# CHAPTER 5 – SYNCHRONOUS GENERATOR

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4. **The Equivalent Circuit of a Synchronous Generator**

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## 1. <u>Synchronous Generator Construction</u>

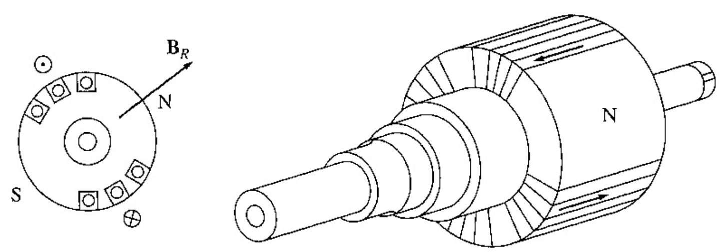
A DC current is applied to the rotor winding, which then produces a rotor magnetic field. The rotor is then turned by a prime mover (eg. Steam, water etc.) producing a rotating magnetic field. This rotating magnetic field induces a 3-phase set of voltages within the stator windings of the generator.

“Field windings” applies to the windings that produce the main magnetic field in a machine, and “armature windings” applies to the windings where the main voltage is induced. For synchronous machines, the field windings are on the rotor, so the terms “rotor windings” and “field windings” are used interchangeably.

Generally a synchronous generator must have at least 2 components:

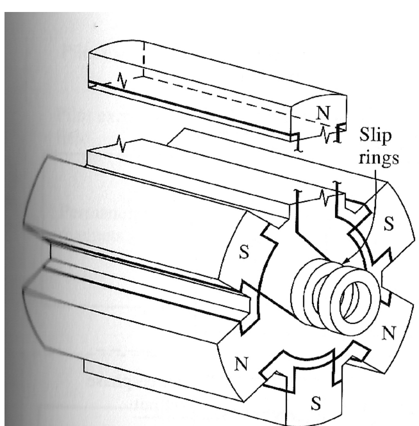
a) Rotor Windings or Field Windings
    a. Salient Pole
    b. Non Salient Pole
b) Stator Windings or Armature Windings

The rotor of a synchronous generator is a large electromagnet and the magnetic poles on the rotor can either be salient or non salient construction. Non-salient pole rotors are normally used for rotors with 2 or 4 poles rotor, while salient pole rotors are used for 4 or more poles rotor.

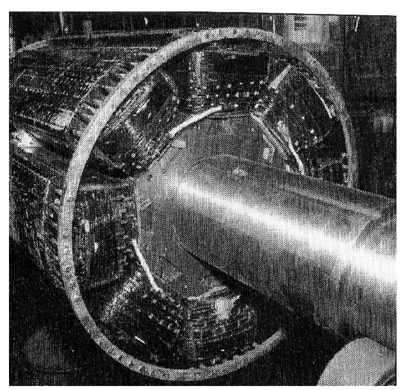



Side View

Non-salient rotor for a synchronous machine




(a)



Salient rotor

A dc current must be supplied to the field circuit on the rotor. Since the rotor is rotating, a special arrangement is required to get the dc power to its field windings. The common ways are:

a) supply the dc power from an external dc source to the rotor by means of slip rings and brushes.
b) Supply the dc power from a special dc power source mounted directly on the shaft of the synchronous generator.

Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. One end of the dc rotor winding is tied to each of the 2 slip rings on the shaft of the synchronous machine, and a stationary brush rides on each slip ring.

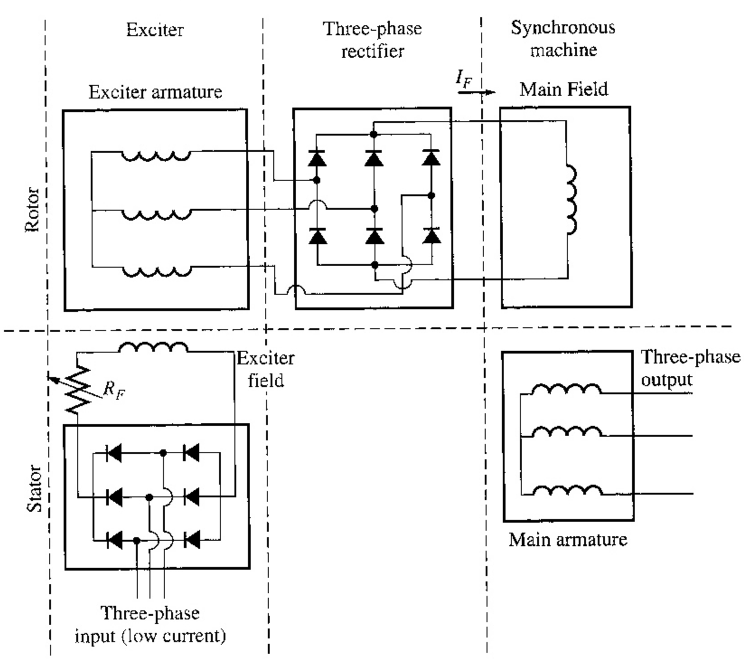
A "brush" is a block of graphitelike carbon compound that conducts electricity freely but has very low friction, hence it doesn't wear down the slip ring. If the positive end of a dc voltage source is connected to one brush and the negative end is connected to the other, then the same dc voltage will be applied to the field winding at all times regardless of the angular position or speed of the rotor.

Some problems with slip rings and brushes:

- They increase the amount of maintenance required on the machine, since the brushes must be checked for wear regularly.
- Brush voltage drop can be the cause of significant power losses on machines with larger field currents.

Small synchronous machines – use slip rings and brushes.
Larger machines – brushless exciters are used to supply the dc field current.

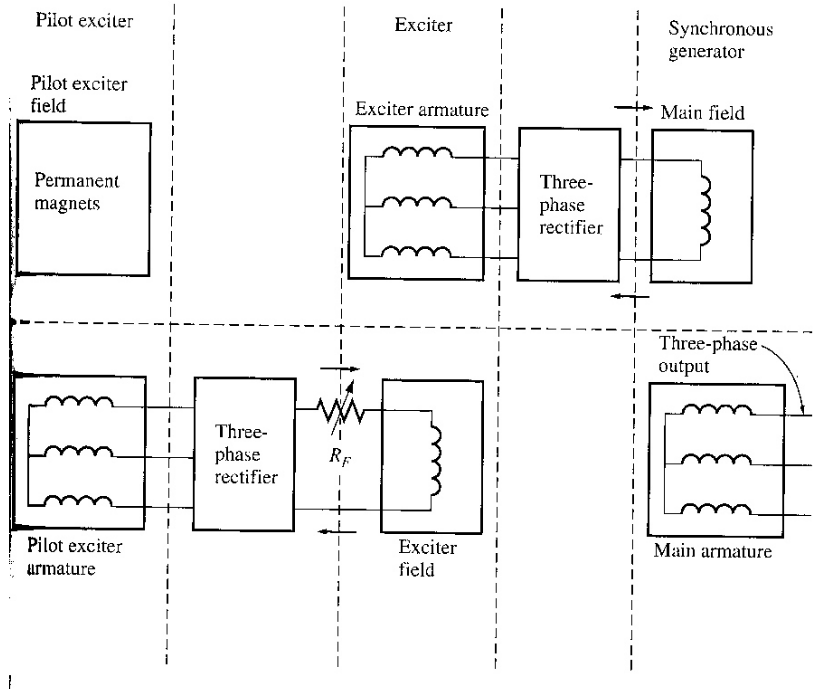
A brushless exciter is a small ac generator with its field circuit mounted on the stator and its armature circuit mounted on the rotor shaft. The 3-phase output of the exciter generator is rectified to direct current by a 3-phase rectifier circuit also mounted on the shaft of the generator, and is then fed to the main dc field circuit. By controlling the small dc field current of the exciter generator (located on the stator), we can adjust the field current on the main machine without slip rings and brushes. Since no mechanical contacts occur between the rotor and stator, a brushless exciter requires less maintenance.




A brushless exciter circuit : A small 3-phase current is rectified and used to supply the field circuit of the exciter, which is located on the stator. The output of the armature circuit of the exciter (on the rotor) is then rectified and used to supply the field current of the main machine.

To make the excitation of a generator completely independent of any external power sources, a small pilot exciter can be used.

A pilot exciter is a small ac generator with permanent magnets mounted on the rotor shaft and a 3-phase winding on the stator. It produces the power for the field circuit of the exciter, which in turn controls the field circuit of the main machine. If a pilot exciter is included on the generator shaft, then no external electric power is required.




A brushless excitation scheme that includes a pilot exciter. The permanent magnets of the pilot exciter produce the field current of the exciter, which in turn produces the field current of the main machine.

Even though machines with brushless exciters do not need slip rings and brushes, they still include the slip rings and brushes so that an auxiliary source of dc field current is available in emergencies.

**2. The Speed of Rotation of a Synchronous Generator**

Synchronous generators are by definition *synchronous*, meaning that the electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator. A synchronous generator's rotor consists of an electromagnet to which direct current is supplied. The rotor's magnetic field points in the direction the rotor is turned. Hence, the rate of rotation of the magnetic field in the machine is related to the stator electrical frequency by:

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

**3. The Internal Generated Voltage of a Synchronous Generator**

Voltage induced is dependent upon flux and speed of rotation, hence from what we have learnt so far, the induced voltage can be found as follows:

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

For simplicity, it may be simplified to as follows:

$$E_A = K\phi\omega$$

$$K = \frac{N_C P}{\sqrt{2}} \left(if \;\; \omega \; in \; electrical \; rads/s\right) \qquad K = \frac{N_C P}{2\sqrt{2}} \left(if \;\; \omega \; in \; mechanical \; rads/s\right)$$

## 4. The Equivalent Circuit of a Synchronous Generator

The voltage $E_A$ is the internal generated voltage produced in one phase of a synchronous generator. If the machine is not connected to a load (no armature current flowing), the terminal voltage will be equivalent to the voltage induced at the stator coils. This is due to the fact that there are no current flow in the stator coils hence no losses. When there is a load connected to the generator, there will be differences between $E_A$ and $V_\phi$. These differences are due to:

