Synchronous Generators

Introduction-One

A synchronous generator is an electrical generator that converts mechanical energy to electrical energy in the form of alternating current.
Due to the need for frequency stability in the production of three phase electrical power, most alternators use a rotating magnetic field with a stationary armature. Occasionally, a linear alternator or a rotating armature with a stationary magnetic field is used.
In principle, any AC electrical generator can be called an alternator, but usually the term refers to small rotating machines driven by automotive and other internal combustion engines.
Alternators in power stations driven by steam turbins are called synchronous generators. Large 50 or 60 Hz three-phase alternators in power plants generate most of the world's electric power, which is distributed by electric power grids.

Introduction-Two

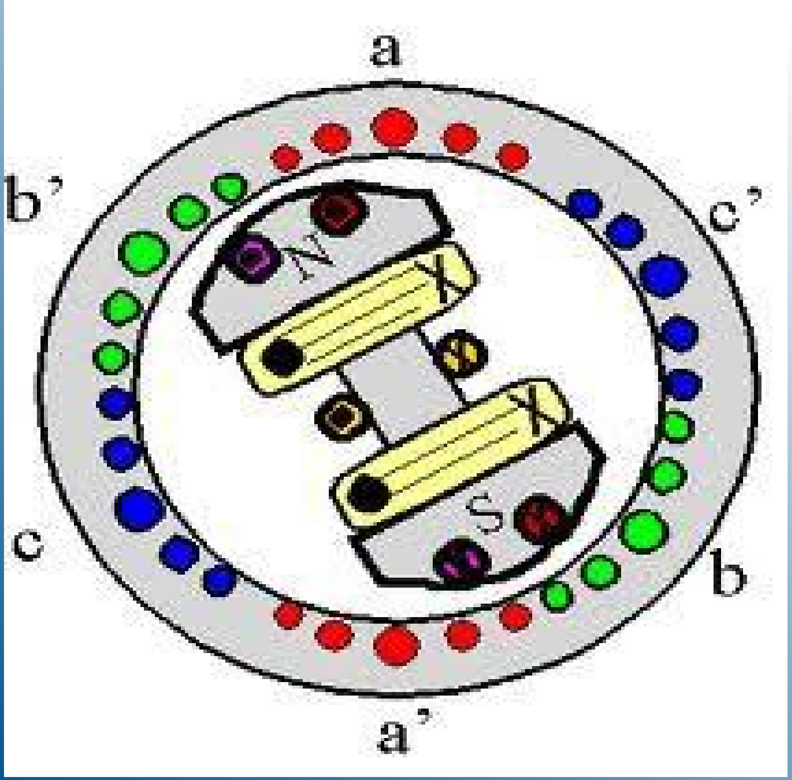
Alternators in power stations driven by steam turbines are called synchronous generators. Large 50 or 60 Hz three-phase alternators in power plants generate most of the world's electric power, which is distributed by electric power grids

Synchronous generators are used in the electrical power production because of their ability to produce three phase power with a constant frequency.

Construction of Synchronous Machine

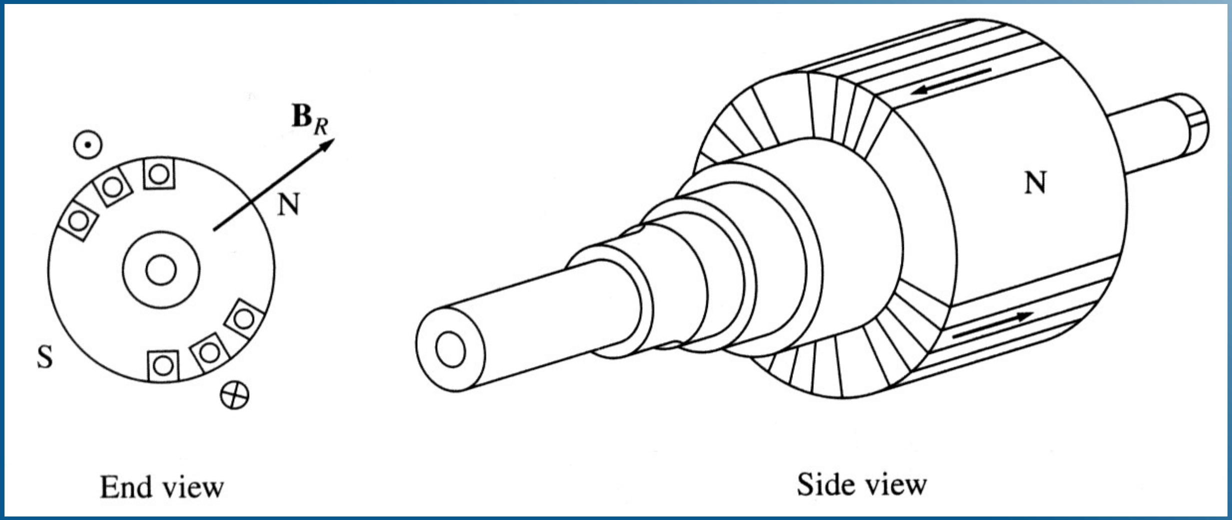
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

- 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 Machine-Part One

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.



Salient-pole rotor: # of poles: large number

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

Rotors are made laminated to reduce eddy current losses.

Construction of Synchronous Machine-Part Two

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.

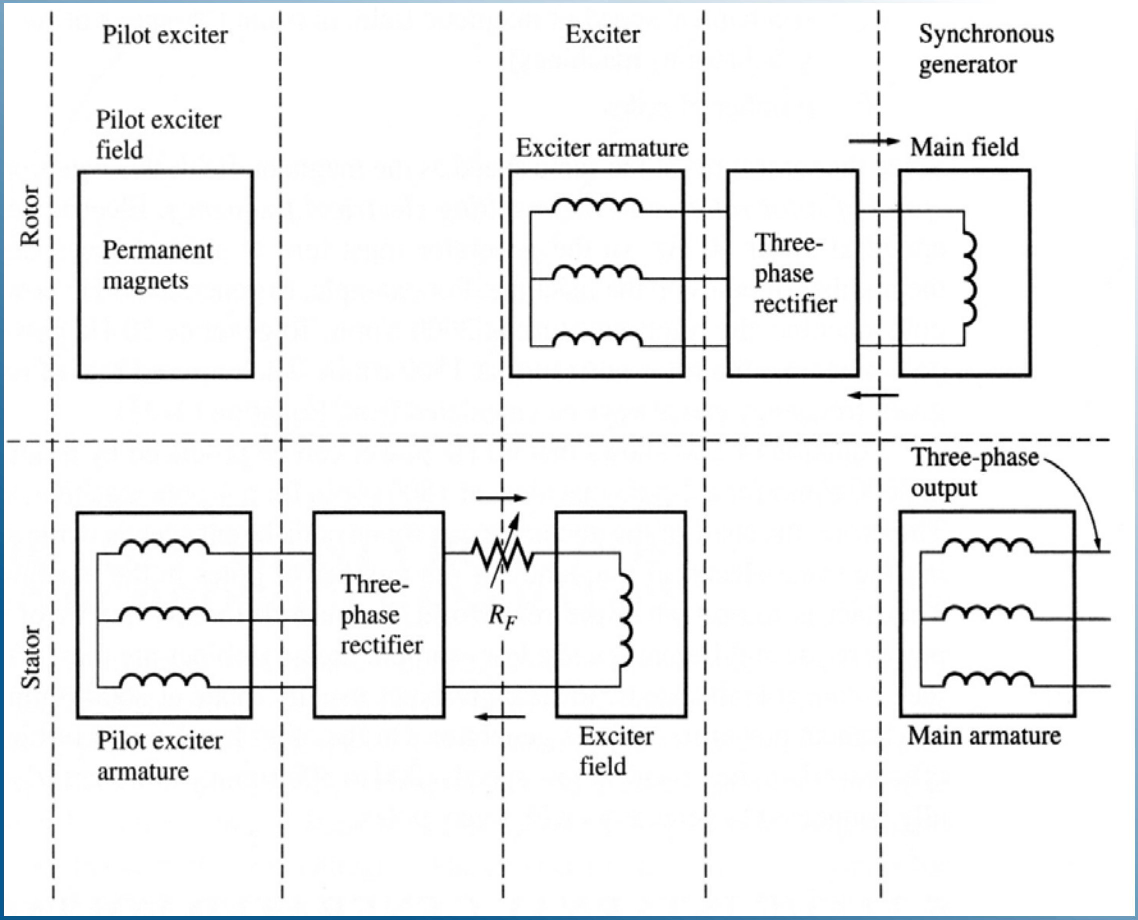
Construction of Synchronous Machine-Part Three

- On large generators, 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 Machine-Part Four

