

# Synchronous Generators

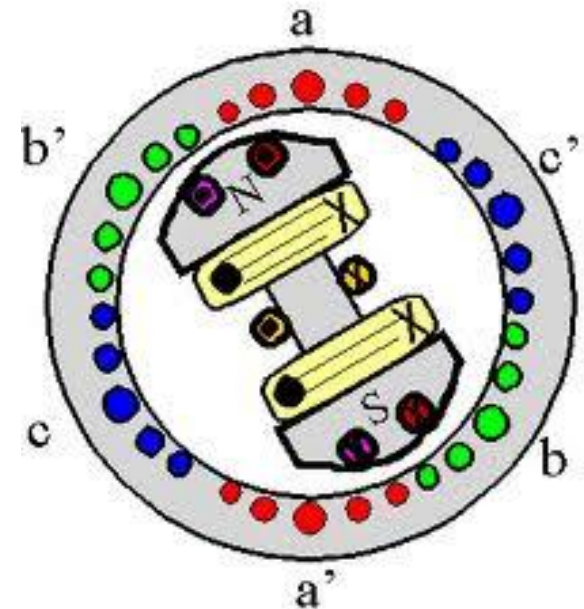
**ECE 740**



# Construction of synchronous machines

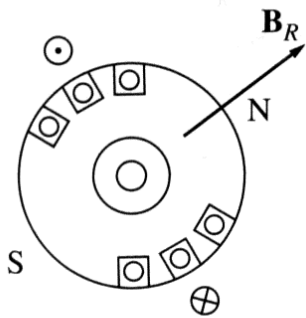
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

- Field windings are the windings producing the main magnetic field (rotor windings)
- armature windings are the windings where the main voltage is induced (stator windings)

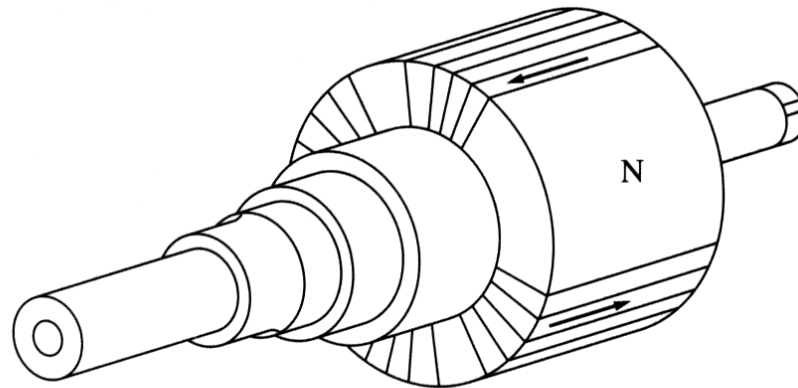


# Construction of synchronous machines

The rotor of a synchronous machine is a large electromagnet. The magnetic poles can be either salient (sticking out of rotor surface) or non-salient construction.



End view



Side view



Non-salient-pole rotor: # of poles: 2 or 4.

Salient-pole rotor: # of poles: large number

Rotors are made laminated to reduce eddy current losses.

# Construction of synchronous machines

Two common approaches are used to supply a DC current to the field circuits on the rotating rotor:

1. Supply the DC power from an external DC source to the rotor by means of slip rings and brushes;
2. Supply the DC power from a special DC power source mounted directly on the shaft of the machine.



Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. Graphite-like carbon brushes connected to DC terminals ride on each slip ring supplying DC voltage to field windings.

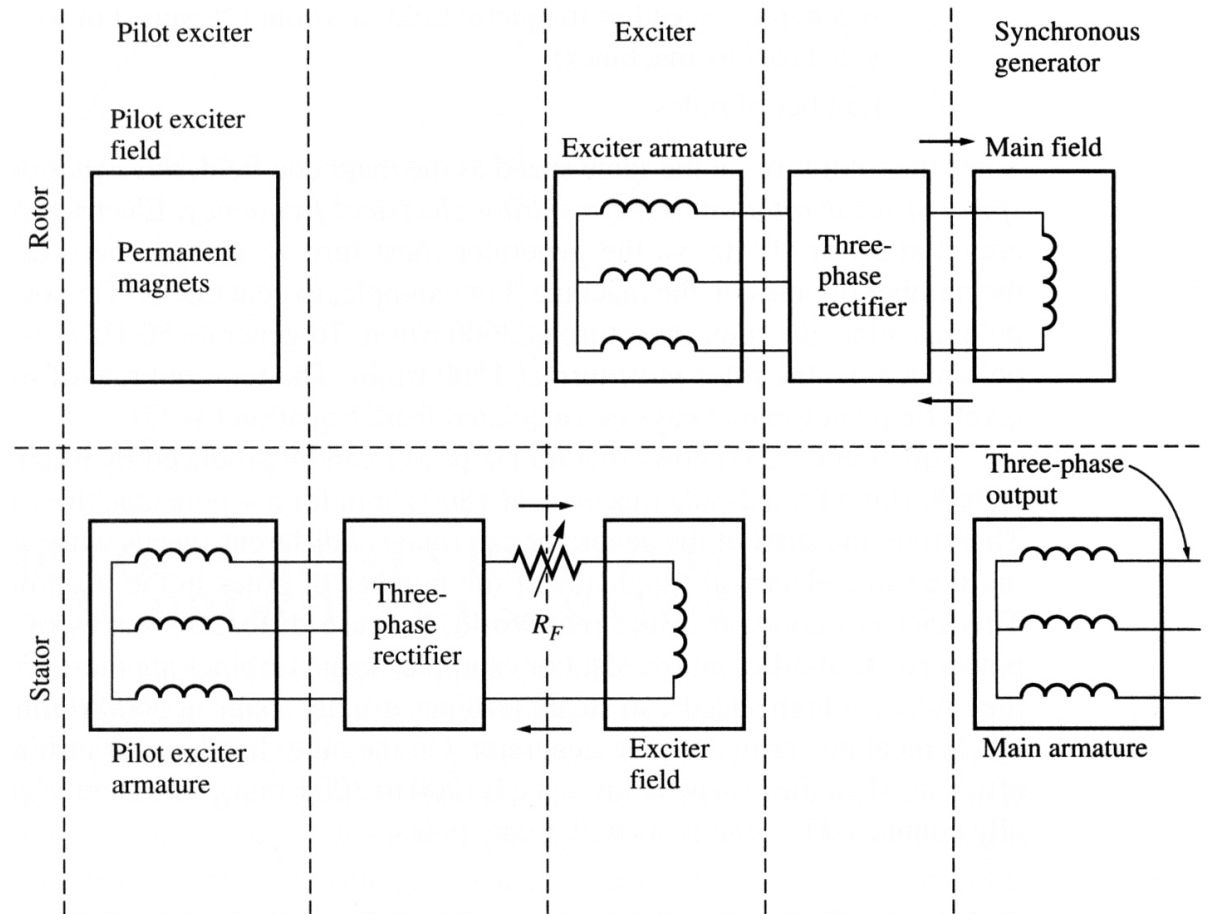
# Construction of synchronous machines

- On large generators and motors, brushless exciters are used.
  - A brushless exciter is a small AC generator whose field circuits are mounted on the stator and armature circuits are mounted on the rotor shaft.
  - The exciter generator's 3-phase output is rectified to DC by a 3-phase rectifier (mounted on the shaft) and fed into the main DC field circuit.
  - It is possible to adjust the field current on the main machine by controlling the small DC field current of the exciter generator (located on the stator).

# Construction of synchronous machines

To make the excitation of a generator completely independent of any external power source, a small pilot exciter is often added to the circuit.

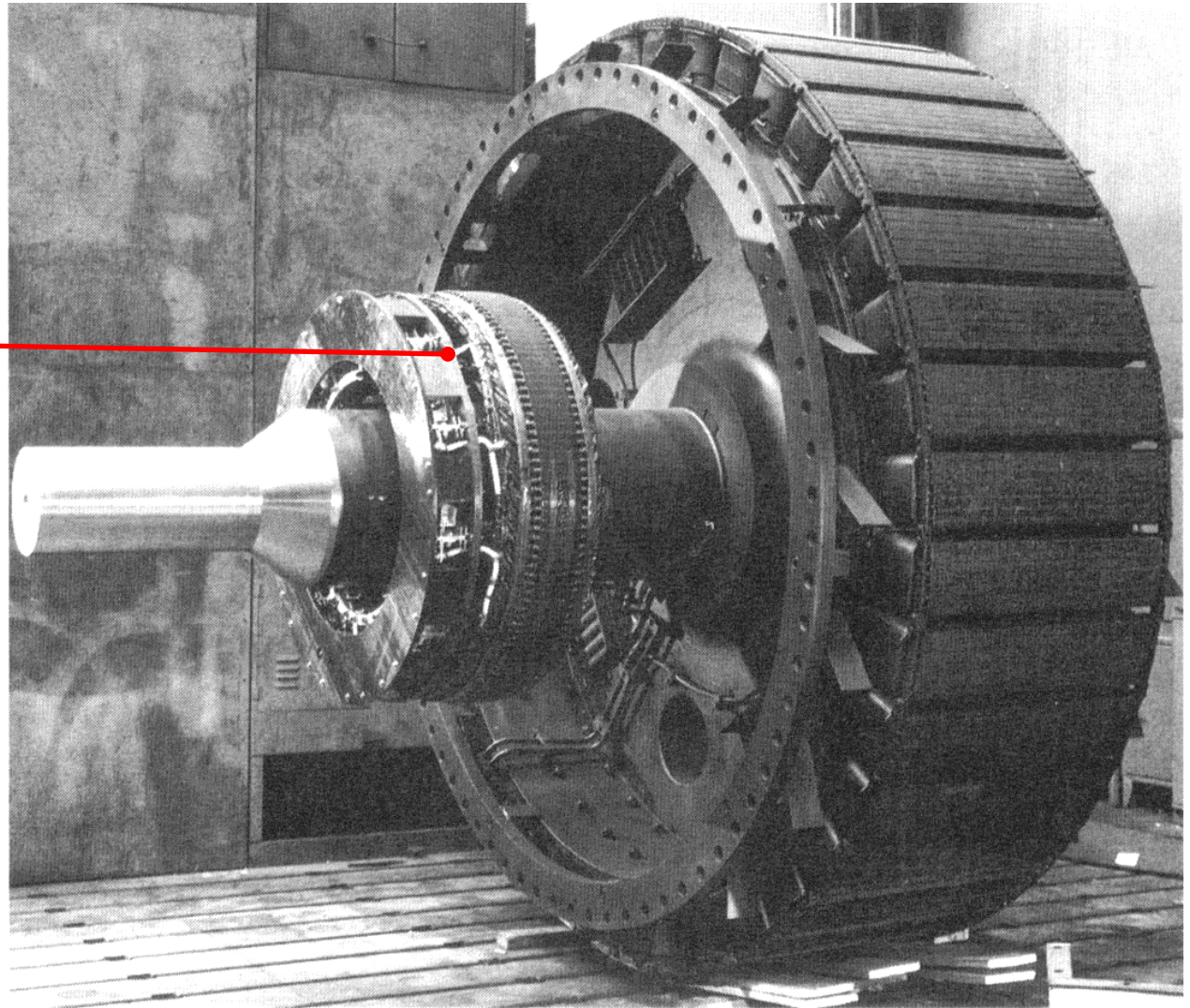
The pilot exciter is an AC generator with a permanent magnet mounted on the rotor shaft and a 3-phase winding on the stator producing the power for the field circuit of the exciter.





