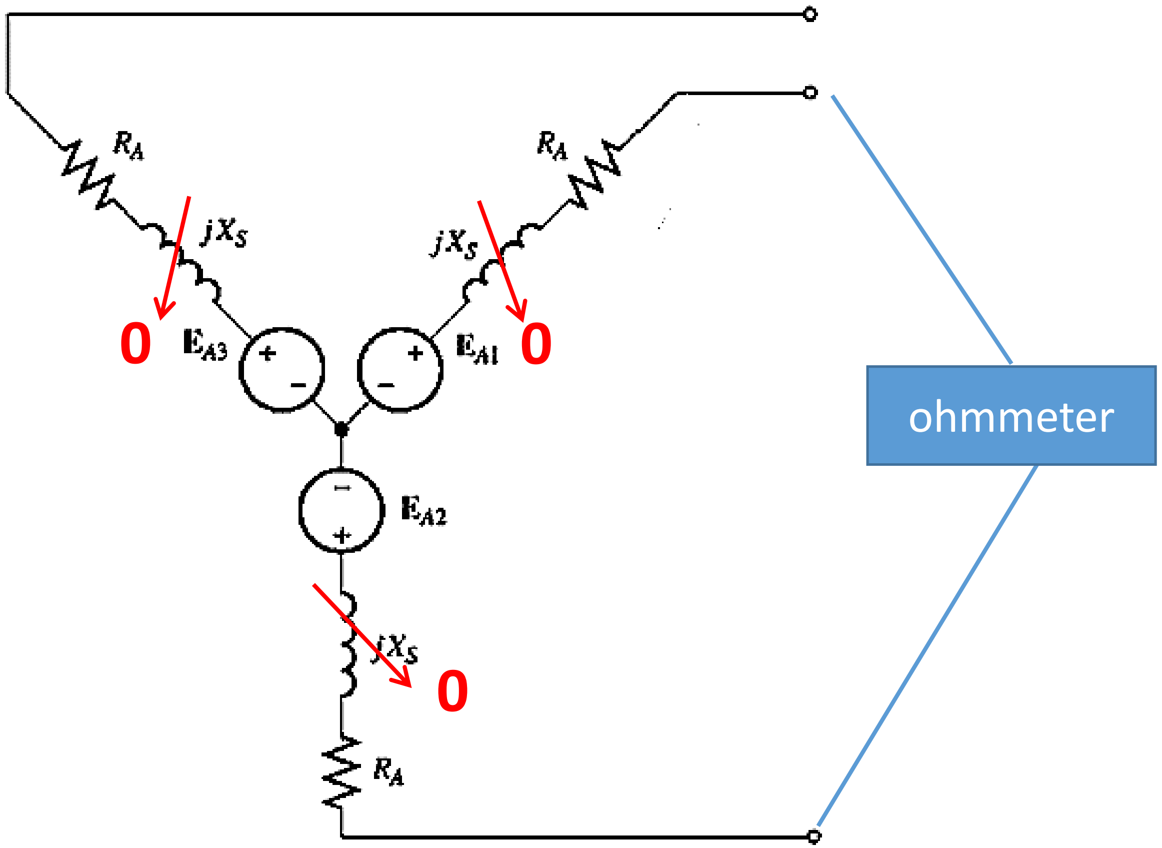


Measuring sync. gen. model parameters

- The **third** test is «***armature resistance measurement test***» on the synchronous generator
- The steps of this test can be listed as:

  - Stop the rotation of the rotor of the synchronous generator
  - Set the **field current** to **zero**
  - Measure the armature resistance by an ohmmeter (ohmmeter uses DC voltage)
  - or apply a DC voltage to the armature windings and meausure the armature current
  - The reason of using DC voltage is to set all reactances to be zero (frequency will be zero)
  - This technique is **not perfectly accurate**, since the **AC resistance** will be larger than **DC resistance** because of the **skin effect**

Measuring sync. gen. model parameters

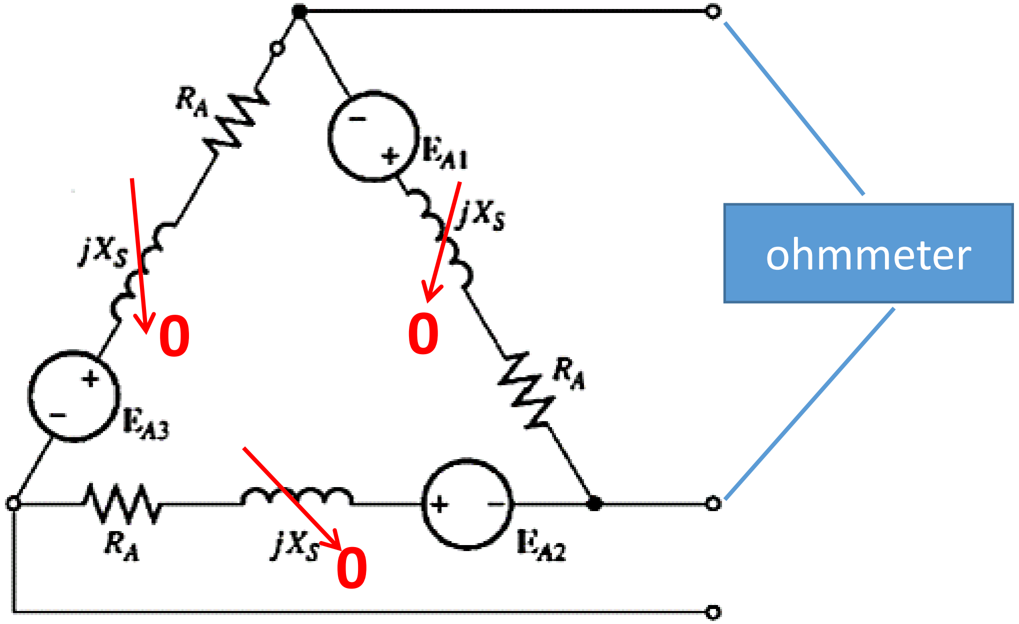


$$ohmmeter\ reading = 2R_A$$

$$R_A = \frac{ohmmeter\ reading}{2}$$

Applying armature resistance measurement test to **Y-connected** stator

Measuring sync. gen. model parameters



$$ohmmeter\ reading = (R_A{+}R_A)\ parallel\ with\ R_A)$$

$$ohmmeter\ reading = \frac{2}{3} R_A$$

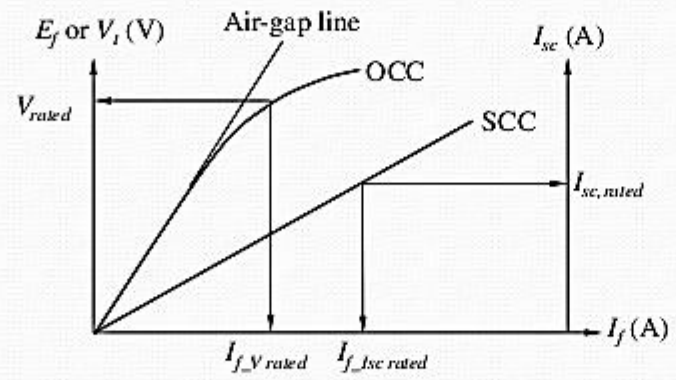
$$R_A = \frac{ohmmeter\ reading}{2/3}$$

Applying armature resistance measurement test to **Δ-connected** stator

Short-circuit ratio

- **The short-circuit ratio (SCR)** of a **synchronous generator** is defined as 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**

- **SCR** is also the reciprocal of the per-unit value of the approximate saturated synchronous reactance



$$SCR = \frac{I_{f\_Vrated}}{I_{f\_Iscrated}}$$

$$= \frac{1}{X_{s\_sat}\,[in\ p.u.]}$$

Short-circuit ratio

Example: A 200-kVA, 480-V, 50-Hz, Y-connected synchronous generator with a rated field current of 5 A was tested, and the following data were taken:

1. $V_{T,OC}$ at the rated field current was measured to be **540 V**
2. $I_{L,SC}$ at the rated field curretn was measured to be **300 A**
3. When a DC voltage of **10 V** was applied to the two of the terminals of the stator, a current of **25 A** was measured.

Find the values of the **armature resistance** and the **approximate synchronous reactance** in ohms that would be used in the generator model at the rated conditions.

Short-circuit ratio

Solution:

From armature resistance measurement test :

Since stator is Y-connected:

$$R_A = \frac{ohmmeter\ reading}{2}$$

$$R_A = \frac{10V/25A}{2} = 0.2\ ohm$$

Short-circuit ratio

Solution:

- The internal generated voltage at the rated field current is equal to:

$$E_A = V_{\emptyset(OC)} = \frac{V_T}{\sqrt{3}} = \frac{540V}{\sqrt{3}} = 311.8\ V$$

- The short-circuit current is equal to the line current, since the generator is Y-connected:

$$I_{A(SC)} = I_{L(SC)} = 300\ A$$

$$|Z_S| = \sqrt{R_A{}^2 + X_S{}^2} = \frac{E_A}{I_A} = \frac{311.8}{300} = 1.039\ ohm$$

Alternative way:

$$X_S \cong \frac{|E_A|}{|I_A|} = \frac{|V_{\emptyset(OC)}|}{|I_A|} = \frac{311.8}{300} = 1.039$$

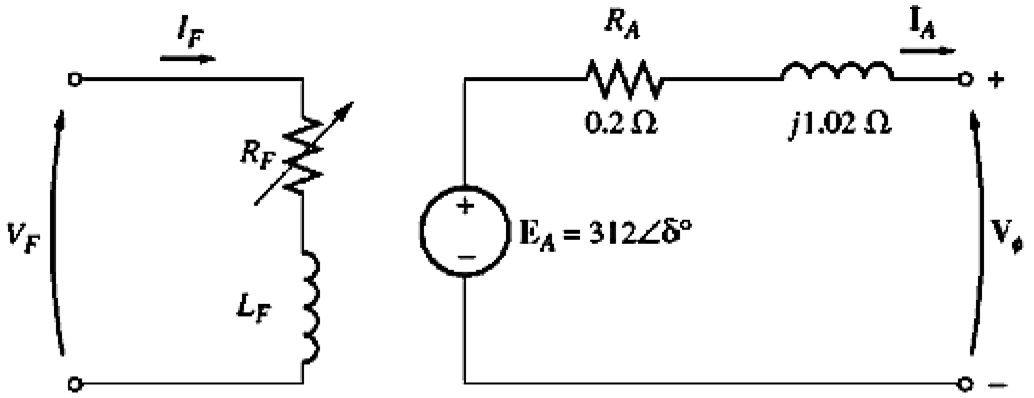
- Since;

$$R_A = 0.2\ ohm \Rightarrow \sqrt{(0.2)^2 + X_S{}^2} = 1.039 \Rightarrow X_S = 1.02\ ohm$$

Short-circuit ratio

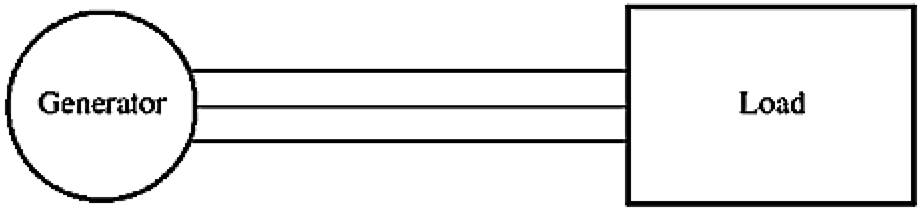
Solution:

- The resulting per-phase equivalent circuit of the synchronous generator is shown below:



Synchronous generator operating alone

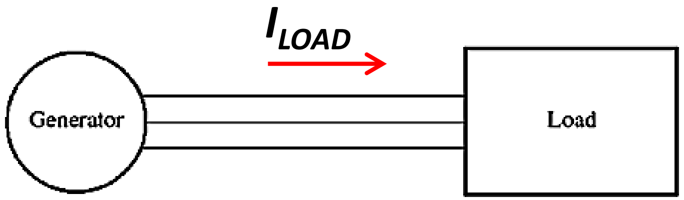
- A sync. generator is **rarely operated alone** for *emergency purposes* or a *few specialized applications*
- We assume that R_A (armature resistance) is generally **ignored** in our analysis
- We assume that **shaft speed** is **constant** (generator output frequency is **constant**, *50 or 60 Hz*)
- If otherwise not stated we can assume that I_F and hence the flux (**ϕ**) is constant in the machine
- The field current on the rotor (I_F) can be controlled if desired



Synchronous generator operating alone (*connected to load*)

Synchronous generator operating alone

- Now assume that the **load of the generator is increased !**
- *What happens now ?*



- ➢ An increase in the load means that the load's **real** and/or **reactive power** taken from the generator is **increased**
- ➢ Such a **load increase** increases the **load current** drawn from the generator

$P_{LOAD} \nearrow$ $I_{LOAD} \nearrow$

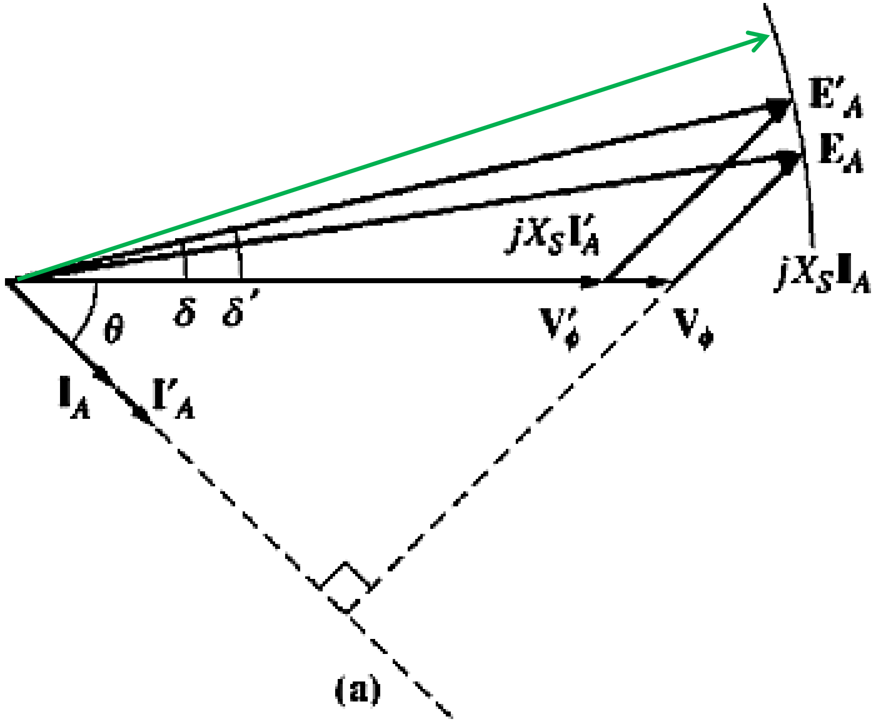
- ➢ The magnitude of the internal generated voltage E_A **<u>does not change</u>** *when the load increases*, because;
  - ✓ we do not change field current I_F, hence the flux in the machine (**ϕ)** is constant
  - ✓ the speed of the prime mover is constant (**w**)

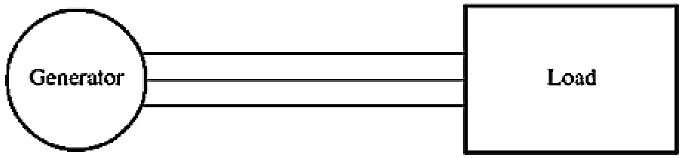
$$\underbrace{|E_A|}_{\textbf{constant}} = K\underset{\textbf{constant}}{\underset{\uparrow\;\uparrow}{\emptyset w}}$$

Synchronous generator operating alone

Lagging power factor case:

$$|E_A| = K\emptyset w = constant$$





Green distance is constant

The results:

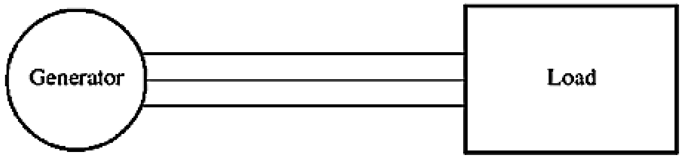
1) Phase voltage of the generator **decreases**
2) Torque angle **increases**

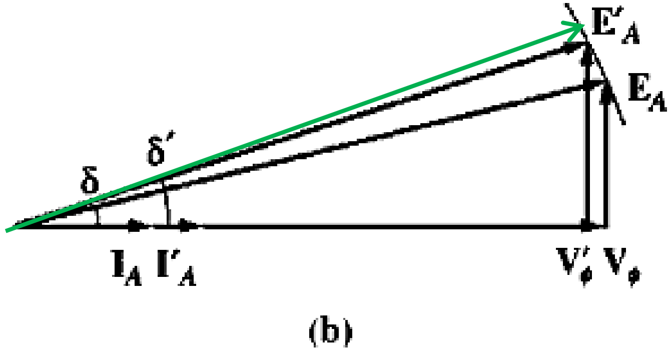
The effect of an increase in the load at **lagging power factor**

Synchronous generator operating alone

Unity power factor case:

$|E_A| = K\emptyset w = constant$





Green distance is constant

The results:

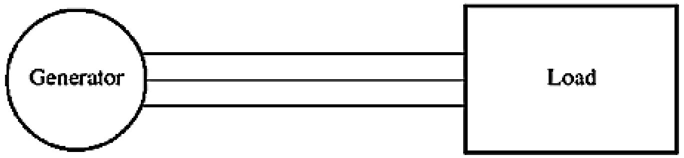
1) Phase voltage of the generator **decreases**
2) Torque angle **increases**