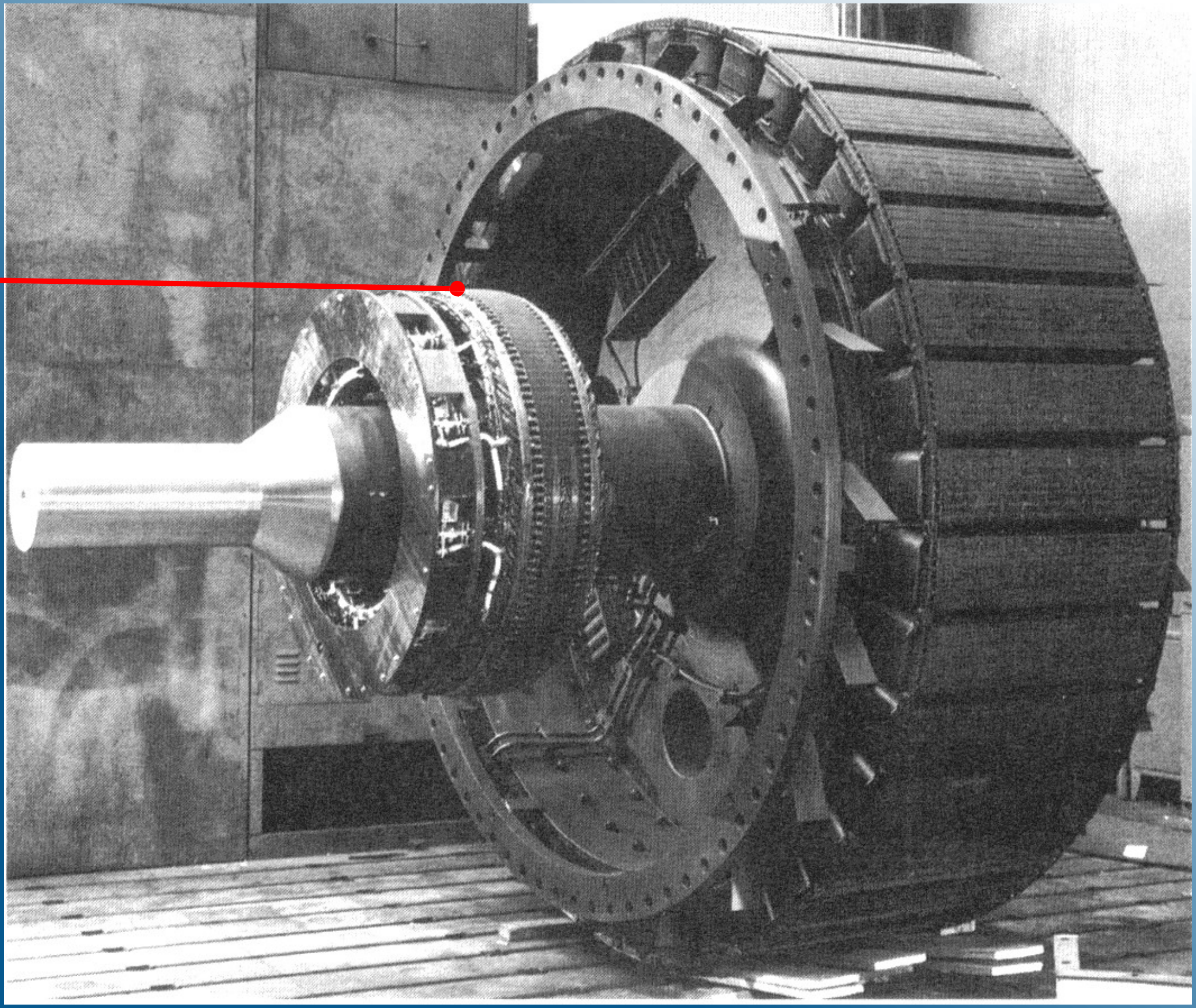
To make the excitation of a generator completely independent of any external power source, a small pilot exciter is often added to the circuit.

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 Machine-Part Five

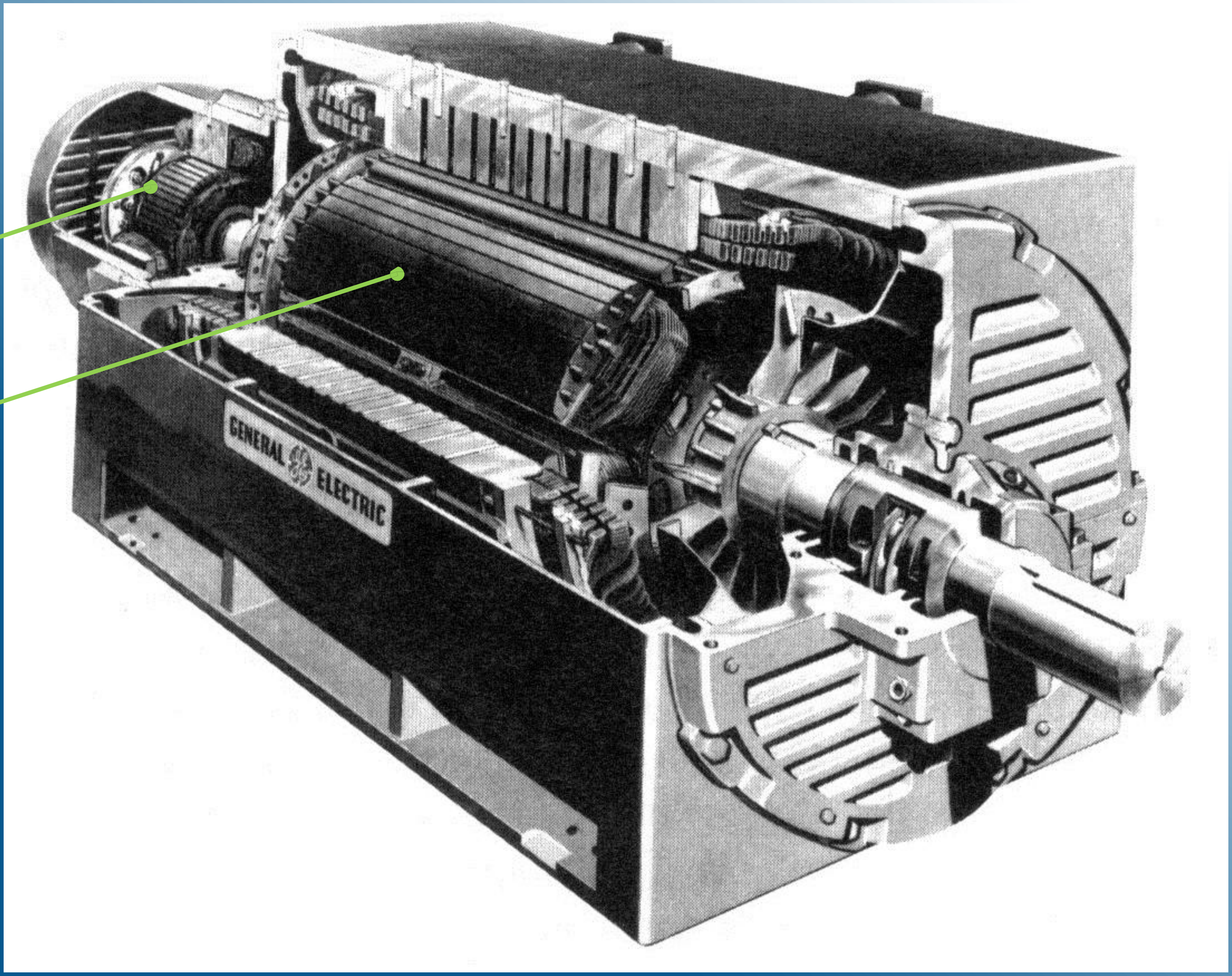
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.



Construction of Synchronous Machine-Part Six

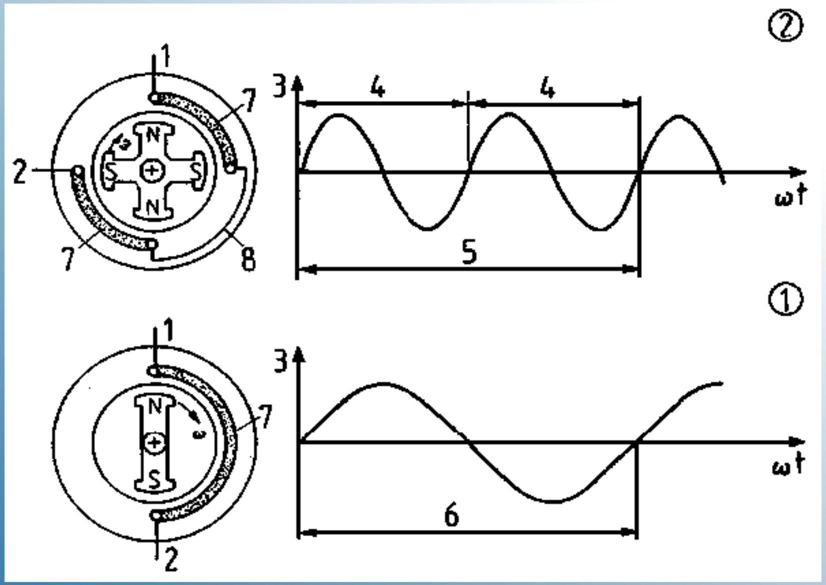
Exciter

Rotor pole.



Rotation speed of synchronous generator

By 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.

- Combined-Cycle gas turbines and 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.