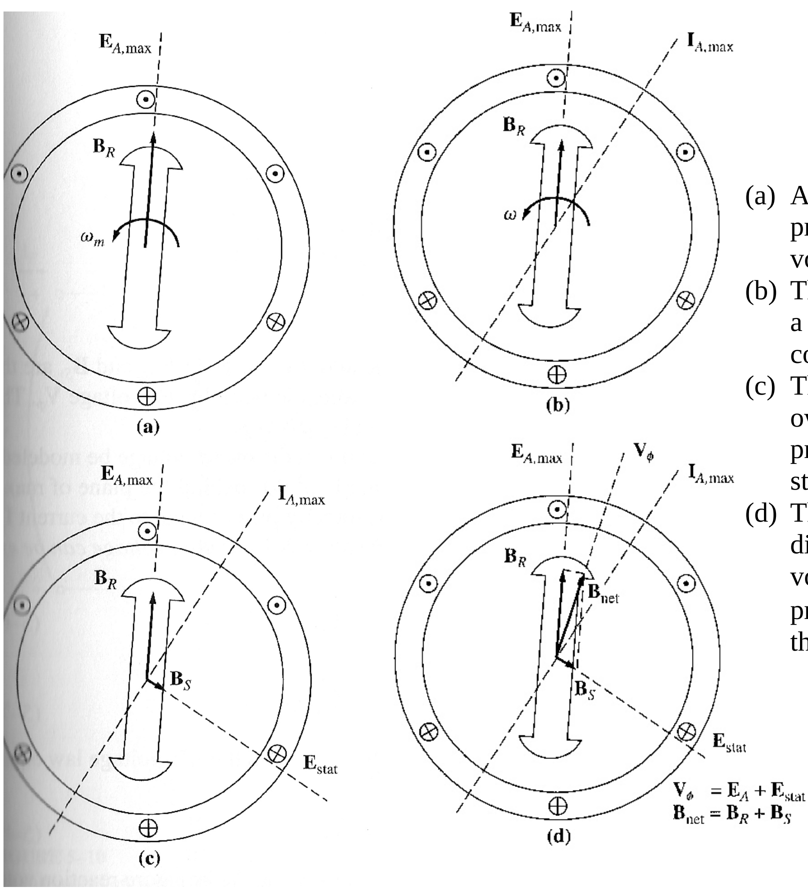
a) Distortion of the air gap magnetic field by the current flowing in the stator called **armature reaction**.
b) Self inductance of the armature coil
c) Resistance of the armature coils
d) The effect of salient pole rotor shapes.

We will explore factors a, b, and c and derive a machine model from them. The effect of salient pole rotor shape will be ignored, and all machines in this chapter are assumed to have nonsalient or cylindrical rotors.

*Armature Reaction*

When the rotor is spun, a voltage $E_A$ is induced in the stator windings. If a load is attached to the terminals of the generator, a current flows. But a 3-phase stator current flow will produce a magnetic field of its own. This stator magnetic field will distorts the original rotor magnetic field, changing the resulting phase voltage. This effect is called armature reaction because the armature (stator) current affects the magnetic field, which produced it in the first place.

Refer to the diagrams below, showing a two-pole rotor spinning inside a 3-phase stator.




(a) A rotating magnetic field produces the internal generated voltage $E_A$.
(b) The resulting voltage produces a lagging current flow when connected to a lagging load.
(c) The stator current produces its own magnetic field $B_S$ which produces its own $E_{stat}$ in the stator windings.
(d) The field $B_S$ adds to $B_R$ distorting it into $B_{net}$. The voltage $E_{stat}$ adds to $E_A$, producing $V_\phi$ at the output of the phase.

(a) There is no load connected to the stator. The rotor magnetic field $B_R$ produces an internal generated voltage $E_A$ whose peak coincides with direction of $B_R$. With no load, there is no armature current and $E_A$ will be equal to the phase voltage $V_\phi$.
(b) When a lagging load is connected, the peak current will occur at an angle behind the peak voltage.
(c) The current flowing in the stator windings produces a magnetic field of its own. This stator magnetic field $B_S$ and its direction are given by the right-hand rule. The stator field produces a voltage of its own called $E_{stat}$.
(d) With 2 voltages and 2 magnetic fields present in the stator windings, the total voltage and the net magnetic field are:

$$V_\phi = E_A + E_{Stat}$$
$$B_{net} = B_R + B_S$$

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

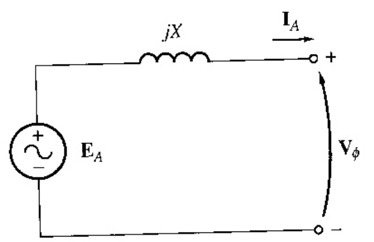
- The voltage $E_{stat}$ lies at an angle of 90° behind the plane of $I_A$.
- The voltage $E_{stat}$ is directly proportional to the current $I_A$.

If X is a constant of proportionality, then the armature reaction voltage can be expressed as:

$$E_{stat} = -jXI_A$$

Therefore:

$$V_\phi = E_A - jXI_A$$




Thus, the armature reaction voltage can be modeled as an inductor in series with the internal generated voltage.

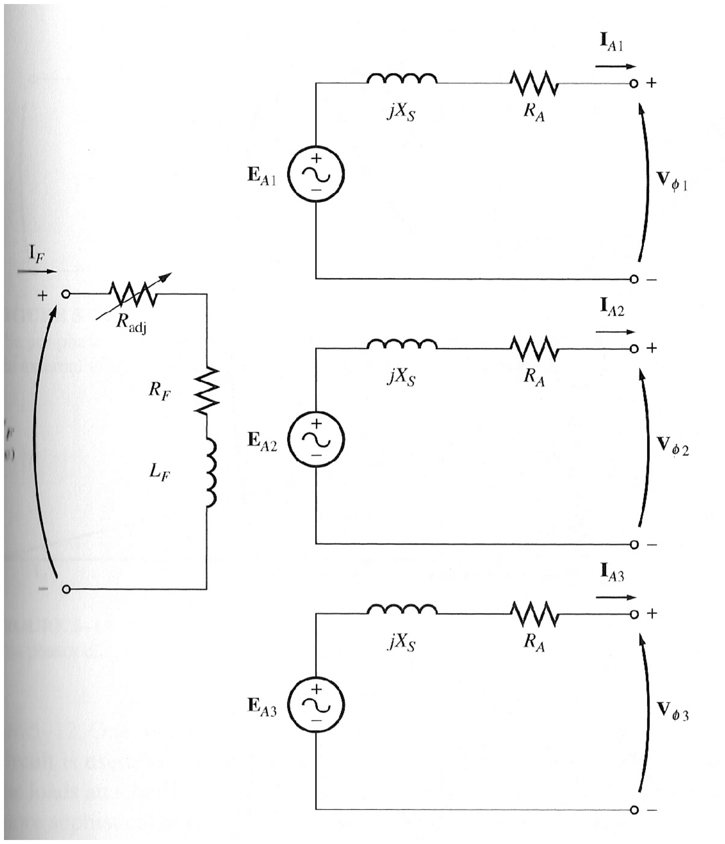
*Self-inductance and Resistance of the Armature Coils*

If the stator self-inductance is called $L_A$ (reactance is $X_A$) while the stator resistance is called $R_A$, then the total difference between $E_A$ and $V_\phi$ is:

$$\begin{aligned} V_\phi &= E_A - jXI_A - jX_AI_A - R_AI_A \\ &= E_A - jX_sI_A - R_AI_A \end{aligned}$$

Where $X_S = X + X_A$

The full equivalent circuit is shown below:



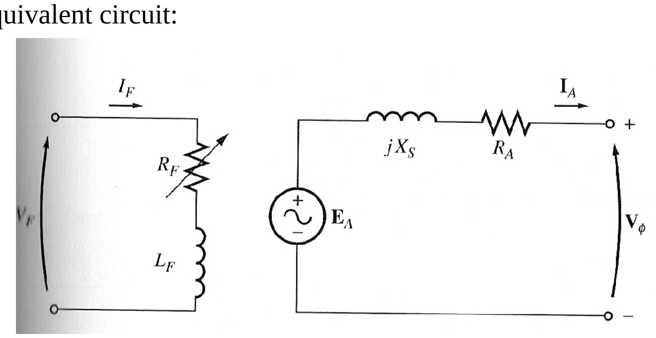

A dc power source is supplying the rotor field circuit, whis is modeled by the coil's inductance and resistance in series. In series with $R_F$ is an adjustable resistor $R_{adj}$ which controls the flow of the field current. The rest of the equivalent circuit consists of the models for each phase. Each phase has an internal generated voltage with a series inductance $X_S$ (consisting of the sum of the armature reactance and the coil's self-inductance) and a series resistance $R_A$.

If the 3 phases are connected in Y or Δ, the terminal voltage may be found as follows:

$$V_T = \sqrt{3}V_\phi \quad (\textit{for Y connection})$$
$$V_T = V_\phi \quad (\textit{for } \Delta \textit{ connection})$$

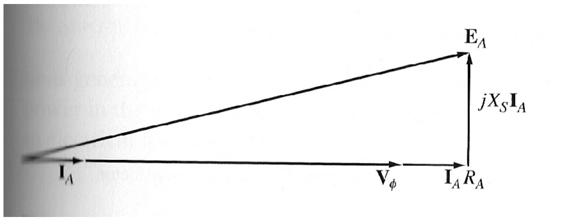
Ideally, the terminal voltage for all 3 phases should be identical since we assume that the load connected is balanced. If it is not balanced, a more in-depth technique is required.