# Construction of synchronous machines

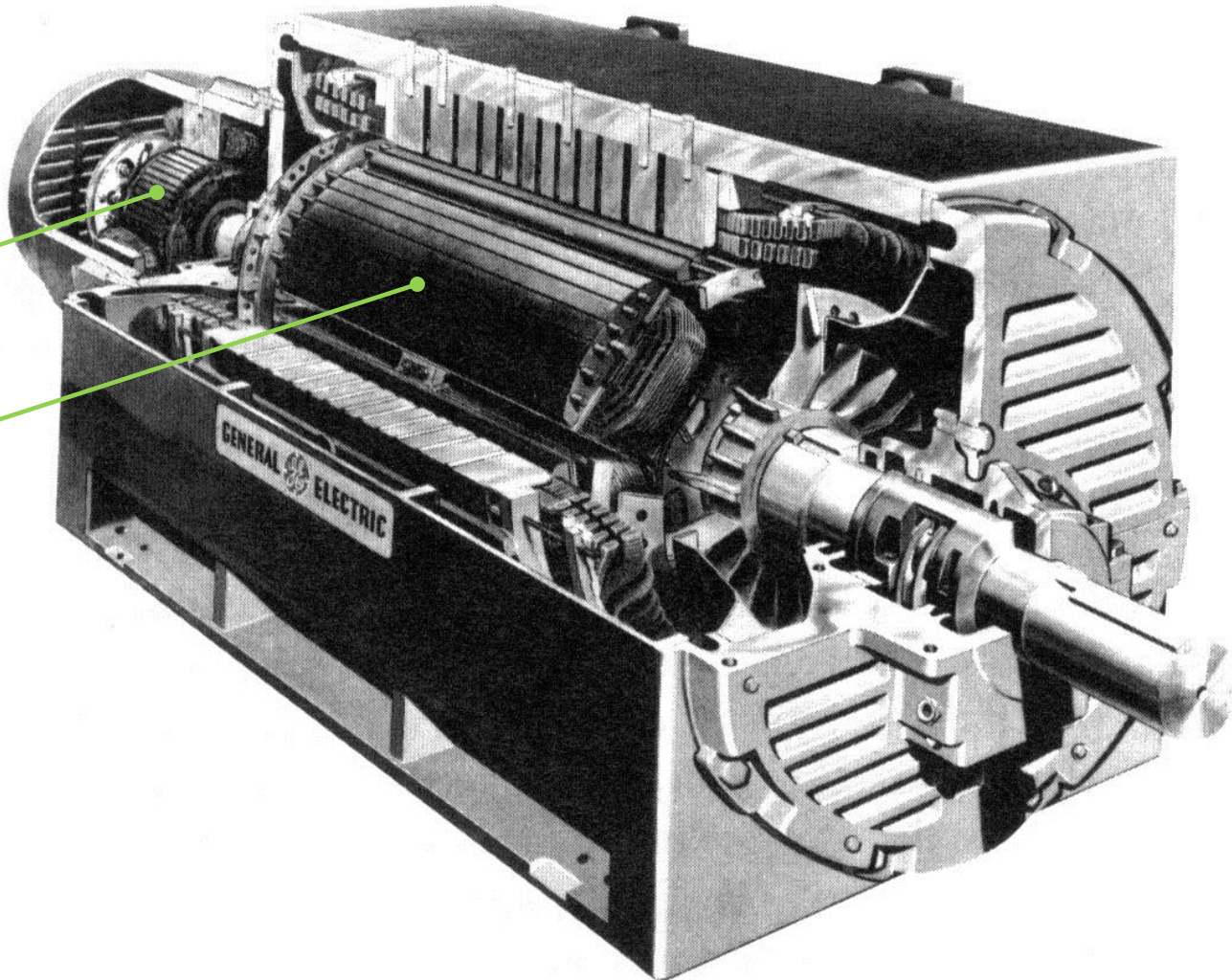
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.



# Construction of synchronous machines

Exciter

Rotor pole.



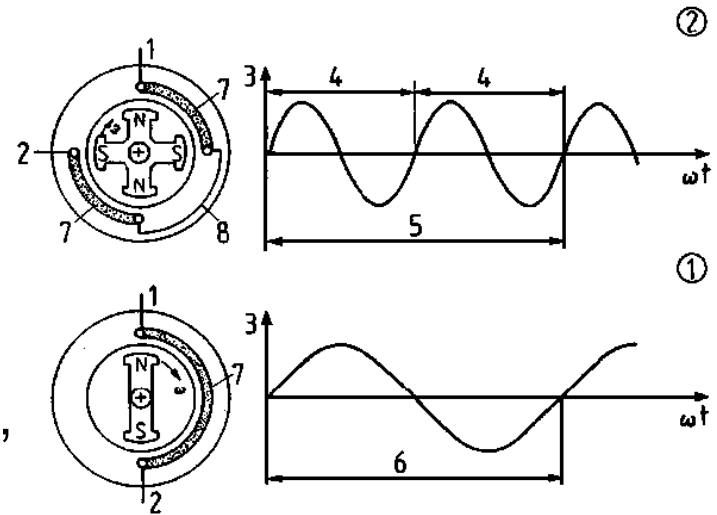


# Rotation speed of synchronous generator

By the definition, synchronous generators produce electricity whose frequency is synchronized with the mechanical rotational speed.

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

Where  $f_e$  is the electrical frequency, Hz;  
 $n_m$  is the rotor speed of the machine,  
 $p$  is the number of poles.



- Steam turbines are most efficient when rotating at high speed; therefore, to generate 60 Hz, they are usually rotating at 3600 rpm (2-pole).
- Water turbines are most efficient when rotating at low speeds (200-300 rpm); therefore, they usually turn generators with many poles.

# The induced voltage in a 3-phase set of coils

In three coils, each of  $N_C$  turns, placed around the rotor magnetic field, the induced in each coil will have the same magnitude and phases differing by  $120^\circ$ :

$$e_{aa'}(t) = N_C \phi \omega_m \cos \omega_m t$$

$$e_{bb'}(t) = N_C \phi \omega_m \cos(\omega_m t - 120^\circ)$$

$$e_{cc'}(t) = N_C \phi \omega_m \cos(\omega_m t - 240^\circ)$$

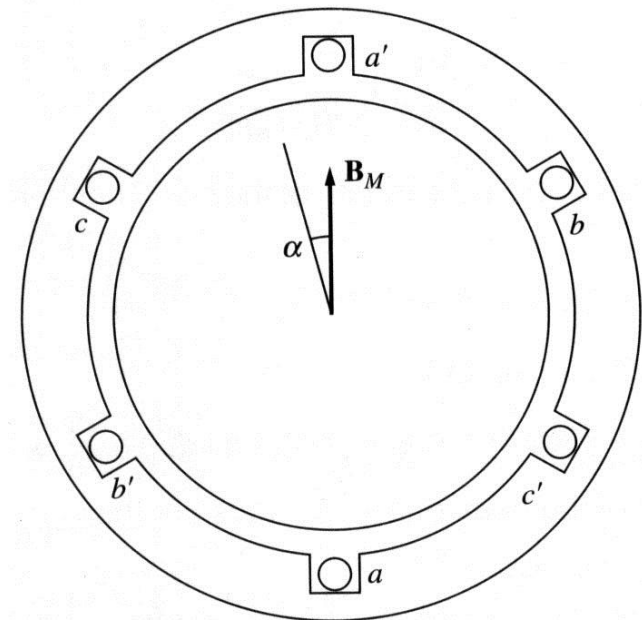
Peak voltage:

$$E_{\max} = N_C \phi \omega_m$$

$$E_{\max} = 2\pi N_C \phi f$$

RMS voltage:

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



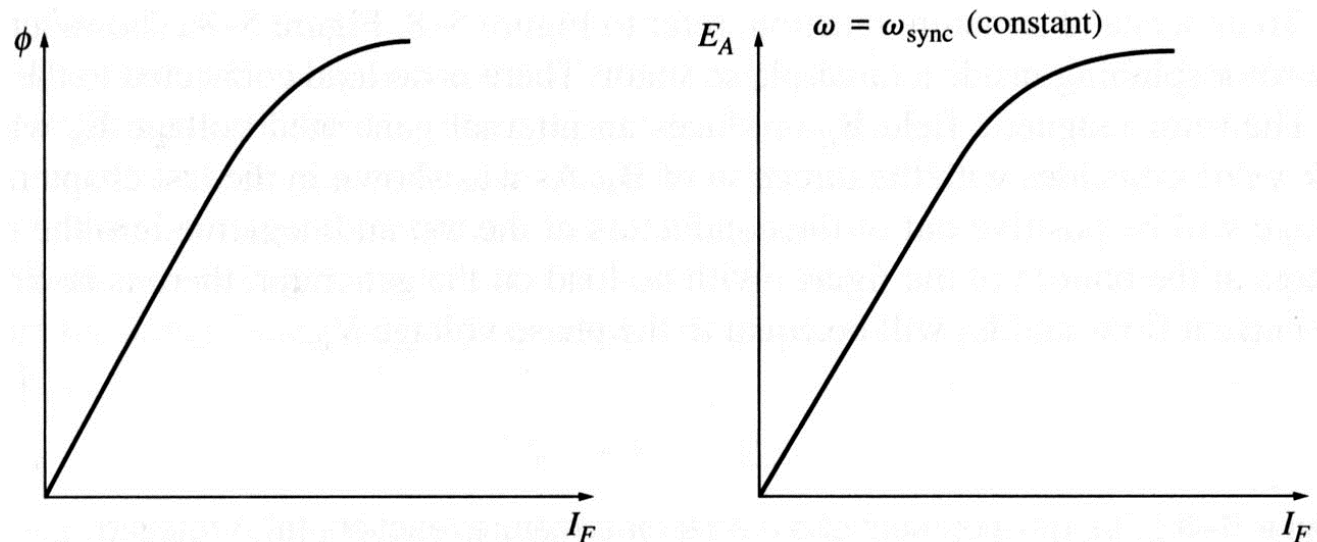
# Internal generated voltage of a synchronous generator

The magnitude of internal generated voltage induced in a given stator is

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

where  $K$  is a constant representing the construction of the machine,  $\phi$  is flux in it and  $\omega$  is its rotation speed.

Since flux in the machine depends on the field current through it, the internal generated voltage is a function of the rotor field current.



Magnetization curve (open-circuit characteristic) of a synchronous machine

# Equivalent circuit of a synchronous generator

The internally generated voltage in a single phase of a synchronous machine  $E_A$  is not usually the voltage appearing at its terminals. It equals to the output voltage  $V_\phi$  only when there is no armature current in the machine. The reasons that the armature voltage  $E_A$  is not equal to the output voltage  $V_\phi$  are:

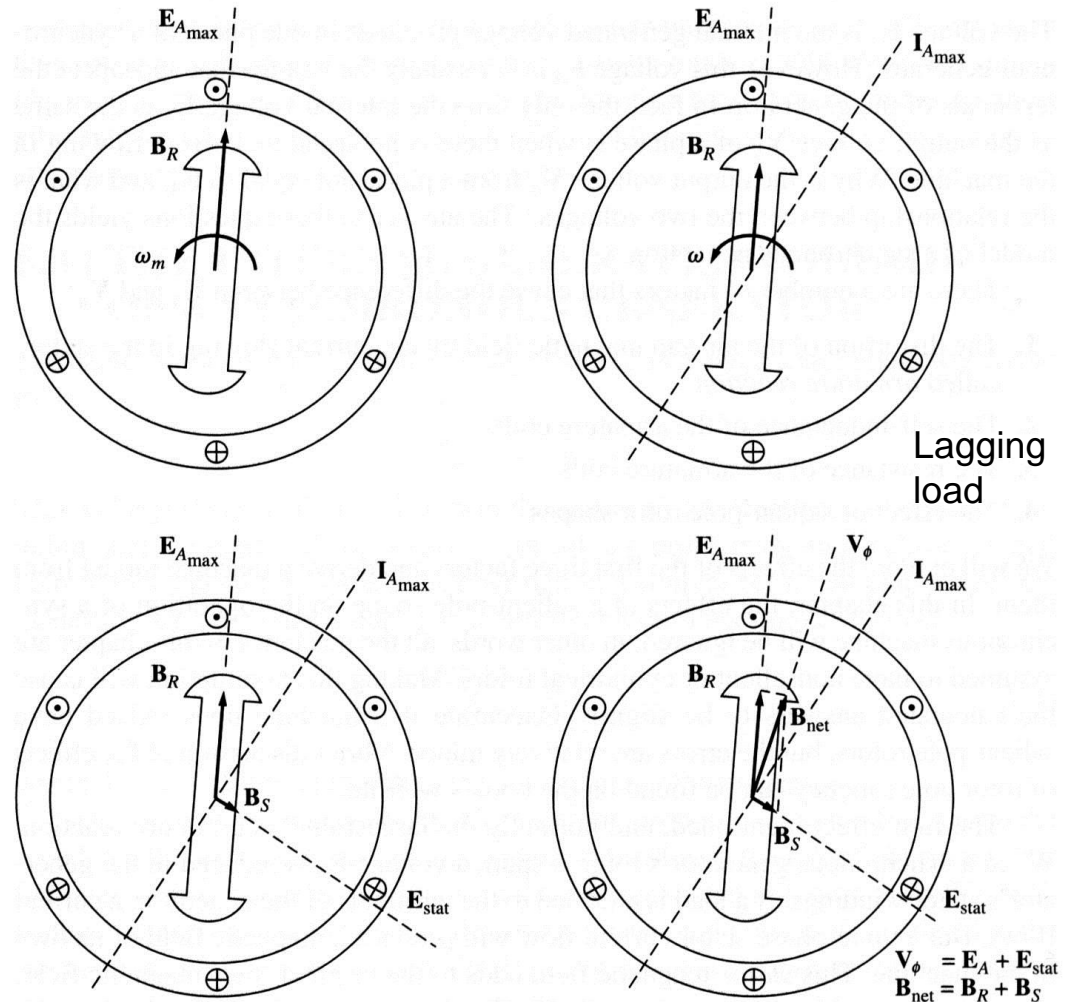
1. Distortion of the air-gap magnetic field caused by the current flowing in the stator (armature reaction);
2. Self-inductance of the armature coils;
3. Resistance of the armature coils;



# Equivalent circuit of a synchronous generator

## Armature reaction:

- When the rotor of a synchronous generator is spinning, a voltage  $E_A$  is induced in its stator.
- When a load is connected, a current starts flowing creating a magnetic field in machine's stator.
- This stator magnetic field  $B_S$  adds to the rotor (main) magnetic field  $B_R$  affecting the total magnetic field and, therefore, the phase voltage.