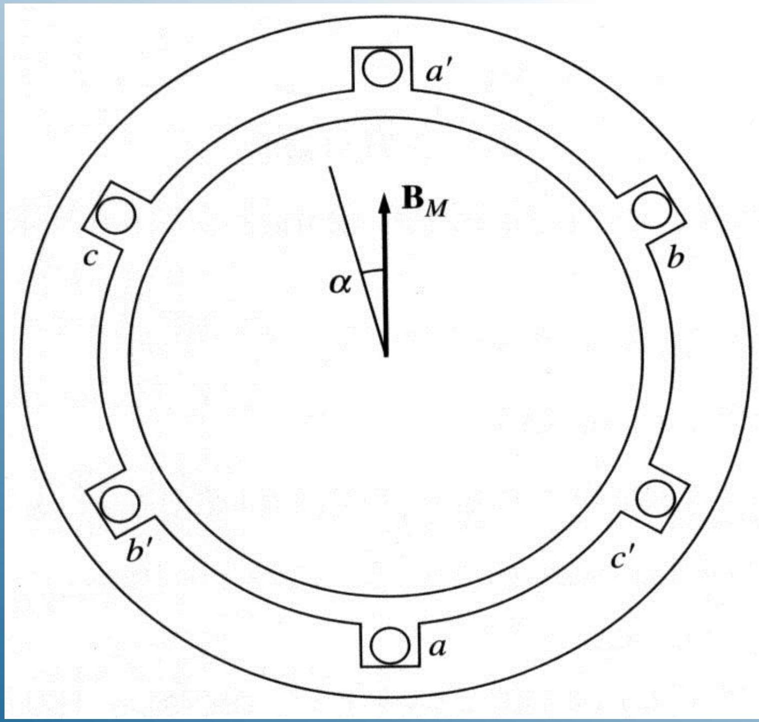
The induced voltage

In three coils, each of N_C turns, placed around the rotor magnetic field, the induction in each coil will have the same magnitude and phases differing by 120^0:

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

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

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



Peak voltage:

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

RMS voltage:

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

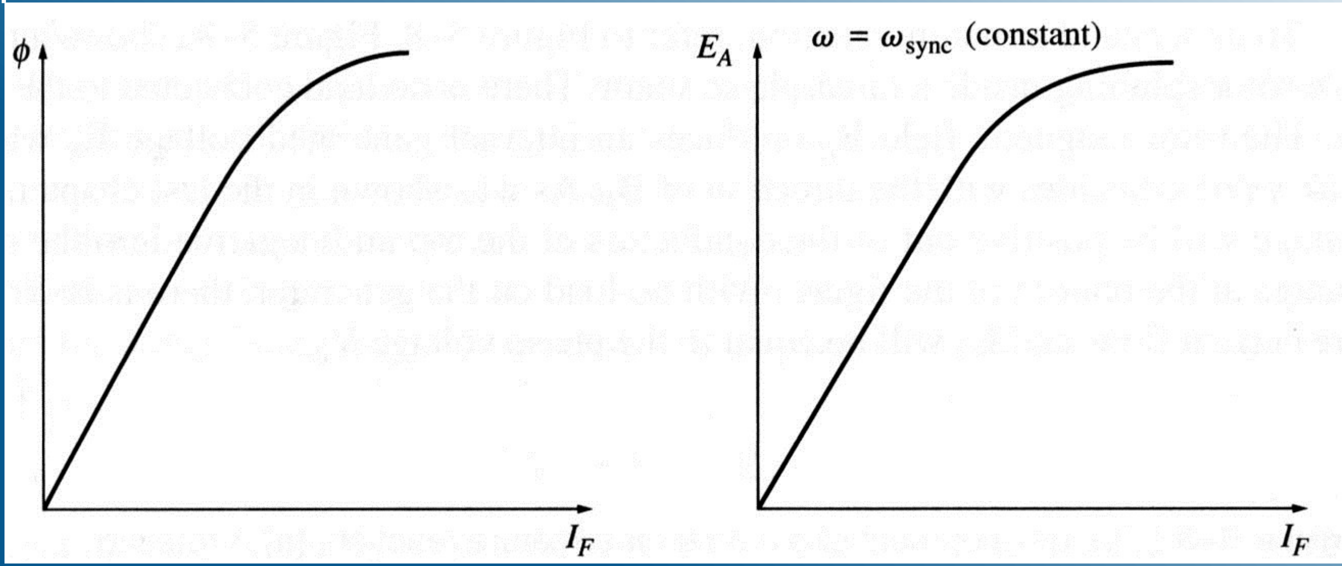
Internal generated voltage of a synchronous generator

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, ϕ is flux in it and ω 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-Part One

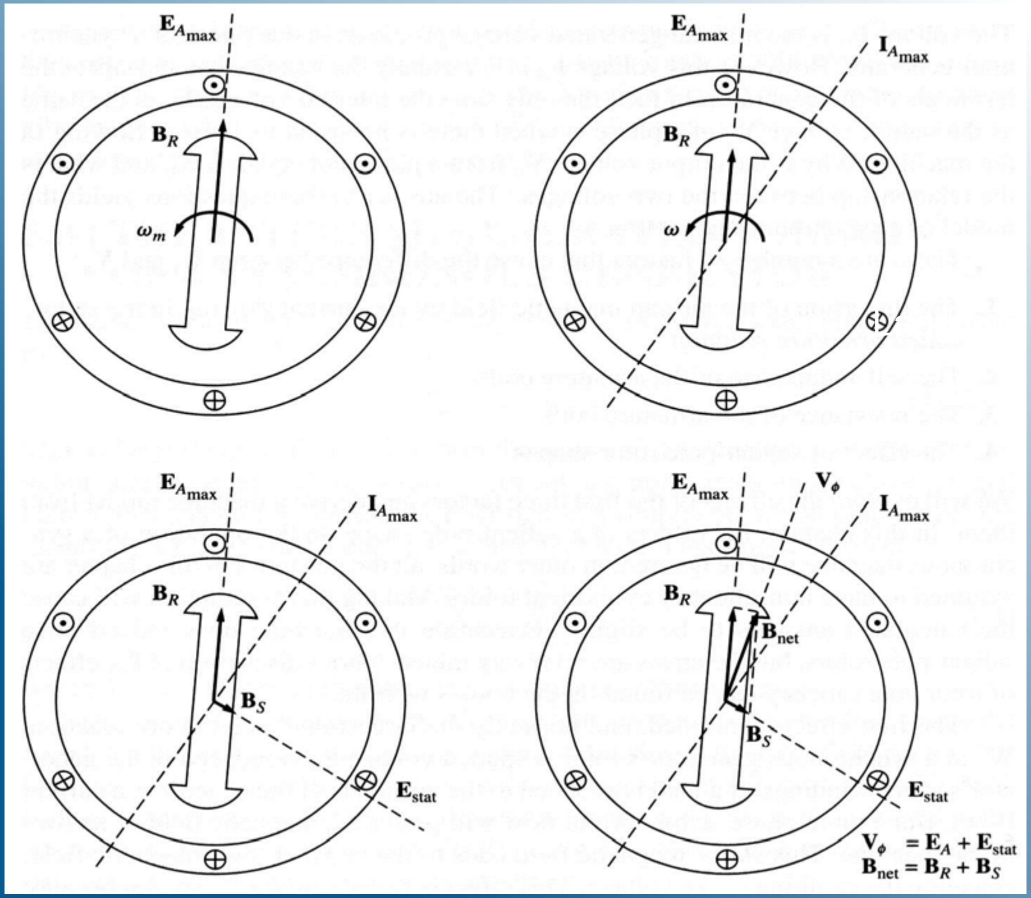
The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals. It equals to the output voltage V_ϕ only when there is no armature current in the machine. The reasons that the armature voltage E_A is not equal to the output voltage V_ϕ 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-Part Two

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 of the voltage.



Equivalent circuit of a synchronous generator-Part Three

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

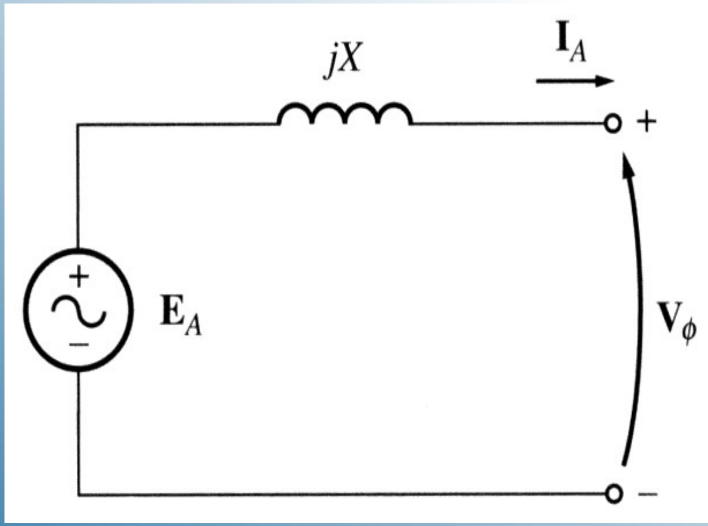
Equivalent circuit of a synchronous generator-Part Four