The per-phase equivalent circuit:

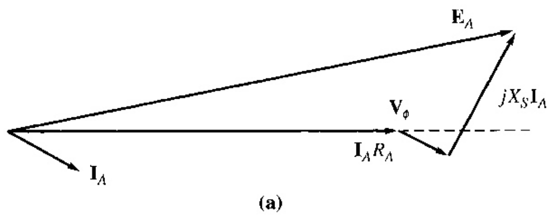


## 5. Phasor Diagram of a Synchronous Generator

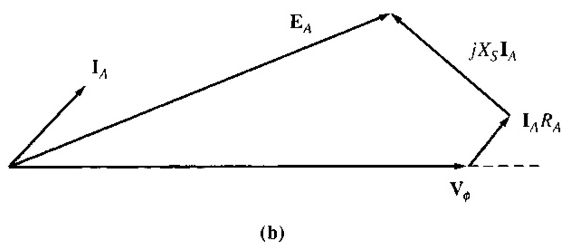
Similar concept as applied in Chapter 2 (Transformers). The phasor diagrams are as follows:




Unity power factor




Lagging power factor




Leading power factor

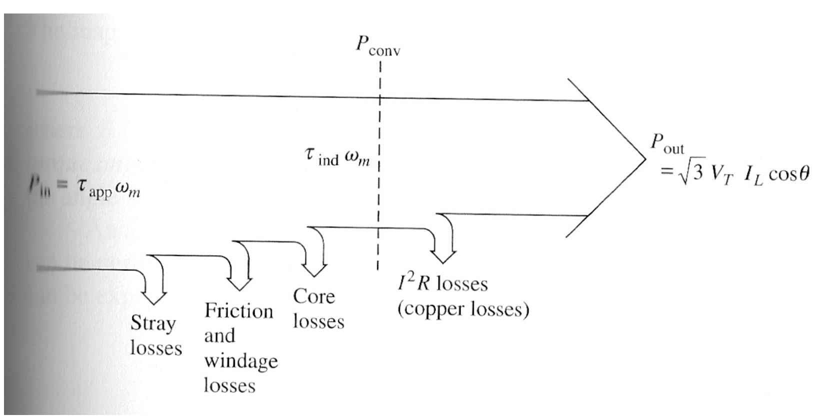
For a given phase voltage and armature current, a larger internal voltage $E_A$ is needed for lagging loads than for leading loads. Thus, a larger field current is needed to get the same terminal voltage because $E_A = k\phi\omega$ because $\omega$ must be kept constant to keep constant frequency.

Alternatively, for a given field current and magnitude of load current, the terminal voltage is lower for lagging loads and higher for leading loads.

## 6. Power and Torque in Synchronous Generators

A generator converts mechanical energy into electrical energy, hence the input power will be a mechanical prime mover, e.g. diesel engine, steam turbine, water turbine or anything similar. Regardless of the type of prime mover, the rotor velocity must remain constant to maintain a stable system frequency.

The power-flow diagram for a synchronous generator is shown:



**Input:** $P_{in} = \tau_{app}\omega_m$

**Losses:** Stray losses, friction and windage losses, core loss

**Converted power:** $P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma$

Where $\gamma$ is the angle between $E_A$ and $I_A$.

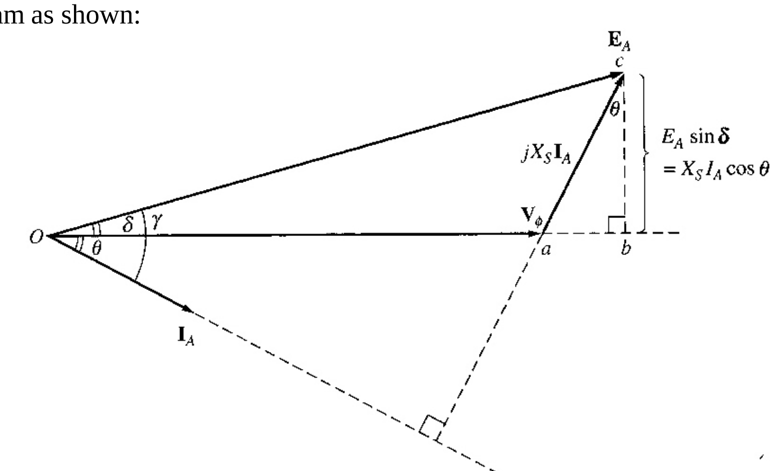
**Losses:** Copper losses

**Output:**

$$P_{out} = \sqrt{3}V_T I_L \cos\theta \qquad or \qquad P_{out} = 3V_\phi I_A \cos\theta$$

$$Q_{out} = \sqrt{3}V_T I_L \sin\theta \qquad or \qquad P_{out} = 3V_\phi I_A \sin\theta$$

Simplifying the phasor diagram, an assumption may be made whereby the armature resistance $R_A$ is considered to be negligible and assuming that load connected to it is lagging in nature. This gives a phasor diagram as shown:




Based upon the simplified phasor diagram:

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

Which gives another form of output power expression (since $R_A$ assumed to be zero):

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

From the above equation, it can be seen that power is dependent upon:

- The angle between $V_\phi$ and $E_A$ which is $\delta$.
- $\delta$ is known as the torque angle of the machine.
- maximum torque may be found when $\sin\delta$ is 1 which gives the maximum power (a.k.a. static stability limit) to be:

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

The basic torque equation:

$$\tau_{ind} = kB_R \times B_s = kB_R \times B_{net} = kB_R B_{net} \sin\delta$$

An alternative expression can be derived from the power expression since $P_{out}=P_{conv}$ when $R_A$ assumed to be zero. Because $P_{conv}=\tau_{ind}\omega_m$, the induced voltage is:

$$\tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_s}$$

## 7. Measuring Synchronous Generator Model Parameters

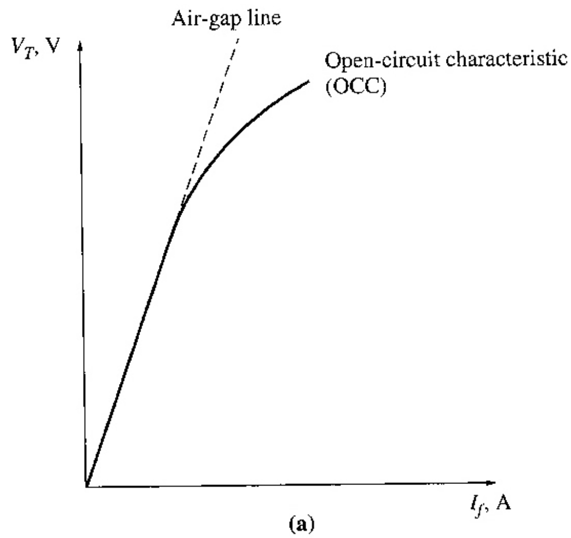
There are basically 3 types of relationship which needs to be found for a synchronous generator:

a) Field current and flux relationship (and thus between the field current and $E_A$)
b) Synchronous reactance
c) Armature resistance

**Open Circuit test**

Steps:
1) Generator is rotated at the rated speed.
2) No load is connected at the terminals.
3) Field current is increased from 0 to maximum.
4) Record values of the terminal voltage and field current value.

With the terminals open, $I_A$=0, so $E_A = V_\phi$. It is thus possible to construct a plot of $E_A$ or $V_T$ vs $I_F$ graph. This plot is called open-circuit characteristic (OCC) of a generator. With this characteristic, it is possible to find the internal generated voltage of the generator for any given field current.




Open-circuit characteristic (OCC) of a generator

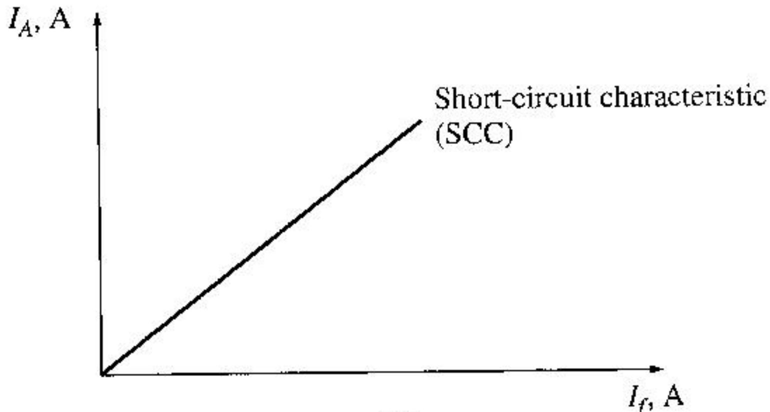
At first the curve is almost perfectly linear, until some saturation is observed at high field currents. The unsaturated iron in the frame of the synchronous machine has a reluctance several thousand times lower than the air-gap reluctance, so at first almost all the mmf is across the air-gap, and the resulting flux increase is linear. When the iron finally saturates, the reluctance of the iron increases dramatically, and the flux increases much more slowly with an increase in mmf. The linear portion of an OCC is called the air-gap line of the characteristic.

**Short circuit test**

Steps:

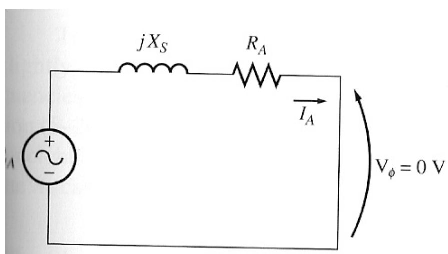
1) Generator is rotated at rated speed.
2) Adjust field current to 0.
3) Short circuit the terminals.
4) Measure armature current or line current as the field current is increased.

Notes: During the short circuit analysis, the net magnetic field is very small, hence the core is not saturated, hence the reason why the relationship is linear.




(b)

SCC is essentially a straight line. To understand why this characteristic is a straight line, look at the equivalent circuit below when the terminals are short circuited.



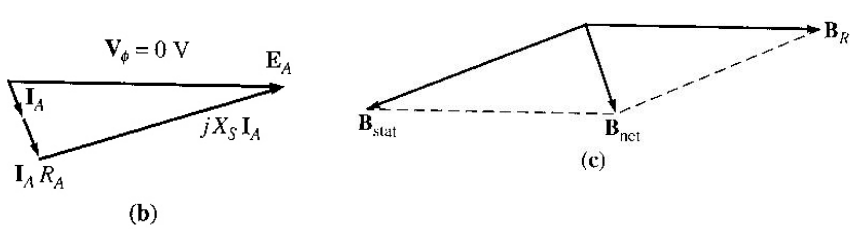

(a)

When the terminals are short circuited, the armature current $I_A$ is:

$$I_A = \frac{E_A}{R_A + jX_S}$$

And its magnitude is: $I_A = \dfrac{E_A}{\sqrt{R_A^2 + X_S^2}}$

The resulting phasor diagram and the corresponding magnetic fields are shown below:




(b) (c)

Since $B_S$ almost cancels $B_R$, the net magnetic field $B_{net}$ is very small (corresponding to internal resistive and inductive drops only). Since the net magnetic field is small, the machine is unsaturated and the SCC is linear.

From both tests, here we can find the internal machine impedance ($E_A$ from OCC, $I_A$ fom SCC):

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

Since $X_s$ >> $R_A$, the equation reduces to:

$$X_s \approx \frac{E_A}{I_A} = \frac{V_{\phi oc}}{I_A}$$

Therefore we may be able to find the synchronous reactances.