# Equivalent circuit of a synchronous generator

The load current  $I_A$  will create a stator magnetic field  $B_S$ , which will produce the armature reaction voltage  $E_{stat}$ . Therefore, the phase voltage will be

$$V_\phi = E_A + E_{stat}$$

The net magnetic flux will be

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

Rotor field

Stator field

# Equivalent circuit of a synchronous generator

Since the armature reaction voltage lags the current by 90 degrees, it can be modeled by

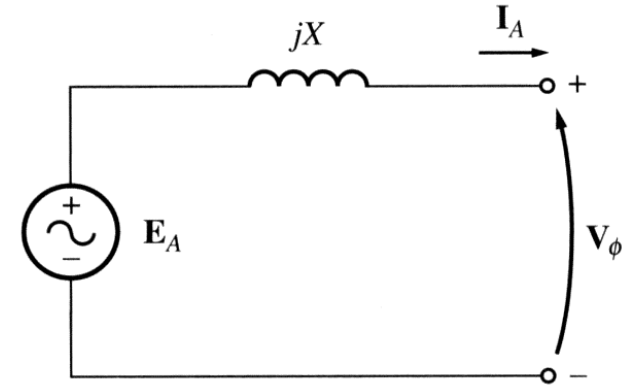
$$E_{stat} = -jXI_A$$

The phase voltage is then

$$V_\phi = E_A - jXI_A$$

However, in addition to armature reactance effect, the stator coil has a self-inductance  $L_A$  ( $X_A$  is the corresponding reactance) and the stator has resistance  $R_A$ . The phase voltage is thus

$$V_\phi = E_A - jXI_A - jX_A I_A - RI_A$$



# Equivalent circuit of a synchronous generator

Often, armature reactance and self-inductance are combined into the synchronous reactance of the machine

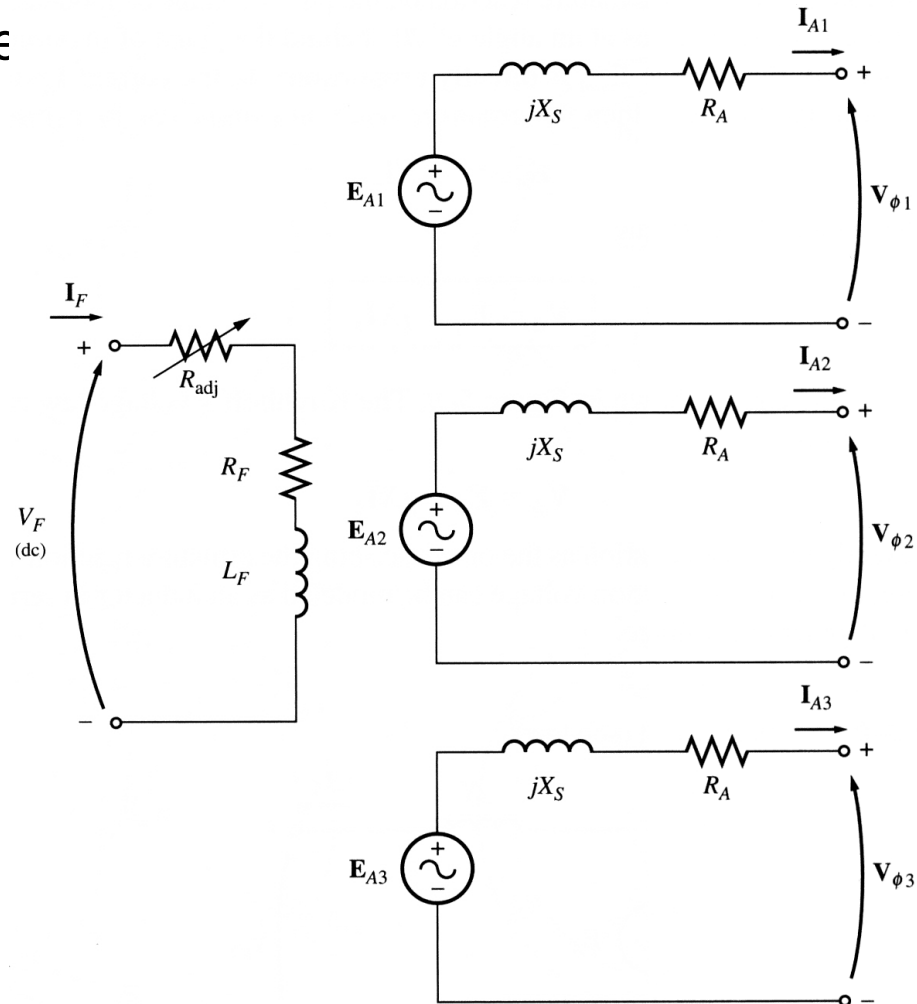
$$X_S = X + X_A$$

Therefore, the phase voltage is

$$V_\phi = E_A - jX_S I_A - R I_A$$

The equivalent circuit of a 3-phase synchronous generator is shown.

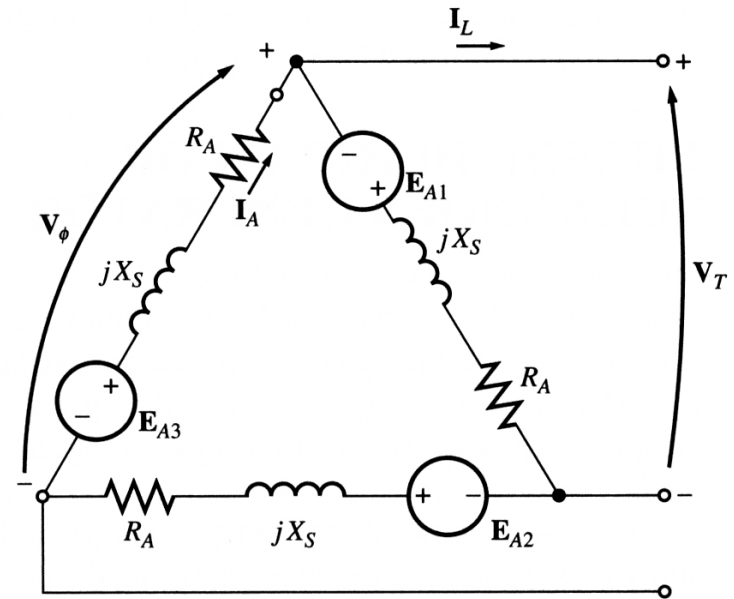
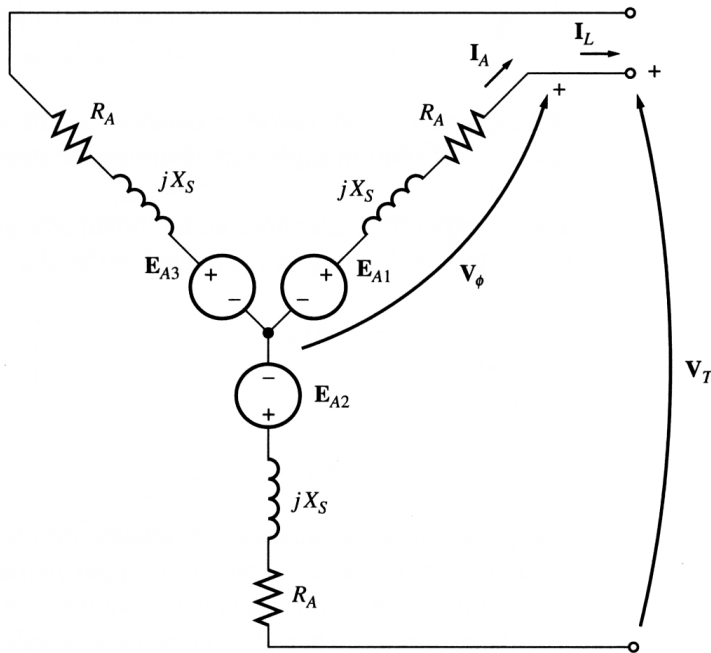
The adjustable resistor  $R_{adj}$  controls the field current and, therefore, the rotor magnetic field.





# Equivalent circuit of a synchronous generator

A synchronous generator can be Y- or  $\Delta$ -connected:



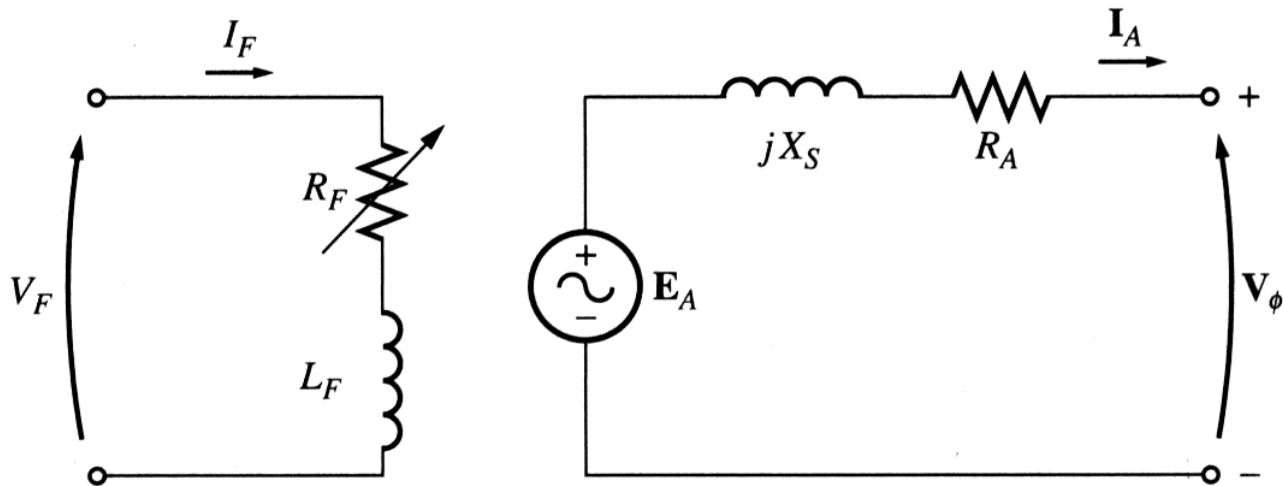
The terminal voltage will be

$$V_T = \sqrt{3}V_\phi \quad - \text{for } Y$$

$$V_T = V_\phi \quad - \text{for } \Delta$$

# Equivalent circuit of a synchronous generator

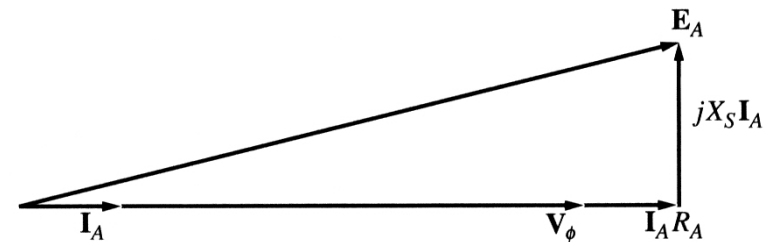
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



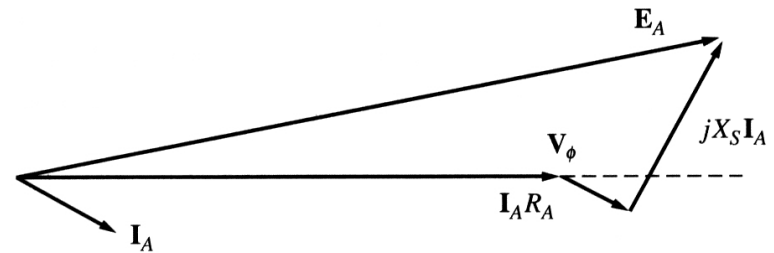
# Phasor diagram of a synchronous generator (similar to that of a transformer)

Since the voltages in a synchronous generator are AC voltages, they are usually expressed as phasors. A vector plot of voltages and currents within one phase is called a phasor diagram.