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

$$V_\phi = E_A - jXI_A - jX_AI_A - RI_A$$

Equivalent circuit of a synchronous generator-Part Five

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

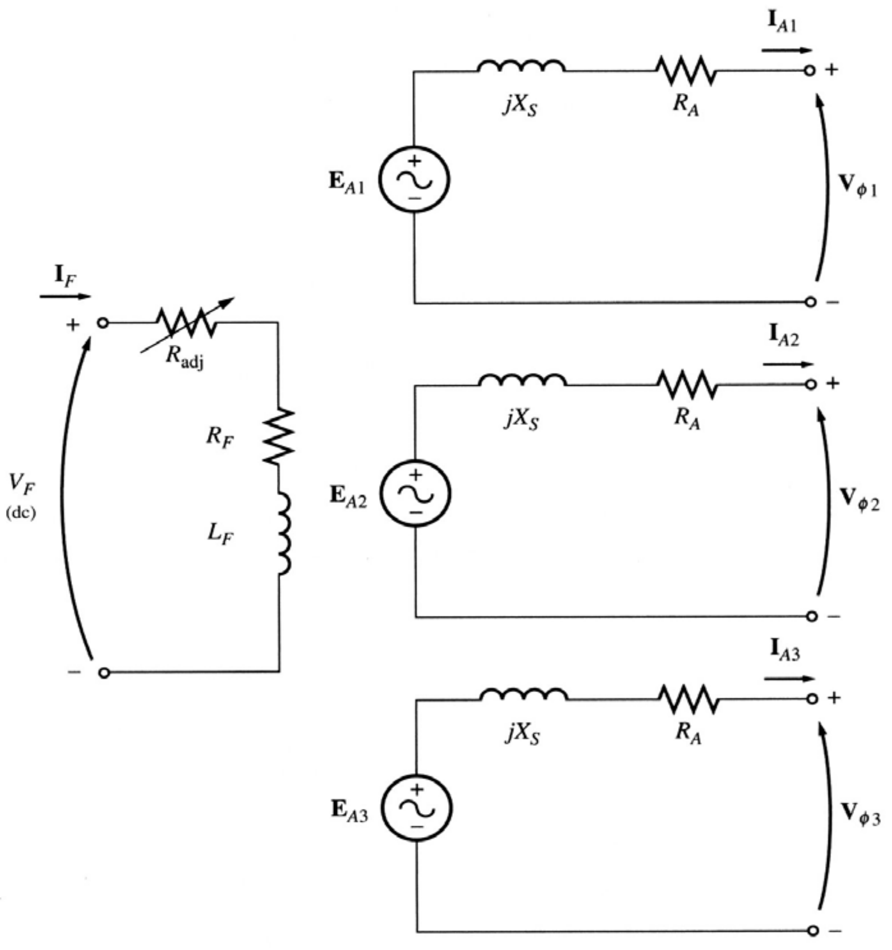
$$X_S = X + X_A$$

Therefore, the phase voltage is

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

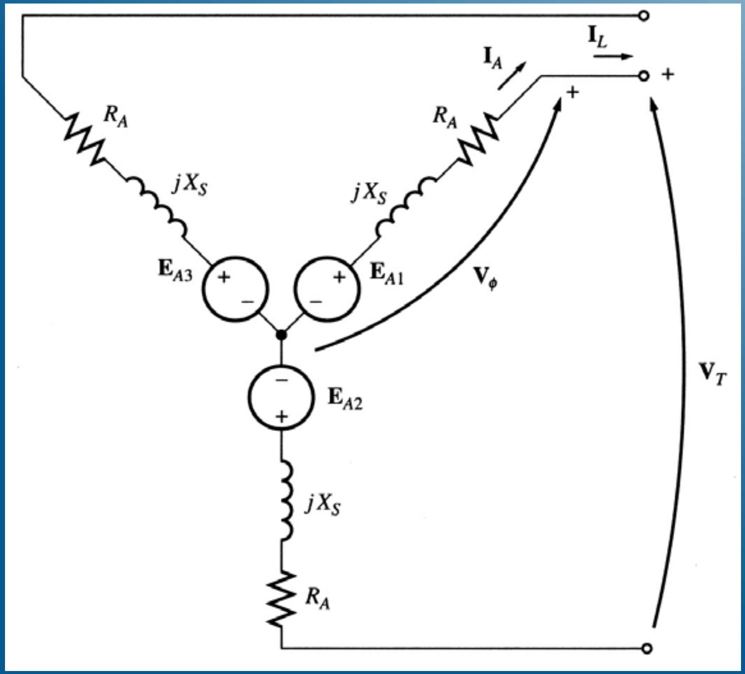
The equivalent circuit of a 3-phase synchronous generator is shown.

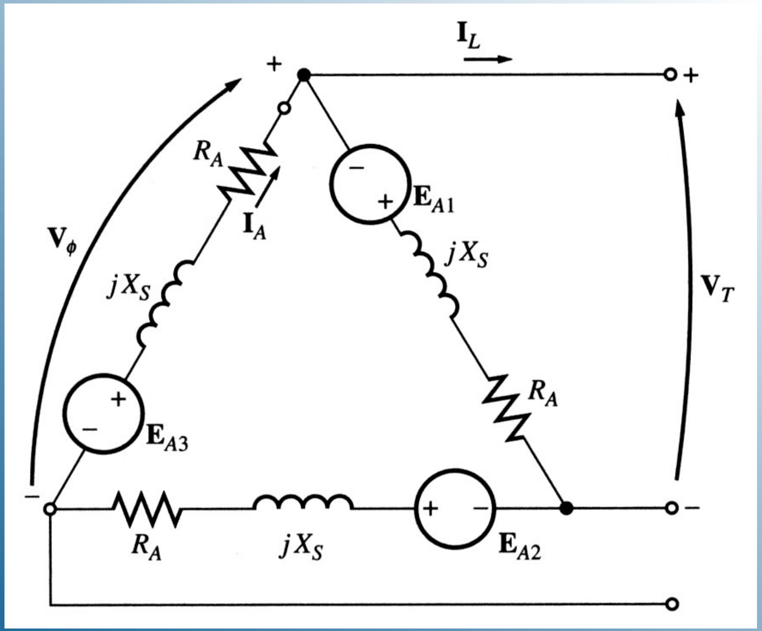
The adjustable resistor R_{adj} controls the field current and, therefore, the rotor magnetic field.



Equivalent circuit of a synchronous generator-Part One

A synchronous generator can be Y- or Δ-connected:



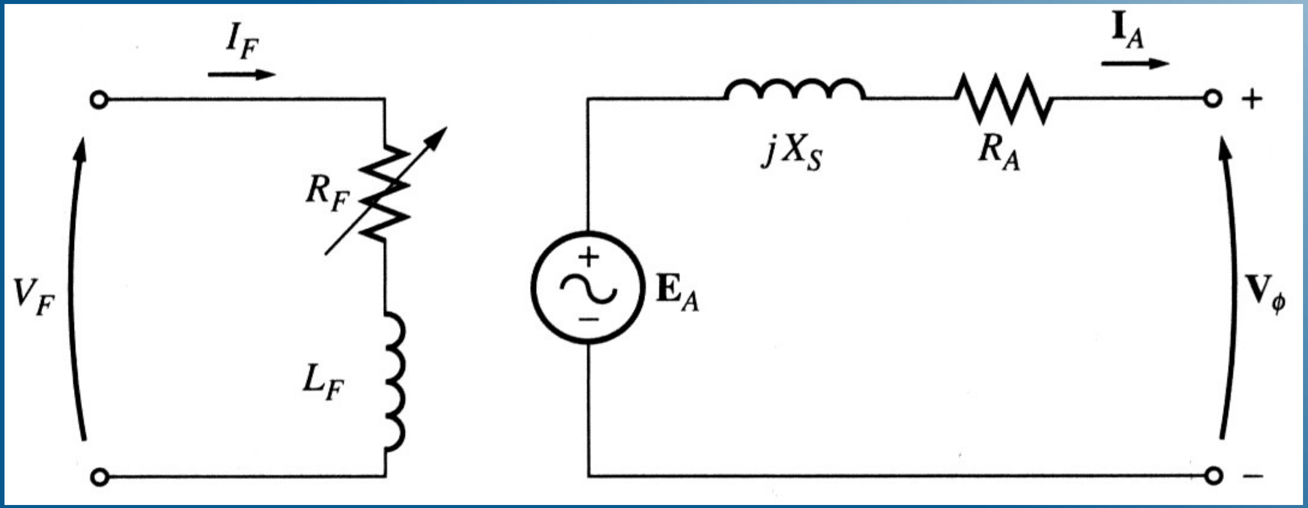


The terminal voltage will be

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

Equivalent circuit of a synchronous generator-Part Two

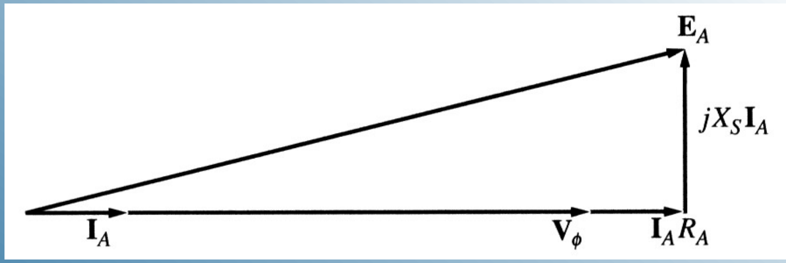
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



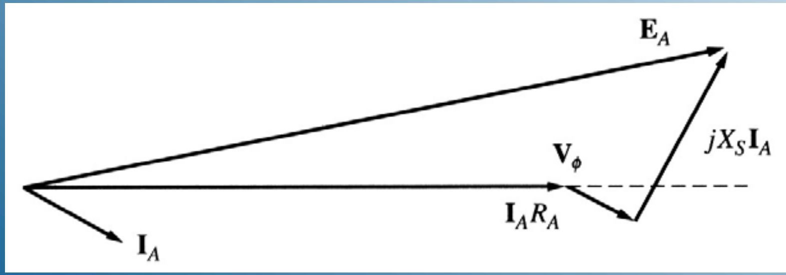
Phasor diagram of a synchronous generator

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.

