Chapter 5: Synchronous Generator (Pt. II)

Synchronous generators are connected to loads and its behavior under load varies depending on the power factor of the load. We will only consider generators operating alone.

5.8. The synchronous generator operating alone

The generator is assumed to be connected to a load.

Assumptions:

- The effect of R_{A} is ignored in all phasor diagrams
- Generator speed ω is constant
- Rotor flux in the generators is constant (i.e. field current is kept constant by not changing the field resistor)

Hence, since the internal generated voltage magnitude $\bar{E}_{\mathrm{A}} = \bar{V}_{\phi} + jX_{\mathrm{S}}\bar{I}_{\mathrm{A}}$

When the load is increased, we observe:

- An increase in real and/or reactive power drawn from the generator.
- Also, an increase in the load current drawn from the generator

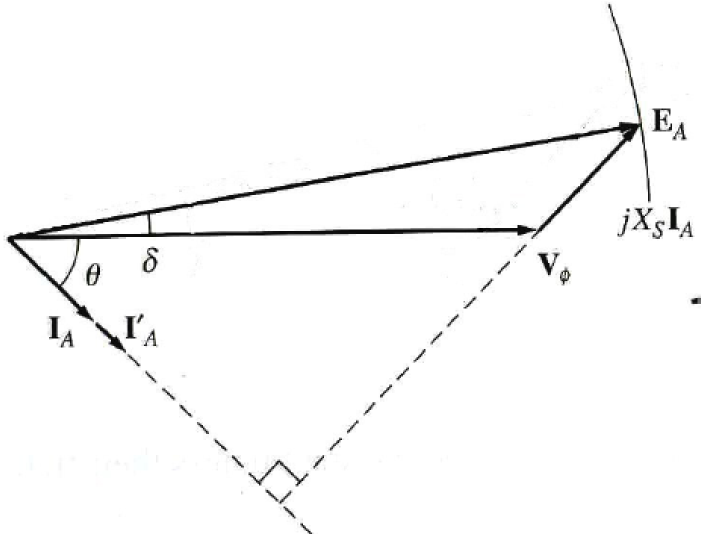
For a initially lagging load:

- Load is increased with the lagging power factor maintained.
- $|\bar{I}_{\mathrm{A}}|$ will increase but it will remain at the same angle with reference to $\bar{V}_{\phi}$ (due to power factor being maintained).
- The **armature reaction voltage $jX_{\mathrm{S}}\bar{I}_{A}$** will also **increase** but at the same angle.

Since, $\bar{E}_{\mathrm{A}} = \bar{V}_{\phi} + jX_{\mathrm{S}}\bar{I}_{\mathrm{A}}$

Hence, $jX_{\mathrm{S}}\bar{I}_{A}$ phasor must:

- increase in magnitude (i.e. size)
- be parallel to its original position (i.e. before increase in load.)
- stretch between $\bar{V}_{\phi}$ at an angle of 0° and $\bar{E}_{\mathrm{A}}$ (i.e. the curve shown because $\bar{E}_{\mathrm{A}}$ is constant)
- Therefore, the only element which would change would be $\bar{V}_{\phi}$. This change may be seen in the phasor diagram in the next page.

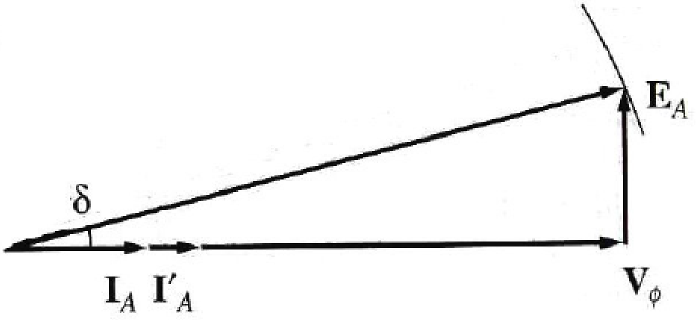


The effect of an increase in generator loads at constant power factor upon its terminal voltage – **lagging power factor.**

Therefore, if the constraints are observed, **as the lagging load increases**, the voltage $\bar{V}_\phi$ ________________________.