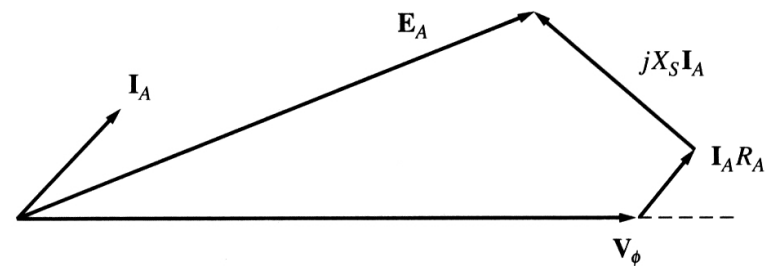
A phasor diagram of a synchronous generator with a unity power factor (resistive load)



Lagging power factor (inductive load): a larger than for leading PF internal generated voltage  $E_A$  is needed to form the same phase voltage.



Leading power factor (capacitive load).



# The Synchronous generator operating alone

The behavior of a synchronous generator varies greatly under load depending on the power factor of the load and on whether the generator is working alone or in parallel with other synchronous generators.

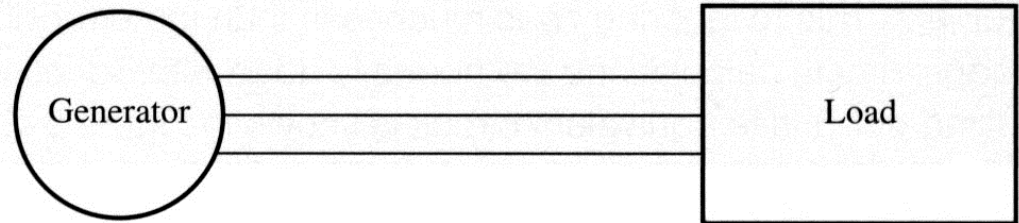
Although most of the synchronous generators in the world operate as parts of large power systems, we start our discussion assuming that the synchronous generator works alone.

Unless otherwise stated, the speed of the generator is assumed constant.



# The Synchronous generator operating alone

A increase in the load is an increase in the real and/or reactive power drawn from the generator.



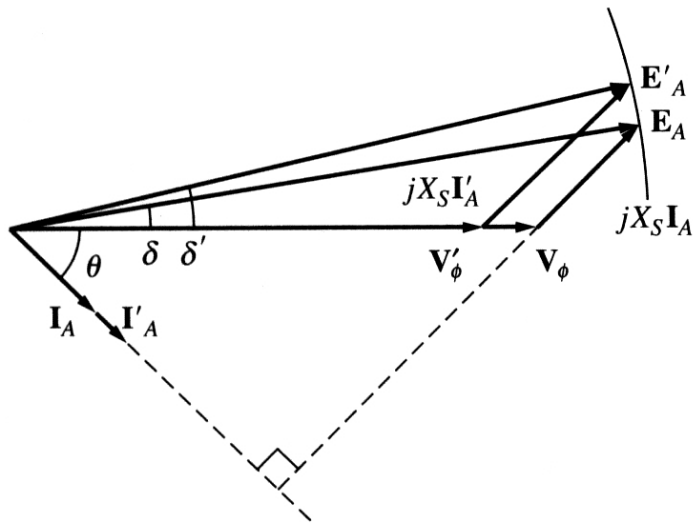
Assuming the same power factor of the load, a change in load will change the magnitude of the armature current  $I_A$ . However, the angle will be the same (for a constant PF). Thus, the armature reaction voltage  $jX_S I_A$  will be larger for the increased load. Since the magnitude of the internal generated voltage is constant

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

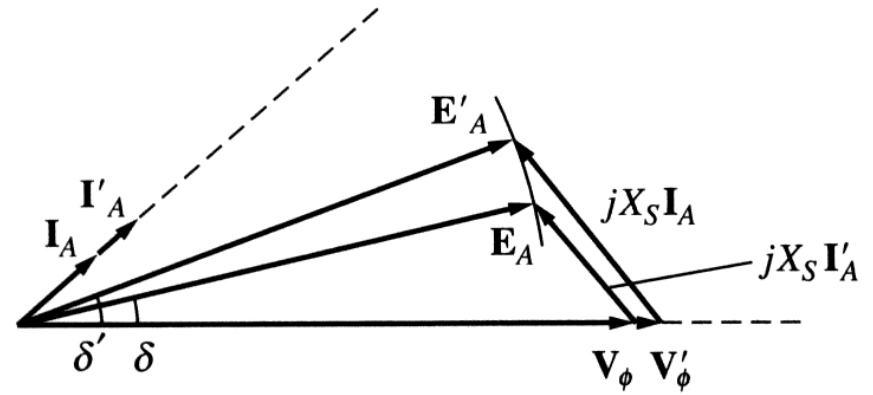
Armature reaction voltage vector will “move parallel” to its initial position.

# The Synchronous generator operating alone

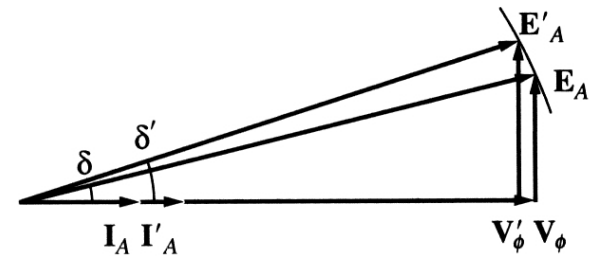
Increase load effect on generators with



Lagging PF



Leading PF



Unity PF

# The Synchronous generator operating alone

Generally, when a load on a synchronous generator is added, the following changes can be observed:

1. For lagging (inductive) loads, the phase (and terminal) voltage decreases significantly.
2. For unity power factor (purely resistive) loads, the phase (and terminal) voltage decreases slightly.
3. For leading (capacitive) loads, the phase (and terminal) voltage rises.

Effects of adding loads can be described by the voltage regulation:

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} 100\%$$

Where  $V_{nl}$  is the no-load voltage of the generator and  $V_{fl}$  is its full-load voltage.

# The Synchronous generator operating alone

- A synchronous generator operating at a lagging power factor has a fairly large positive voltage regulation.
- A synchronous generator operating at a unity power factor has a small positive voltage regulation.
- A synchronous generator operating at a leading power factor often has a negative voltage regulation.

Normally, a constant terminal voltage supplied by a generator is desired. Since the armature reactance cannot be controlled, an obvious approach to adjust the terminal voltage is by controlling the internal generated voltage  $E_A = K\phi\omega$ . This may be done by changing flux in the machine while varying the value of the field resistance  $R_F$ , which is summarized:

1. Decreasing the field resistance increases the field current in the generator.
2. An increase in the field current increases the flux in the machine.
3. An increased flux leads to the increase in the internal generated voltage.
4. An increase in the internal generated voltage increases the terminal voltage of the generator.



# Power and torque in synchronous generators

A synchronous generator needs to be connected to a prime mover whose speed is reasonably constant (to ensure constant frequency of the generated voltage) for various loads.

The applied mechanical power

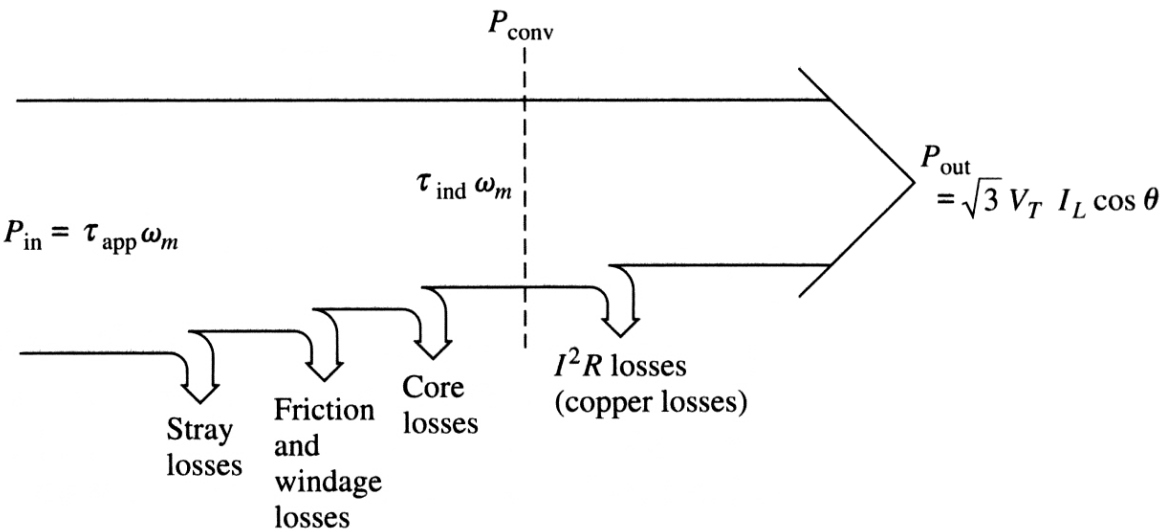
$$P_{in} = \tau_{app} \omega_m$$

is partially converted to electricity

$$P_{conv} = \tau_{ind} \omega_m = 3E_A I_A \cos \gamma$$

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

The power-flow diagram of a synchronous generator.



# Power and torque in synchronous generators

The real and reactive output powers of the synchronous generator are

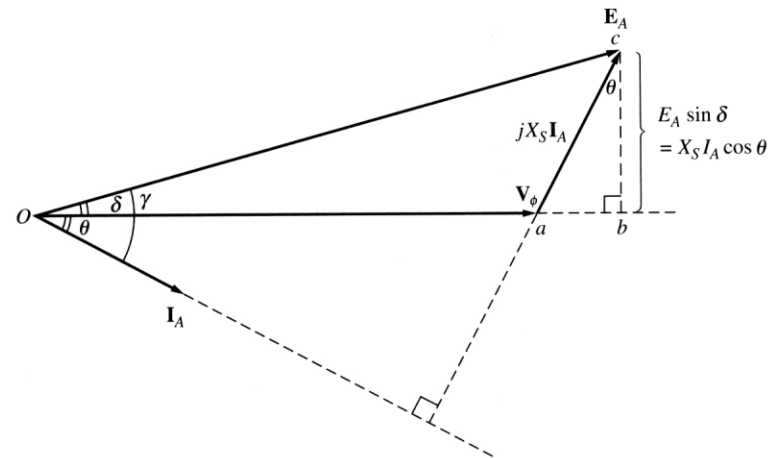
$$P_{out} = \sqrt{3}V_T I_L \cos \theta = 3V_\phi I_A \cos \theta$$

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

Recall that the power factor angle  $\theta$  is the angle between  $V_\phi$  and  $I_A$  and **not** the angle between  $E_A$  and  $I_A$ .

In real synchronous machines of any size, the armature resistance  $R_A \ll X_S$  and, therefore, the armature resistance can be ignored. Thus, a simplified phasor diagram indicates that

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



# Power and torque in synchronous generators

Then the real output power of the synchronous generator can be approximated as

$$P_{out} \approx \frac{3V_{\phi} E_A \sin \delta}{X_S}$$

We observe that electrical losses are assumed to be zero since the resistance is neglected. Therefore:

$$P_{conv} \approx P_{out}$$

Here  $\delta$  is the power angle of the machine – the angle between  $V_{\phi}$  and  $E_A$ . This is different from the power factor angle  $\theta$

The maximum power can be supplied by the generator when  $\delta = 90^\circ$ :

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

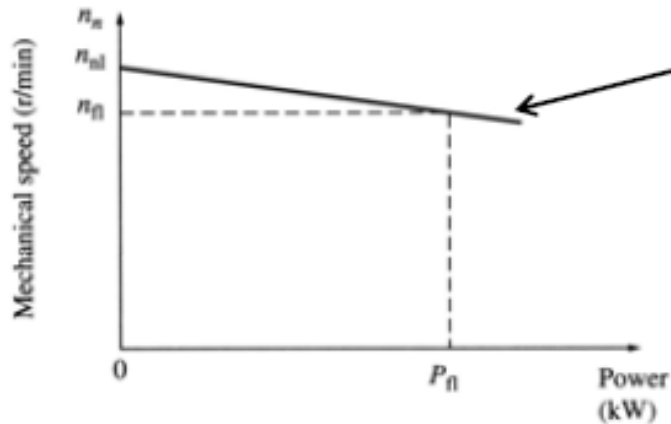
# Generator P-f Curve

- All generators are driven by a prime mover, such as a steam, gas, water, wind turbines, diesel engines, etc.
- Regardless the power source, most of prime movers tend to slow down with increasing the load.
- The speed drop (SD) of a prime mover is defined as:

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

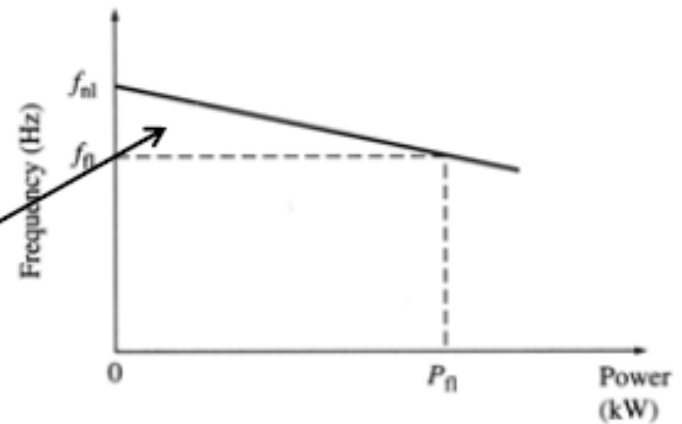
- Most prime movers have a speed drop from 2% to 4%. Most governors have a mechanism to adjust the turbine's no-load speed (set-point adjustment).