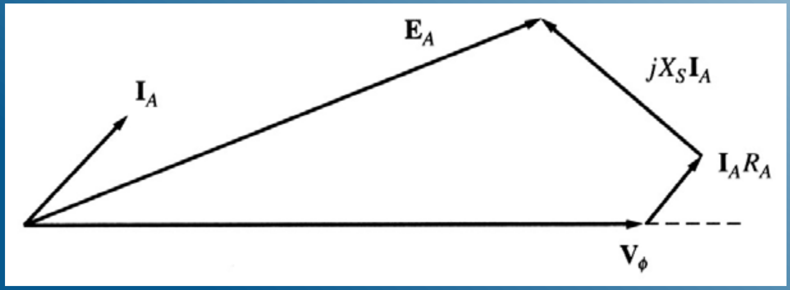
- A phasor diagram of a synchronous generator with a unity power factor. (resistive load)



- 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-Part One

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-Part Two

- An increase in the load is an increase in the real or reactive power drawn from the generator

- Since the field resistor is unaffected, the field current is constant and, therefore, the flux ϕ is constant too. Since the speed is assumed as constant, the magnitude of the internal generated voltage is constant also.

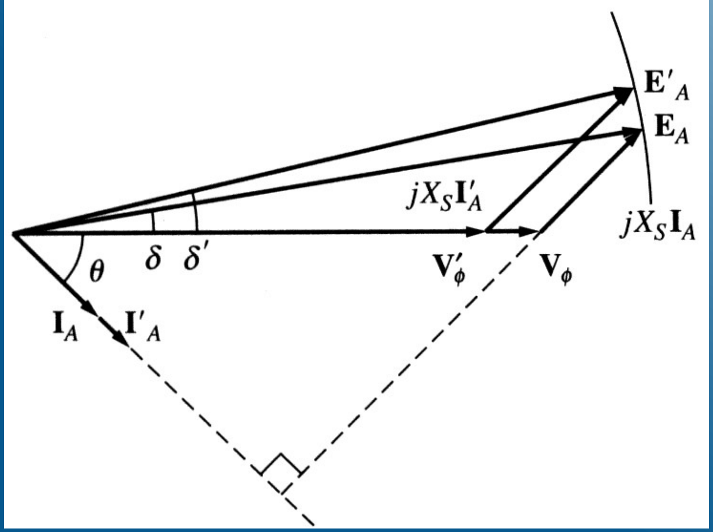
- Assuming the same power factor of the load, change in load will change the magnitude of the armature current I_A. However, the angle will be the same (for a constant PF). Thus, the armature reaction voltage jX_SI_A will be larger for the increased load. Since the magnitude of the internal generated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

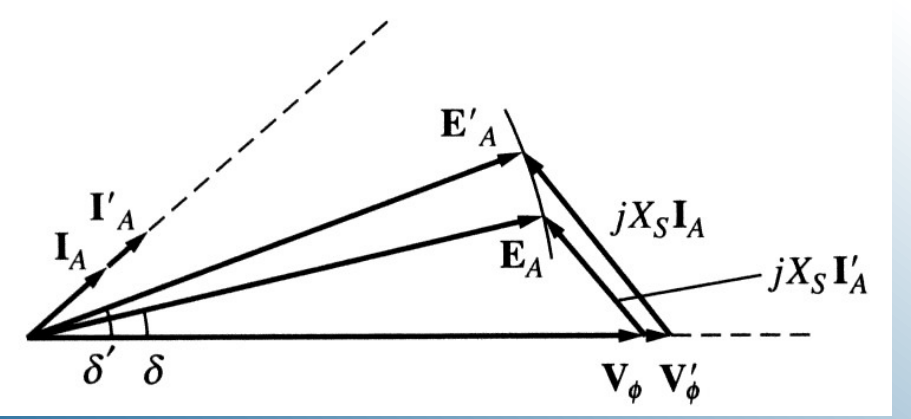
$$E_A = V_\phi + jX_S I_A$$

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

The Synchronous generator operating alone-Part Three

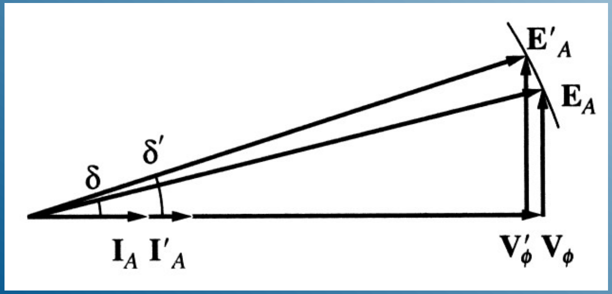
Increase load effect on generators with





Leading PF

Lagging PF



Unity PF

The Synchronous generator operating alone-Part Four

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-Part Five

- 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-Part One

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.

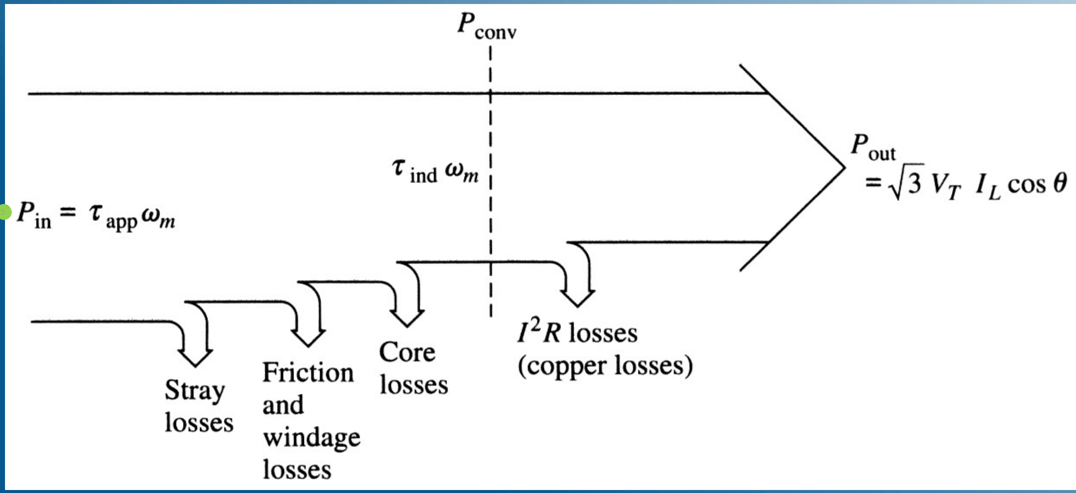
The applied mechanical power $P_{in} = \tau_{app}\omega_m$

is partially converted to electricity

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

Where γ is the angle between E_A and I_A.

The power-flow diagram of a synchronous generator.



Power and torque in synchronous generators-Part Two

The real output power of the synchronous generator is

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

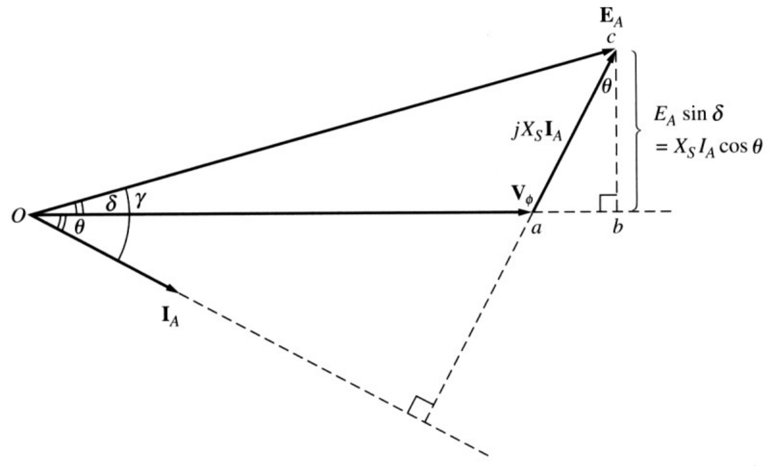
The reactive output power of the synchronous generator is

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

Recall that the power factor angle θ is the angle between V_ϕ and I_A and **not** the angle between E_A and I_A.

In real synchronous machines of any size, the armature resistance $R_A << X_S$ 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-Part Three

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

$$\boxed{P_{out} \approx \frac{3V_{\phi}E_{A}\sin\delta}{X_S}}$$

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

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

Here δ is the power angle of the machine – the angle between V_{ϕ} and E_A. This is Different from the power factor angle/

The maximum power can be supplied by the generator when $\delta = 90^0$:

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

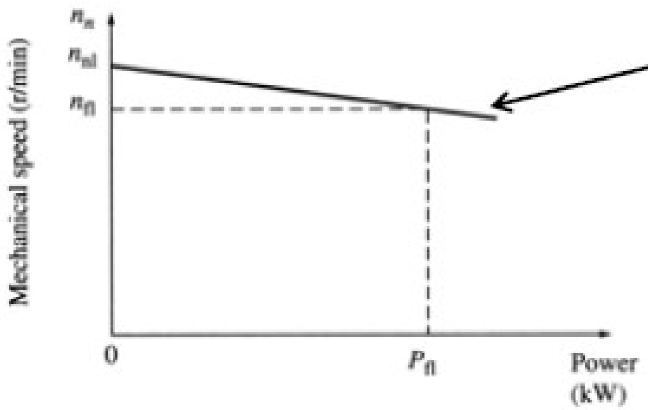
Generator P-f Curve-Part One

- 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:

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

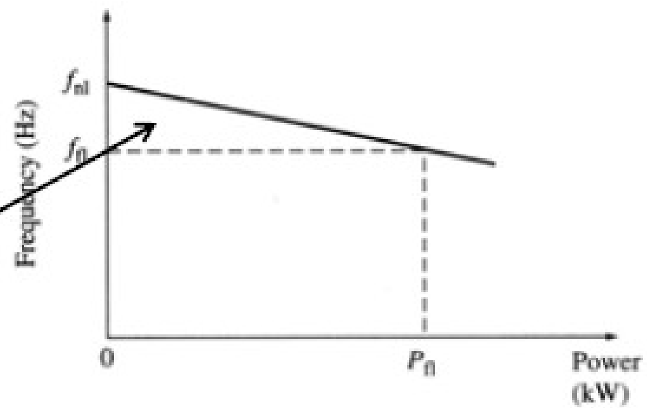
- Most prime movers have a speed drop from 2% to 4%. Most governors have a mechanism to adjust the turbine's no-load speed (set-point adjustment).