For an initially **unity-power-factor load:**

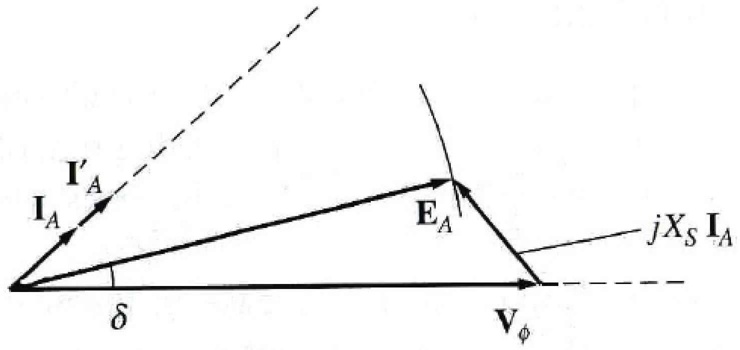
- **Load is increased** with the unity **power factor maintained**.
- $\bar{I}_A$ and $jX_S\bar{I}_A$ will **increase in magnitude** but maintaining the **same angle** with reference to $\bar{V}_\phi$ (due to the maintained power factor).
- Since $\bar{E}_A$ **has to remain constant,** $\bar{V}_\phi$ will have to change as seen in the phasor diagram below.



Hence, with the same constraints as before (i.e. with the lagging load), it is observed that **with an increasing unity load**: $\bar{V}_\phi$ ____________________________

For a **leading load:**

- **Load is increased** with the leading **power factor maintained**.
- $\bar{I}_\text{A}$ and $jX_\text{S}\bar{I}_\text{A}$ will **increase in magnitude** but maintaining the **same angle** with reference to $\bar{V}_\phi$
- Furthermore, $jX_\text{S}\bar{I}_\text{A}$will now lie parallel but **outside** its **previous value**.
- As observed before, $\bar{E}_\text{A}$ **has to remain constant** causing $\bar{V}_\phi$ to change. This can be seen in the phasor diagram.



Conclusions drawn from the synchronous generator behaviour with changing loads:

	$\bar{V}_\phi$	$\text{VR} = \frac{V_{\phi\text{nl}} - V_{\phi\text{fl}}}{V_{\phi\text{fl}}} \times 100\%$
Lagging load	Decreases significantly	
Unity power factor	Decreases slightly	
Leading load	Increases	

$V_{\phi\text{nl}}$ = generator no-load voltage,
$V_{\phi\text{fl}}$ = generator full-load voltage

Normally, it is desirable to keep the output voltage of a generator constant with changes in load.

Hence, $\bar{E}_\text{A}$ **has to be controlled** to compensate for changes in load. Recall that,

$$E_\text{A} = K\phi\omega$$

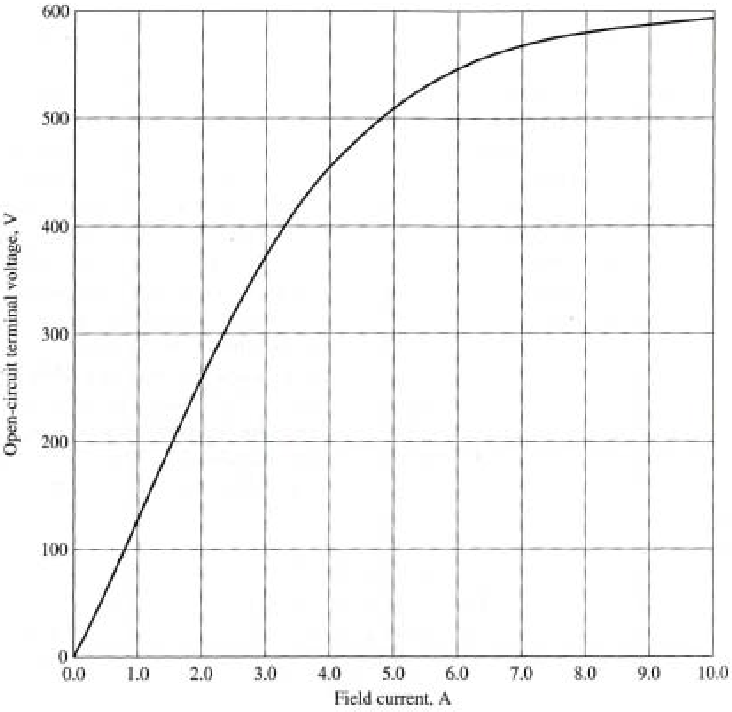
Thus, $|\bar{E}_\text{A}|$can be controlled by: varying the flux in the machine

Note: Varying $\bar{I}_F$ will vary the flux in the core which will then vary $\bar{E}_A$ accordingly (refer OCC).