# Generator P-f Curve



A typical speed vs. power plot

A typical frequency vs. power plot



Since the shaft speed is connected to the electrical frequency as

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

the power output from the generator is related to its frequency:

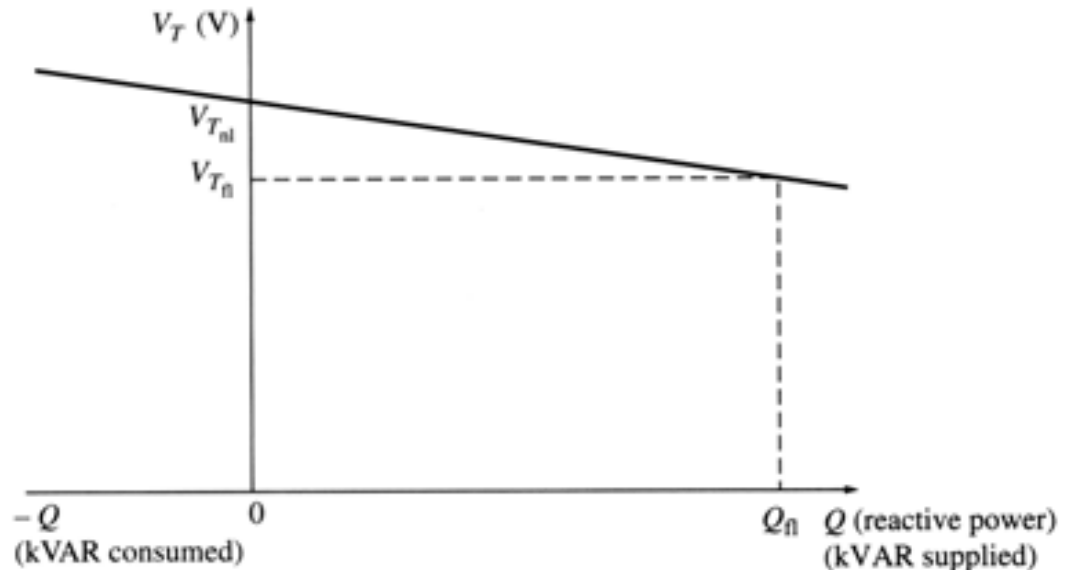
$$P = s_p (f_{nl} - f_{sys})$$

Slope of curve, W/Hz

Operating frequency of the system

# Generator Q-V Curve

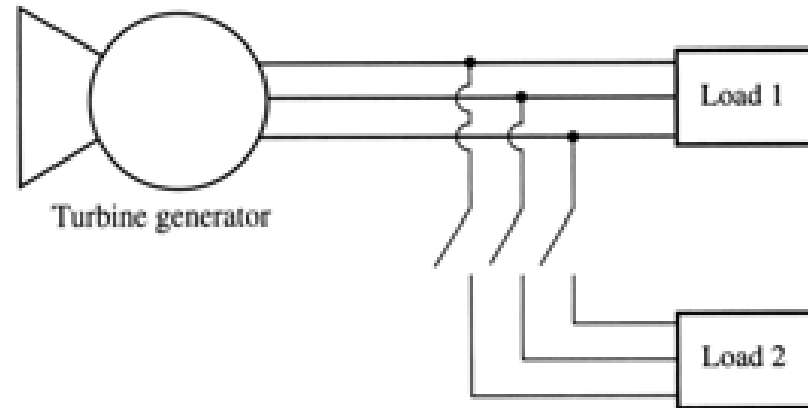
- A similar relationship can be derived for the reactive power  $Q$  and terminal voltage  $V_T$ .
  - When supplying a lagging load to a synchronous generator, its terminal voltage decreases.
  - When adding a leading load to a synchronous generator, its terminal voltage increases.



- Both the frequency-power and terminal voltage vs. reactive power characteristics are important for parallel operations of generators.

# Example

A generator with no-load frequency of 61.0 Hz and a slope of 1 MW/Hz is connected to Load 1 consuming 1 MW of real power at 0.8 PF lagging. Load 2 (that to be connected to the generator) consumes a real power of 0.8 MW at 0.707 PF lagging.



1. Find the operating frequency of the system before the switch is closed. (ans. 60 Hz)
2. Find the operating frequency of the system after the switch is closed. (ans. 59.2 Hz)
3. What action could an operator take to restore the system frequency to 60 Hz after both loads are connected to the generator? (ans. increase the governor no-load set point by 0.8 Hz)



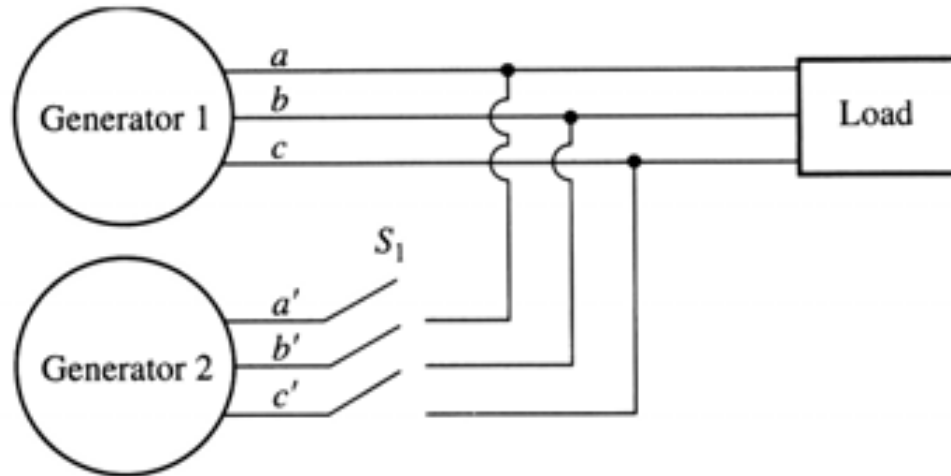
## Generator Operating Alone

- When a generator is operating alone,
  - The real and reactive powers generated are the amounts demanded by the load.
  - The governor of the generator controls the operating frequency of the circuit.
  - The field current controls the terminal voltage of the circuit.

# Generators connected in parallel

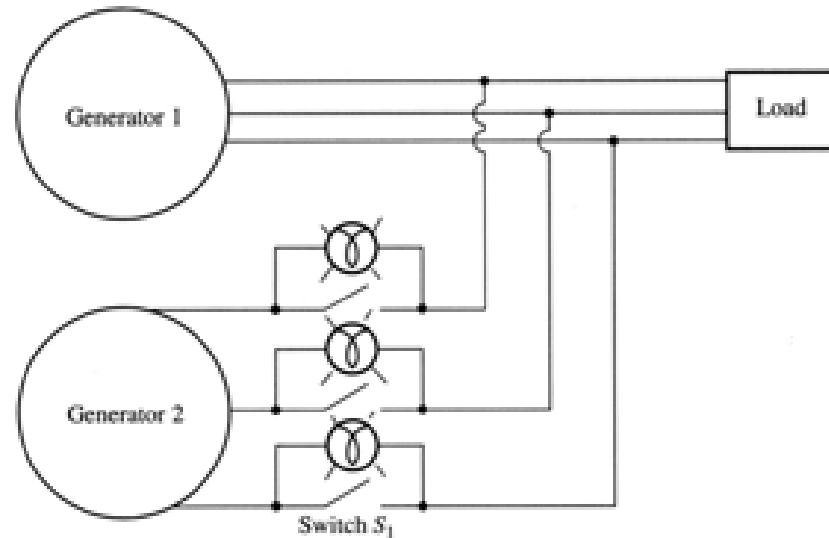
- Most of synchronous generators are operating in parallel with other synchronous generators to supply power to the same power system.
- Obvious advantages of this arrangement are:
  - Several generators can supply a bigger load;
  - A failure of a single generator does not result in a total power loss to the load, thus increasing reliability of the power system;
  - Individual generators may be removed from the power system for maintenance without shutting down the load;
  - A single generator not operating at near full load might be quite inefficient. While having several generators in parallel, it is possible to turn off some, and operate the rest at near full-load condition.

# Conditions required for paralleling generators



- Closing the switch **arbitrarily** can cause severe damage. If voltages are not the same (magnitude, frequency, phase, sequence) in both lines, a very large current will flow when the switch is closed.
- To avoid this, the following conditions must be met:
  - The rms line voltages of the two generators must be equal.
  - The two generators must have the same phase sequence.
  - The phase angles of two “a” phases must be equal.
  - The frequency of the oncoming generator must be slightly higher than the frequency of the running system.

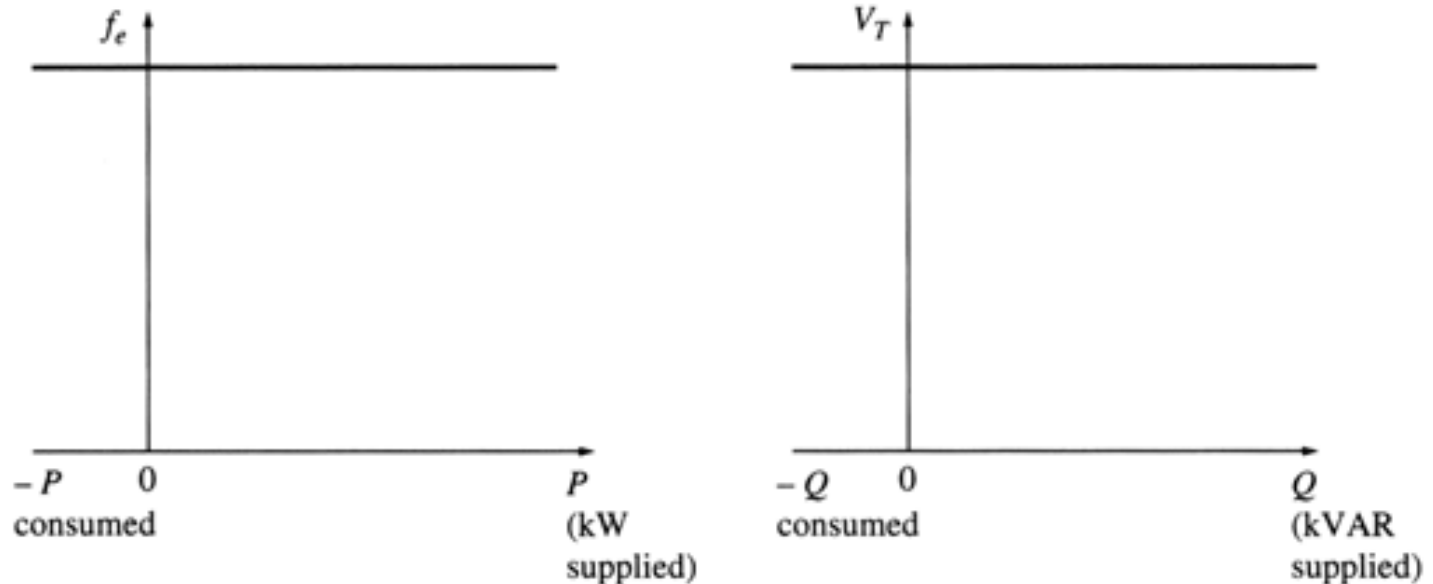
# Steps for paralleling generators (3-light bulb method)



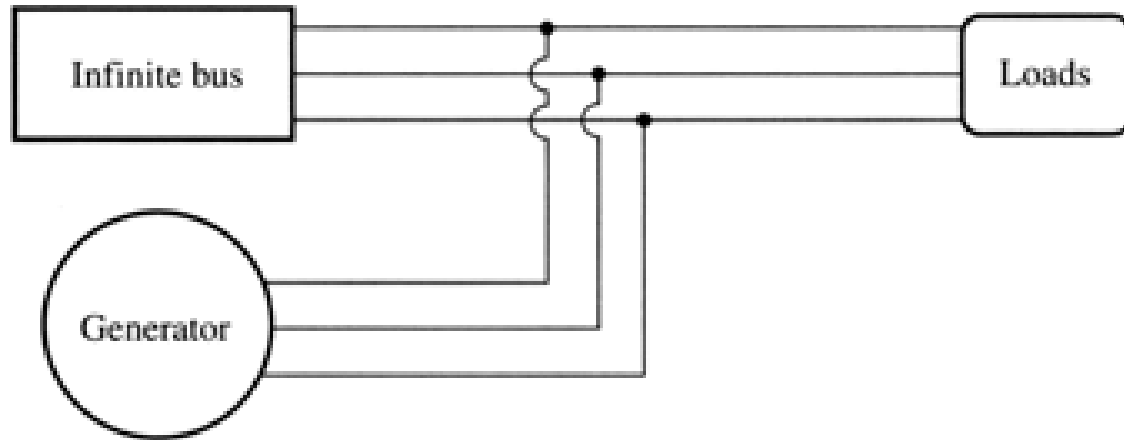
1. Adjust the field current of the oncoming generator to make its terminal voltage equal to the line voltage of the system (use a voltmeter).
2. Compare the phase sequences of the oncoming generator and the running system by examining the three light bulbs. If all three bulbs get bright and dark together, both generators have the same phase sequences. If not, two of the conductors must be altered.
3. The frequency of the oncoming generator is adjusted to be slightly higher than the system's frequency.
4. When all three lights go out, the voltage across them is zero and, therefore, machines are in phase. This is the time to close the switch.