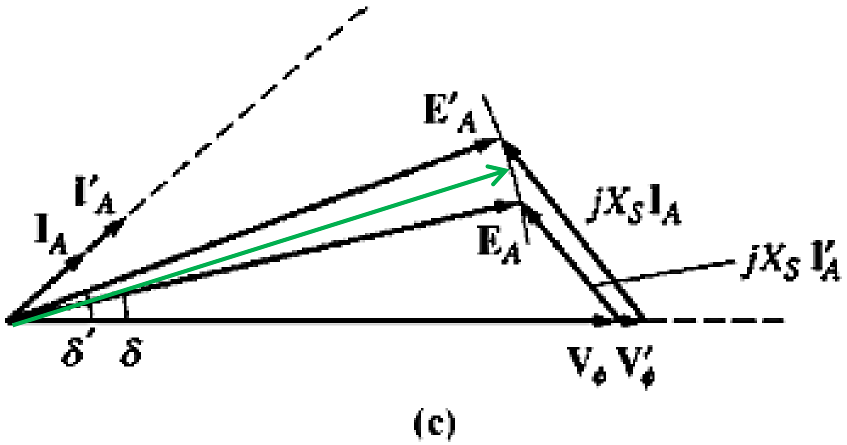
The effect of an increase in the load at **unity power factor**

Synchronous generator operating alone

Leading power factor case:

$|E_A| = K\emptyset w = constant$





Green distance is constant

The results:

1) Phase voltage of the generator **increases**

2) Torque angle **increases**

The effect of an increase in the load at **leading power factor**

Synchronous generator operating alone

- In summary:

If we increase the load connected to the sychronous generator;

- Phase voltage (and also terminal voltage) **decreases** if the load has a **lagging power factor**
- Phase voltage (and also terminal voltage) **decreases** if the load has a **unity power factor**
- Phase voltage (and also terminal voltage) **increases** if the load has a **leading power factor**

- And **torque angle increases for all cases**

Synchronous generator operating alone

Voltage Regulation and Load type:

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} x100\%$$

1) If load is **lagging power factor load**:

$$V_{fl} < V_{nl} \; \rightarrow VR > 0$$

2) If load is **unity power factor load**:

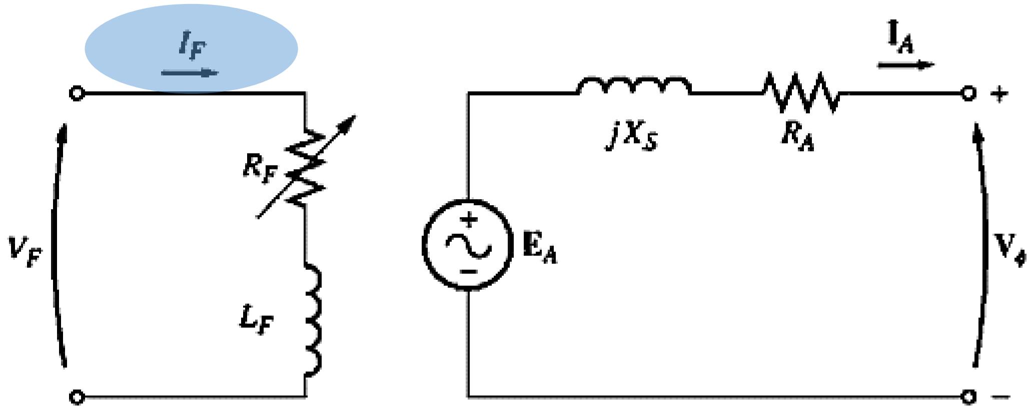
$$V_{fl} < V_{nl} \; \rightarrow VR > 0$$

3) If load is **leading power factor load**:

$$V_{fl} > V_{nl} \; \rightarrow VR < 0$$

Synchronous generator operating alone

- We see that in previous section, **terminal voltage of generator changes when load changes**.
- So what can we do to restore the voltage to its previous value ?
- **<u>The solution:</u>** **Adjust field current**
- **<u>Our purpose:</u>** $VR \approx 0$



$R_F \downarrow \quad I_F \uparrow \quad \emptyset \uparrow \qquad \uparrow |E_A| = K\emptyset w \quad \uparrow |V_\emptyset| \quad \uparrow |V_T|$

Synchronous generator operating alone

Example 1: A 480-V, 60-Hz, delta-connected, four-pole synchronous generator has the OCC shown in the figure. This generator has a synchronous reactance of j0.1 ohm and armature resistance of 0.0125 ohm. At full-load , the machine supplies 1200A at 0.8 PF lagging. Under full-load conditions. the friction and windage losses are 40 kW and the core losses are 30 kW. Ignore any field circuit losses.

(a) What is the speed of rotation of this generator?

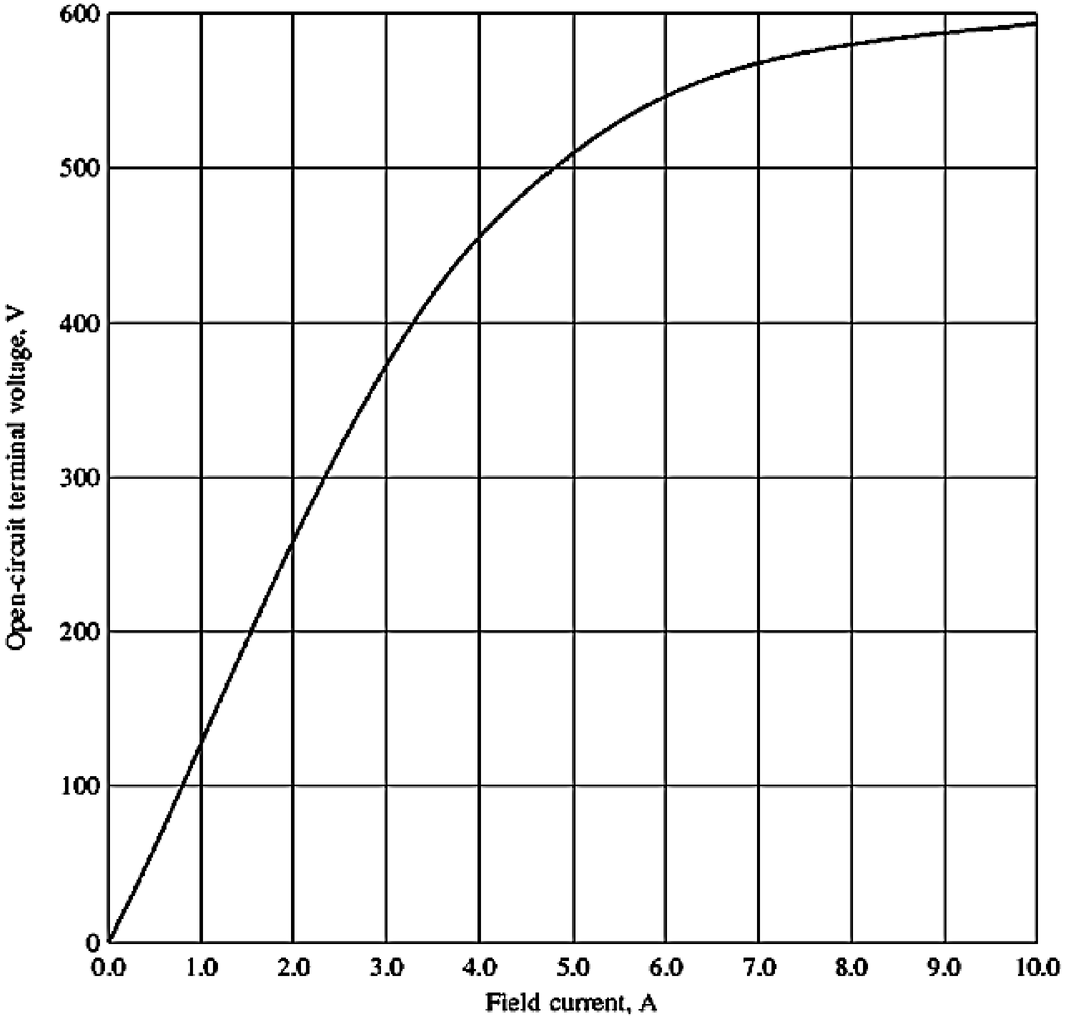
(b) How much field current must be supplied to the generator to make the terminal voltage 480 V at no load?

(c) If the generator is now connected to a load and the load draws 1200 A at 0.8 PF lagging, how much field current will be required to keep the terminal voltage equal to 480 V?

(d) How much power is the generator now supplying? How much power is supplied to the generator by the prime mover? What is this machine's overall efficiency?

(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?
(j) Finally, suppose that the generator is connected to a load drawing 1200 A at 0.8 PF *leading.* How much field current would be required to keep VT at 480 V?

Synchronous generator operating alone



OCC characteristics of the synchronous generator

Synchronous generator operating alone

Example 2: A 480-V, 50-Hz, Y-connected, six-pole synchronous generator has a per-phase synchronous reactance of 1.0 ohm. Its full-load armature current is 60 A at 0.8 PF lagging. This generator has friction and windage losses of 1.5 kW and core losses of 1.0 kW at 60 Hz at full load. Since the armature resistance is being ignored, assume that the copper losses are negligible. The field current has been adjusted so that the terminal voltage (VT) is 480 V at no load.

(a) What is the speed of rotation of this generator?

(b) What is the terminal voltage of this generator if the following are true?

1. It is loaded with the rated current at 0.8 PF lagging.
2. It is loaded with the rated current at 1.0 PF.
3. It is loaded with the rated current at 0.8 PF leading.

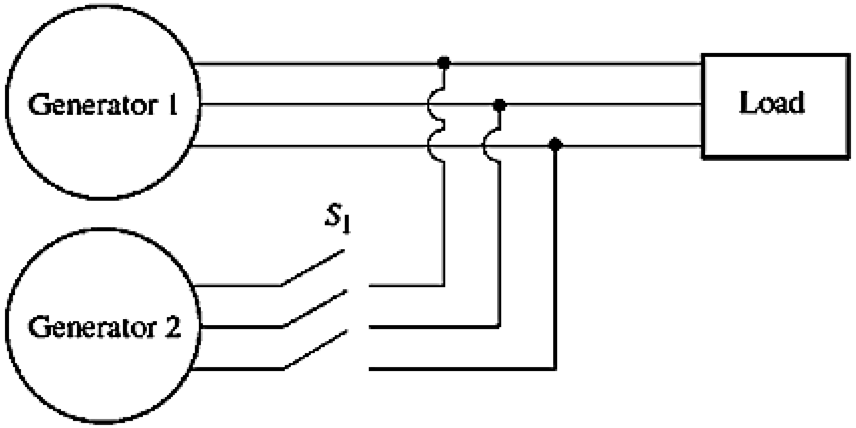
(c) What is the efficiency of this generator (*ignoring electrical losses*) when it is operating at the rated current and 0.8 PF lagging?

(d) How much shaft torque must be applied by the prime mover at full load? How large is the induced torque ?

(e) What is the voltage regulation of this generator at 0.8 PF lagging? At 1.0 PF? At 0.8 PF leading?

Parallel operation of AC generators

Why do we need parallel operation of AC generators?



- Several generators can supply a bigger load than one machine by itself.

- Having many generators increases the reliability of the power system, since the failure of anyone of them does not cause a total power loss to the load.

- Having many generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.

- If only one generator is used and it is not operating at near full load, then it will be relatively inefficient. With several smaller machines in parallel, it is possible to operate only a fraction of them. The ones that do operate are operating near full load and thus more efficiently.

Conditions required for paralleling

- Before paralleling (*closing switch S1*) some conditions should be satisfied:

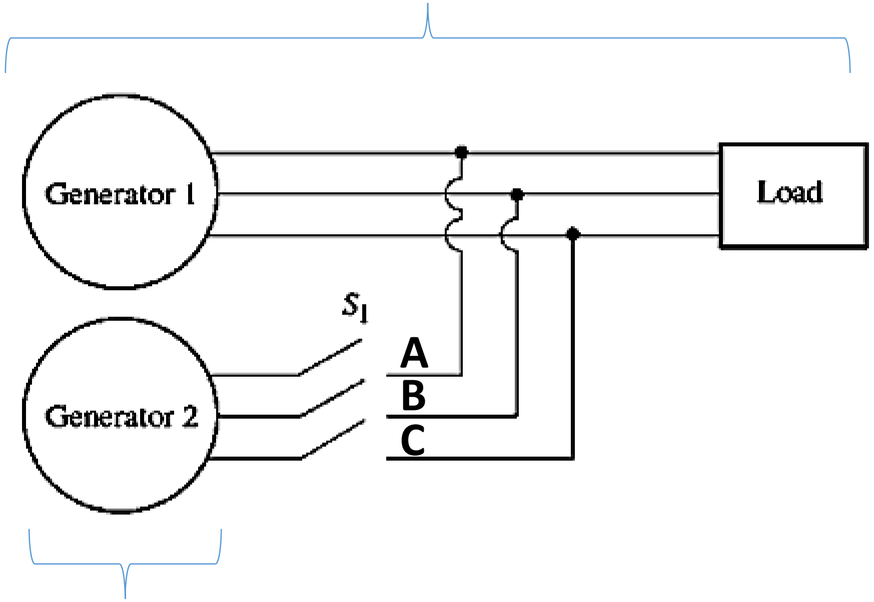
1) The **rms line voltages** of the two generators must be **equal**

$$|VAB|\ for\ G1 = |VAB|\ for\ G2$$

$$|VBC|\ for\ G1 = |VBC|\ for\ G2$$

$$|VCA|\ for\ G1 = |VCA|\ for\ G2$$

Running system

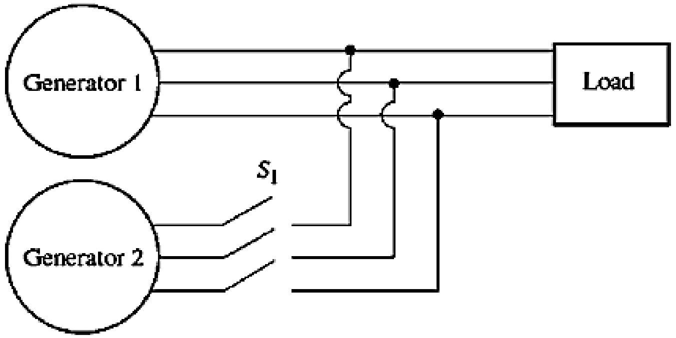


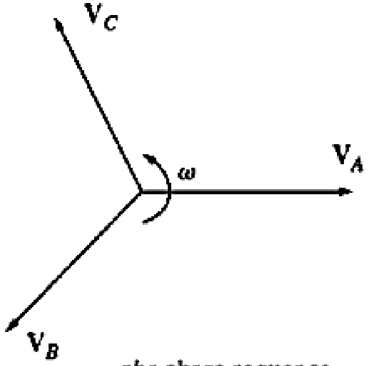
Oncoming generator

- Adjusting the line voltage of the *oncoming generator* is done by adjusting its **field current**.
- By using **voltmeter**, the field current of the oncoming generator should be adjusted until its terminal voltage becomes equal to the line voltage of the running system.