How must a generator's field current be adjusted to keep the terminal voltage constant as the load changes?

Example 5-2 (page 291)

A 480-V, 60 Hz,Δ -connected, four-pole synchronous generator has the OCC shown below. This generator has a synchronous reactance of 0.1 W and an armature resistance of 0.015 W. At full load, the machine supplies 1200 A 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 the machine's overall efficiency?
(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?

(f) Finally suppose that the generator is connected to a load drawing 1200 A at 0.8PF *leading*. How much field current would be required to keep V_T at 480 V?

Example 5-3 (page 294):

A 480-V, 50 Hz, Y-connected, 6-pole synchronous generator has a per-phase synchronous reactance of 1.0 W. It's 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 full load. Since the armature resistance is being ignored, assume that the I^2R losses are negligible. The field current has been adjusted so that the terminal voltage is 480 V at no load.

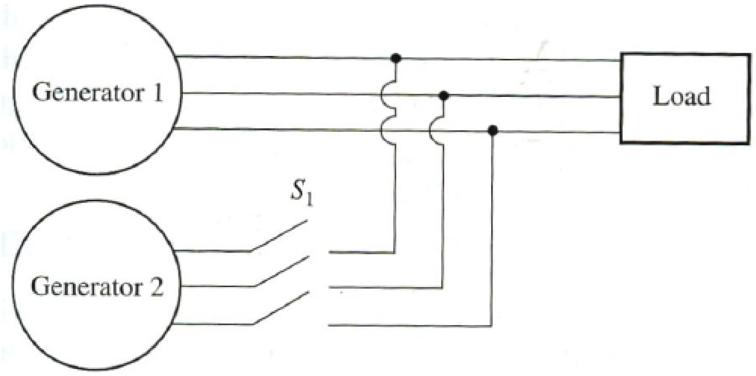
(a) What is the speed of rotation of this generator?
(b) What is the terminal voltage of this generator if the following are true?
  1. It is loaded with the rated current at 0.8PF lagging.
  2. It is loaded with the rated current at 1.0PF.
  3. It is loaded with the rated current at 0.8PF leading.
(c) What is the efficiency of this generator (ignoring the unknown electrical losses) when it is operating at the rated current and 0.8PF lagging?
(d) How much shaft torque must be applied to the prime mover at full load? How large is the induced countertorque?
(e) What is the voltage regulation of this generator at 0.8PF lagging? At 1.0PF? At 0.8PF leading?

Parallel operation of AC generators

Advantages for operating in parallel:
- Ability to handle larger loads
- Increased power system reliability
- Ability to carry out maintenance without power disruption
- Increased efficiency

Conditions required for paralleling:

Figure below shows a synchronous generator G_1 supplying a load with another generator G_2 about to be paralleled with G_1 by closing the switch S_1.



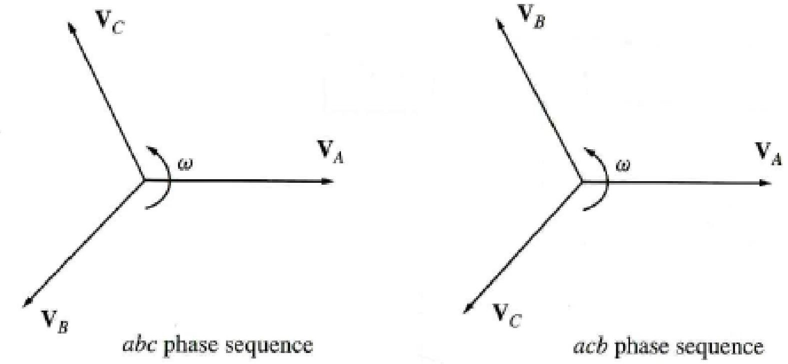
If the switch is closed arbitrarily at some moment, the generators are liable to be **severely damaged and the load may lose power**.

Hence, paralleling 2 or more generators must be done carefully as to avoid generator or other system component damage.

Conditions required for paralleling are as follows:

a) **RMS line voltages must be**. Equal (i.e. **same voltage magnitude and phase angle)** If the voltages are not exactly the same, there will be a very large current flow when the switch is closed.