# Synchronizing a generator with the utility grid

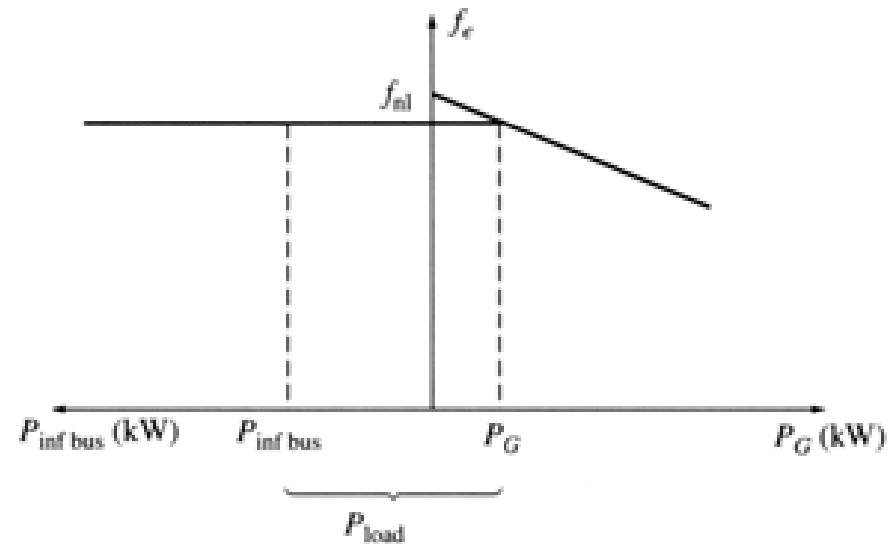
- When a synchronous generator is added to a power system, that system is so large that one additional generator does not cause observable changes to the system.
- An **infinite bus** is a power system that is so large that its voltage and frequency do not vary regardless of how much real and reactive power is drawn from or supplied to it (i.e., the power-frequency and reactive power-voltage characteristics are horizontal:



# Synchronizing a generator with the utility grid

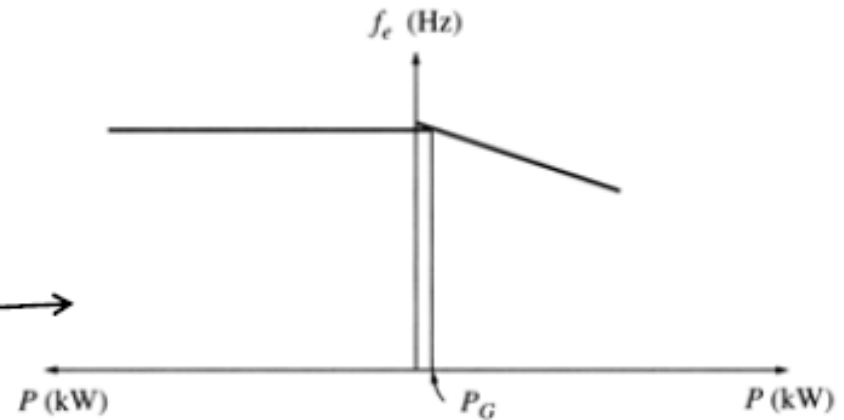


- Consider adding a generator to an infinite bus supplying a load.
- The frequency and terminal voltage of all machines must be the same.
- Therefore, their power-frequency and reactive power-voltage characteristics can be plotted with a common vertical axis.



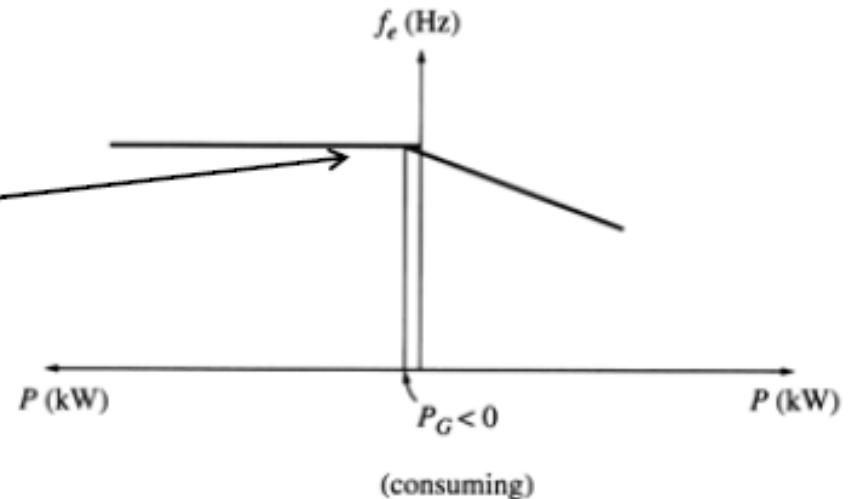
# Synchronizing a generator with the utility grid

If the no-load frequency of the oncoming generator is slightly higher than the system's frequency, the generator will be "floating" on the line supplying a small amount of real power and little or no reactive power.



If the no-load frequency of the oncoming generator is slightly lower than the system's frequency, the generator will supply a negative power to the system: the generator actually consumes energy acting as a motor!

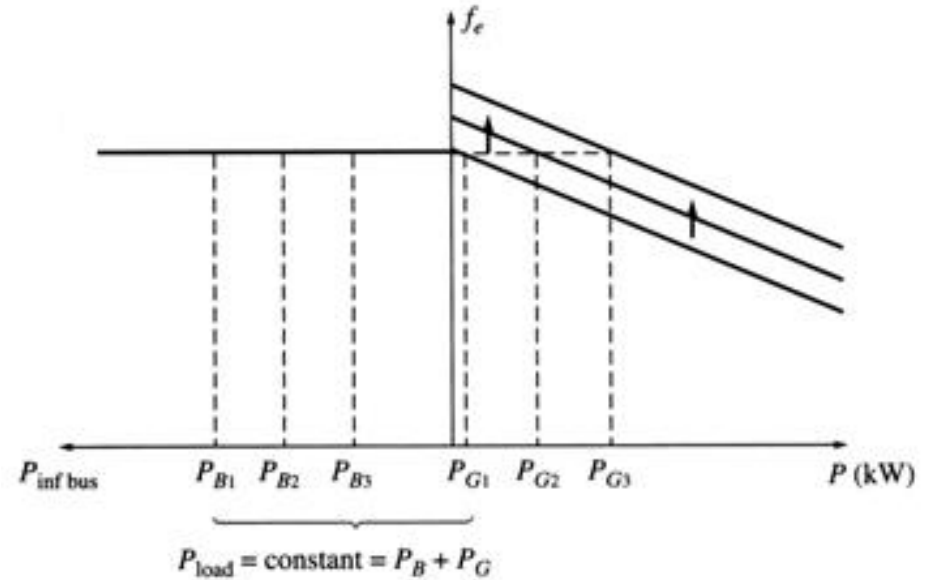
Many generators have circuitry automatically disconnecting them from the line when they start consuming energy.



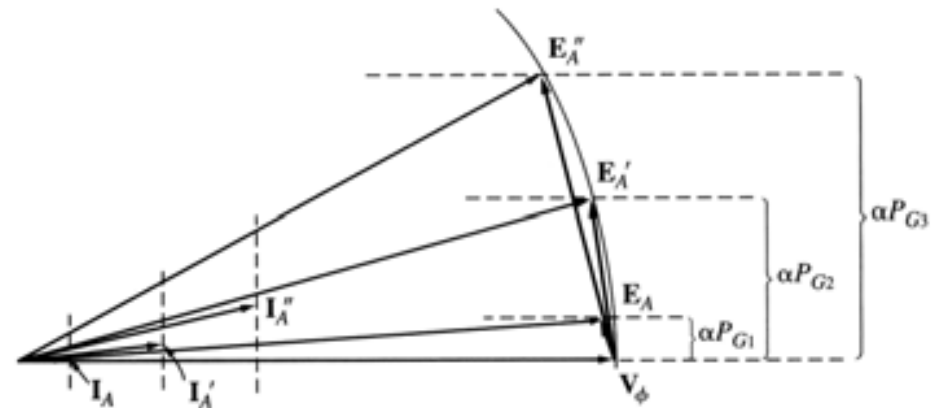


# Parallel operation with the utility grid

- If an attempt is made to increase the speed of the generator after it is connected to the infinite bus, the system frequency cannot change and the power supplied by the generator increases.



- Note an increase in power (with  $V_t$  and  $E_A$  staying constant), results in an increase in the power angle  $\delta$ .

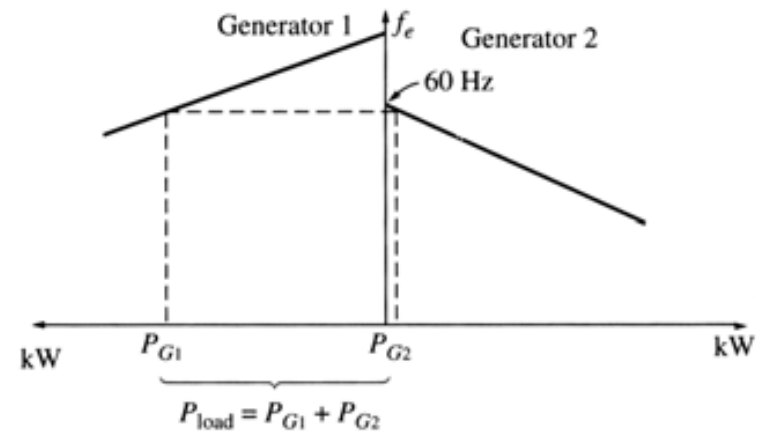
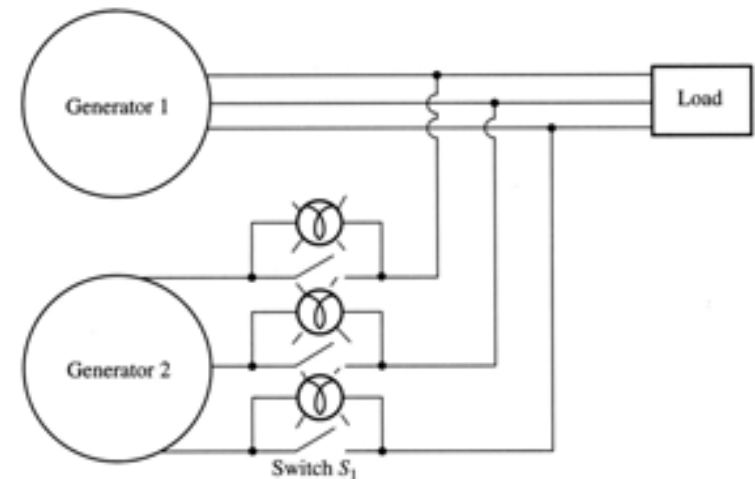


# Parallel operation with the utility grid

- By adjusting the field current of the machine, it is possible to make it to make the generator supply or consume reactive power  $Q$ .
- When the generator is operating in parallel to an infinite bus:
  - The frequency and terminal voltage of the generator are controlled by the system to which it is connected.
  - The governor set points of the generator control the real power supplied by the generator to the system.
  - The generator's field current controls the reactive power supplied by the generator to the system.