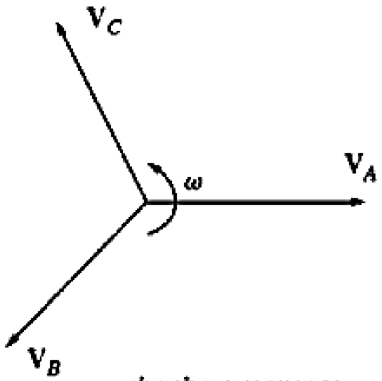
Conditions required for paralleling

2) The two generators must have the **same phase sequence**



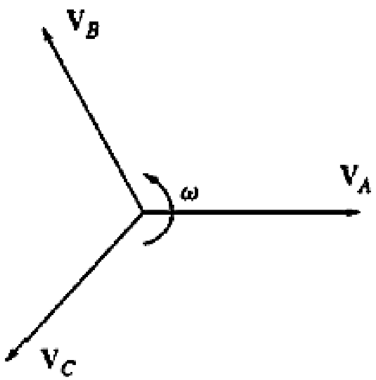


abc phase sequence

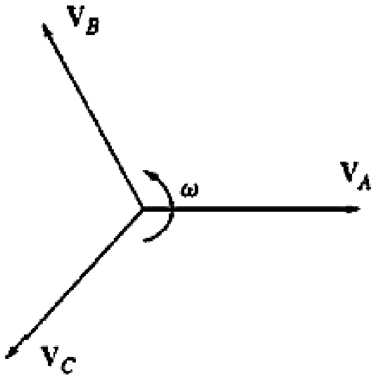


abc phase sequence

Gen1 Positive phase sequence **Gen2**



acb phase sequence

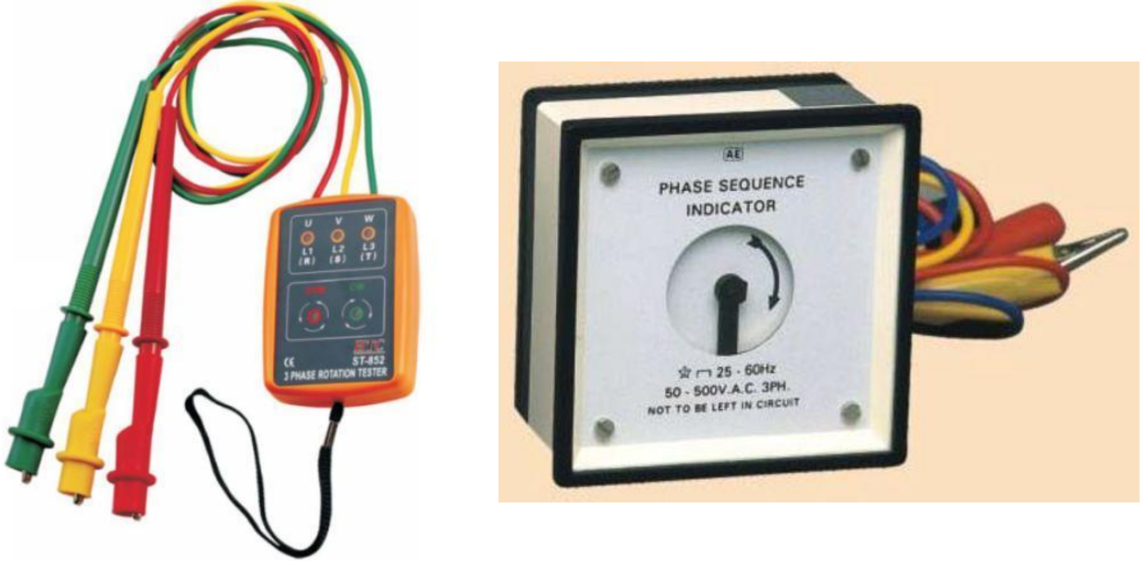


acb phase sequence

Gen1 Negative phase sequence **Gen2**

Conditions required for paralleling

- To check phase sequences we have three options:

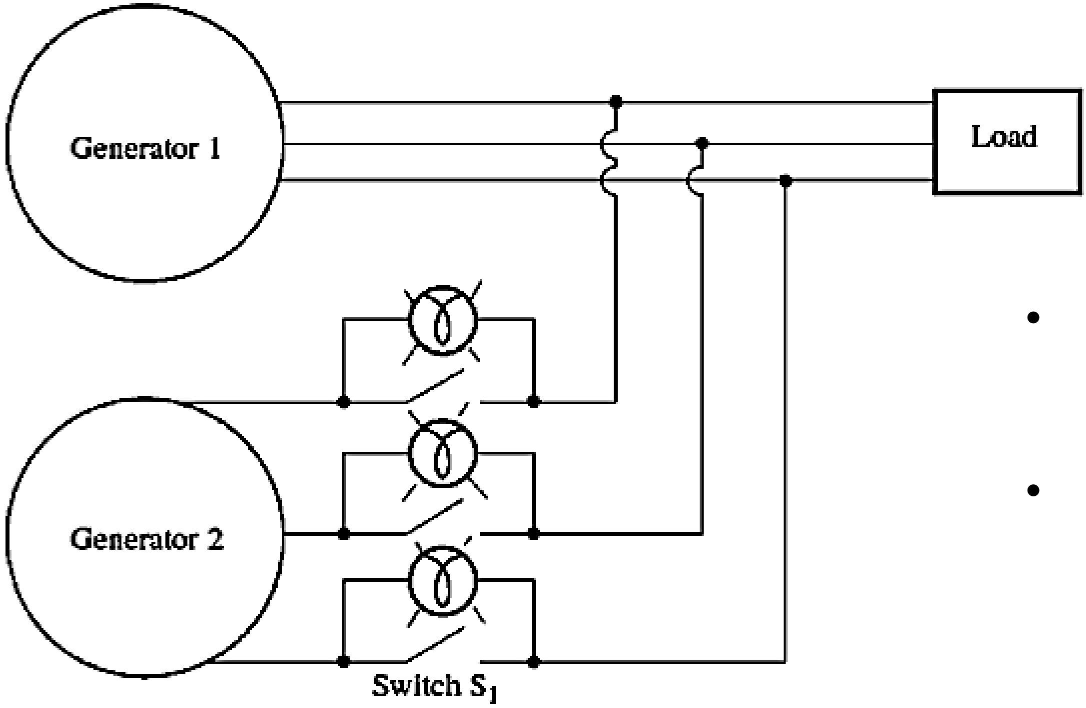


Option 1: use phase sequence indicator

Option 2: use a small three-phase induction motor and observe its rotation direction

Conditions required for paralleling

- To check phase sequences we have three options:

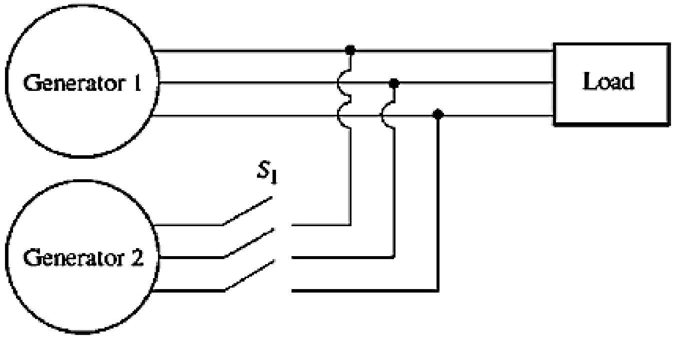


- If all three bulbs **get bright and dark together**, this means that both generators have the same phase sequence
- If the bulbs **brighten in succession**, this means that the generators have the opposite phase sequence, and two phases of the Gen 2 **must be exchanged**

Option 3: Use three-bulbs connected as shown

Conditions required for paralleling

3) The **frequency of the oncoming generator** must be adjusted to be **slightly higher** than the frequency of the running system. So that when it is connected, it will come on the line supplying power as a **generator**, instead of consuming the power as a **motor**



This check can be done by **two options**:

1) Use a frequency meter

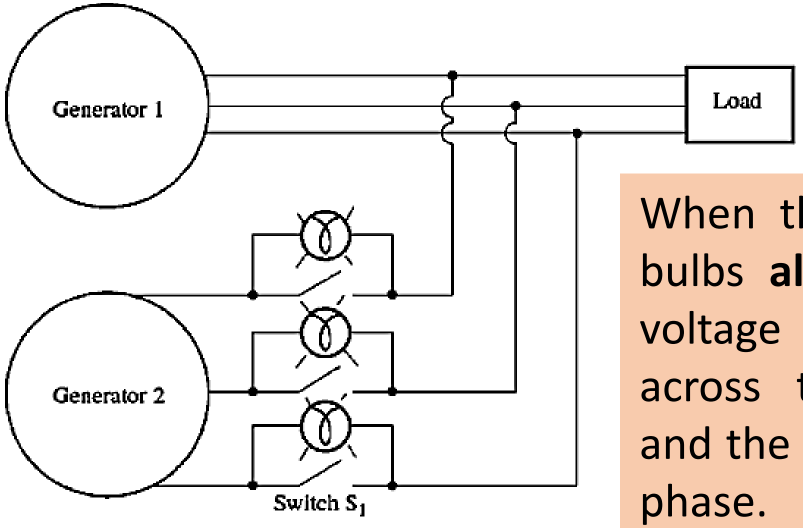
2) Use a tachometer to measure the shaft speed of Gen 2

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

Conditions required for paralleling

4) The **phase angles** of the same phases must be **equal**.

- To check phase angles we have **two options:**



When the three light bulbs **all go out**, the voltage difference across them is **zero** and the systems are in phase.

Option 1: Use three-bulbs method

Conditions required for paralleling

Option 2: Use a synchroscope

A ***synchroscope*** is a meter that measures the phase angle difference between the ***a-phases*** of the two systems.

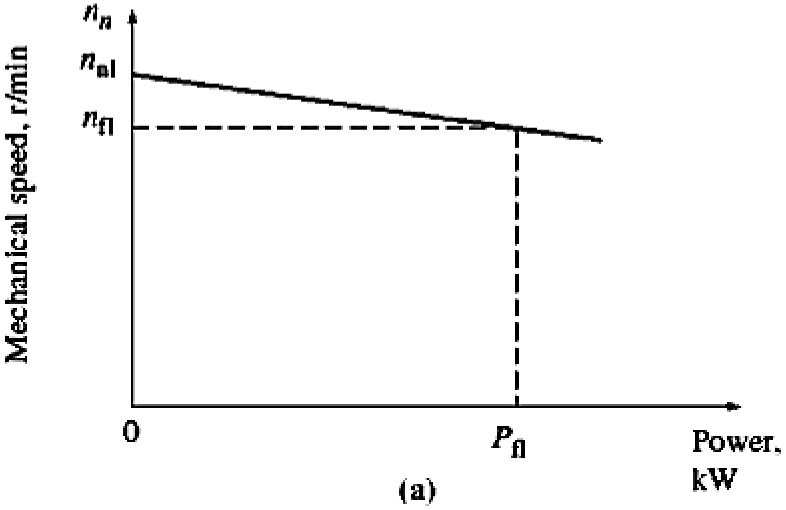
How can we use synchronoscope ?

- The needle should **rotate slowly**.
- ***If it rotates to the right***: This means that the oncoming generator is **faster** than the running system (***the desired situation***)
- ***If it rotates to the left***: This means that the oncoming generator is **slower** than the running system
- When the synchroscope needle is **in the vertical position**, **we can close switch S1**

Frequency-Power characteristics

- All generators are driven by a *prime mover*, which is the generator's source of mechanical power. Examples are steam turbine, diesel engines, gas turbines, water turbines, wind turbines, etc...

- All prime movers tend to behave in a similar fashion: **The power drawn from them increases, the speed at which they turn decreases.**



The speed vs power characteristics for a typical prime mover

Frequency-Power characteristics

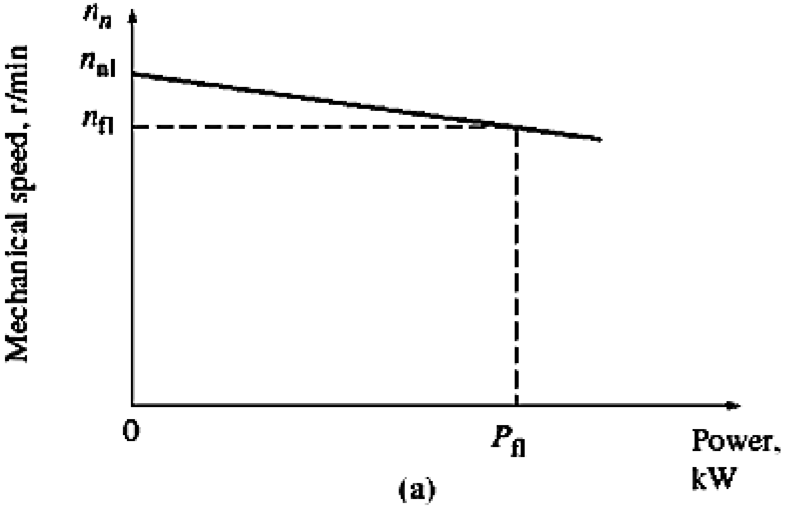
- The speed droop (**SD**) of a prime mover is defined by the following equation:

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} x100\%$$

n_{nl} → No-load speed of the prime mover

n_{fl} → Full-load speed of the prime mover

- Most generator prime movers have a speed droop of **2 to 4 %**

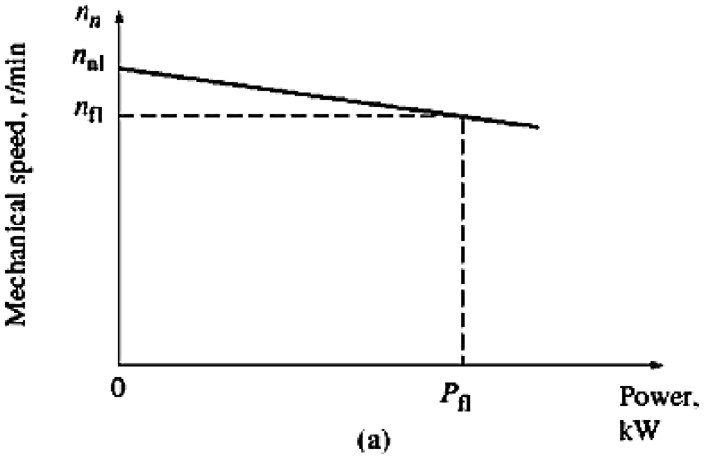


Frequency-Power characteristics

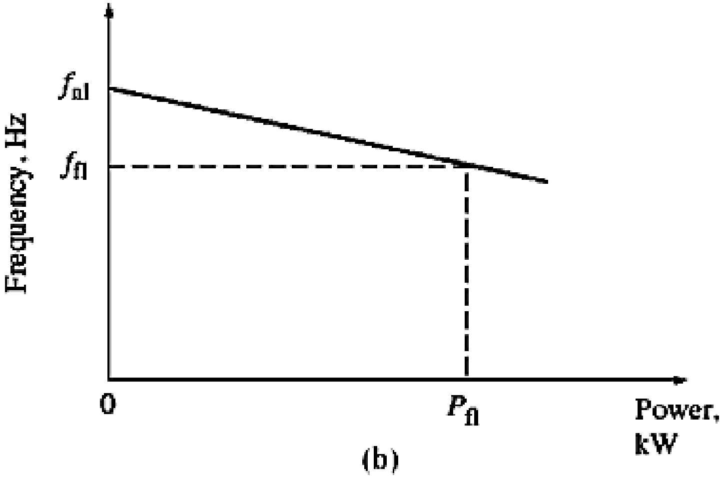
- Since the shaft of the synchronous generator (*rotor*) is connected to the prime mover, the prime mover speed defines the electrical frequency output of the generator:

prime mover speed

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



(a)



(b)

Frequency-Power characteristics

- According to the figure:

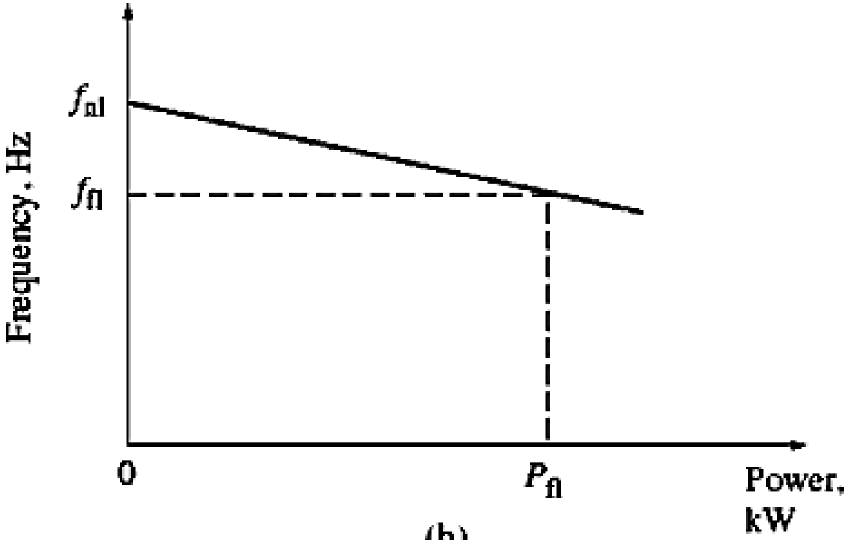
P_{fl} is the **full-load power** at frequency f_{fl}

Power output is **0** at frequency f_{nl}

- The equation for this line:

$$P = sp\left(f_{nl} - f_{sys}\right)$$

P is the **power output** of the generator
f_{nl} is the **no-load frequency** of the generator
f_{sys} is the **operating frequency of the system**
sp is the **slope of curve** (kW/Hz or MW/Hz)



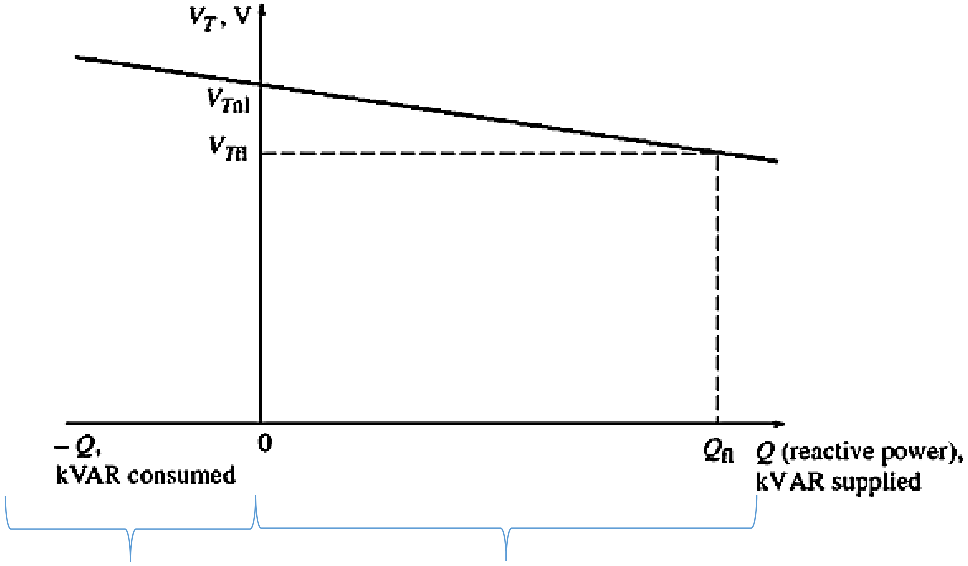
(b)

Voltage-Reactive power characteristics

- When a **lagging (or unity) power factor load** is connected to a synchronous generator, **terminal voltage drops.**
- When a **leading load** is connected to a synchronous generator, **terminal voltage increases**.
- The equation for this line:

$$\mathrm{Q} = m(VT_{nl} - V_T)$$

Q is the **reactive power output** of the generator
V_{Tnl} is the **no-load terminal voltage** of the generator
V_T is the **terminal voltage of the generator** at the **operating point**
m is the **slope of curve** (kVAR/Volt or MVAR/Volt)

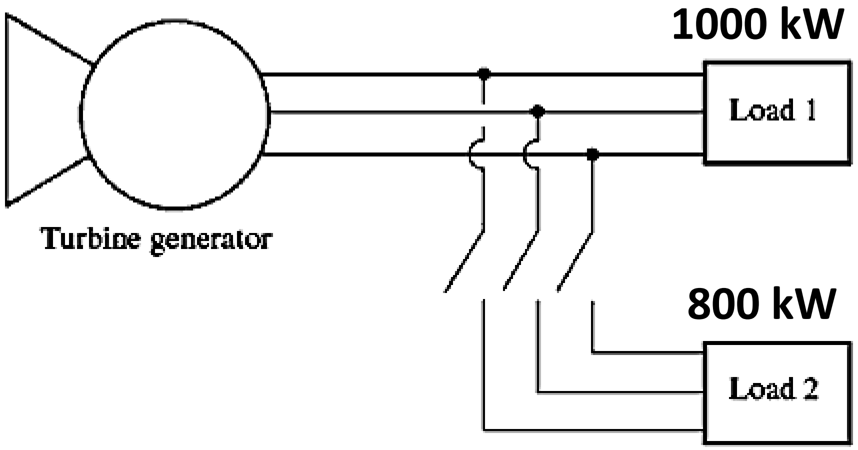


Leading PF load **Lagging (or unity) PF load**

Example:

Figure shows a generator supplying a load. A second load is to be connected in parallel with the first one. The generator has a no-load frequency of **61.0 Hz** and a slope ***sp*** of **1MW/Hz**. **Load 1** consumes a real power of **1000 kW** at 0.8 PF lagging, while **Load 2** consumes a real power of **800 kW** at 0.707 PF lagging.