Therefore, an approximate method for determining the synchronous reactance $X_S$ at a given field current is:

1. Get the internal generated voltage $E_A$ from the OCC at that field current.
2. Get the short circuited current flow $I_{A,SC}$ at that field current from the SCC.
3. Find $X_S$ by applying the equation above.

**Problem with this method:**

$E_A$ is taken from the OCC whereby the core would be *partially saturated* for large field currents while $I_A$ is taken from the SCC where the core is *not saturated* at all field currents. Therefore $E_A$ value taken during the OCC may not be the same $E_A$ value in the SCC test. Hence the value of $X_S$ is only an approximate.

Hence to gain better accuracy, the test should be done at low field currents which looks at the linear region of the OCC test.

To find out on the resistive element of the machine, it can simply be found by applying a DC voltage to the machine terminals with the rotor stationary. Value obtained in this test ($R_A$) may increase the $X_S$ accuracy.

**Short Circuit Ratio**

Definition:

Ratio of the field current required for the rated voltage at open circuit to the field current required for rated armature current at short circuit.

Example 5-1

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

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

## 8. The synchronous generator operating alone

The behaviour of a synchronous generator under load varies greatly depending on the power factor of the load and on whether the generator is operating alone or in parallel with other synchronous generator. The next discussion, we shall disregard $R_A$ and rotor flux is assumed to be constant unless it is stated that the field current is changed. Also, the speed of the generator will be assumed constant, and all terminal characteristics are drawn assuming constant speed.

### The Effect of Load Changes on a Synchronous Generator Operating Alone

Assume a generator is connected to a load.

**Load increase:**
An increase of load is an increase in real and reactive power drawn from the generator. Such a load increase increases the load current drawn from the generator.

**Assumptions:**
- Field resistor has not been changed, field current is kept constant, hence flux is constant.
- Generator rotor speed is maintained constant.
- Therefore $E_A$ is constant.

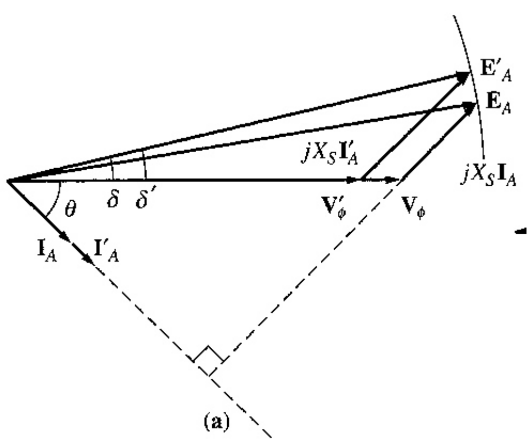
*If* $E_A$ *is constant, what actually varies with a changing load??*

**Initially lagging load:**
- Load is increased with the lagging power factor maintained.
- Magnitude of $I_A$ will increase but will maintain the same angle with reference to $V_\phi$. (due to power factor is maintained lagging)
- $X_S I_A$ will also increase and will maintain the same angle. Since

$$E_A = V_\phi + jX_s I_A$$

  j $X_S I_A$ must strecth between $V_\phi$ at an angle of 0° and $E_A$, which is constrained to be of the same magnitude as before the load increase.

- Note that $E_A$ has to remain constant (refer to the assumption stated earlier)
- Hence the only element which would change to compensate would be $V_\phi$. This change may be seen in the phasor diagram.



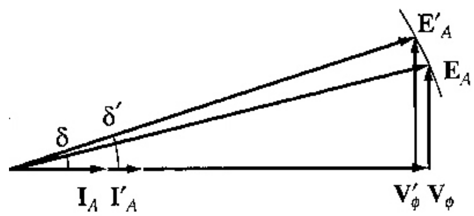

The effect of an increase in generator loads at constant power factor upon its terminal voltage – lagging power factor.

**Initially unity load:**

- Load is increased with the unity power factor maintained.
- Magnitude of $I_A$ will increase but will maintain the same angle with reference to $V_\phi$. (due to power factor is maintained unity)
- $X_S I_A$ will also increase and will maintain the same angle. Since

$$E_A = V_\phi + jX_s I_A$$

- Note that $E_A$ has to remain constant (refer to the assumption stated earlier)
- Hence the only element which would change to compensate would be $V_\phi$. This change may be seen in the phasor diagram.



(b)

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

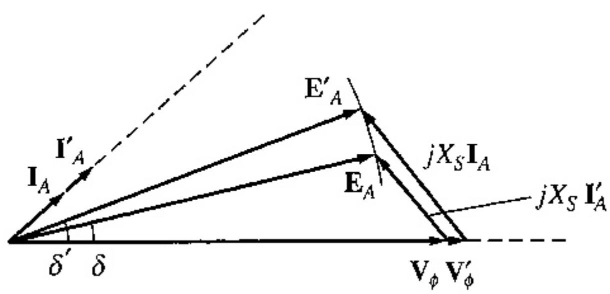
- Changes in $V_\phi$ would be decreasing but it would be less significant as compared to when the load is lagging.

**Initially leading load:**

- Load is increased with the leading power factor maintained.
- Magnitude of $I_a$ will increase but will maintain the same angle with reference to $V_\phi$. (due to power factor is maintained leading)
- $X_s I_a$ will also increase and will maintain the same angle. Since

$$E_A = V_\phi + jX_s I_A$$

- Note that $E_a$ has to remain constant (refer to the assumption stated earlier)
- Hence the only element which would change to compensate would be $V_\phi$. This change may be seen in the phasor diagram.



(c)

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

An alternative way to explain this is via the **voltage regulation formulae**.

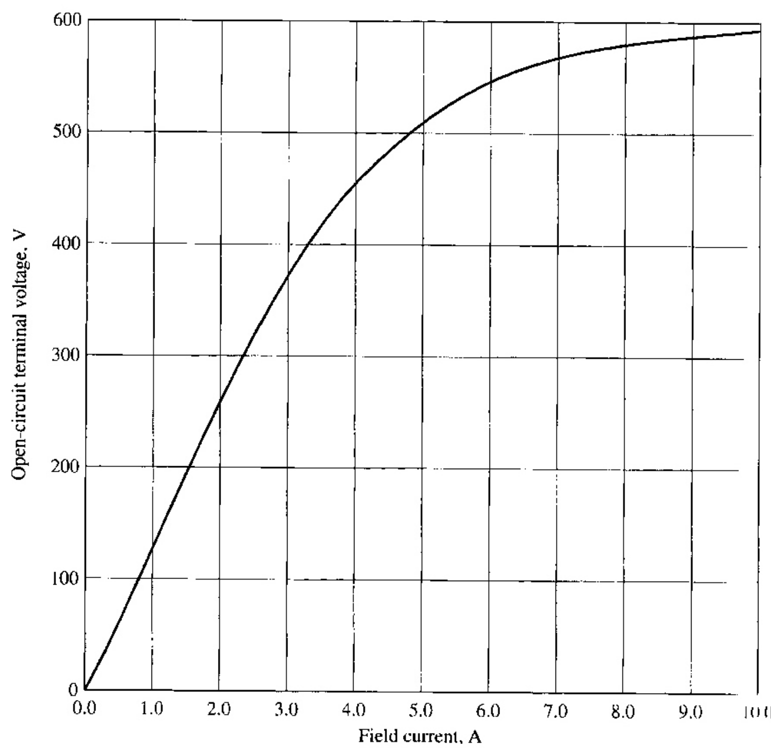
- For lagging loads, VR would be very positive.
- For leading loads, VR would be very negative.
- For unity loads, VR would be positive.

However, in practical it is best to keep the **output voltage of a generator to be constant**, hence **$E_A$ has to be controlled** which can be done by **controlling the field current $I_F$. Varying $I_F$ will vary the flux in the core which then will vary $E_A$ accordingly (refer OCC).**

*How must a generator's field current be adjusted to keep $V_T$ constant as the load changes?*

<u>Example 5-2</u>

A 480V, 60Hz, Δ-connected, 4-pole synchronous generator has the OCC as shown below. This generator has a synchronous reactance of 0.1Ω and an armature resistance of 0.015 Ω. At full load, the machine supplies 1200A at 0.8 PF lagging. Under full-load conditions, the friction and windage losses are 40kW, and the core losses aree 30kW. Ignore any field circuit losses.




(a) hat is the speed of rotation of this generator?
(b) How much field current must be supplied to the generator to make the terminalvoltage 480V at no load?
(c) If the generator is now connected to a load and the load draws 1200A at 0.8 PF lagging, how much field current will be required to keep the terminal voltage equal to 480V?
(d) How much power is the gen 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?
(f) Finally, suppose that the generator is connected to a load drawing 1200A at 0.8 PF leading. How much field current would be required to keep $V_T$ at 480V?

Example 5-3

A 480V, 50Hz, Y-connected, 6-pole synchronous generator has a per-phase synchronous reactance of 1Ω. Its full-load armature current is 60A at 0.8PF lagging. This generator has friction and windage losses of 1.5kW and core losses of 1 kW at 60Hz at 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 480V 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 efficieny of this generator (ignoring the unknown electrical losses) when it is operating at the rated current and 0.8 PF lagging?
(d) How much shaft torque must applied by the prime mover at full load? How large is the induced countertorque?
(e) What is the voltage regulation of this generator at 0.8 PF lagging? At 1.0 PF? At 0.8 PF leading?

## 9. Parallel Operation of AC Generators

Reasons for operating in parallel:

a) Handling larger loads.
b) Maintenance can be done without power disruption.
c) Increasing system reliability.
d) Increased efficiency.

### Conditions required for Paralleling

The figure below shows a synchronous generator G1 supplying power to a load, with another generator G2 about to be paralleled with G1 by closing switch S1. What conditions must be met before the switch can be closed and the 2 generators connected?

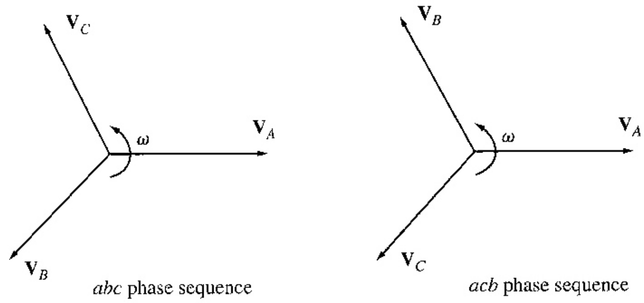
If the switch is closed arbitrarily at some moment, the generators are liable to be severely damaged, and the load may lose power.