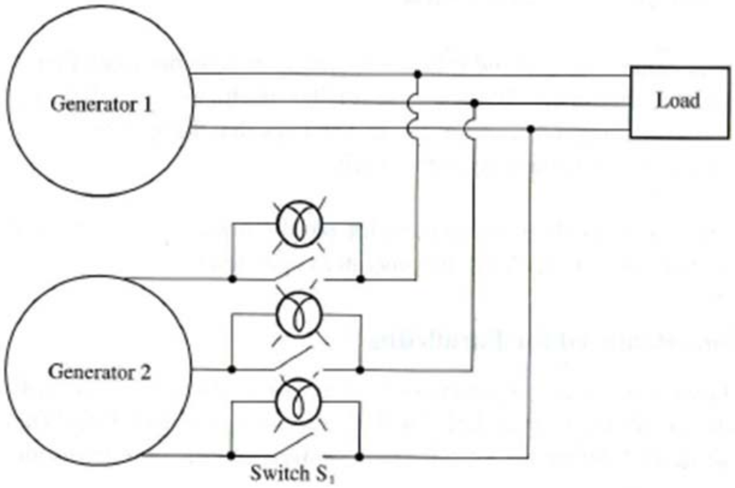
b) The generators to be paralleled must have the **same phase sequence**
If the phase sequence is different (as shown below), then even though one pair of voltages (phase 'a') are in phase, the other two pairs are 120° out of phase. Thus, large currents will flow in the two out-of-phase lines which can damage both machines.



c) Generator output **phase angles must be the same**.
d) The **oncoming generator** must have a **slightly higher frequency** as compared to the system frequency (but the frequencies **cannot be equal**!). This is done so that the phase angles of the oncoming machine will change slowly with respect to the phase angles of the running system (when observed) to facilitate closing of S_1 when the systems are exactly in phase.

General procedure for paralleling generators

Suppose that generator G_2 is to be connected to the running system as shown below:



1. Using voltmeters, the field current of the oncoming generator should be adjusted until its terminal voltage is equal to the line voltage of the running system.

2. Check and verify that the phase sequence of the oncoming generator is identical to the system phase sequence. There are two suggested methods to do this:
a) Alternately connect a small induction motor to the terminals of each of the two generators. If the motor rotates in the same direction each time, then the phase sequence is the same for both generators. If the motor rotates in opposite directions, then the phase sequences differ and 2 of the conductors on the incoming generator must be reversed.
b) Using the three-light-bulb method, whereby three light bulbs are stretched across the open terminals of the switch connecting the generator to the system (as shown in the figure on the previous page).

As the phase changes between the two systems, the light bulbs first get bright (large phase difference) and then get dim (small phase difference). If all three bulbs get bright and dark together, then the systems have the same phase sequence. If the bulbs brighten in succession, then the systems have the opposite phase sequence, and one of the sequences must be reversed.

3. Check and verify the oncoming generator frequency is slightly higher than the system frequency. This is done by watching a frequency meter until the frequencies are close and then by observing changes in the phase between the systems.

4. Once the frequencies are very nearly equal, the voltages in the two systems will change phase with respect to each other very slowly. The phase changes are observed, and when the phase angles are equal, the switch connecting the two systems is shut.

How to verify that the two systems are finally in phase?

Use the:

- **Three-light-bulb method** (when all three bulbs go out, the voltage difference across them is zero and the systems are in phase)
- **Synchroscope** - a meter that measures the phase '*a*' angle difference between the two systems (*it does not check for phase sequence*)

5.10. Synchronous generator ratings

There are certain basic limits to the speed and power that may be obtained from a synchronous generator, which are expressed as **ratings** on the machine. The purpose is **to protect the generator from damage** due to improper operation.

The voltage, speed and frequency ratings

Frequency rating:
Rated frequency depends on the power system at which the generator is connected (50Hz in Europe and Asia, 60Hz in USA and 400Hz in special-purpose and control applications).

Speed rating:
Rated speed corresponds to the frequency rating for a given number of poles and is related by

$$\boldsymbol{f}_{\mathbf{e}} = \frac{\boldsymbol{n}_{\mathbf{m}}\boldsymbol{P}}{\mathbf{120}}$$

There is only one possible speed for a given number of poles at a fixed frequency.