(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?
(c) After Load 2 is connected, what action could an operator take to restore the system frequency to 60 Hz?

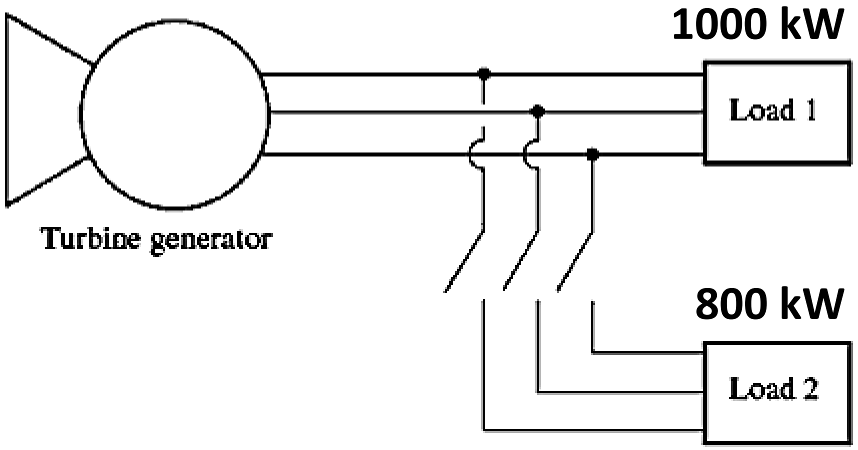


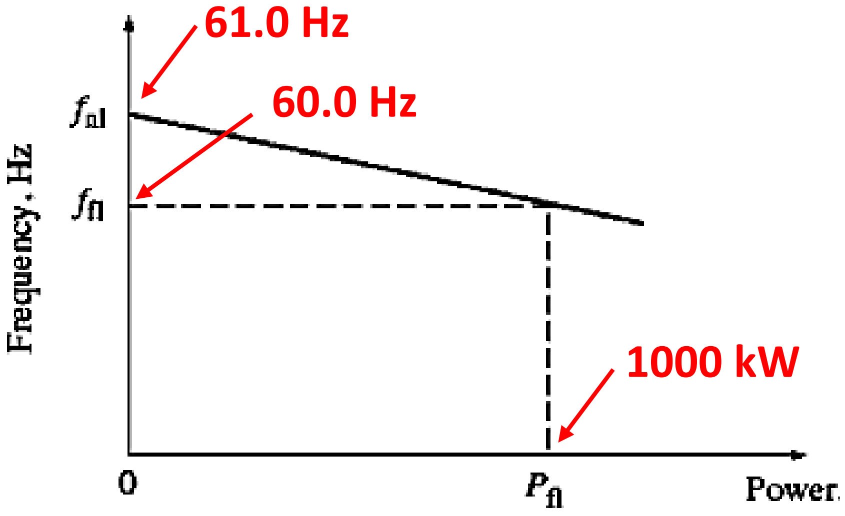
Solution:

(a) Before the switch is closed, the operating frequency of the system is found as follows:

$$P = s_P\left(f_{nl} - f_{sys}\right)$$

$$1000\ kW = \frac{1MW}{Hz}\left(61.0\ Hz - f_{sys}\right) \Rightarrow f_{sys} = 60\ Hz$$



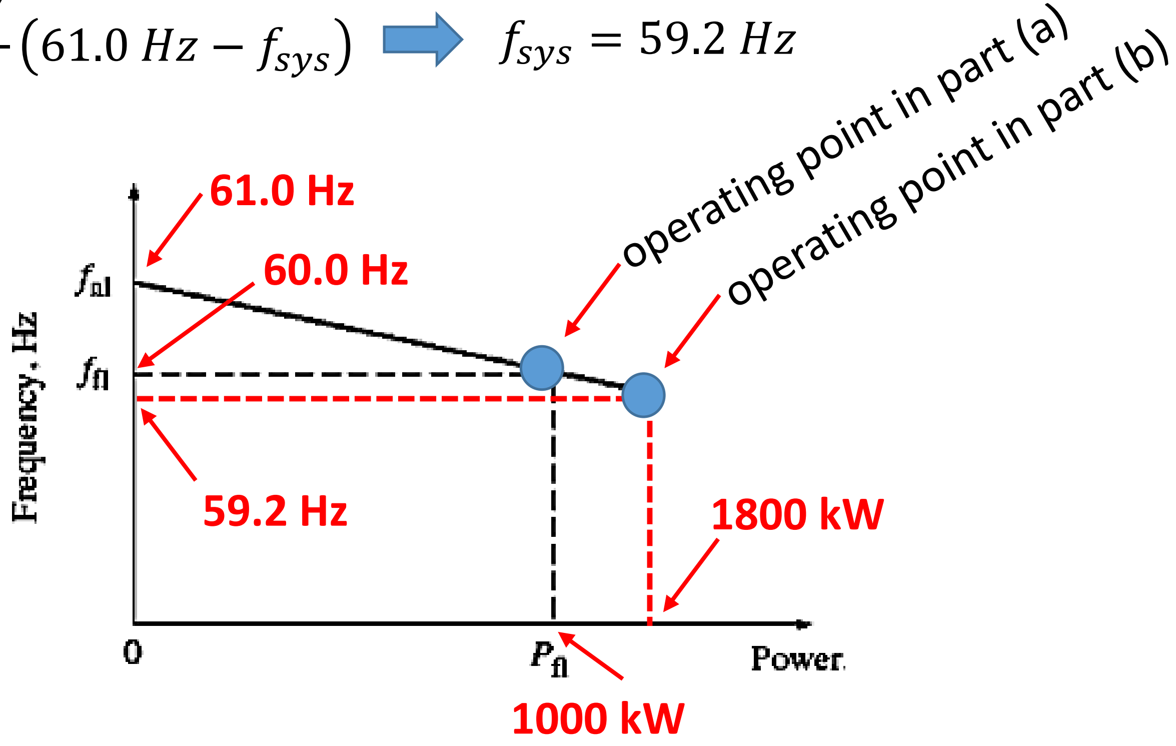


Solution:

(b) After **Load 2** is connected, the operating frequency of the system is found as follows:

$$P = sp\left(f_{nl} - f_{sys}\right)$$

$$(1000\ kW + 800\ kW) = \frac{1MW}{Hz}\left(61.0\ Hz - f_{sys}\right) \Rightarrow f_{sys} = 59.2\ Hz$$



As seen, **adding the load decreases the frequency** of the system from **60 Hz** to **59.2 Hz**

Solution:

(c) After **Load 2** is connected, how can we increase system frequency from **59.2 Hz** to **60.0 Hz ?**

We should **increase** the **governor no-load set point** from **60.0 Hz** to **61.8 Hz**.

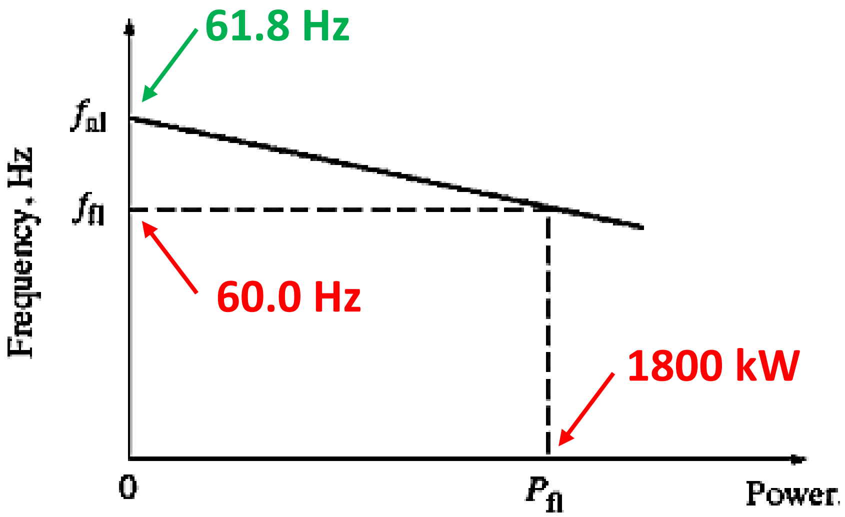
Let's check it:

$$P = sp\left(f_{nl} - f_{sys}\right)$$

$$1800\ kW = \frac{1MW}{Hz}\left(61.8\ Hz - f_{sys}\right)$$

$$\left(61.8\ Hz - f_{sys}\right) = 1.8\ Hz$$

$$f_{sys} = 60.0\ Hz$$



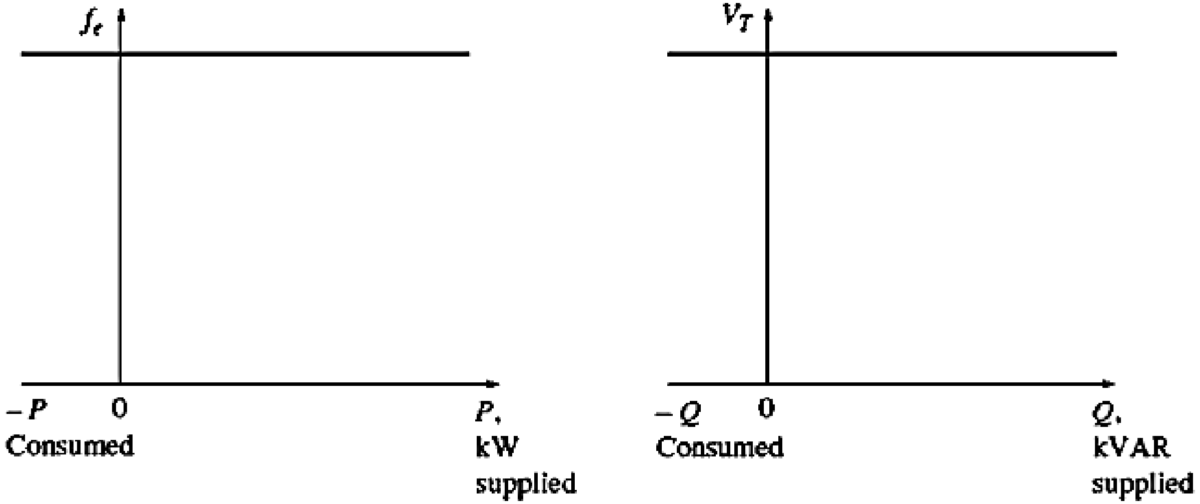
Operation of synchronous generators in parallel with infinite bus

- When a synchronous generator is connected to a huge power system, the power system's capacity is too large so that a connection of a generator does not effect the **voltage** and the **frequency** of the power system.

- An example of this situation is that Turkey's installed power ≈ **89000 MW** (*@ Jan2019*). So if a **100 MW** generator is connected to the system, **it can not change the voltage and the frequency of the overall country**.

Definition of infinite bus

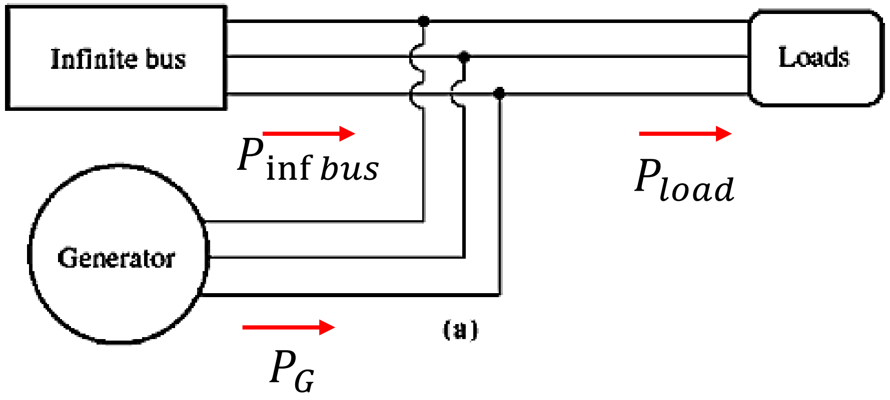
- An **infinite bus** is a power system so large that its **voltage** and **frequency** do not vary regardless of how much **real** and **reactive power** is drawn from or supplied to it.
- The ***P-f*** and ***Q-V*** characteristics of an infinite bus are shown below.

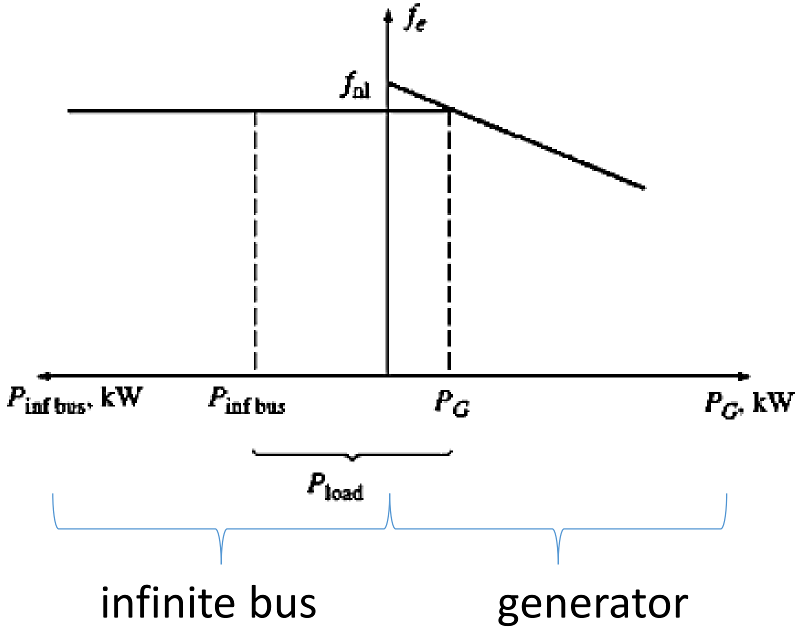


Infinite bus

- When a **generator** is connected in parallel with **another generator** or a **large system**, the **frequency** and **terminal voltage** of **all the machines must be** **same**.
- The **house diagram** is the combination of the **real power** *versus* **frequency** characteristics of the **generator** and the **infinite bus.**
- The real **power-frequency characteristics** of the generator and the infinite bus are plotted **back-to-back** with a **common vertical axis**.