Generator P-f Curve-Part Two



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:

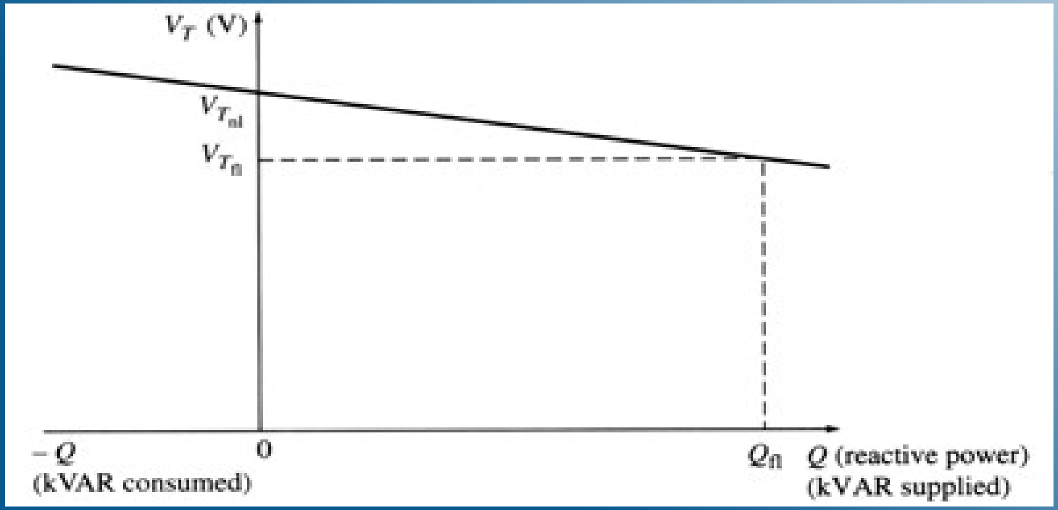
$$\boxed{P = s_p \left(f_{nl} - f_{sys} \right)}$$

Slope of curve, W/Hz

Operating frequency of the system

Generator P-f Curve-Part Three

- 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.

Generator Operating Alone

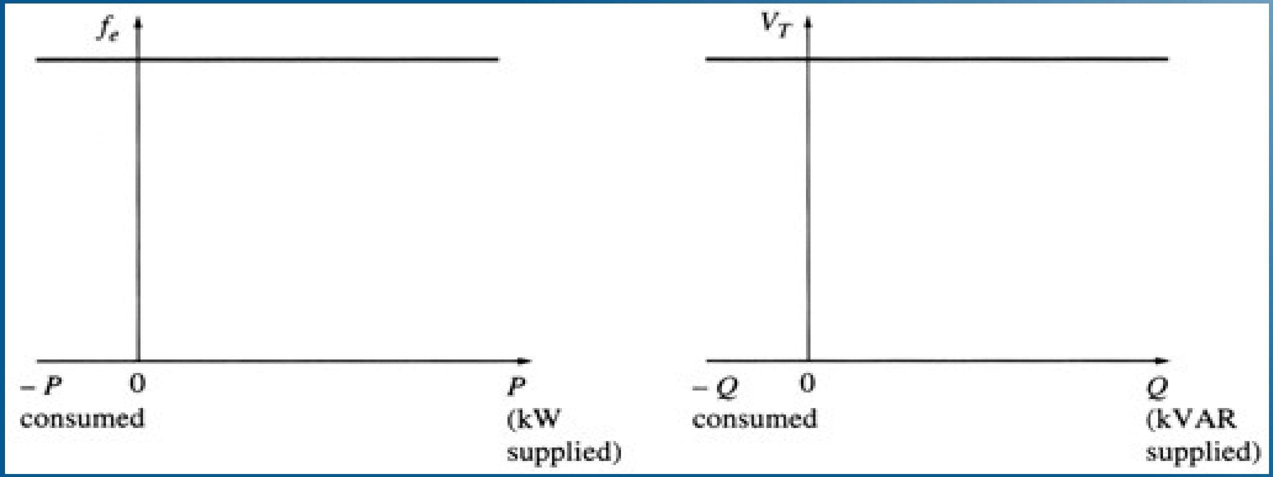
- When a generator is operating alone supplying the load:
  - The real and reactive powers are the amounts demanded by the load.
  - The governor of the generator controls the operating frequency of the system.
  - The field current controls the terminal voltage of the power system.

Generators connected in parallel

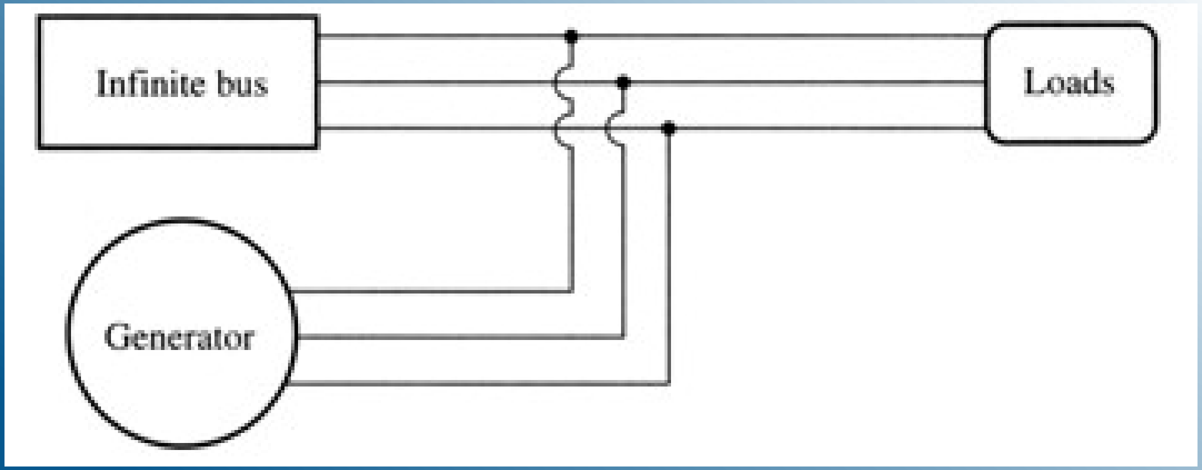
- Most of synchronous generators are operating in parallel with other synchronous generators to supply power to the same power system.
- Obvious advantages of this arrangement are:
  - Several generators can supply a bigger load;
  - A failure of a single generator does not result in a total power loss 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.

Synchronizing a generator with the utility grid-Part One

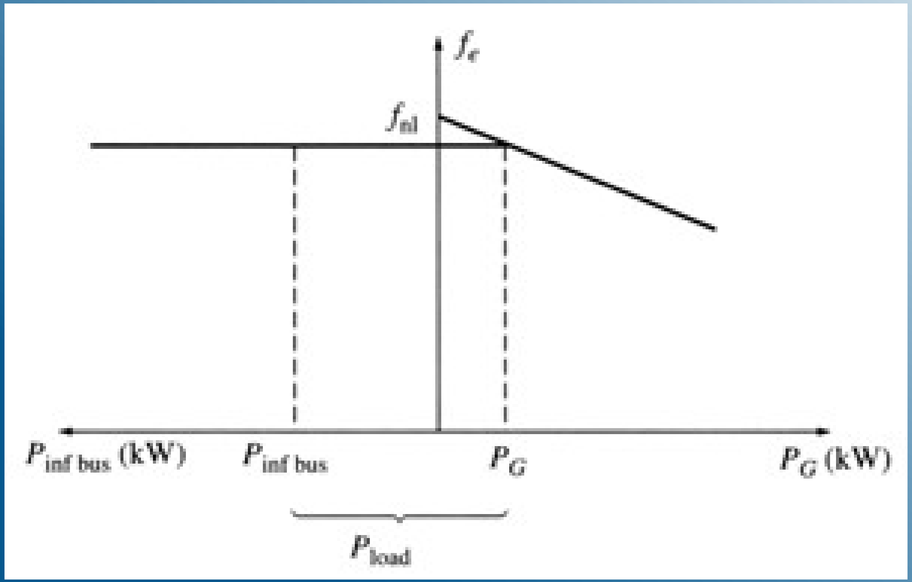
- When a synchronous generator is added to a power system, that system is so large that one additional generator does not cause observable changes to the system.
- An **infinite bus** is a power system that is so large that its voltage and frequency do not vary regardless of how much real and reactive 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-Part Two

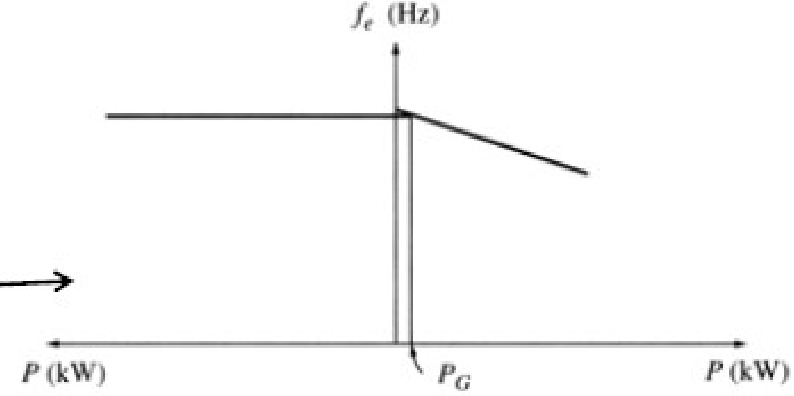


- Consider adding a generator to an infinite bus supplying a load.
- The frequency and terminal voltage of all machines must be the same.
- Therefore, their power-frequency and reactive power-voltage characteristics can be plotted with a common vertical axis.