# Parallel operation of generators of similar size

- Unlike the case of an infinite bus, the slope of the frequency-power curve of G1 is of the same order of magnitude as that of G2.
- The power-frequency diagram right after G2 is connected to the system is shown to the right.
- As indicated previously, in order for G2 to come in as a generator, its frequency should be slightly higher than that of G1.



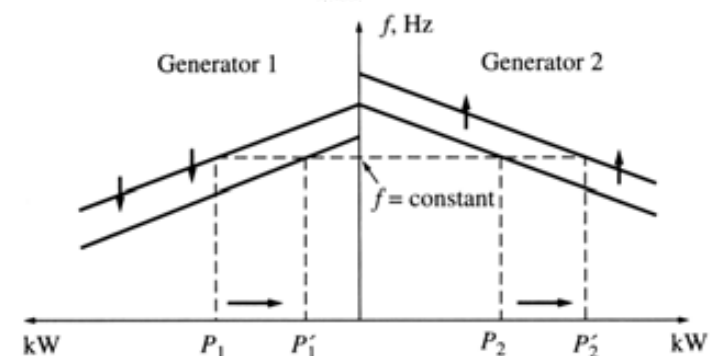
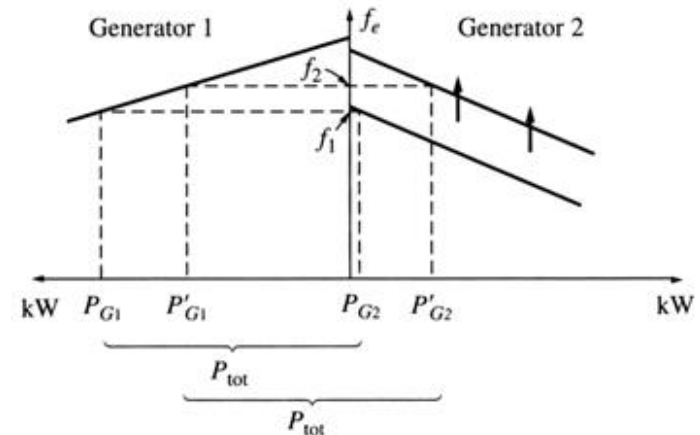
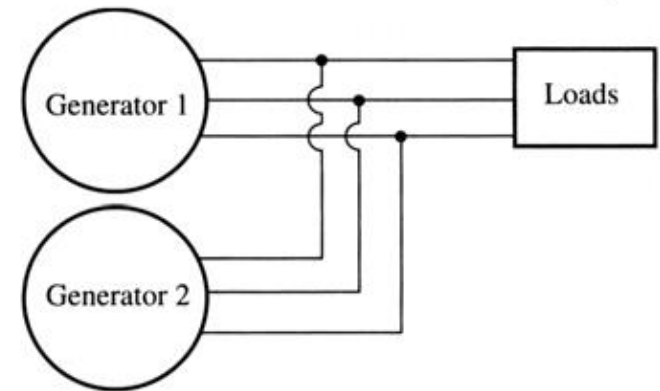
# Parallel operation of generators of similar size

- Note that the sum of the real and reactive powers supplied by the two generators must equal the real and reactive powers demanded by the load:

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

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

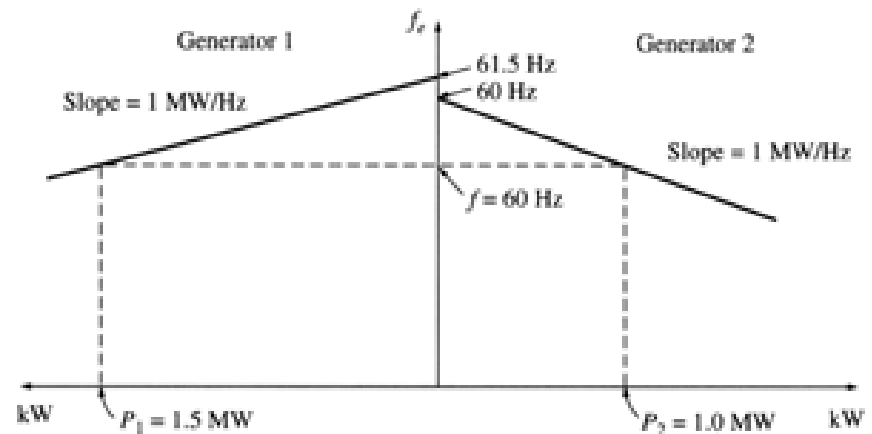
- If the speed of G2 is increased, its power-frequency diagram shifts upwards. This will in turn
  - increase the real power supplied by G2
  - reduce the real power supplied by G1
  - increase the system frequency.
  - To bring the frequency down, the speed of G2 must be reduced.



# Example

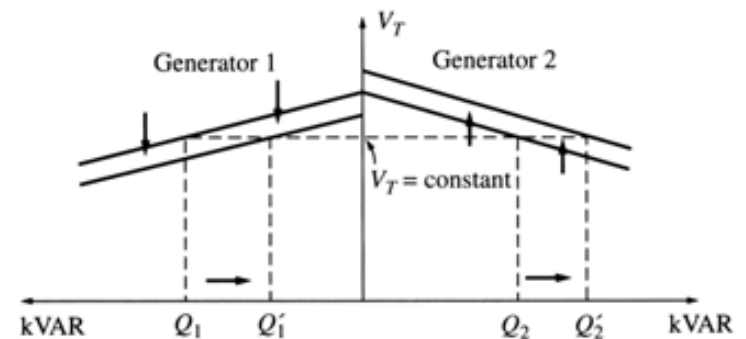
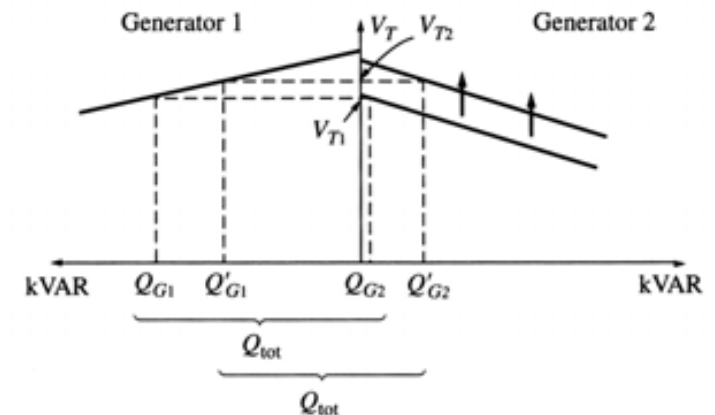
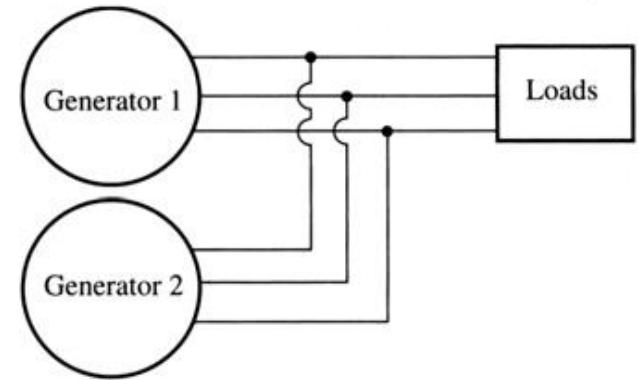
Two generators are set to supply the same load. G1 has a no-load frequency of 61.5 Hz and a slope  $sp1$  of 1 MW/Hz. G2 has a no-load frequency of 61.0 Hz and a slope  $sp2$  of 1 MW/Hz. The two generators are supplying a real load of 2.5 MW at 0.8 PF lagging.

- System frequency? Ans. 60 Hz
- Power generated by G1 and G2? Ans. 1.5 MW and 1 MW
- An additional load of 1 MW is added, find the system frequency and the generator powers? Ans. 59.5 Hz, 2 MW, and 1.5 MW
- Repeat c) after the no-load frequency of G2 is increased by 0.5 Hz? Ans. 59.75 Hz, 1.75 MW and 1.75 MW.



# Parallel operation of generators of similar size

- Similarly, an increase in the field current of G1 will result in
  - An increase of the reactive power supplied G1,
  - A reduction of the reactive power supplied G2.
  - An Increase of the system terminal voltage.
  - To bring the voltage down, the field current of G1 must be reduced.



# Synchronous Generator Rating

- The purpose of ratings is to protect the machine from damage. Typical ratings of synchronous machines are **voltage, speed, apparent power (kVA), power factor, field current** and **service factor**.
  - The **rated frequency** of a synchronous machine depends on the power system to which it is connected. Once the operation frequency is determined, only one rotational speed is possible for the given number of poles.
  - For a given design, the **rated voltage** is limited by the flux that is capped by the field current. The rated voltage is also limited by the windings insulation breakdown limit.
  - The maximum acceptable armature current sets the **apparent power** rating for a generator. The power factor of the armature current is irrelevant for heating the armature windings.



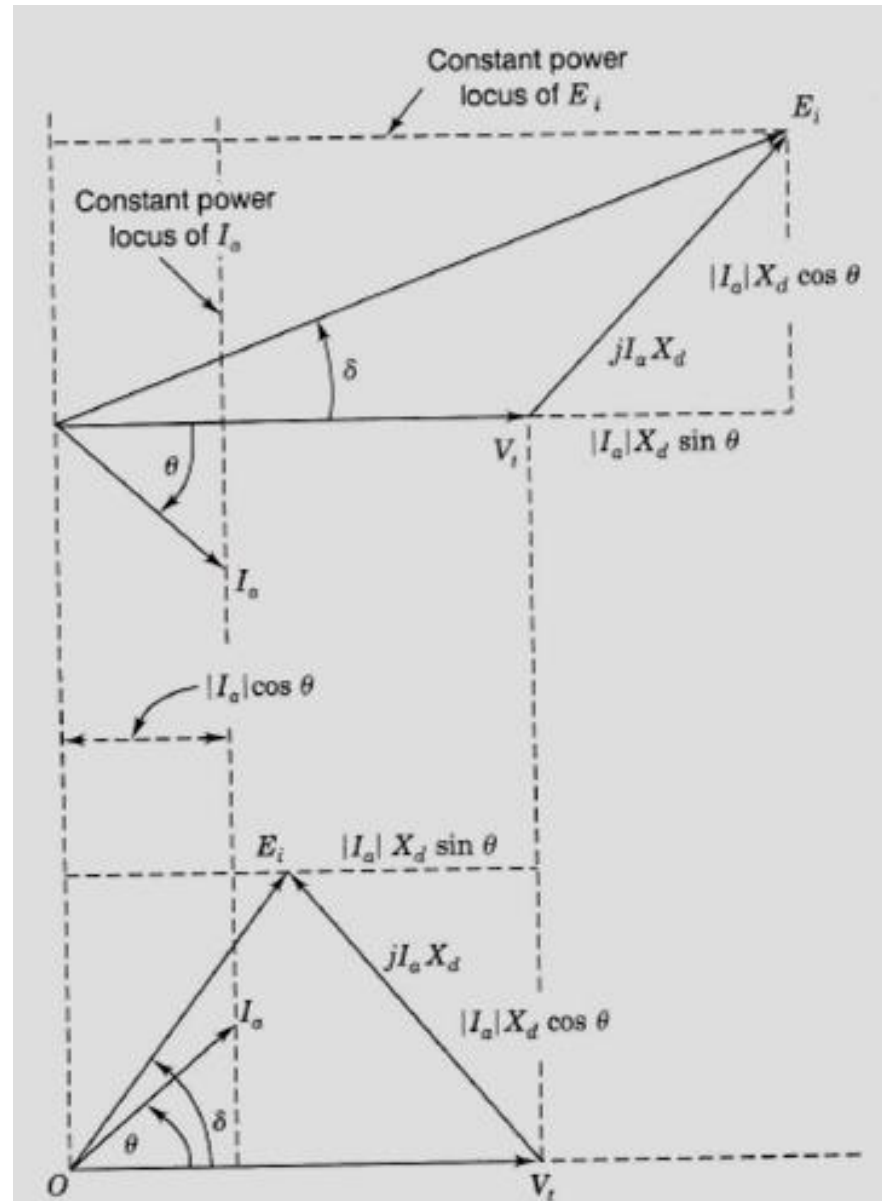
# Synchronous Generator Real and Reactive Power