$$P_{load} = P_{\inf bus} + P_G$$

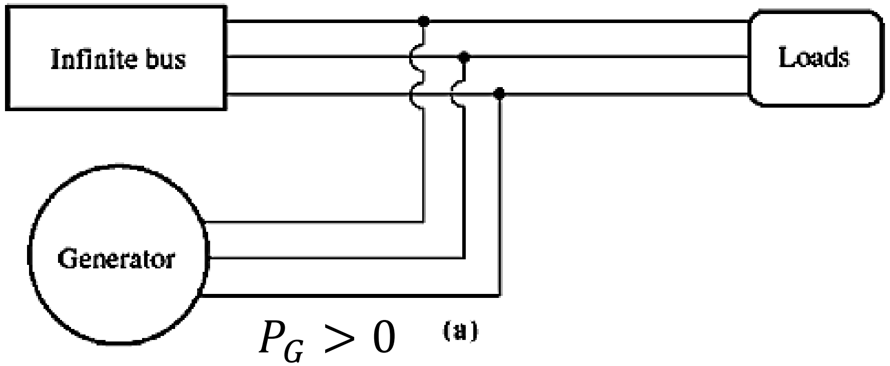




House diagram

Infinite bus

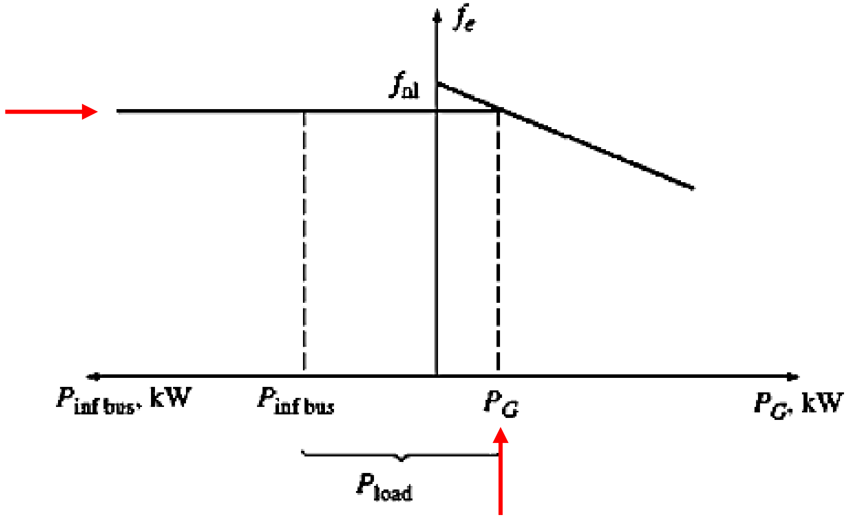
- **No-load frequency** of the generator should be **slightly greater** than the **frequency of the infinite bus**. If this is so, the **real power** drawn by the generator becomes **positive** and the synchronous machine is operating like a **generator, supplying real power**



$P_G > 0$

$f_{nl} > f_{\inf bus} \Rightarrow P_G > 0$

$f_{\inf bus} = 50\ Hz$



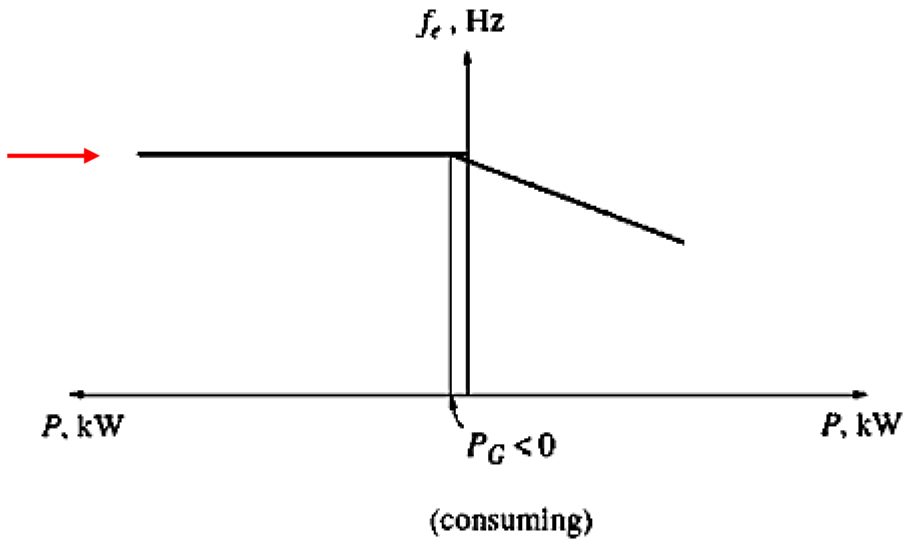
$P_G > 0$

Infinite bus

- If **no-load frequency** of the generator is **smaller** than the **frequency of the infinite bus**, the **real power** drawn by the generator becomes **negative** and the synchronous machine is operating like a **motor, consuming real power**

$$f_{nl} < f_{\inf bus} \Rightarrow P_G < 0$$

$$f_{\inf bus} = 50\ Hz$$



This situation is not desired !

Infinite bus

- Assume that the generator has been connected to infinite bus and supplying real power of P_{G1}, what happens when **its governor set-point** is **increased**?

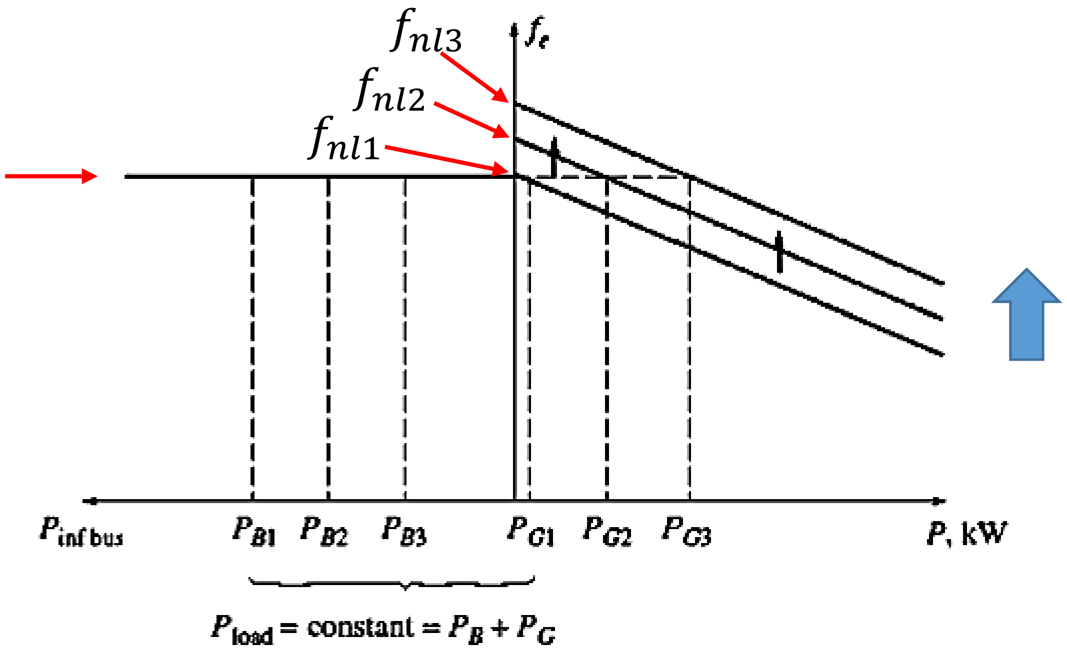
  1) The **no-load frequency** of the generator **shifts upward**.

  $$f_{nl2} > f_{nl1}$$

  2) The **real power** supplied by the generator **increases**.

  $$P_{G2} > P_{G1}$$

$f_{\inf bus} = 50\ Hz$



governor set point is increased

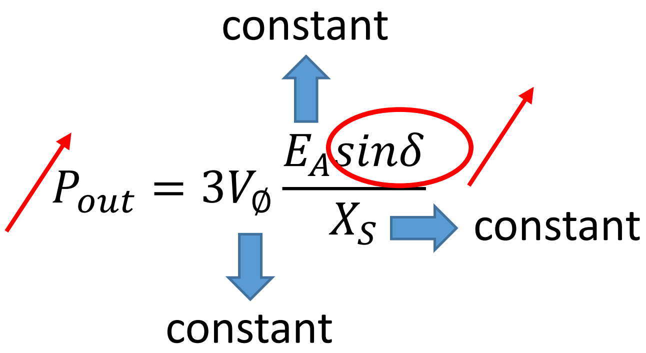
- If we further increase the governor set-point:

$$f_{nl3} > f_{nl2}$$

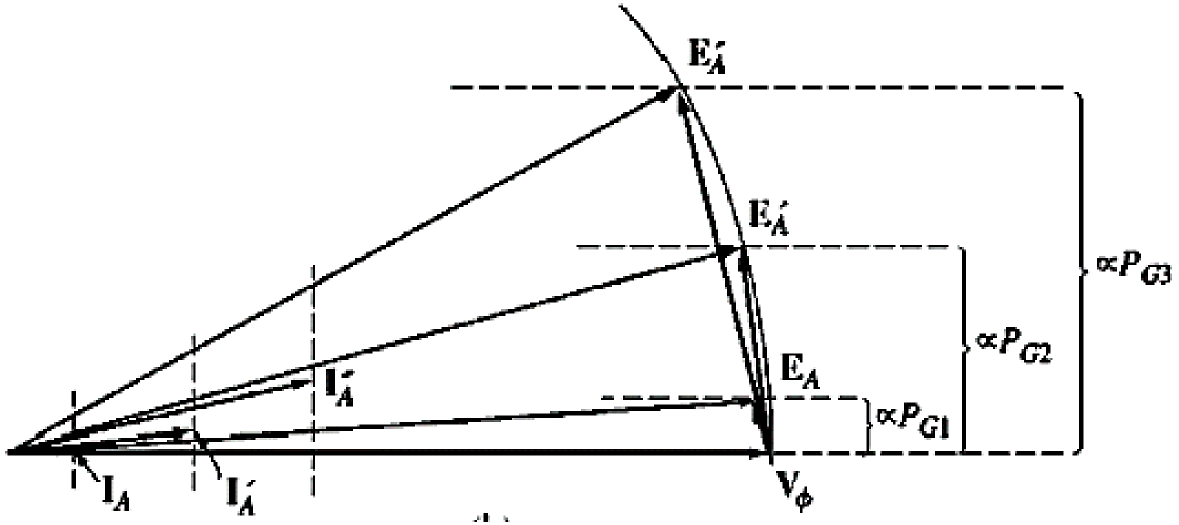
$$P_{G3} > P_{G2}$$

Infinite bus

- Now, what happens to the **phasor diagram** of the generator if **its governor set-point** is **increased**?
- We know that (*from previous slide*) the **real power** supplied by the generator **increases**.



$$P_{out} = 3V_{\emptyset}\frac{E_A \sin\delta}{X_S}$$



$$P_{G3} > P_{G2} > P_{G1}$$

$$\delta_3 > \delta_2 > \delta_1$$

- According to this equation, **sinδ or torque angle “δ“ must increase**

Infinite bus

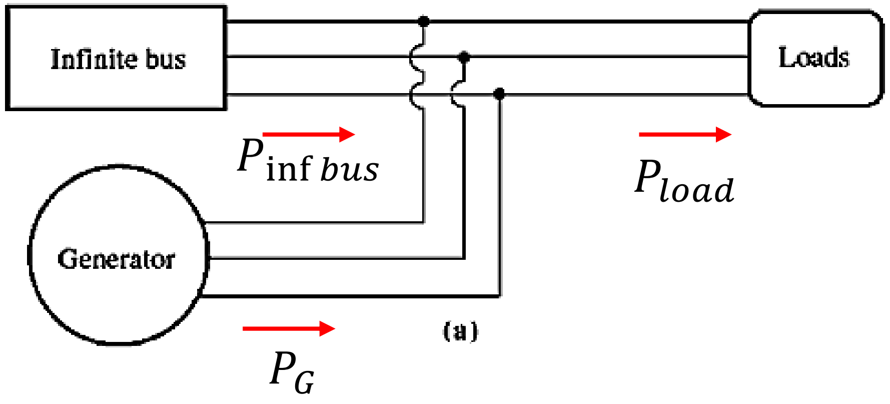
- What happens now, if the output of the generator is **further increased** so that it **exceeds** the power consumed by the load?

$$P_G > P_{load}$$

- If this occurs, the **extra power** generated by the generator **flows back into the infinite bus**.
- For example;

$$P_{load} = 1000\ kW$$
$$P_G = 1300\ kW$$

$$P_{\inf bus} = -300\ kW \quad (\textbf{generated})$$



$$P_{load} = P_{\inf bus} + P_G$$

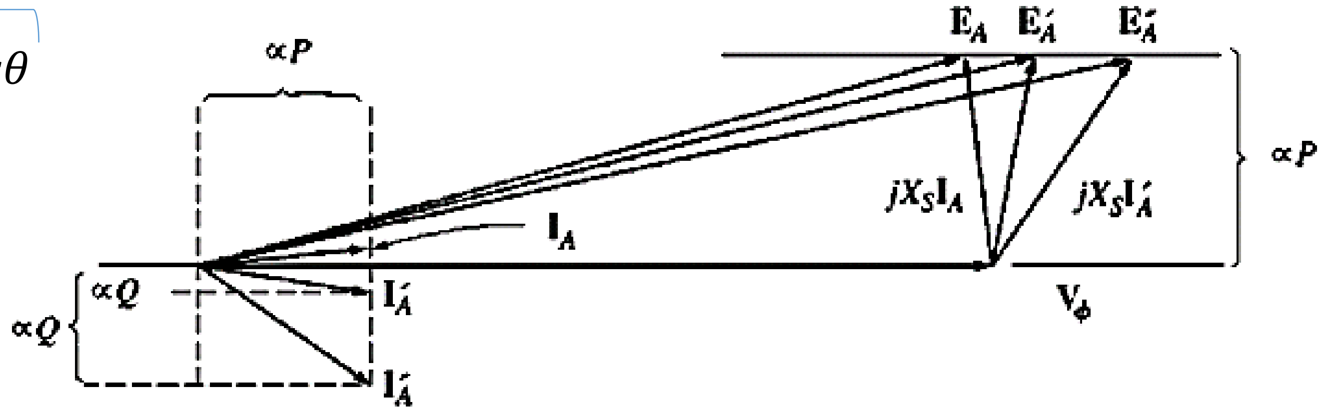
- Let's remember the infinite bus, by definition, the infinite can **supply** or **consume any amount of power** without **a change in frequency**, so the **extra power is consumed**.

Infinite bus

- So far we have seen that what happens to a synchronous generator connected to infinite bus when the **governor set-point** is **increased**?
- Now, the next question will be what happens to a synchronous generator connected to infinite bus if **its field current is increased? (governor set-point is unchanged)**

$$\underset{\text{constant}}{\underset{\Downarrow}{P_{out}}} = 3.\underset{\text{constant}}{\underset{\Downarrow}{V_{\emptyset}}}.\overbrace{I_A.cos\theta}^{\text{must be constant}}$$

$$\nearrow Q_{out} = 3.\underset{\text{constant}}{\underset{\Downarrow}{V_{\emptyset}}}.\underbrace{I_A.sin\theta}_{\text{increases}}$$



$$\underset{\text{constant}}{\underset{\Downarrow}{P_{out}}} = 3\underset{\text{constant}}{\underset{\Downarrow}{V_{\emptyset}}}\frac{\overbrace{E_A sin\delta}^{\text{must be constant}}}{X_S} \Rightarrow \text{constant}$$

Infinite bus

- In summary, what happens to a synchronous generator connected to infinite bus if **its field current is increased? (governor set-point is unchanged)**

- The **real power output** of the generator **<u>does not change</u>** (*since governor set-point is unchanged*)
- Since **real power output** of the generator is **constant** $E_A sin\delta$ must be **constant**
- Since **real power output** of the generator is **constant** $I_A cos\theta$ must be **constant**
- The **magnitude** (rms) of the armature current $|I_A|$ **increases**
- Since $|I_A|$ **increases** and $I_A cos\theta$ is **constant,** then $I_A sin\theta$ must **increase**
- Since $I_A sin\theta$ **increases**, Q_{out} **increases** as well.

So, **<u>as a result:</u>**

- ***<u>increasing the field current</u> in a synchronous generator operating in parallel with an infinite bus increases the <u>reactive power output</u> of the generator***

Infinite bus

To summarize;

- **When a single generator is operating alone:**

1) The real and reactive powers supplied by the generator are fixed, and constrained to be equal to the power demanded by the load

2) The frequency and terminal voltage are varied by the governor set points and the field current, respectively.

- **When a generator is operating in parallel with an infinite bus:**

1) The frequency and terminal voltage of the generator are controlled by the system to which it is connected.

2) The governor set points of the generator control the real power supplied by the generator to the system.

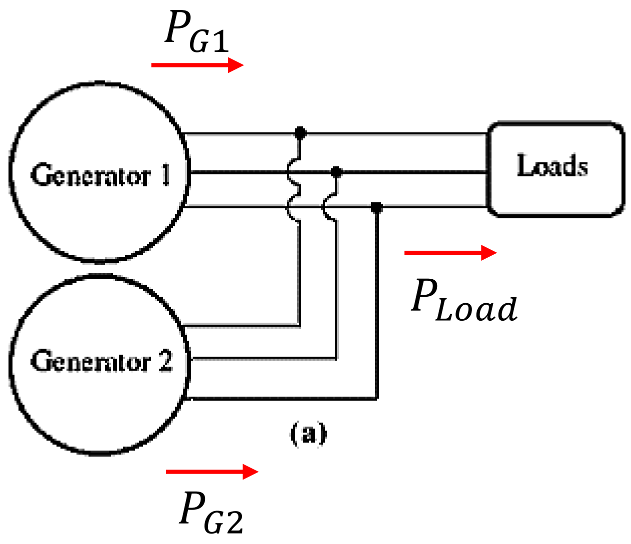
3) The field current in the generator controls the reactive power supplied by the generator to the system.