If the voltages are not exactly the same in each conductor being tied together, there will be a very large current flow when the switch is closed. To avoid this problem, each of the three phases must have exactly the same voltage magnitude and phase angle as the conductor to which it is connected.

Thus, paralleling 2 or more generators must be done carefully as to avoid generator or other system component damage. Conditions are as follows:

a) RMS line voltages must be equal.

b) The generators to be paralleled must have the same phase sequence. If the phase sequence is different (as shown here), then even though one pair of voltages (the *a* phase) is in phase, the other 2 pairs of voltages are 120° out of phase. If the generators were connected in this manner, there would be no problem with phase *a*, but huge currents would flow in phases *b* and *c*, damaging both machines.



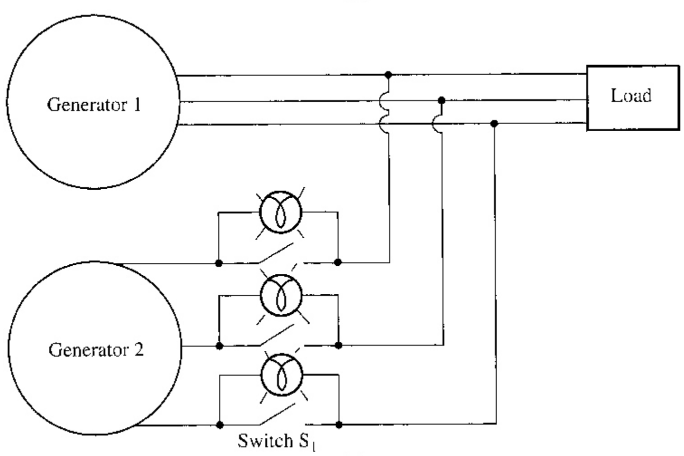
(a)

c) Generator output phase angles must be the same.

d) The **oncoming generator** (the new generator) must have a slightly higher operating frequency as compared to the system frequency. This is done so that the phase angles of the incoming machine will change slowly with respect to the phase angles of the running system.

**General Procedure for Paralleling Generators**

Suppose that generator G2 is to be connected to the running system as shown below:



(b)

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 **phase sequence** to be identical to the system phase sequence. There are 2 methods to do this:
   i. Alternately connect a small induction motor to the terminals of each of the 2 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.

   ii. Another way is using the 3 light bulb method, where the bulbs are stretched across the open terminals of the switch connecting the generator to the system (as shown in the figure above). As the phase changes between the 2 systems, the light bulbs first get bright (large phase difference) and then get dim (small phase difference). If all 3 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.

iii. Using a Synchroscope – a meter that measures the difference in phase angles (it does not check phase sequences only phase angles).

3. Check and verify **generator frequency** to be 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 phase between the systems.

4. Once the frequencies are nearly equal, the voltages in the 2 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 2 systems is shut.

## Frequency-Power and Voltage-Reactive Power Characteristics of a Synchronous Generator

All generators are driven by a prime mover, which is the generator's source of mechanical power. All prime movers tend to behave in a similar fashion – as the power drawn from them increases, the speed at which they turn decreases. The decrease in speed is in general non linear, but some form of governor mechanism is usually included to make the decrease in speed linear with an increase in power demand.

Whatever governor mechanism is present on a prime mover, it will always be adjusted to provide a slight drooping characteristic with increasing load. The speed droop (SD) of a prime mover is defined as:

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$$

Where $n_{nl}$ is the no-load prime mover speed and $n_{fl}$ is the full-load prime mover speed.

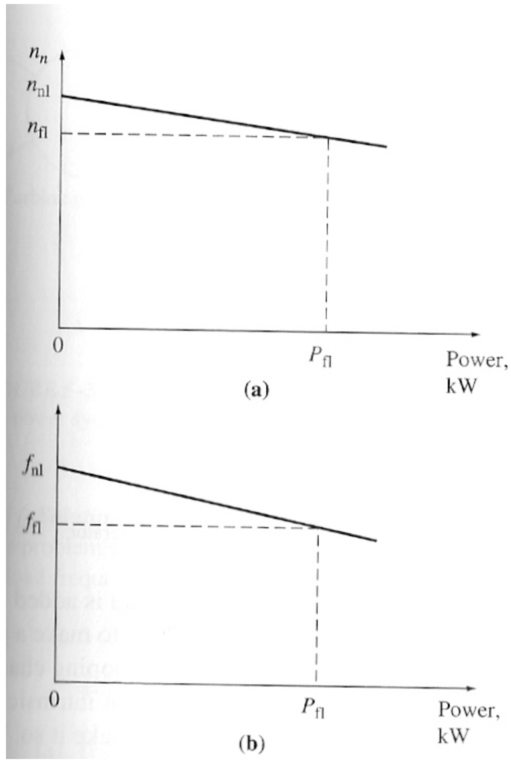
Typical values of SD are 2% – 4%. Most governors have some type of set point adjustment to allow the no-load speed of the turbine to be varied. A typical speed vs. power plot is as shown below.

Since mechanical speed is related to the electrical frequency and electrical frequency is related with the output power, hence we will obtain the following equation:

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

Where
P = output power
$f_{nl}$ = no-load frequency of the generator
$f_{sys}$ = operating frequency of system
$s_P$ = slope of curve in kW/Hz or MW/Hz

If we look in terms of reactive power output and its relation to the terminal voltage we shall see a similar shape of curve as shown in the frequency power curve.




In conclusion, for a **single** generator:

a) For any given real power, the governor set points control the generator operating frequency
b) For any given reactive power, the field current controls the generator's terminal voltage.
c) Real and reactive power supplied will be the amount demanded by the load attached to the generator – the P and Q supplied cannot be controlled by the generator's controls.

Example 5-5

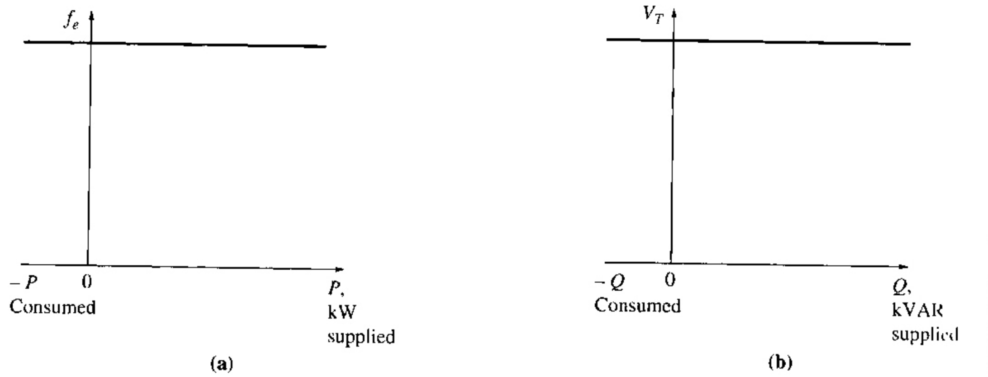
Figure below shows a generator supplying a load. A second load is to be connected in parallel with the first one. The generator has a no-load frequency of 61.0 Hz and a slope $s_p$ of 1 MW/Hz. Load 1 consumes a real power of 1000kW at 0.8 PF lagging, while load 2 consumes a real power of 800kW at 0.707 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 60Hz?

**Operation of Generators in Parallel with Large Power Systems**

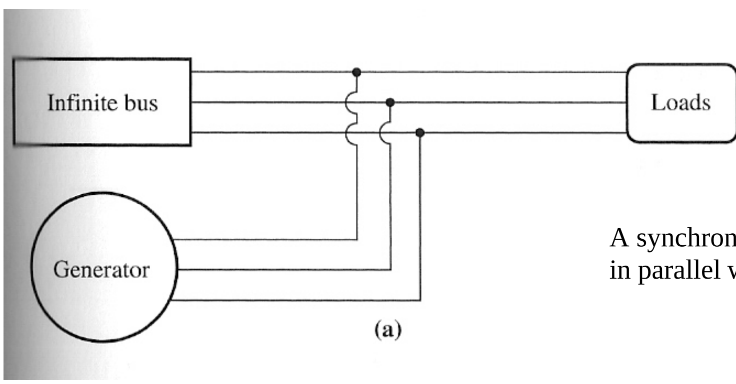
Changes in one generator in large power systems may not have any effect on the system.

A large power system may be represented as an **infinite bus** system. 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 power-frequency characteristic and the reactive power-voltage characteristic are shown below:

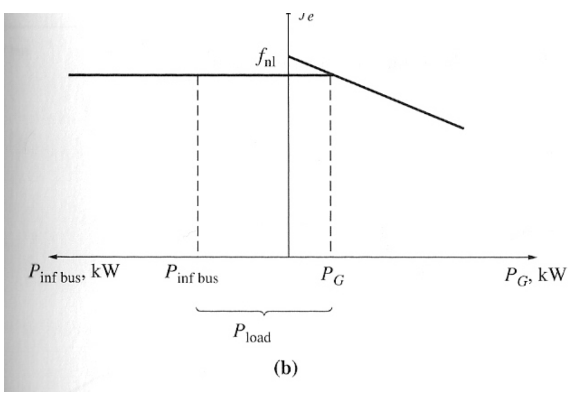



Now consider a generator connected to an infinite bus system feeding into a load. We shall consider the action or changes done to the generator and its effect to the system. Assume that the generator's prime mover has a governor mechanism, but that the field is controlled manually by a resistor.

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 the same, since their output conductors are tied together. Thus, their real power-frequency and reactive power-voltage characteristics can be plotted back to back, with a common vertical axis. Such a sketch is called a *house diagram*, as shown below:

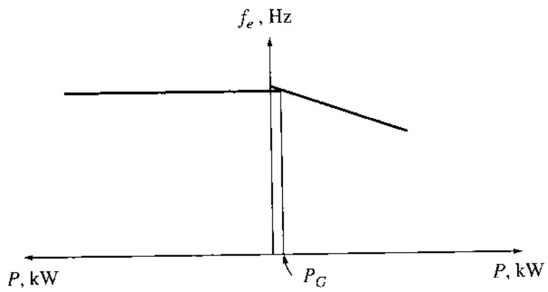



A synchronous generator operating in parallel with an infinite bus

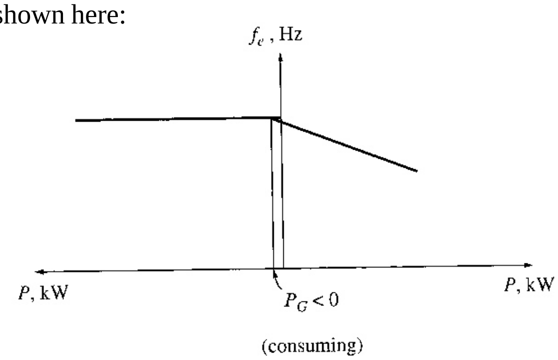



The frequency-power diagram (house diagram) for a synchronous generator in parallel with an infinite bus.