Voltage rating:

- Generated voltage is dependent on the flux, the speed of rotation and mechanical construction of the machine.
- For a given mechanical frame size and speed, the **desired voltage is proportional to the flux required**.
- However, the **flux level has a limit** dependent on the generator material and maximum allowable field current.

Hence, **voltage ratings** may **give a rough idea on the maximum flux level possible and** also **maximum allowable voltage before the winding insulation breaks down**.

Apparent power and power factor ratings

Power limits of electrical machines **depend on**:

- **Mechanical strength** (mechanical torque on the shaft)
- **Winding insulation limits** (heating of its windings)

In all practical synchronous motors and generators, the **shaft is strong enough** to handle much larger steady-state power than the machine is rated for.

Hence, the practical steady-state **limits are set by heating in the machine windings**.

There are **two windings** in a synchronous generator that has to be protected from overheating, i.e.:
(a) Armature winding
(b) Field winding

For the armature winding:

If the rated voltage is known, the **maximum apparent power rating** (rated kilovoltamperes) for the generator is **determined by** the **maximum** acceptable **armature current** $\boldsymbol{I_{\mathrm{A,max}}}$:

$$S_{\text{rated}} = 3V_{\phi,\text{rated}}I_{\text{A,max}}$$

The **heating effect of the stator copper losses** are given by

and this is **independent of the armature current power factor** (i.e. the angle of I_{A} with respect to V_{ϕ}).

This is why the machines are rated in kilovoltamperes and not kilowatts.
For the field winding:

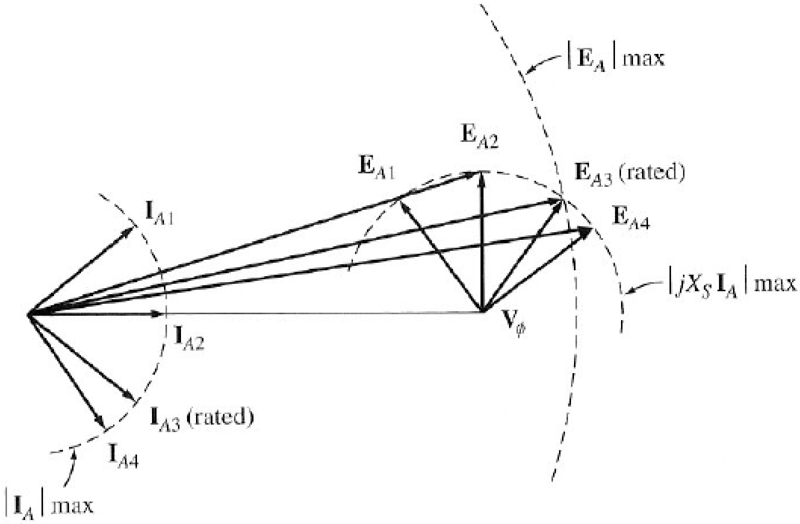
The field copper losses are given by,

$$P_{\mathrm{RCL}} = I_{\mathrm{F}}^2 R_{\mathrm{F}}$$

so the **maximum allowable heating** $P_{\mathrm{RCL,max}}$ **sets** a **maximum field current** $\boldsymbol{I_{\mathrm{F,max}}}$ for the machine, which in turn **sets the maximum acceptable size for** $\boldsymbol{E_{\mathrm{A}}}$ (since, $E_{\mathrm{A}} = K\phi\omega$), i.e. $\boldsymbol{E_{\mathrm{A,max}}}$.

Having a **maximum** $\boldsymbol{I_{\mathrm{F}}}$ **and maximum** $\boldsymbol{E_{\mathrm{A}}}$ causes a restriction on the **lowest PF** of the generator when operating **at rated apparent power**.

Below is the phasor diagram of a generator operated at rated voltage and armature current:



- The armature current $\boldsymbol{I_{\mathrm{A}}}$ can assume many different angles
- The internal generated voltage $\bar{E}_{\mathrm{A}} = \bar{V}_\phi + jX_{\mathrm{S}}\bar{I}_{\mathrm{A}}$
- **For some current angles,** $\boldsymbol{E_{\mathrm{A}} \gg E_{\mathrm{A,max}}}$**.** If generator were operated at rated $\boldsymbol{I_{\mathrm{A}}}$ and this power factor, **field winding would burn up**.