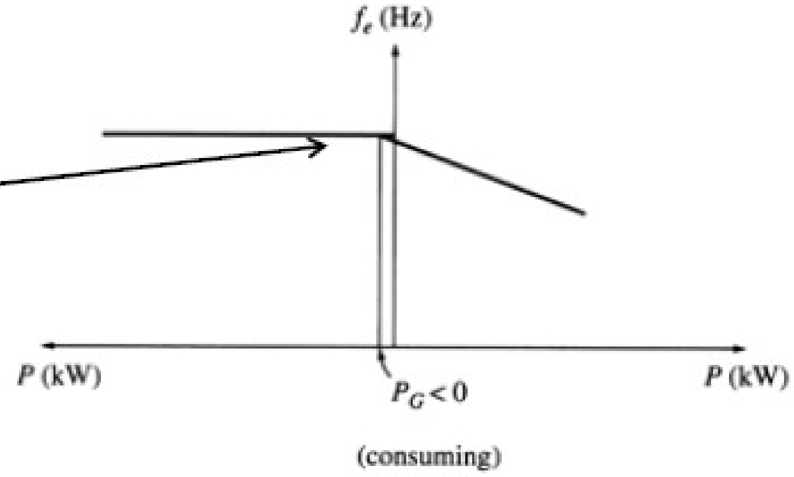


Synchronizing a generator with the utility grid-Part Three

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.

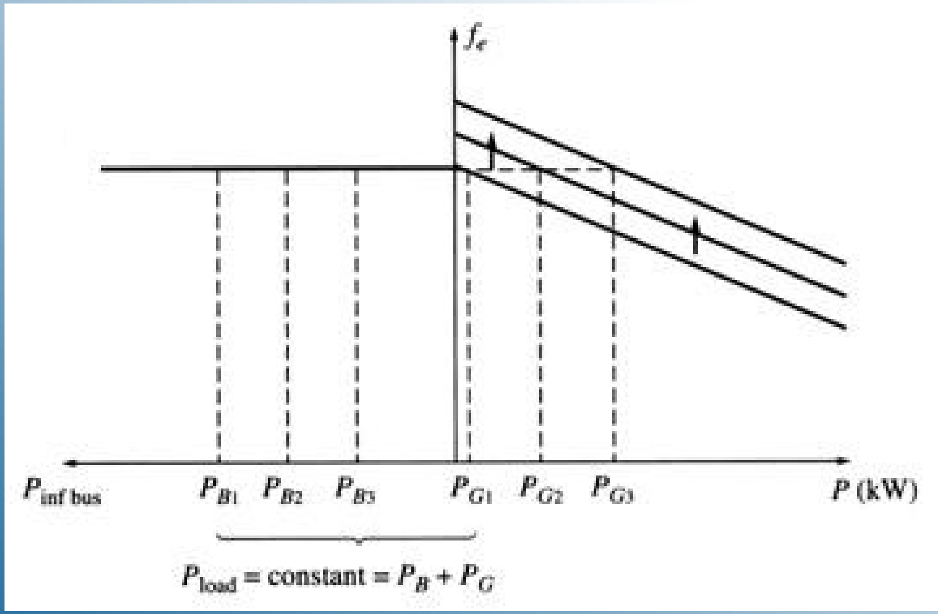


If the no-load frequency of the oncoming generator is slightly lower than the system's frequency, the generator will supply a negative power to the system: the generator actually consumes energy acting as a motor!
Many generators have circuitry automatically disconnecting them from the line when they start consuming energy.

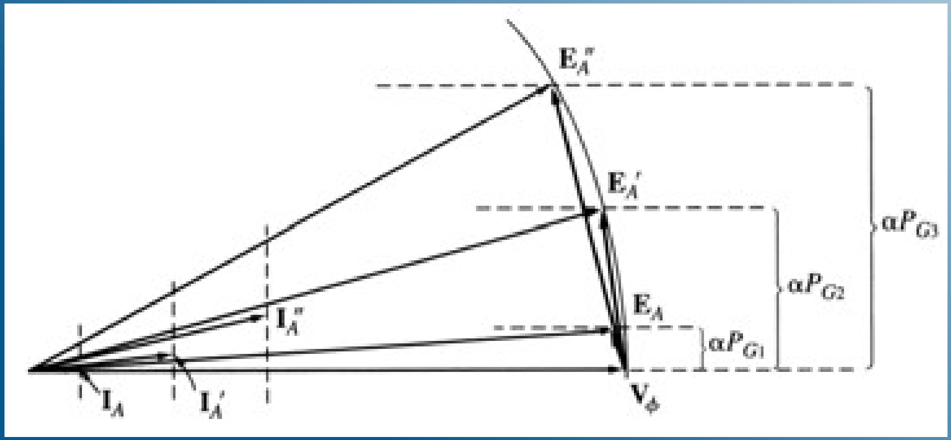


Parallel operation with the utility grid-Part One

- 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 δ.

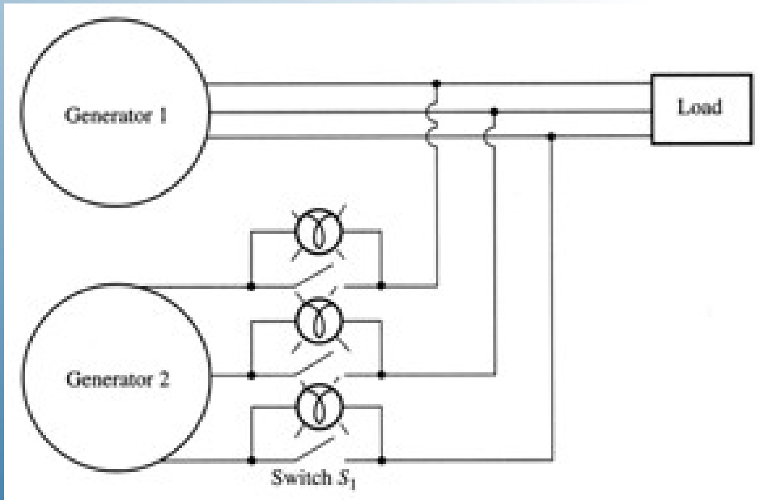


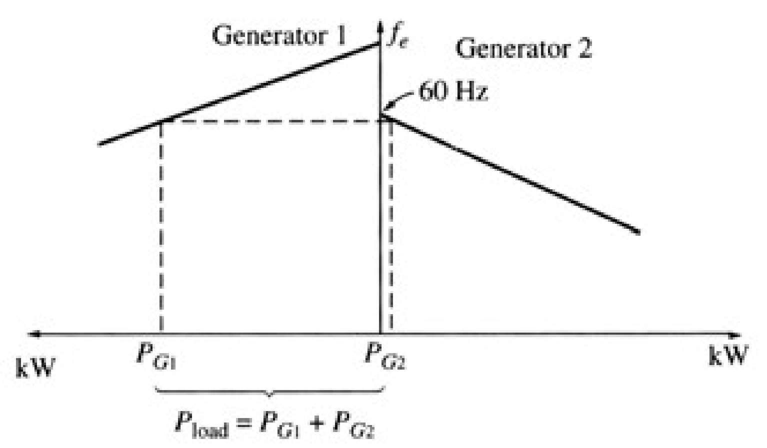
Parallel operation with the utility grid-Part Two

- Adjusting the field current of the machine, it is possible to make it to make the generator supply or consume reactive power *Q.*
- Summarizing, 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-Part One

- 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.