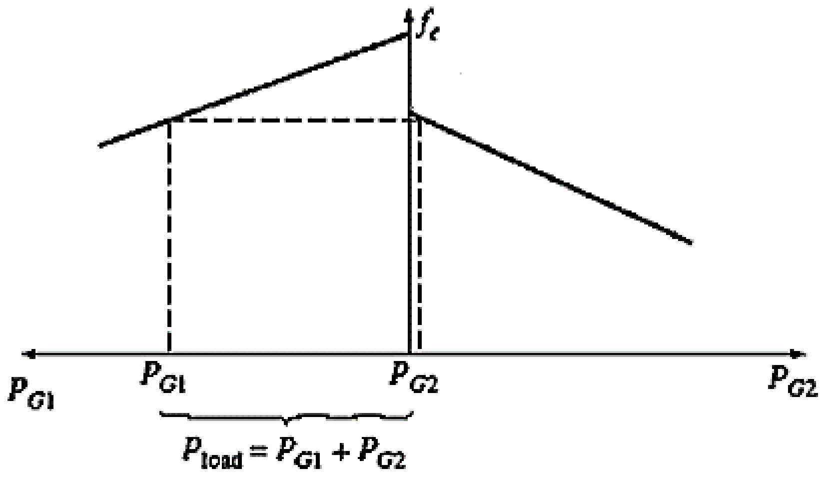
Parallel operation of generators with the same size

- If two generators are connected in parallel as shown in the figure, the real and reactive power of the load is shared between the generators.

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

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

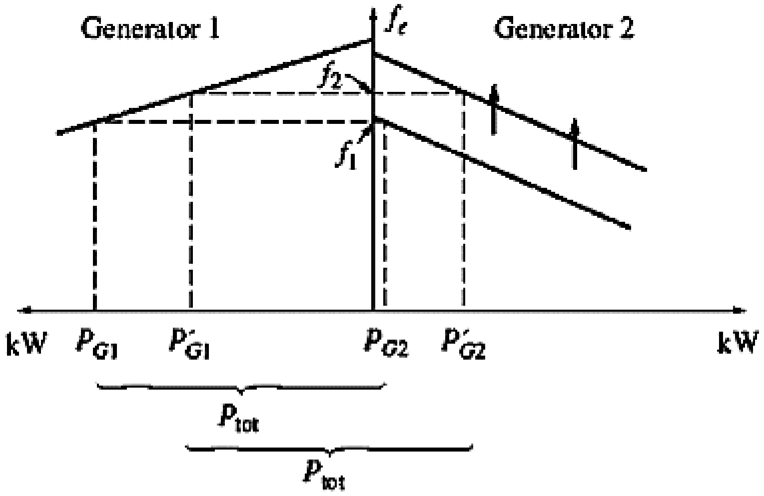




Two house diagrams shown together

Parallel operation of generators with the same size

- What happens if the **governor set point of Gen-2** is **increased**?



1) Increases the **real power** supplied by **Gen-2**, while reducing the **real power** supplied by **Gen-1**.

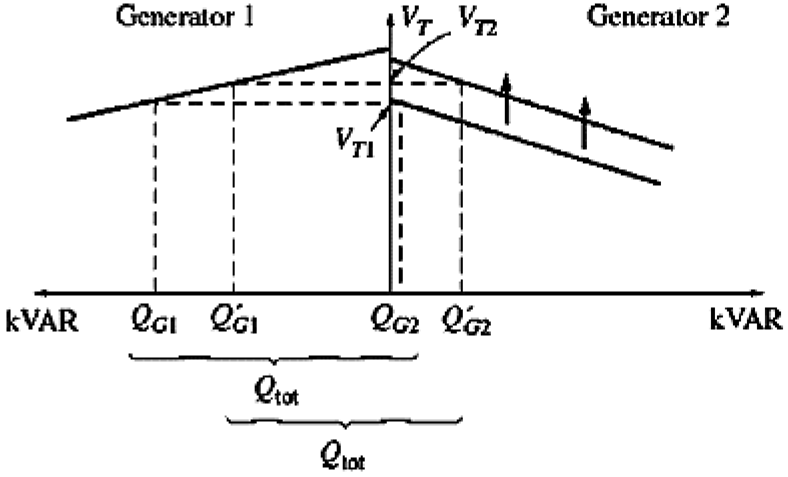
$$\overrightarrow{P_{Load}} = P_{G1}\swarrow + P_{G2}\nearrow$$

2) Increases overall system frequency.

$$f_2 > f_1$$

Parallel operation of generators with the same size

- What happens if the **field current of Gen-2** is **increased**?



1) Increases the **reactive power** supplied by **Gen-2**, while reducing the **reactive power** supplied by **Gen-1**.

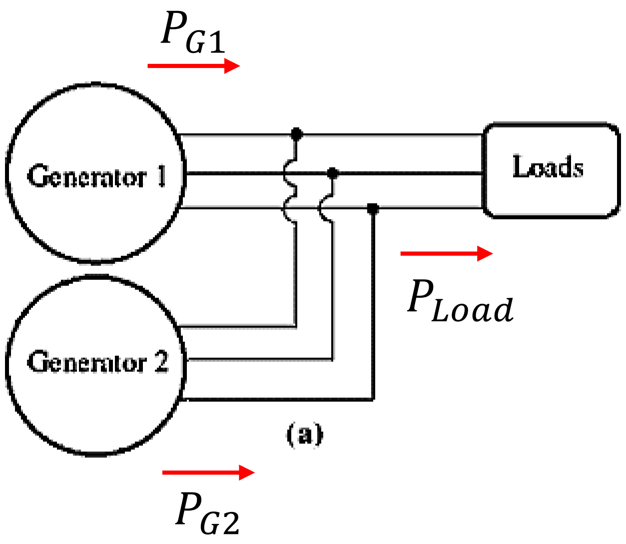
$$\overrightarrow{Q_{Load}} = Q_{G1}\downarrow + Q_{G2}\uparrow$$

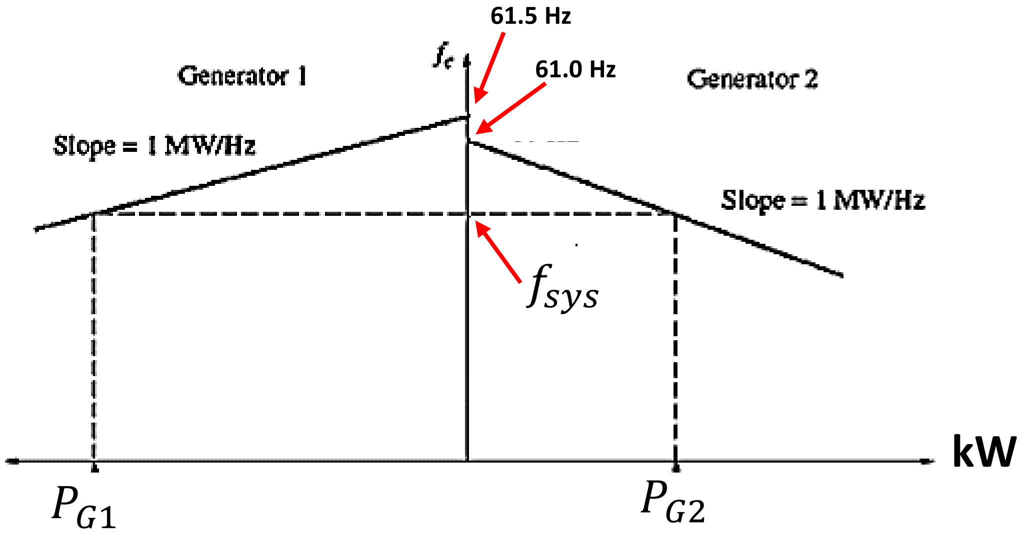
2) Increases system terminal voltage.

$$V_{T2} > V_{T1}$$

Example: Parallel operation of generators with the same size

Example: The figure shows two generators supplying a load. Generator 1 has a no-load frequency of **61.5 Hz** and a slope **sp1** of **1MW/Hz**. Generator 2 has a no-load frequency of **61.0 Hz** and a slope **sp2** of **1MW/Hz**. The two generators are supplying a load of **2.5 MW** at 0.8 PF lagging. The resulting system power-frequency or house diagram is shown below.



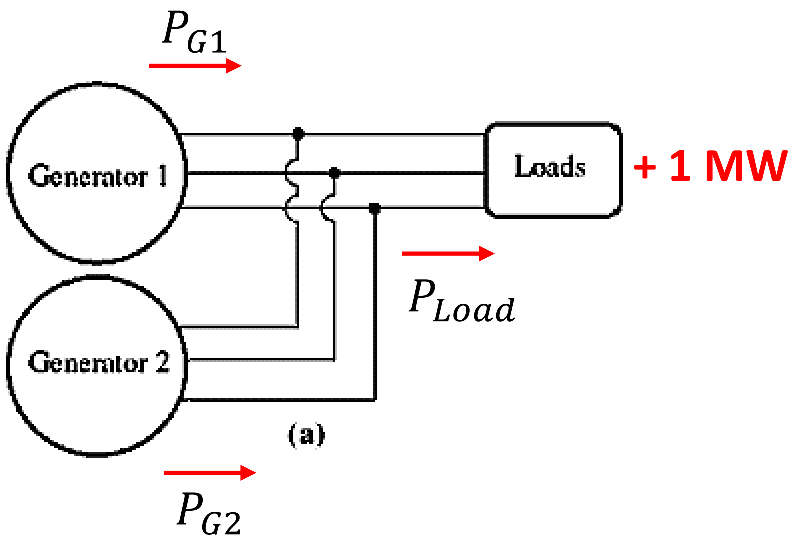


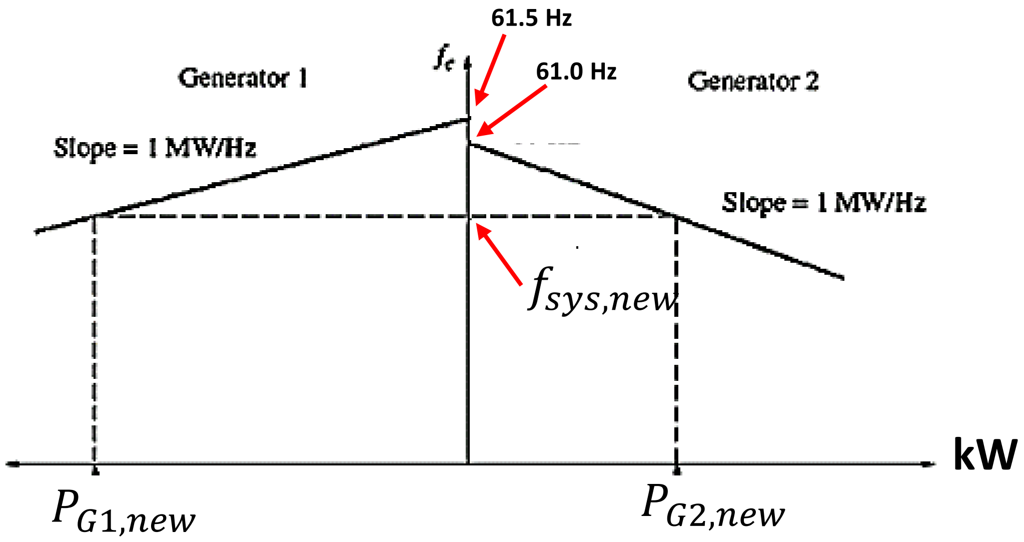
$$\left.\begin{aligned} P_{Load} &= P_{G1} + P_{G2} = 2.5\ MW \\ P_{G1} &= sp1\left(f_{nl1} - f_{sys}\right) \\ P_{G2} &= sp2\left(f_{nl2} - f_{sys}\right) \end{aligned}\right\}$$

Required equations to find f_{sys}, P_{G1}, P_{G2}

Example: Parallel operation of generators with the same size

<u>Example:</u> (*continue*): Suppose an **additional 1-MW load** is attached to this power system. What would the new system frequency be, and how much power would G1 and G2 supply now?





$$\left.\begin{aligned} P_{Load} &= P_{G1,new} + P_{G2,new} = 3.5\ MW \\ P_{G1,new} &= sp1\left(f_{nl1} - f_{sys,new}\right) \\ P_{G2,new} &= sp2\left(f_{nl2} - f_{sys,new}\right) \end{aligned}\right\}$$

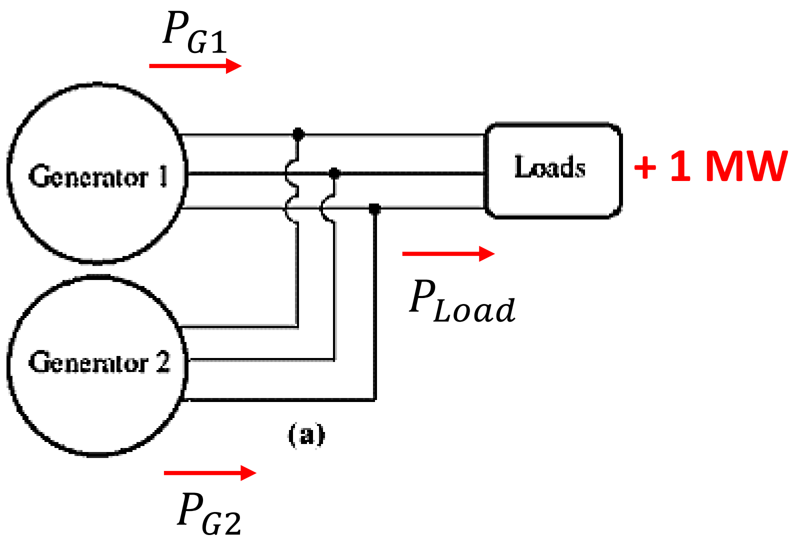
Required equations to find $f_{sys,new}$

$P_{G1,new}$

$P_{G2,new}$

Example: Parallel operation of generators with the same size

Example: (*continue*): With the system in the configuration described in previous condition, what will the system frequency and generator powers be if the governor set point on G2 is increased by **0.5 Hz**?



$$f_{nl2,new} = 61.5\ Hz$$

$$\left.\begin{aligned} P_{Load} &= P_{G1,new} + P_{G2,new} = 3.5\ MW \\ P_{G1,new} &= sp1\left(f_{nl1} - f_{sys,new}\right) \\ P_{G2,new} &= sp2\left(f_{nl2,new} - f_{sys,new}\right) \end{aligned}\right\}$$

Required equations to find $f_{sys,new}$

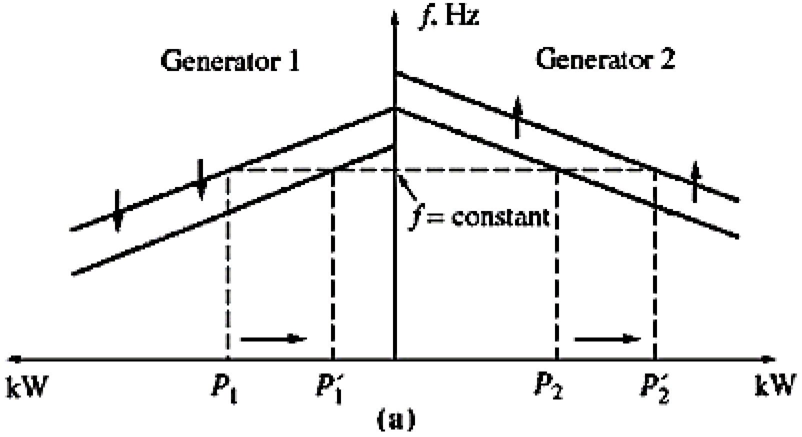
$P_{G1,new}$

$P_{G2,new}$

Parallel operation of generators with the same size

- We see that if **governor set point** of one generator is **increased**, the **system frequency increases**.
- So how can we **adjust the power sharing** of each generator **without changing system frequency**?

- The solution is
- To **decrease** the **governor set point of the other generator** so as to **keep the system frequency constant**



$$P_{Load} = P_1 + P_2 = constant$$

$$P_{Load} = P_1' + P_2' = constant$$

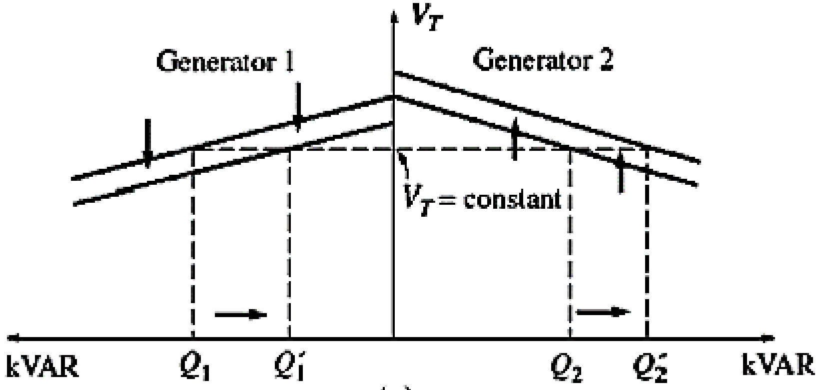
$$P_2' > P_2$$

$$P_1' < P_1$$

Parallel operation of generators with the same size

- We see that if **field current** of one generator is **increased**, the **system voltage increases**.
- So how can we **adjust the reactive power sharing** of each generator **without changing system voltage?**

- The solution is
- To **decrease** the **field current of the other generator** so as to **keep the system voltage constant**



(c)

$$Q_{Load} = Q_1 + Q_2 = constant$$

$$Q_{Load} = Q_1{}' + Q_2{}' = constant$$

$$Q_2' > Q_2$$

$$Q_1' < Q_1$$

Parallel operation of generators with the same size

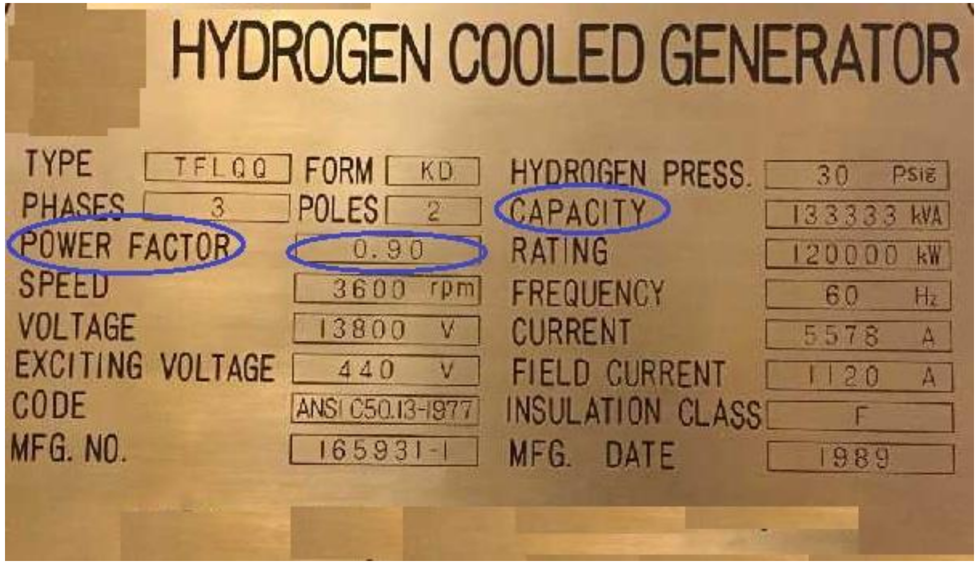
- The other two cases:

- To **adjust f_{sys} without changing the real power sharing of the generators**, **simultaneously increase or decrease** both **generators' governor set points**.