Rated power factor: Angle of $\boldsymbol{I_{\mathrm{A}}}$ that requires maximum possible $\boldsymbol{E_{\mathrm{A}}}$ **at rated** $\boldsymbol{V_\phi}$.

It is possible to **operate at a lower (more lagging) PF** than rated value, but only **by cutting back on the kVA supplied** by generator.
Synchronous generator capability curves

Generator capability diagram

Graphical plot of stator and rotor heat limits, together with **any other external limits** on a synchronous generator.

The capability curve is a **plot of $S = P + jQ$**.

The powers in a synchronous generator are given by:

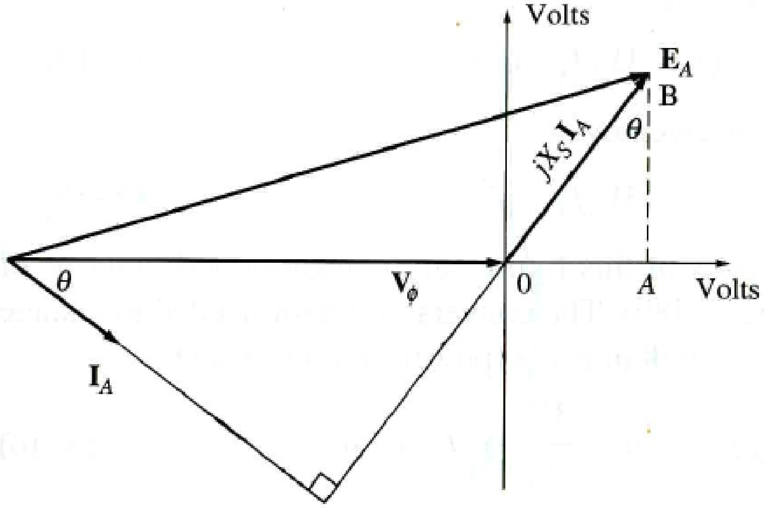
- **Real power :** $P = 3V_{\phi}I_{\mathrm{A}} \cos\theta$
- **Reactive power :** $Q = 3V_{\phi}I_{\mathrm{A}} \sin\theta$
- **Apparent power**: $S = 3V_{\phi}I_{\mathrm{A}}$

It **can be derived back from the phasor diagram** of a synchronous generator

Note that the **capability curve** must **represent power limits of the generator**, hence **need to convert**:

Voltage phasor to power phasor.

Below is the phasor diagram of a synchronous generator operating at a **lagging power factor** and its rated voltage.

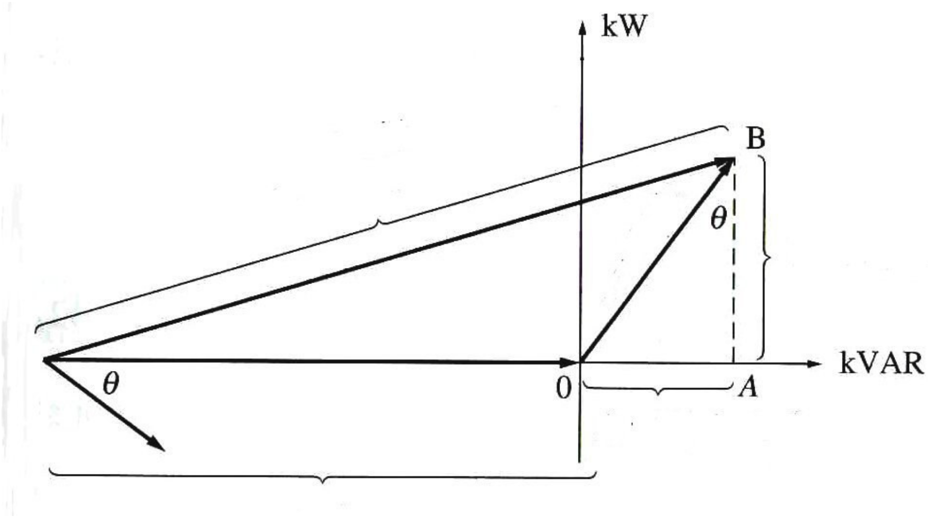


To convert voltage phasors into power phasors:

1. Draw an **orthogonal set of axes** on the diagram with its **origin at the tip** of V_{ϕ} with unit volts.
    a. Length of vertical segment AB =
    b. Length of horizontal segment 0A =

2. Hence, the **vertical and horizontal axes** of the phasor diagram can be **recalibrated in terms of real and reactive power** as shown below.