Assume that the generator has just been paralleled with the infinite bus according to the procedure described previously.  Thus, the generator will be "floating" on the line, supplying a small amount of real power and little or no reactive power. This is shown here:




Suppose the generator had been paralleled to the line but instead of being at a slightly higher frequency than the running system, it was at a slightly lower frequency. In this case, when paralleling is completed, the resulting situation is as shown here:

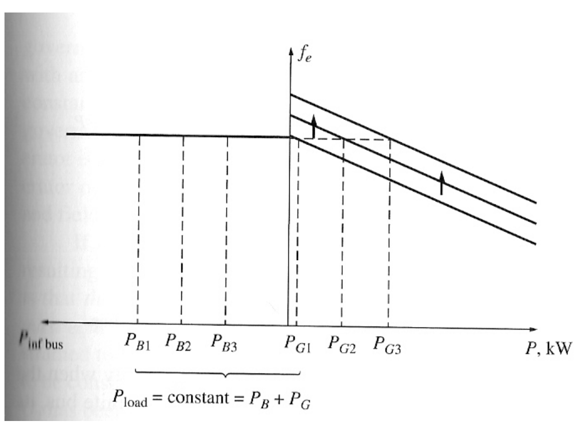



Notice that here the no-load frequency of the generator is less than the system's frequency.  At this frequency, the power supplied by the generator is actually negative.  In other words, when the generator's no-load frequency is less than the system's operating frequency, the generator actually consumes electric power and runs as a motor.   It is to ensure that a generator comes on line supplying power instead of consuming in that the oncoming machine's frequency is adjusted higher than the running system's frequency.

Assume that the generator is already connected, what effects of governor control and field current control has to the generator?

**Governor Control Effects:**

In theory, if the governor set points is increased, the no load frequency will also increase (the droop graph will shift up). Since in an infinite bus system frequency does not change, the overall effect is to increase the generator output power (another way to explain that it would look as if the generator is loaded up further). Hence the output current will increase.




The effect of increasing the governor's set point on the house diagram

The effect of increasing the governor's set point on the phasor diagram

Notice that in the phasor diagram that $E_A \sin \delta$ (which is proportional to the power supplied as long as $V_T$ is constant) has increased, while the magnitude of $E_A$ ($=K\phi\omega$) remains constant, since both the field current $I_F$ and the speed of rotation $\omega$ is unchanged. As the governor set points are further increased the no-load frequency increases and the power supplied by the generator increases. As the power output increases, $E_A$ remains at constant magnitude while $E_A \sin \delta$ is further increased.

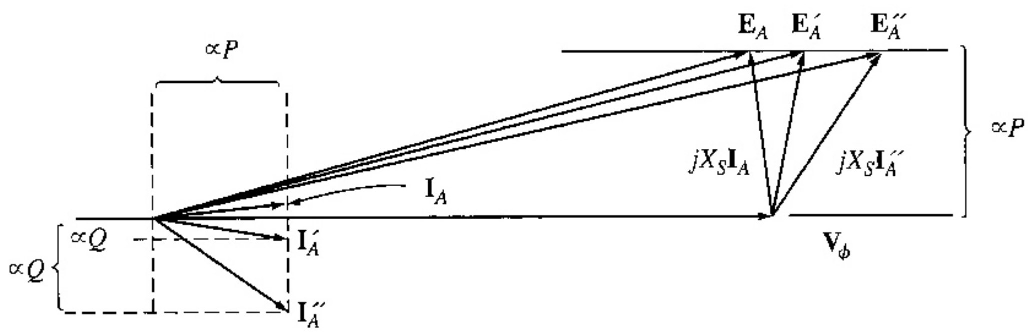
If the governor is set as such that it exceeds the load requirement, the excess power will flow back to the infinite bus system. The infinite bus, by definition, can supply or consume any amount of power without a change in frequency, so the extra power is consumed.

**Field Current Control Effects:**

Increasing the governor set point will increase power but will cause the generator to absorb some reactive power. The question is now, how do we supply reactive power Q into the system instead of absorbing it? This can be done by adjusting the field current of the generator.

**Constraints:** Power into the generator must remain constant when $I_F$ is changed so that power out of the generator must also remain constant. The power into a generator is given by the equation $P_{in}=\tau_{ind}\omega_m$ . Now, the prime mover of a synchronous generator has a fixed-torque speed characteristic for any given governor setting. This curve changes only when the governor set points are changed. Since the generator is tied to an infinite bus, its speed cannot change. If the generator's speed does not change and the governor set points have not been changed, the power supplied by the generator must remain constant.

If the power supplied is constant as the field current is changed, then the distances proportional to the power in the phasor diagram ($I_A \cos \theta$ and $E_A \sin \delta$) cannot change. When the field current is increased, the flux $\phi$ increases, and therefore $E_A$ ($=K \phi\uparrow \omega$) increases. If $E_A$ increases, but $E_A \sin \delta$ must remain constant, then the phasor $E_A$ must "slide" along the line of constant power, as shown below.




The effect of increasing the generator's field current on the phasor diagram of the machine.

Since $V_\phi$ is constant, the angle of $jX_SI_A$ changes as shown, and therefore the angle and magnitude of $I_A$ change. Notice that as a result the distance proportional to Q ($I_A\sin\theta$) increases.

In other words, increasing the field current in a synchronous generator operating in parallel with an infinite bus increases the reactive power output of the generator.

**Hence, for a generator operating in parallel with an infinite bus:**

a) **Frequency and terminal voltage of generator is controlled by the connected system.**
b) **Changes in Governor set points will control real power to be supplied.**
c) **Changes in Field Current will control the amount of reactive power to be supplied.**

*Note that these effects are only applicable for generators in a large system only.*

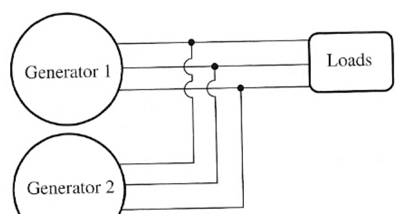
**<u>Operation of Generators in Parallel with Other Generators of the Same Size</u>**

When a single generator operated alone, the real and reactive powers supplied by the generators are fixed, constrained to be equal to the power demanded by the load, and the frequency and terminal voltage were varied by the governor set points and the field current.

When a generator is operating in parallel with an infinite bus, the frequency and terminal voltage were constrained to be constant by the infinite bys, and the real and reactive powers were varied by the governor set points and the field current.

*What happens when a synchronous generator is connected in parallel not with an infinite bus, but rather with another generator of the same size?*
*What will be the effect of changing governor set points and field currents?*

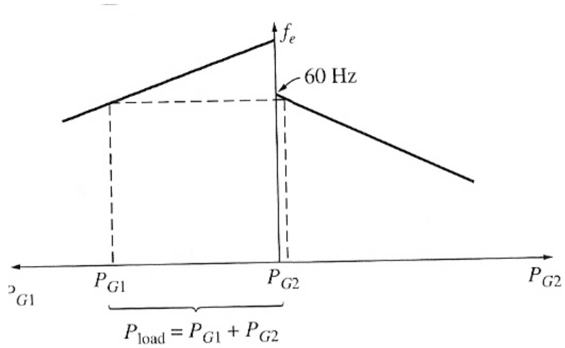
The system is as shown here:



(a)

In this system, the basic constraint is that the sum of the real and reactive powers supplied by the two generators must equal the P and Q demanded by the load.  The system frequency is not constrained to be constant, and neither is the power of a given generator constrained to be constant.

The power-frequency diagram for such a system immediately after $G_2$ has been paralleled to the line is shown below:



(b)

The house diagram at the moment $G_2$ is paralleled with the system

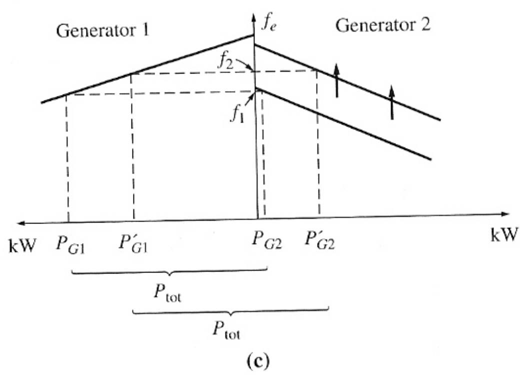
The total power $P_{tot}$ (which is equal to $P_{load}$) and reactive power respectively are given by:

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

$Q_{tot} = Q_{load} = Q_{G1} + Q_{G2}$

*What happens if the governor set points of $G_2$ are increased?*

As a result, the power-frequency curve of $G_2$ shifts upward as shown here:




The effect of increasing $G_2$'s governor set points on the operation of the system.

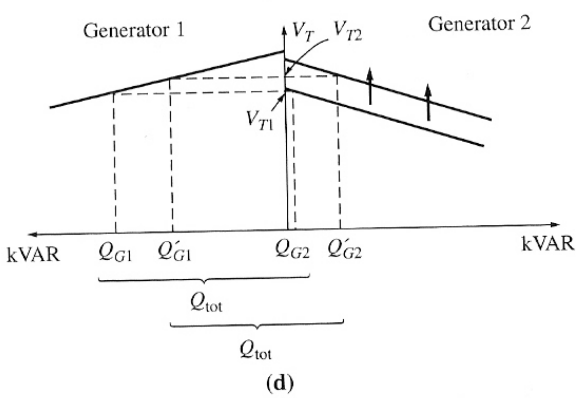
The total power supplied to the load must not change. At the original frequency $f_1$, the power supplied by $G_1$ and $G_2$ will now be larger than the load demand, so the system cannot continue to operate at the same frequency as before. In fact, there is only one frequency at which the sum of the powers out of the two generators is equal to $P_{load}$. That frequency $f_2$ is higher than the original system operating frequency. At that frequency, $G_2$ supplies more power than before, and $G_1$ supplies less power than before.