- To **adjust V_T without changing the reactive power sharing of the generators**, **simultaneously increase or decrease both generators' field currents**

Synchronous generator ratings

- There are certain basic limits to the speed and power that may be obtained from a synchronous generator.
- These limits are expressed as ratings on the machine.
- The purpose of the ratings is to **protect the generator** from **damage due to improper operation**.
- Each machine has a number of ratings listed on a nameplate attached to it (*see figure*).
- Typical ratings of a synchronous machine are ***voltage***, ***frequency***, ***speed***, ***apparent power*** **(*kilovoltamperes*)**, ***power factor***, ***field current***, and ***service factor.***

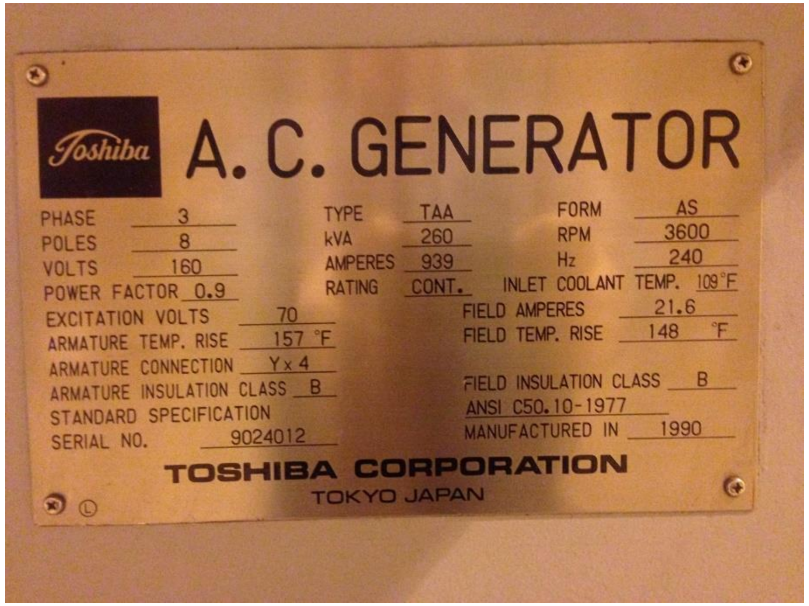


[redacted]

HYDROGEN COOLED GENERATOR

TYPE	TFLQQ	FORM	KD	HYDROGEN PRESS.	30 Psig
PHASES	3	POLES	2	CAPACITY	133333 kVA
POWER FACTOR		0.90		RATING	120000 kW
SPEED		3600 rpm		FREQUENCY	60 Hz
VOLTAGE		13800 V		CURRENT	5578 A
EXCITING VOLTAGE		440 V		FIELD CURRENT	1120 A
CODE		ANSI C50.13-1977		INSULATION CLASS	F
MFG. NO.		165931-1		MFG. DATE	1989

[redacted]



Toshiba A. C. GENERATOR

PHASE	3	TYPE	TAA	FORM	AS
POLES	8	kVA	260	RPM	3600
VOLTS	160	AMPERES	939	Hz	240
POWER FACTOR	0.9	RATING	CONT.	INLET COOLANT TEMP.	109°F
EXCITATION VOLTS	70			FIELD AMPERES	21.6
ARMATURE TEMP. RISE	157 °F			FIELD TEMP. RISE	148 °F
ARMATURE CONNECTION	Y x 4				
ARMATURE INSULATION CLASS	B			FIELD INSULATION CLASS	B
STANDARD SPECIFICATION				ANSI C50.10-1977	
SERIAL NO.	9024012			MANUFACTURED IN	1990

TOSHIBA CORPORATION
TOKYO JAPAN

Frequency rating of synchronous generator

- The **rated frequency** of a synchronous generator **depends on the power system** to which it is connected.
- The commonly used power system frequencies today are **50 Hz** (*in Europe, Asia, etc.*), **60 Hz** (*in the USA, Canada*), and **400 Hz** (*in special purpose and control applications*).
- If the **operating frequency** is **known**, there **is only one possible rotational speed** for a given **number of poles**.

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

- is it possible to operate a **60-Hz generator** at **50-Hz system**?

$$\left.\begin{aligned} E_A &= K\emptyset \mathrm{w} \\ w &= 2\pi f \end{aligned}\right\} \quad \swarrow E_A = K\emptyset 2\pi f \swarrow$$

- The answer is **Yes**. But we have to **<u>derate</u>** (*reduce*) **the voltage rating of the generator.**
- Otherwise in order to get the same voltage, we need **more flux**. That can cause **saturation** of the machine.

Apparent power and power-factor ratings

- The **maximum allowable armature current** $\left|\boldsymbol{I_{A(max)}}\right|$ is determined by the **maximum current carrying capacity** of the **conductors in stator**. So;

$$0 \leq |I_A| \leq \left|I_{A(max)}\right|$$

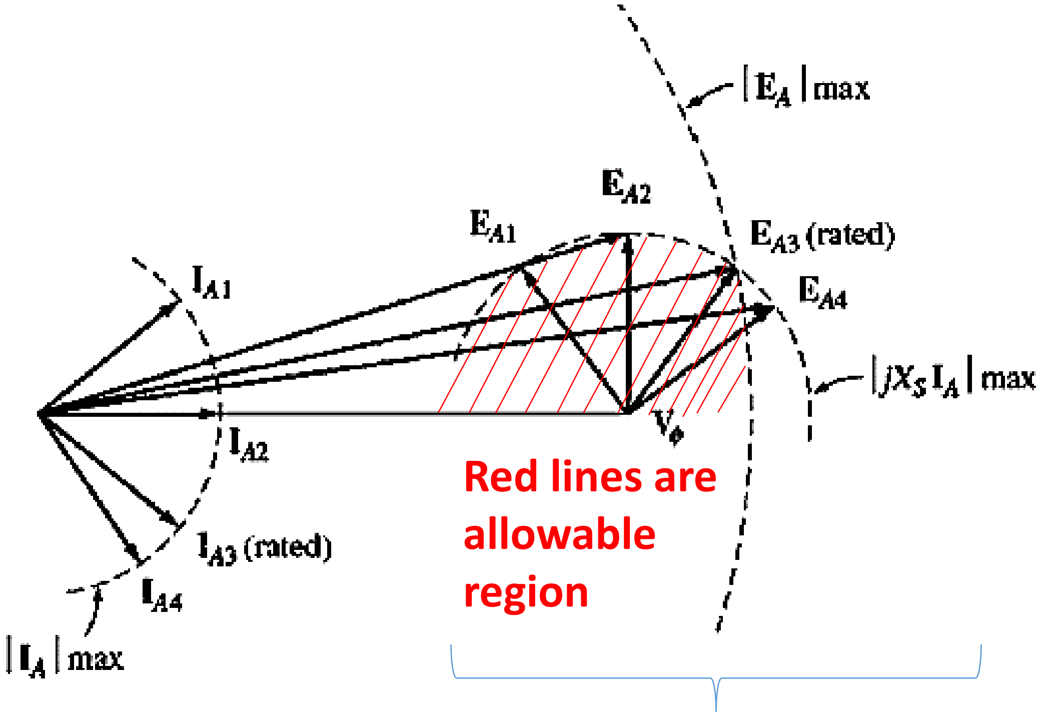
- This current limit defines **apparent power rating** of the generator. That is;

$$S_{rated} = 3V_{\emptyset,rated}I_{A(max)}$$

- Similarly, the **maximum allowable field current** $\left|\boldsymbol{I_{F(max)}}\right|$ is determined by **maximum current carrying capacity** of the **conductors in rotor**. So;

$$0 \leq |\boldsymbol{I_F}| \leq \left|\boldsymbol{I_{F(max)}}\right|$$

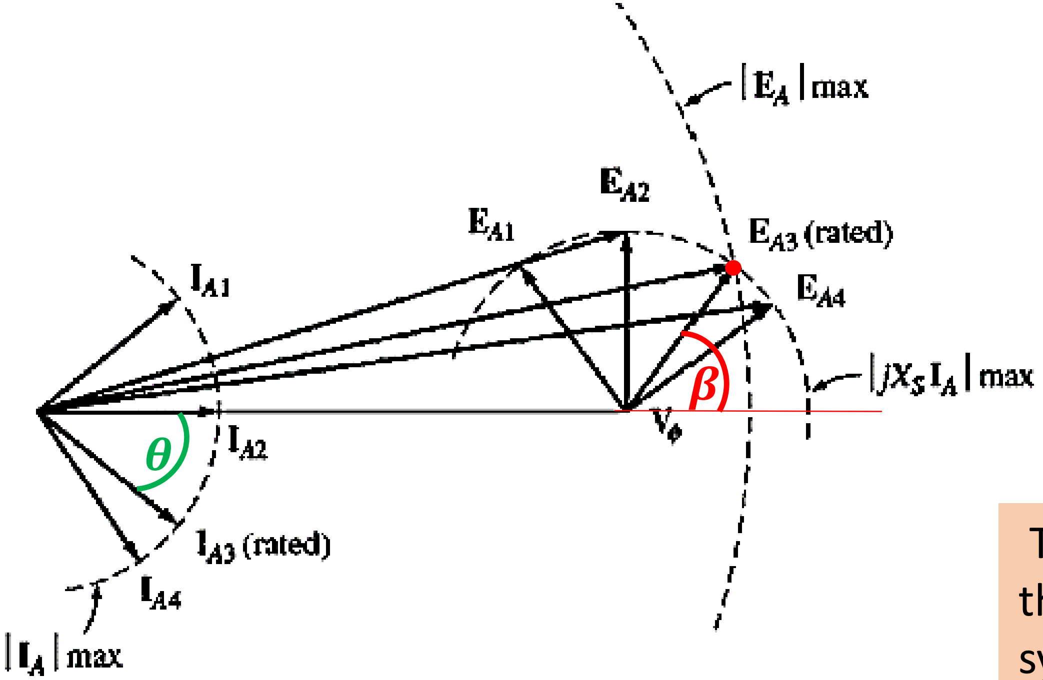
Apparent power and power-factor ratings



Red lines are allowable region

The **intersection** of **small** and **big** circles defines the **phase angle** that **armature current** can have

Apparent power and power-factor ratings



The angle $\boldsymbol{\beta}$ **can not be decreased further (minimum limit) without reducing** $|I_{A(max)}|$

- Since;

$$\beta = 90^\circ - \theta$$

$$\theta_{max} = 90^\circ - \beta_{min}$$

The **possible maximum value** of the **power factor angle** of the synchronous generator → $PF_{min} = \cos(\theta_{max})$

The **possible minimum value** of the **(lagging) power factor** of the synchronous generator

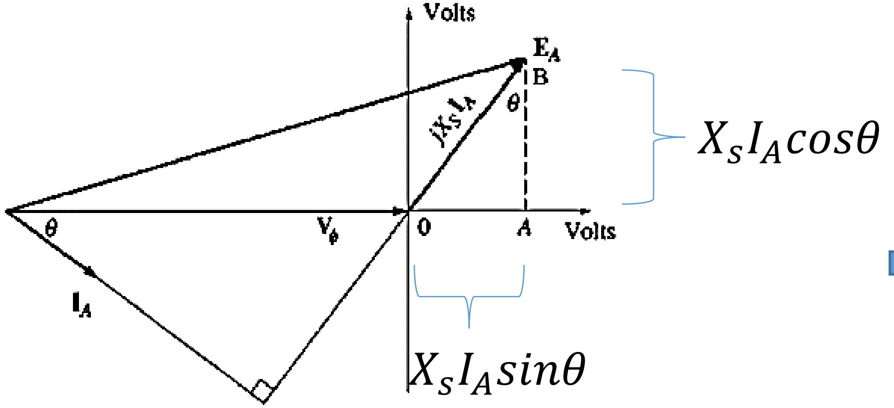
Synchronous generator capability curve

- **Capability curve** of a synchronous generator is a plot of the **complex power (S=P+jQ**) of the generator.

- **Capability curve** is derived from the **phasor diagram** of the generator.

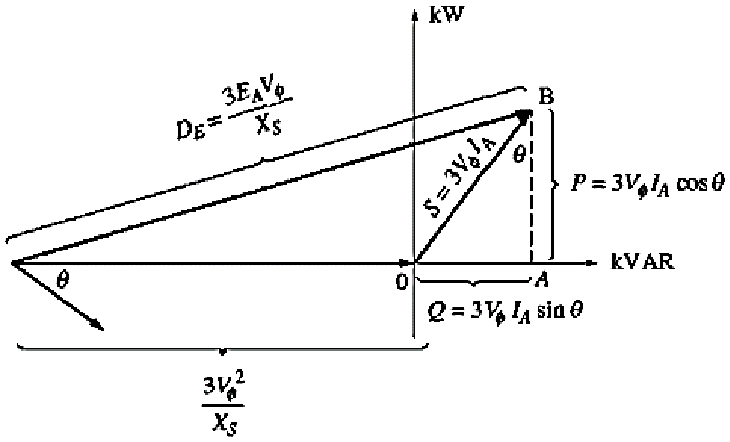
- We assume that;
  - Phase voltage of the generator ($V_{\emptyset}$) is **constant** (generator is connected to infinite bus)
  - Armature resistance R_A is **ignored**
  - Power factor of the load is **lagging**