Conversion factor (from volts to voltamperes) = $\mathbf{3\, V_\phi / X_S}$



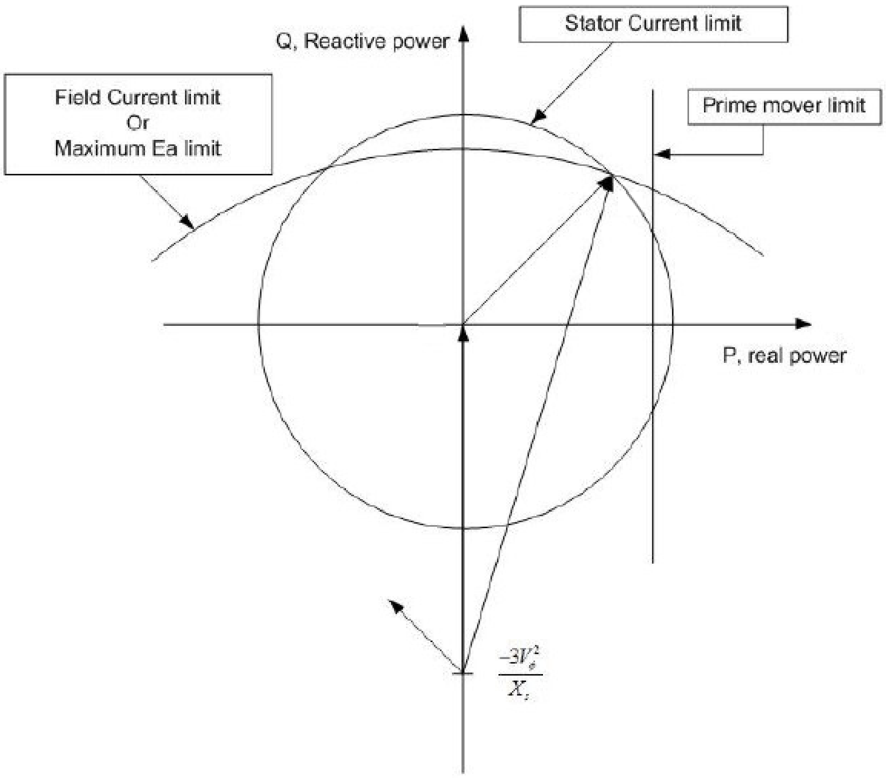
3. Origin of phasor diagram on the voltage axes = $-V_\phi$ on the horizontal axis. Hence, the horizontal origin on the power diagram is at:

4. The field current is proportional to the machine's flux and flux is proportional to $E_A = K\phi\omega$. Therefore, the **length corresponding to** E_A on the power diagram is:

$$D_E = 3\frac{E_A V_\phi}{X_S}$$

5. The armature current I_A is proportional to $X_S I_A$, and the **length corresponding to** $X_S I_A$ on the phasor diagram is $3V_\phi I_A$.

6. Next step is to **reflect the recalibrated phasor diagram** with the kVAR axis as the reference and **rotate this phasor 90° anticlockwise**, put the reactive and active power reference axis to be vertical and horizontal, respectively.



A capability diagram for the generator

It is a plot of P vs Q (P on horizontal axis and Q on vertical axis).

- **Stator (armature) current limit-** corresponds to **rated I_A** and plotted as concentric circle around origin with radius of $3V_\phi I_A$ (i.e. rated kVA). It shows the **armature heating limit**.
- **Field current limit** - corresponds to lines of **rated I_F or E_A** shown as circle centered on the point $Q = -\frac{3V_\phi^2}{X_S}$ with radius of $= 3V_\phi E_A / X_S$. It shows the **field heating limit**.
- **Any point that lies within both circles is a safe operating point for the generator.**

Example 5-8 (page 332):

A 480-V, 50 Hz, Y-connected, six-pole synchronous generator is rated at 0.8 PF lagging. It has a synchronous reactance of 1.0 W per phase. Assume that the 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.

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

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

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

d) If the generator supplied 30 kW of real power, what is the maximum amount of reactive power that can be simultaneously supplied?