Thus, when 2 generators are operating together, an increase in governor set points on one of them

1. increases the system frequency.
2. increases the power supplied by that generator, while reducing the power supplied by the other one.

*What happens if the field current of $G_2$ is increased?*

The resulting behaviour is analogous to the real-power situation as shown below:



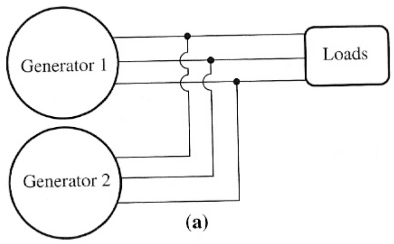

The effect of increasing $G_2$'s field current on the operating of the system.

When 2 generators are operating together and the field current of $G_2$ is increased,

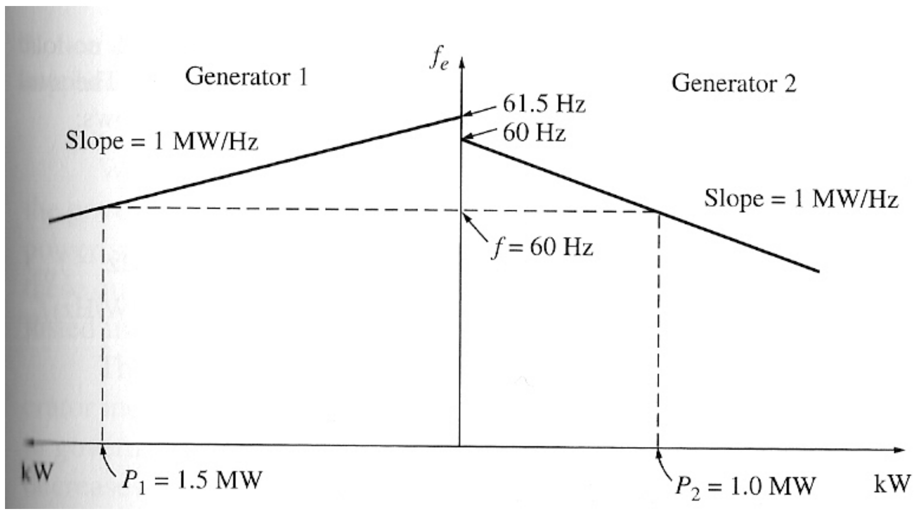
1. The system terminal voltage is increased.
2. The reactive power Q supplied by that generator is increased, while the reactive power supplied by the other generator is decreased.

If the slopes and no-load frequencies of the generator's speed droop (frequency-power) curves are known, then the powers supplied by each generator and the resulting system frequency can be determined quantitatively. Example 5-6 shows how this can be done.

Example 5-6




$G_1$ has a no-load frequency of 61.5 Hz and a slope $s_{P1}$ of 1MW/Hz. $G_2$ has a no-load frequency of 61Hz and a slope $s_{P1}$ of 1MW/Hz. The 2 generators are supplying a real load totalling 2.5 MW at 0.8 PF lagging. The resulting system power-frequency or house diagram is shown below.

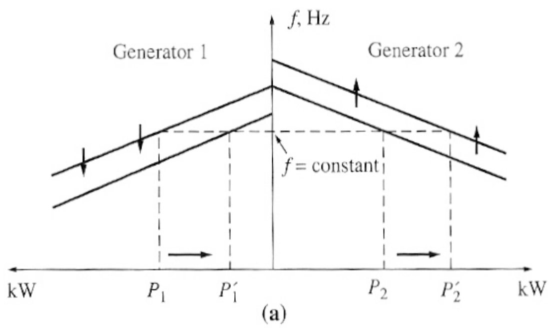



(a) At what frequency is this system operating, and how much power is supplied by each of the 2 generators?
(b) Suppose an additional 1-MW load were attached to this power system. What would the new system frequency be, and how much power would $G_1$ and $G_2$ supply now?
(c) With the system in the configuration described in part b, what will the system frequency and generator powers be of the governor set points on $G_2$ are increased by 0.5 Hz?

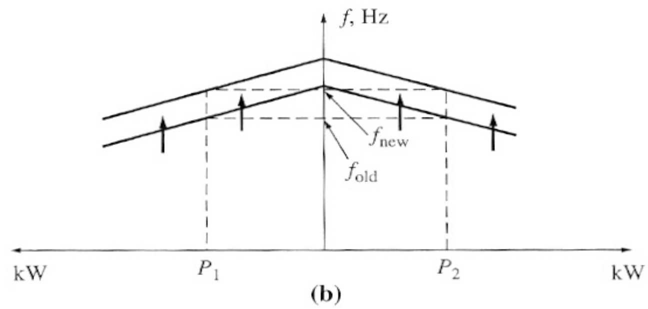
When 2 generators of similar size are operating in parallel, a change in the governor set points of one of them changes both the system freq and the power sharing between them.

*How can the power sharing of the power system be adjusted independently of the system frequency, and vice versa?*

An increase in governor set points on one generator increases that machine's power and increases the system frequency. A decrease in governor set points on the other generator decreases that machine's power and decreases the system frequency. Therefore, to adjust power sharing without changing the system frequency, increase the governor set points of one generator and simultaneously decrease the governor set points of the other generator. (and same goes when adjusting the system frequency). This is shown below:

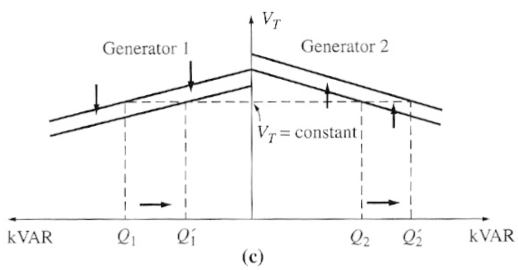



Shifting power sharing without affecting system frequency

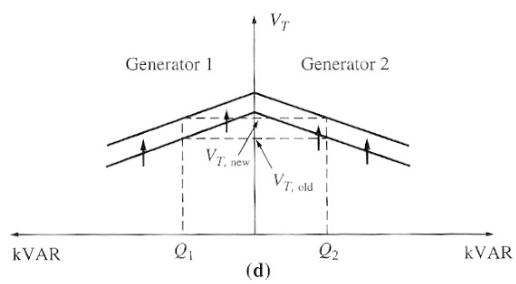



Shifting system frequency without affecting power sharing

Reactive power and terminal voltage adjustment work in an analogous fashion. To shift the reactive power sharing without changing $V_T$, simultaneously increase the field current on one generator and decrease the field current on the other. (and same goes when adjusting the terminal voltage). This is shown below:

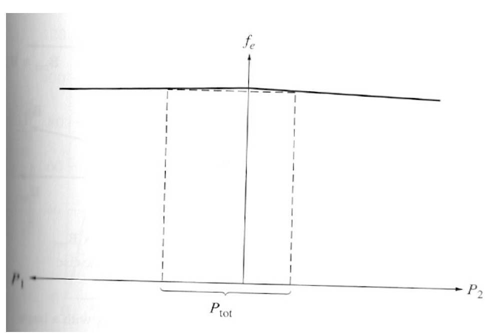



Shifting reactive power sharing without affecting terminal voltage




Shifting terminal voltage without affecting reactive power sharing

It is very important that any synchronous generator intended to operate in parallel with other machines have a drooping frequency-power characteristic. If two generators have flat or nearly flat characteristics, then the power sharing between them can vary widely with only the tiniest changes in no-load speed. This problem is illustrated below:



Notice that even very tiny changes in $f_{nl}$ in one of the generators would cause wild shifts in power sharing. To ensure good control of power sharing between generators, they should have speed droops in the range of 2-5%.

## 10. Synchronous Generator Ratings

### The Voltage, Speed and Frequency Ratings

**Frequency Ratings:** Rated frequency will depend upon the system at which the generator is connected.

**Voltage Ratings:** Generated voltage is dependent upon flux, speed of rotation and mechanical constants. However, there is a ceiling limit of flux level since it is dependent upon the generator material. Hence voltage ratings may give a rough idea on its maximum flux level possible and also maximum voltage to before the winding insulation breaks down.

### Apparent Power and Power Factor Ratings

Constraints for electrical machines generally dependent upon mechanical strength (mechanical torque on the shaft of the machine) and also its winding insulation limits (heating of its windings). For a generator, there are 2 different windings that has to be protected which are:

a) Armature winding
b) Field Winding

Hence the maximum armature current flow can be found from the maximum apparent power, S:

$$S = 3V_\phi I_A$$

If the rated voltage is known, we may find the maximum $I_A$ allowed.

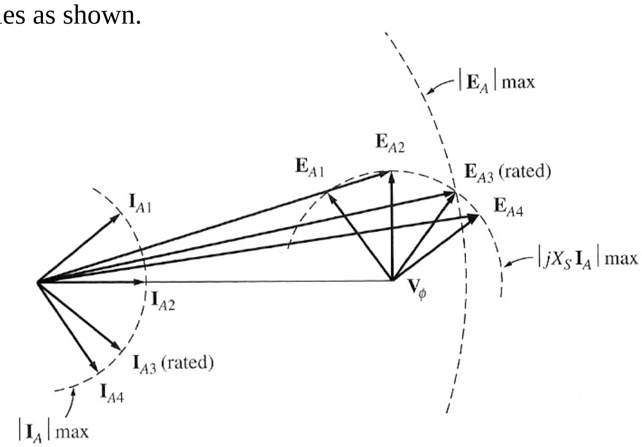
The heating effect of the stator copper losses is given by:

$$P_{SCL} = 3\ I_A^2\ R_A$$

The field copper losses:

$$P_{RCL} = I_F^2 R_F$$

Maximum field current will set the maximum $E_A$ permissible. And since we can find the maximum field current and the maximum $E_A$ possible, we may be able to determine the lowest PF changes possible for the generator to operate at rated apparent power. Figure below shows the phasor diagram of a synchronous generator with the rated voltage and armature current. The current can assume many different angles as shown.