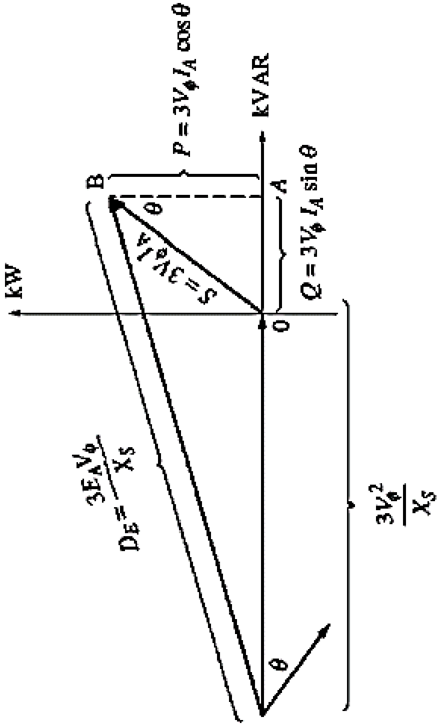
Synchronous generator capability curve



$X_sI_Acos\theta$

$X_sI_Asin\theta$

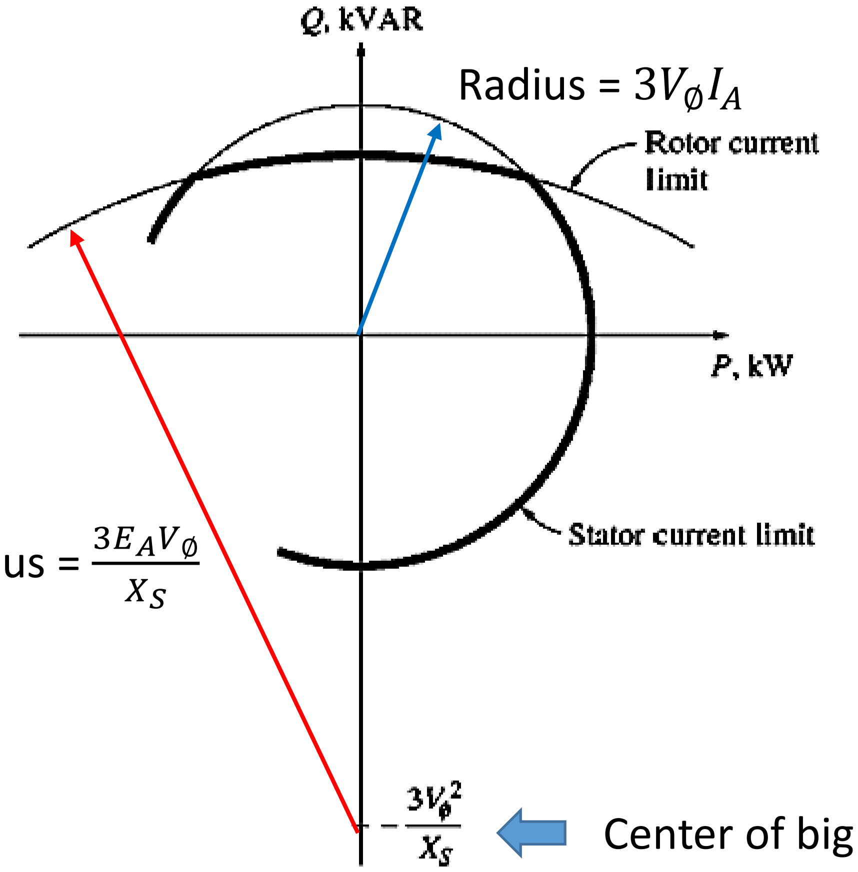




$X_sI_Acos\theta$ x $\frac{3V_\emptyset}{X_s}$ → $P = 3V_\emptyset I_Acos\theta$

$X_sI_Asin\theta$ x $\frac{3V_\emptyset}{X_s}$ → $Q = 3V_\emptyset I_Asin\theta$

Synchronous generator capability curve

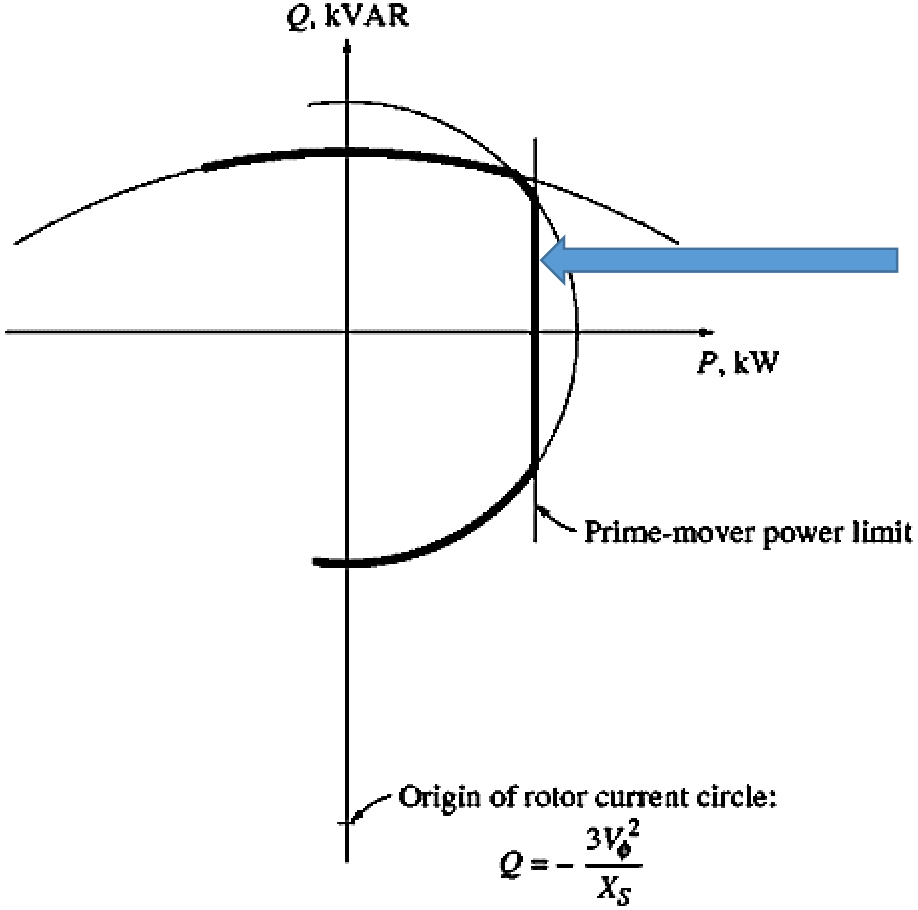


Radius = $3V_\emptyset I_A$

Radius = $\frac{3E_A V_\emptyset}{X_S}$

Center of big circle

Synchronous generator capability curve



Prime mover power limit is considered

Example: Synch. generator capability curve

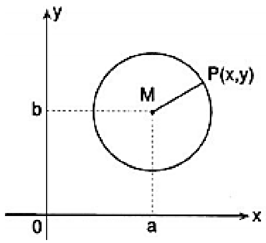
Example: A 480-V, 50-Hz, Y-connected, six-pole synchronous generator is rated at 50 kVA at 0.8 PF lagging. It has a synchronous reactance of 1.0 ohm per phase. Assume that this generator is connected to a steam turbine capable of supplying up to 45 kW. The friction and windage losses are 1.5 kW, and the core losses are 1.0 kW.
Answer the following questions:

(a) Sketch the capability curve for this generator, including the prime-mover power limit.

(b) Can this generator supply a line current of 56A at 0.7 PF lagging? Why or why not?

(c) What is the maximum amount of reactive power that this generator can produce?

(d) If the generator supplies 30 kW of real power, what is the maximum amount of reactive power that can be simultaneously supplied? (***Hint:*** *Use circle equation*)



$$\boxed{(x-a)^2 + (y-b)^2 = r^2}$$

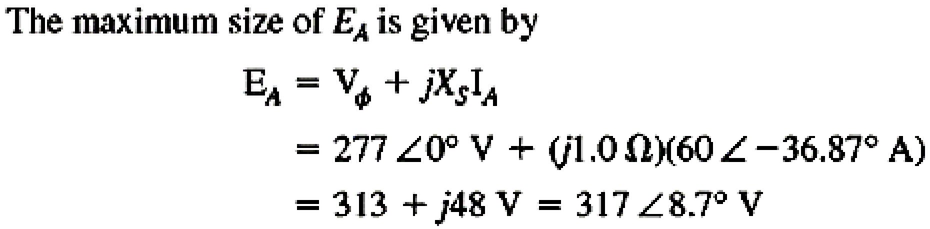
Example: Synch. generator capability curve

<u>Solution a):</u> The maximum armature current of the generator is found from:

$$S_{rated} = 3V_{\emptyset}I_{A(max)}$$

$$V_{\emptyset} = \frac{480}{\sqrt{3}} = 277\ V$$

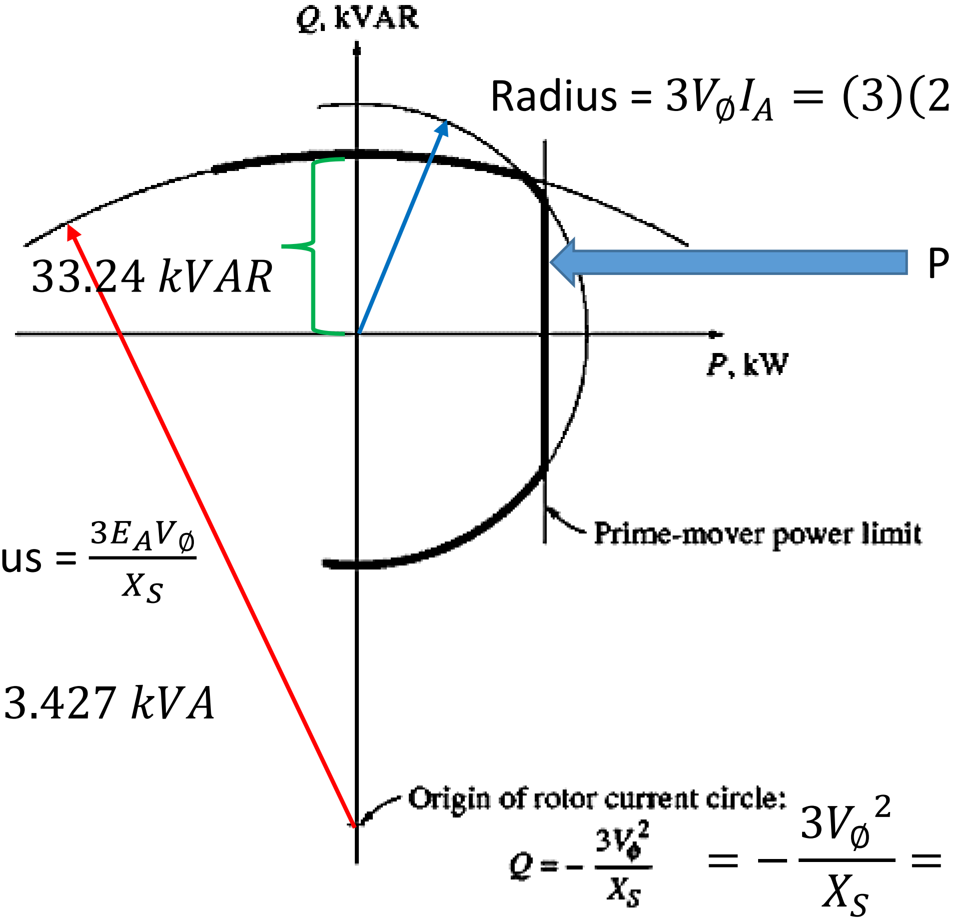
$$I_{A(max)} = \frac{S_{rated}}{3V_{\emptyset}} = \frac{50kVA}{3(277V)} = 60\ A$$



The maximum size of E_A is given by

$$\begin{aligned} \mathrm{E}_A &= \mathrm{V}_\phi + jX_S\mathrm{I}_A \\ &= 277\angle 0° \text{ V} + (j1.0\ \Omega)(60\angle -36.87° \text{ A}) \\ &= 313 + j48 \text{ V} = 317\angle 8.7° \text{ V} \end{aligned}$$

Example: Synch. generator capability curve



Radius = $3V_\emptyset I_A = (3)(277)(60) = 49.86\ kVA$

Prime mover power limit is considered $= 45\ kW$

$33.24\ kVAR$

Radius = $\frac{3E_A V_\emptyset}{X_S}$

$$= \frac{3E_A V_\emptyset}{X_S} = \frac{(3)(317)(277)}{1} = 263.427\ kVA$$

$$= -\frac{3V_\emptyset{}^2}{X_S} = -230.187\ \text{kVAR}$$

Example: Synch. generator capability curve

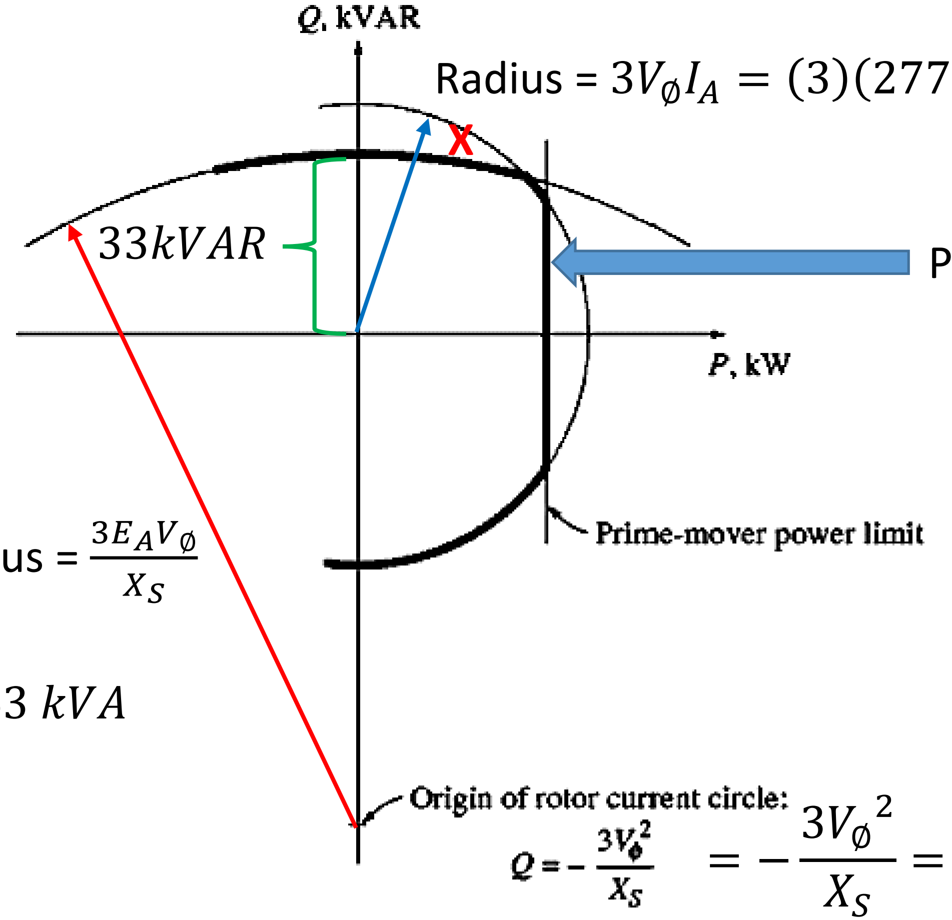
Solution b):

A current of 56 A at 0.7 PF lagging produces a real power of

$$P = 3V_\phi I_A \cos\theta$$
$$= 3(277\ \text{V})(56\ \text{A})(0.7) = 32.6\ \text{kW}$$

and a reactive power of

$$Q = 3V_\phi I_A \sin\theta$$
$$= 3(277\ \text{V})(56\ \text{A})(0.714) = 33.2\ \text{kVAR}$$



Radius = $3V_\emptyset I_A = (3)(277)(60) = 49.86\ kVA$

Prime mover power limit is considered

$= 45\ kW$

Radius = $\dfrac{3E_A V_\emptyset}{X_S}$

$$= \frac{3E_A V_\emptyset}{X_S} = \frac{(3)(317)(277)}{1} = 263\ kVA$$

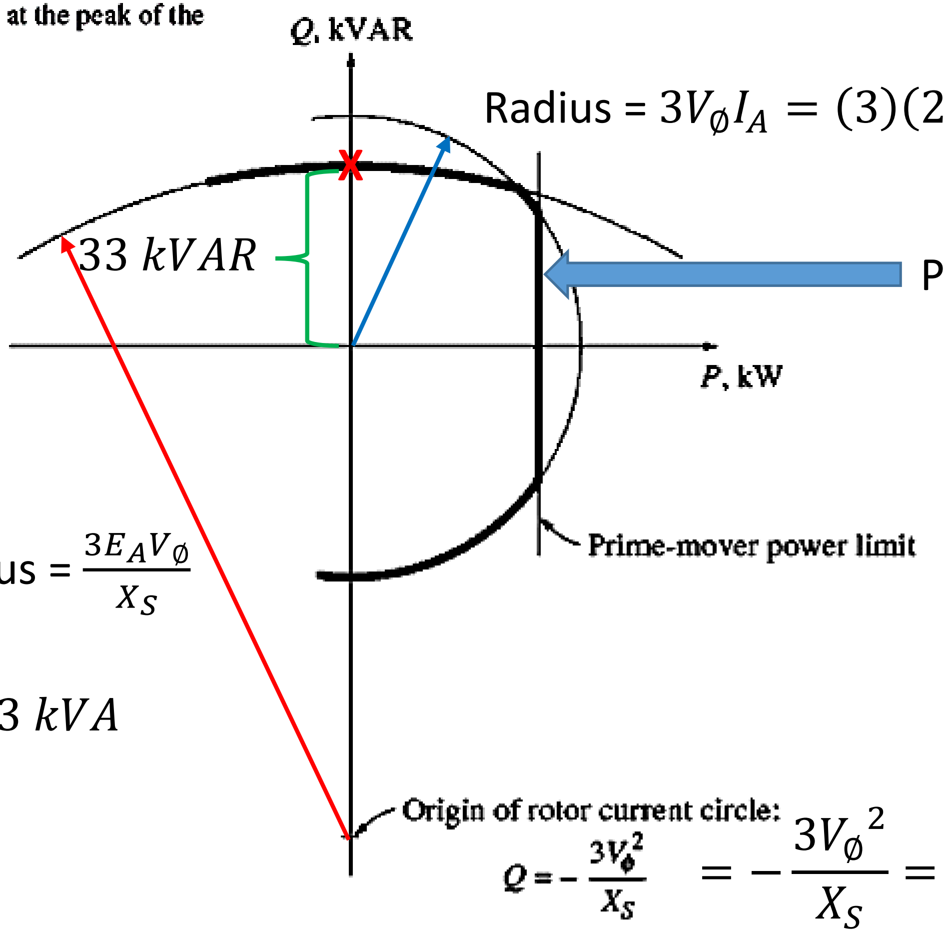
$$Q = -\frac{3V_\phi^2}{X_S} = -\frac{3V_\emptyset{}^2}{X_S} = -230.\ \text{kVAR}$$

Example: Synch. generator capability curve

Solution c):

When the real power supplied by the generator is zero, the reactive power that the generator can supply will be maximum. This point is right at the peak of the capability curve. The Q that the generator can supply there is

$$Q = 263 \text{ kVAR} - 230 \text{ kVAR} = 33 \text{ kVAR}$$



Radius = $3V_\emptyset I_A = (3)(277)(60) = 49.86\ kVA$

Prime mover power limit is considered $= 45\ kW$

Radius = $\frac{3E_A V_\emptyset}{X_S}$

$$= \frac{3E_A V_\emptyset}{X_S} = \frac{(3)(317)(277)}{1} = 263\ kVA$$

$$= -\frac{3V_\emptyset{}^2}{X_S} = -230 \text{ kVAR}$$

END OF CHAPTER 2

SYNCHRONOUS GENERATORS