$$P = V_t I_a \cos \theta$$

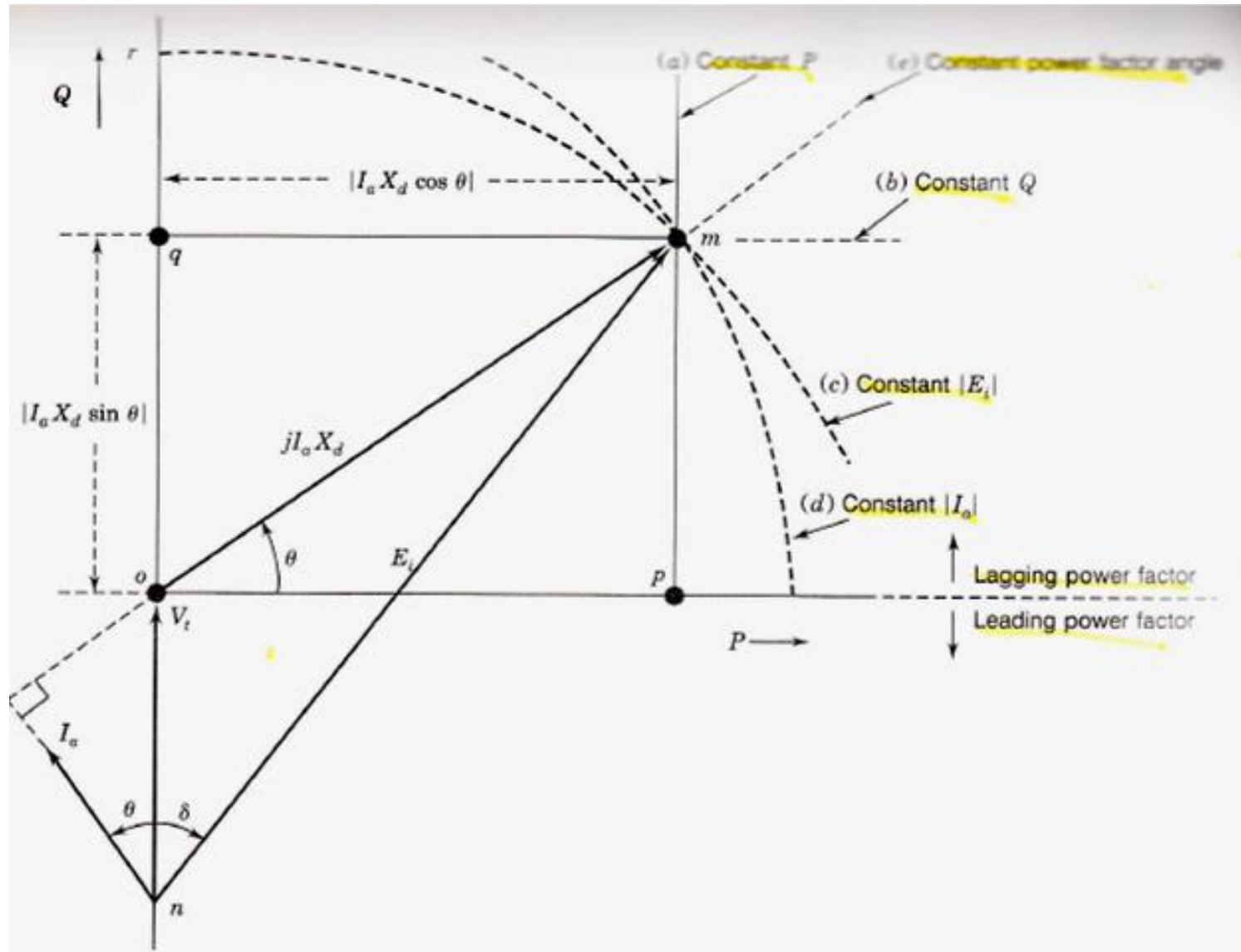
$$Q = V_t I_a \sin \theta$$

$$P = \frac{V_t}{X_d} E_i \sin \delta$$

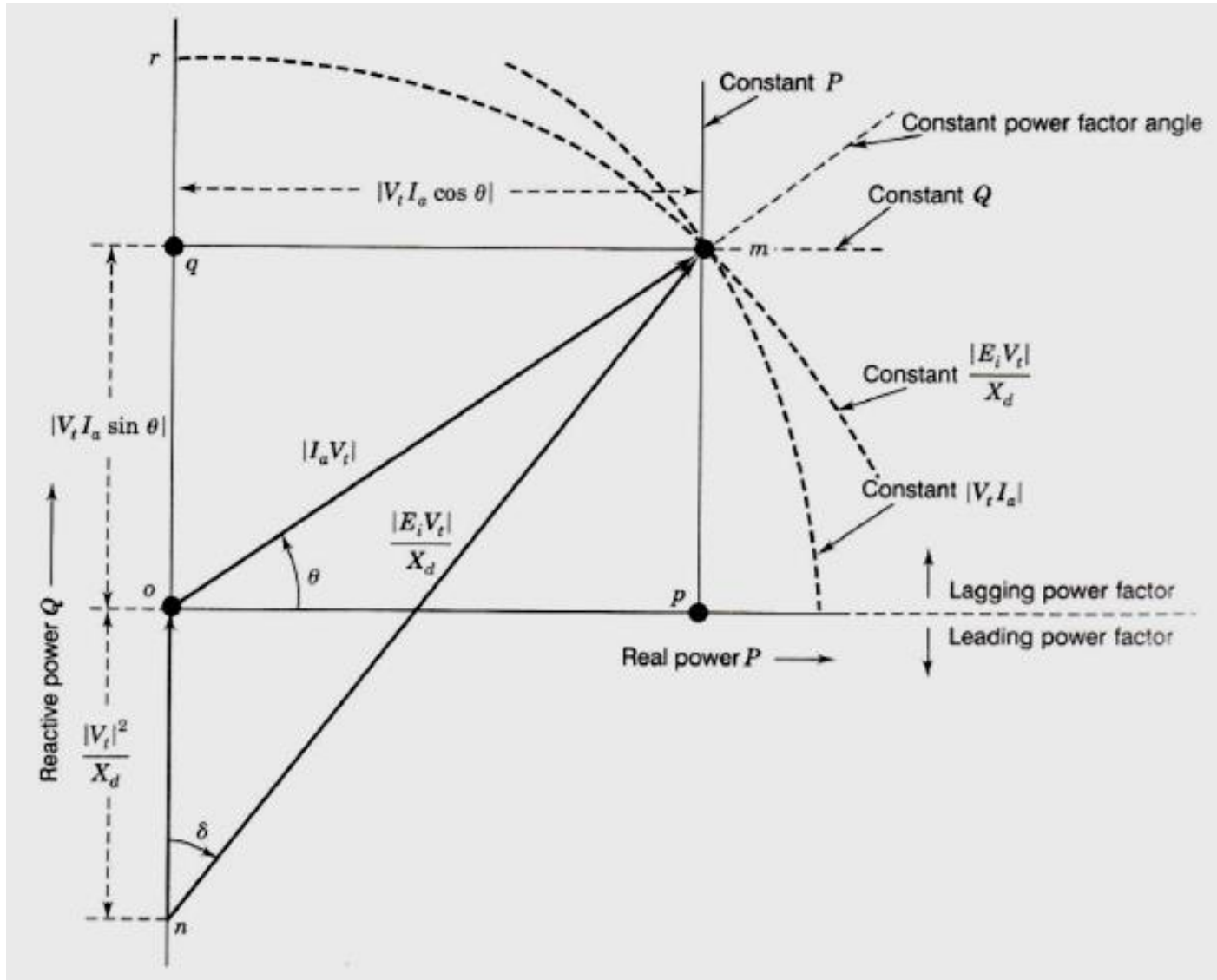
$$Q = \frac{V_t}{X_d} \{E_i \cos \delta - V_t\}$$



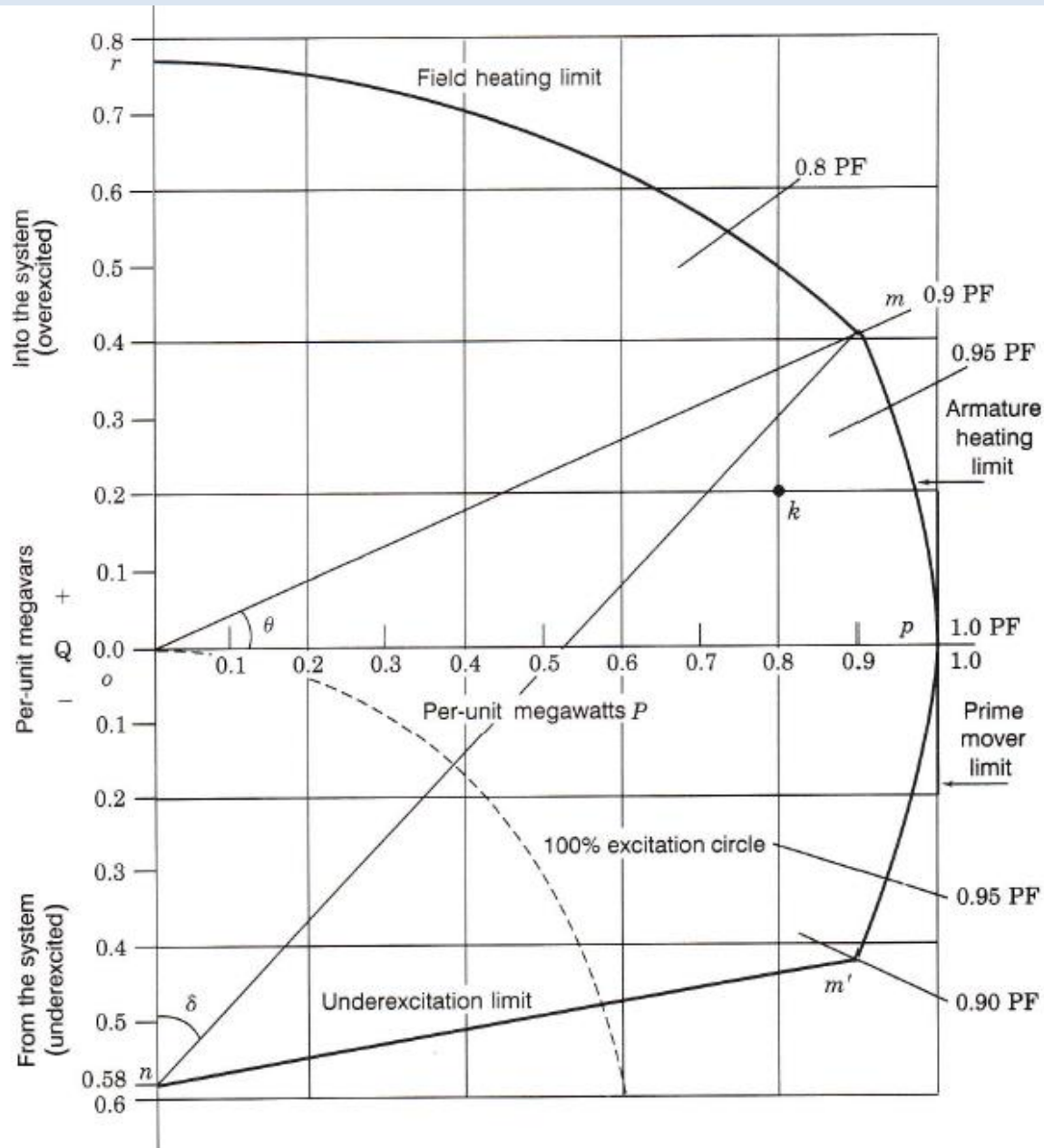
# Generator Loading Capability Diagram



# Generator Loading Capability



# Generator Loading Capability Curve



# Static Load Models

- ZIP model:

$$P = P_0 \left[ a_1 \left( \frac{V}{V_0} \right)^2 + a_2 \left( \frac{V}{V_0} \right) + a_3 \right]$$

$$Q = Q_0 \left[ a_4 \left( \frac{V}{V_0} \right)^2 + a_5 \left( \frac{V}{V_0} \right) + a_6 \right],$$

- Exponential model:  $P = P_0 \left( \frac{V}{V_0} \right)^{n_p}$  and  $Q = Q_0 \left( \frac{V}{V_0} \right)^{n_q}$ ,

$$P = P(V) \left[ 1 + k_{\text{Ppf}} \frac{\Delta f}{f_0} \right]$$

- Frequency dependent model:

$$Q = Q(V) \left[ 1 + k_{\text{Qpf}} \frac{\Delta f}{f_0} \right],$$