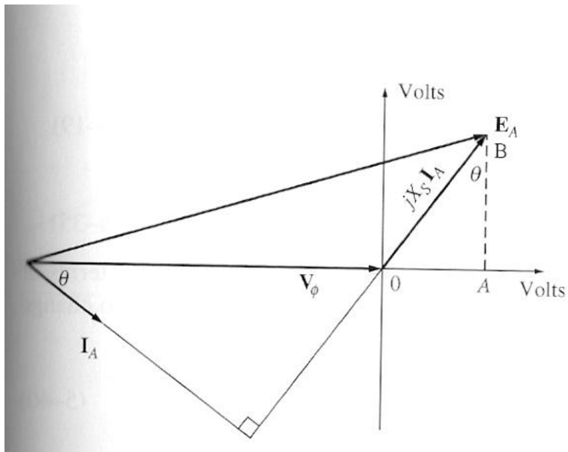


The internal generated voltage $E_A$ is the sum of $V\phi$ and $jX_SI_A$. Notice that for some possible current angles the required $E_A$ exceeds $E_{A,max}$. If the generator were operated at the rated armature current and these power factors, the field winding would burn up.
The angle of $I_A$ that requires the max possible $E_A$ while $V\phi$ remains at the rated value gives the rated power factor of the generator. It is possible to operate the generator at a lower (more lagging) power factor than the rated value, but only by cutting back on the kVA supplied by the generator.

**Synchronous Generator Capability Curves.**

Based upon these limits, there is a need to plot the capability of the synchronous generator. This is so that it can be shown graphically the limits of the generator.

A capability diagram is a plot of complex power S=P+jQ. The capability curve can be derived back from the voltage phasor of the synchronous generator. Assume that a voltage phasor as shown, operating at lagging power factor and its rated value:



(a)

Note that the capability curve of the must represent power limits of the generator, hence there is a need to convert the **voltage phasor** into **power phasor**.

The powers are given by:

$$P = 3\, V\phi\, I_A \cos\theta$$
$$Q = 3\, V\phi\, I_A \sin\theta$$
$$S = 3\, V\phi\, I_A$$

Thus,

The conversion factor to change the scale of the axes from V to VA is $3\, V\phi/X_S$.

On the voltage axes, the origin of the phasor diagram is at -Vϕ on the horizontal axis, so the origin on the power diagram is at:

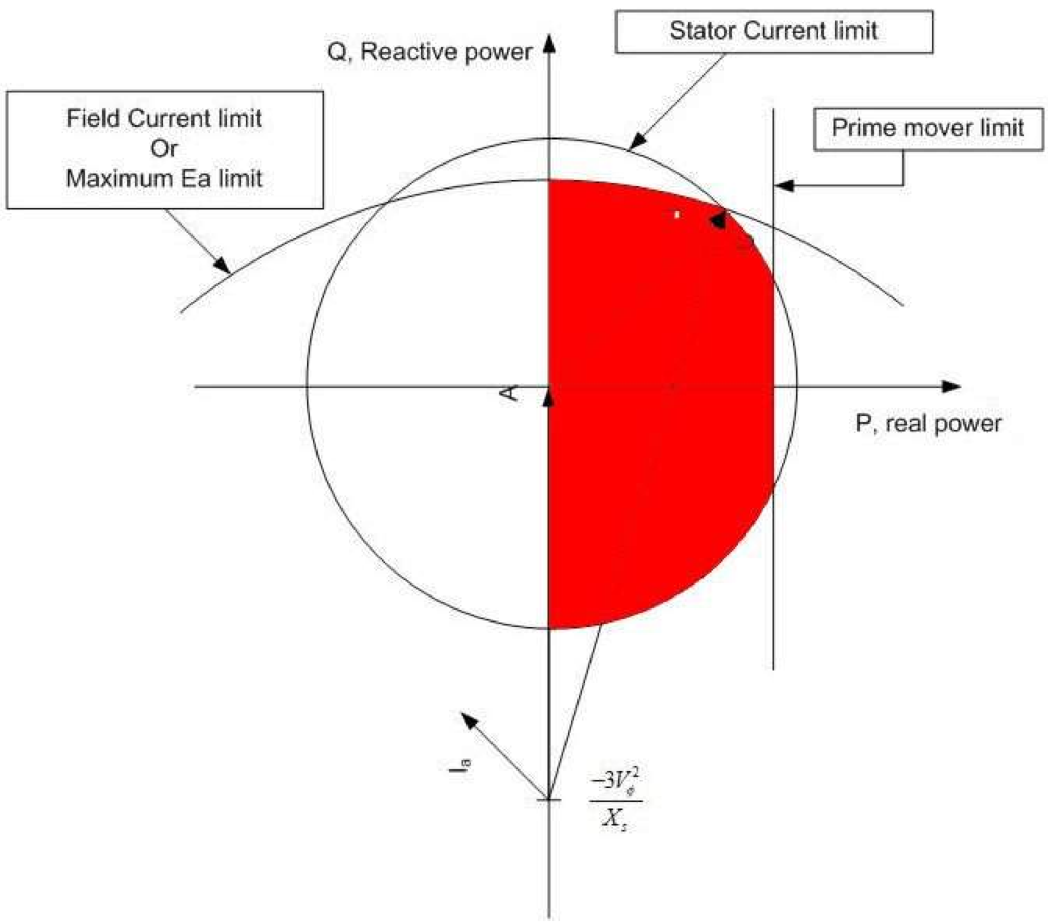
$$Q = \frac{3V_\phi}{X_S}\left(-V_\phi\right) = -\frac{3V_\phi}{X_S}$$

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

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

The armature current $I_A$ is proportional to $X_S I_A$ , and the length corresponding to $X_S I_A$ on the power diagram is $3V\phi I_A$.

The final capability curve is shown below:




It is a plot of P vs Q. Lines of constant armature current $I_A$ appear as lines of constant $S = 3V\phi I_A$, which are concentric circles around the origin. Lines of constant field current correspond to lines of constant $E_A$, which are shown as circles of magnitude $3E_A V\phi/X_S$ centered on the point

$$Q = -\frac{3V_\phi^2}{X_S}$$

The armature current limit appears as the circle corresponding to the rated $I_A$ or rated KVA, and the field current limit appears as a circle corresponding to the rated $I_F$ or $E_A$. Any point that lies within both circles is a safe operating point for the generator.

Example 5-8

A 480V, 50 Hz, Y-connected, 6-pole, synchronous generator is rated at 50kVA at 0.8 PF lagging. It has a synchronous reactance of 1 ohm per phase. Assume that this generator is connected to a steam turbine capable of supplying up to 45kW. 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 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 max amount of reactive power this generator can produce?
(d) If the generator supplies 30kW of real power, what is the maximum amount of reactive power that can be simultaneously supplied?

**Chapter 6: Synchronous Motor**

In general, a synchronous motor is very similar to a synchronous generator with a difference of function only.

**Steady State Operations**

A synchronous motor are usually applied to instances where the load would require a constant speed. Hence for a synchronous motor, its torque speed characteristic is constant speed as the induced torque increases. Hence SR = 0%.

Since,

$$\tau_{ind} = kB_R B_{net} \sin\delta$$

$$\tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_s}$$

Maximum torque (pullout torque) is achieved when sin δ = 1. If load exceeds the pullout torque, the rotor will slow down. Due to the interaction between the stator and rotor magnetic field, there would be a torque surge produced as such there would be a loss of synchronism which is known as **slipping poles**.

Also based upon the above equation, maximum induced torque can be achieved by increasing $E_a$ hence increasing the field current.

**Effect of load changes**

Assumption:

> *A synchronous generator operating with a load connected to it. The field current setting are unchanged.*

Varying load would in fact slow the machine down a bit hence increasing the torque angle. Due to an increase to the torque angle, more torque is induced hence spinning the synchronous machine to synchronous speed again.

The overall effect is that the synchronous motor phasor diagram would have a bigger torque angle δ. In terms of the term $E_a$, since $I_f$ is set not to change, hence the magnitude of $E_a$ should not change as shown in the phasor diagram (fig.6-6). Since the angle of d changes, the armature current magnitude and angle would also change to compensate to the increase of power as shown in the phasor diagram (fig. 6-6).

**Effect of field current changes on a synchronous motor**

Assumption:

> *The synchronous generator is rotating at synchronous speed with a load connected to it. The load remains unchanged.*

As the field current is increased, $E_a$ should increase. Unfortunately, there are constraints set to the machine as such that the power requirement is unchanged. Therefore since P is has to remain constant, it imposes a limit at which $I_a$ and $jX_sI_a$ as such that $E_a$ tends to slide across a horizontal limit as shown in figure 6-8. $I_a$ will react to the changes in $E_a$ as such that its angle changes from a leading power factor to a lagging power factor or vice versa.

This gives a possibility to utilise the synchronous motor as a power factor correction tool since varying magnetic field would change the motor from leading to lagging or vice versa.

This characteristic can also be represented in the V curves as shown in figure 6-10.

**Synchronous motor as a power factor correction**

Varying the field current would change to amount of reactive power injected or absorbed by the motor. Hence if a synchronous motor is incorporated nearby a load which require reactive power, the synchronous motor may be operated to inject reactive power hence maintaining stability and lowering high current flow in the transmission line.

**Starting Synchronous Motors**

Problem with starting a synchronous motor is the initial production of torque which would vary as the stator magnetic field sweeps the rotor. As a result, the motor will vibrate and could overheat (refer to figure 6-16 for diagram explanations).

There are 3 different starting methods available:

a) Reduced speed of stator magnetic field – the aim is to reduce it slow enough as such that the stator will have time to follow the stator magnetic field.
b) External prime mover to accelerate the synchronous motor.
c) Damper windings or amortisseur windings.

**Stator magnetic field speed reduction**

The idea is to let the stator magnetic field to rotate slow enough as such that the rotor has time to lock on to the stator magnetic field. This method used to be impractical due to problems in reducing stator magnetic field.

Now, due to power electronics technology, frequency reduction is possible hence makes it a more viable solution.

**Using a prime mover**

This is a very straightforward method.

**Motor Starting using Amortisseur windings**

This is the most popular way to start an induction motor. Amortisseur windings are a special kind of windings which is shorted at each ends. Its concept is near similar to an induction motor hence in depth explanation can be obtained in the text book (page 345-348).

The final effect of this starting method is that the rotor will spin at near synchronous speed. Note that the rotor will never reach synchronous speed unless during that time, the field windings are switched on hence will enable the rotor to lock on to the stator magnetic field.

**Effect of Amortisseur windings**

The advantage of this starting method is that it acts as a damper as such that during transient cases at which the system frequency would vary significantly (varying frequency would affect the synchronous speed) hence the amortisseur windings may act as a dampening effect to slow down a fast machines and to speed up slow machines,