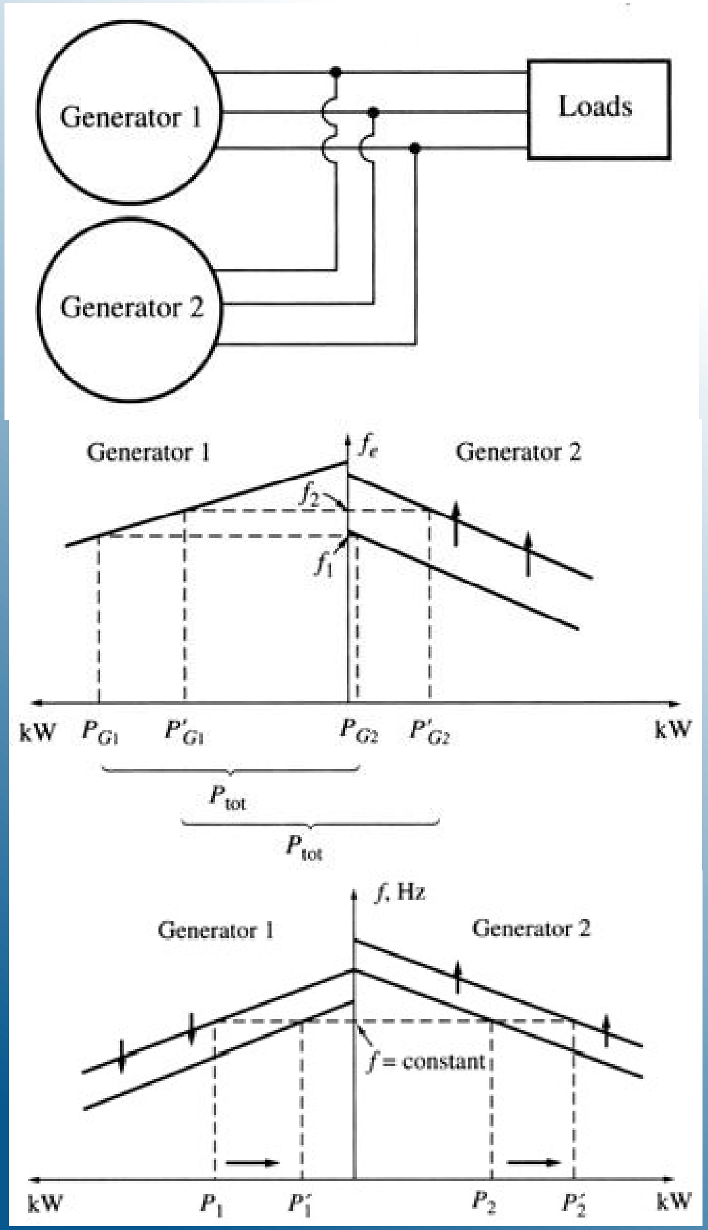


Parallel operation of generators of similar size-Part Two

- 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.



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 in 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.

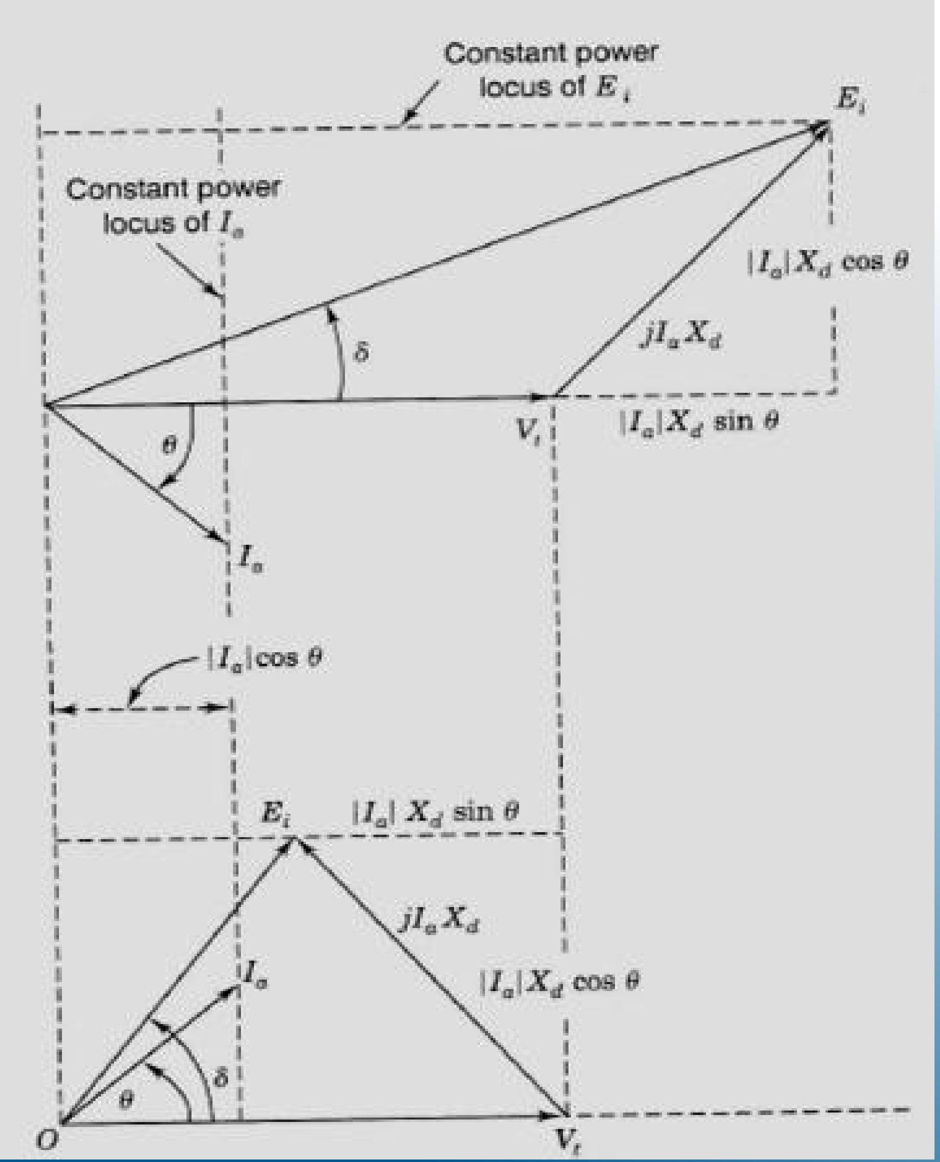
Synchronous Generator Real and Reactive Power

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

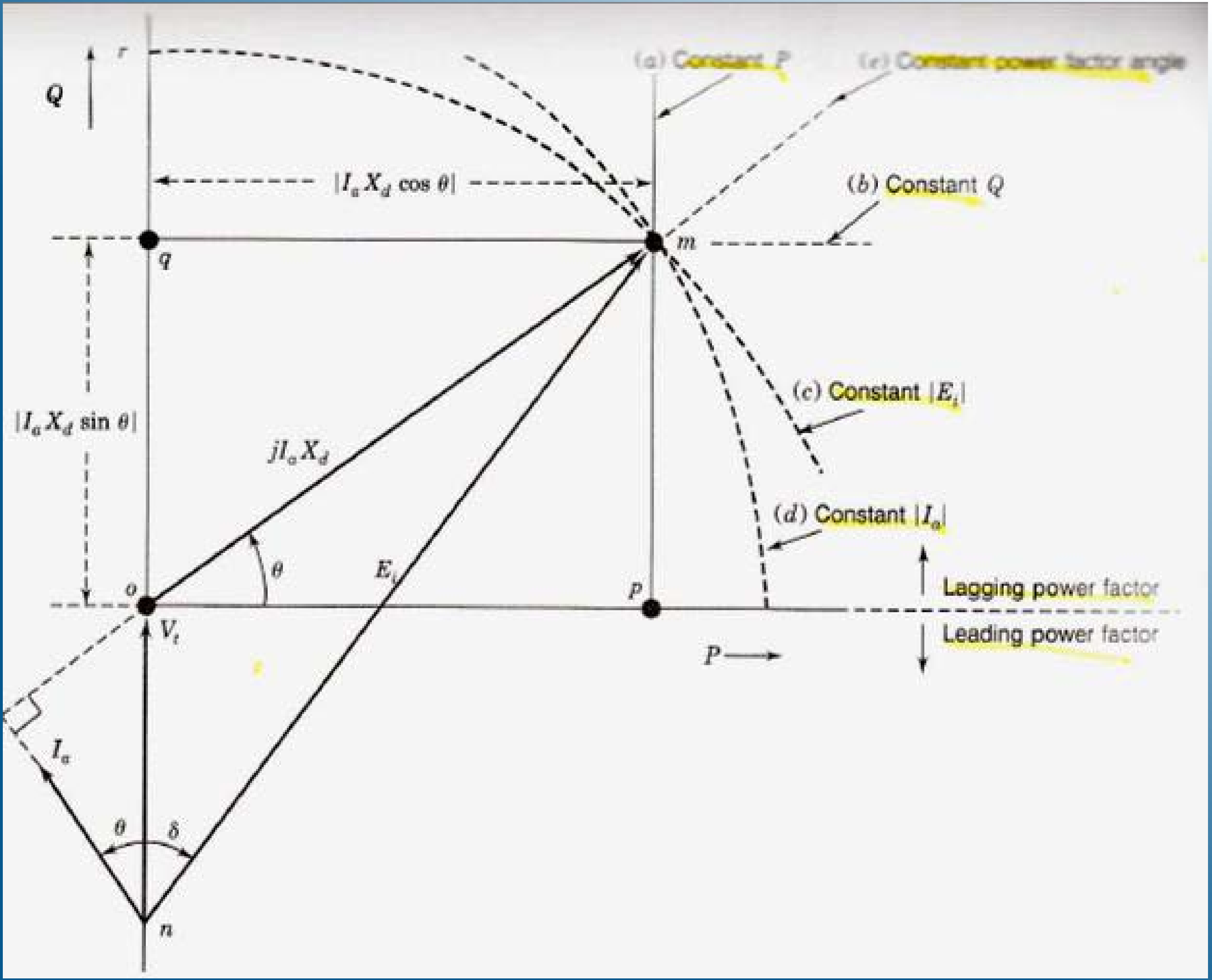
$$Q = V_t I_a \sin\theta$$

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

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



Generator Loading Capability Diagram



Generator Loading Capability Curve