SYNCHRONOUS MACHINE-I

CONTENTS

CONSTRUCTIONAL FEATURES

Synchronous machines are principally used as ***alternating current (AC) generators***. They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural, and domestic.

Synchronous generators usually operate together (or in parallel), forming a large power system supplying electrical energy to the loads or consumers.

Synchronous generators are built in large units, their rating ranging from tens to hundreds of megawatts.

Synchronous generator converts mechanical power to ac electric power. The source of mechanical power, ***the prime mover***, may be a diesel engine, a steam turbine, a water turbine, or any similar device.

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For high-speed machines, the prime movers are usually ***steam turbines*** employing fossil or nuclear energy resources.

Low-speed machines are often driven by ***hydro-turbines*** that employ water power for generation.

Smaller synchronous machines are sometimes used for private generation and as standby units, with diesel engines or gas turbines as prime movers.

CONT…

<u>**Types of Synchronous Machine**</u>

According to the ***arrangement of the field and armature windings***, synchronous machines may be classified as ***rotating-armature type*** or ***rotating-field type***.

Rotating-Armature Type: The armature winding is on the rotor and the field system is on the stator.

Rotating-Field Type: The armature winding is on the stator and the field system is on the rotor.

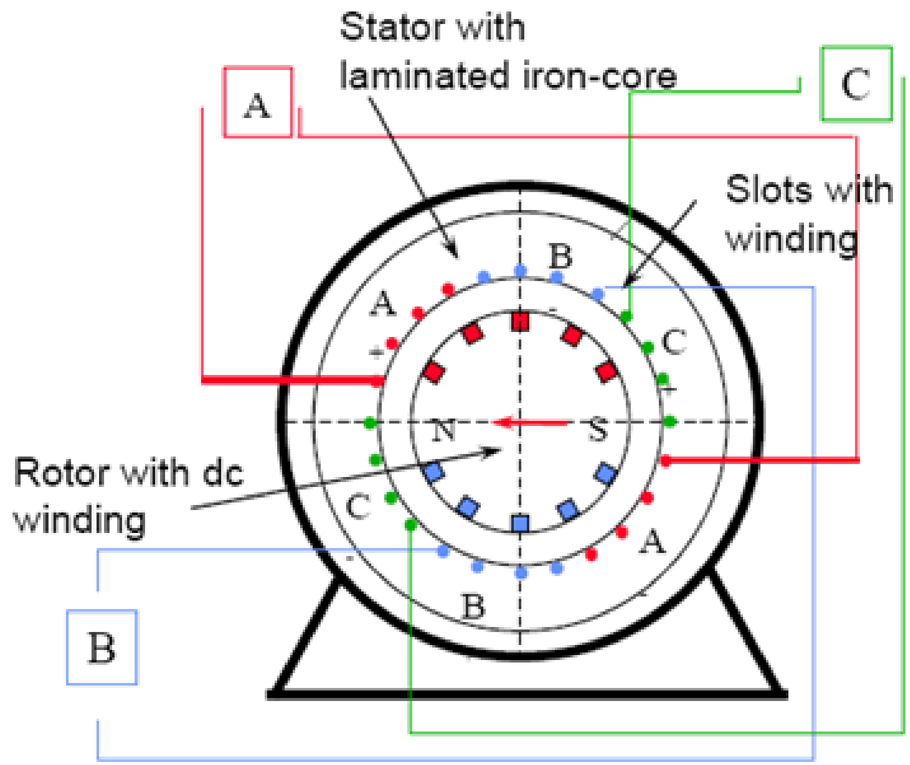
CONT…

According to the shape of the field, synchronous machines may be classified as ***cylindrical-rotor*** (***non-salient pole***) ***machines*** and ***salient-pole machines***

Round Rotor Machine

- The stator is a ring shaped laminated iron-core with slots.
- Three phase windings are placed in the slots.
- Round solid iron rotor with slots.
- A single winding is placed in the slots. Dc current is supplied through slip rings.

Concept (two poles)



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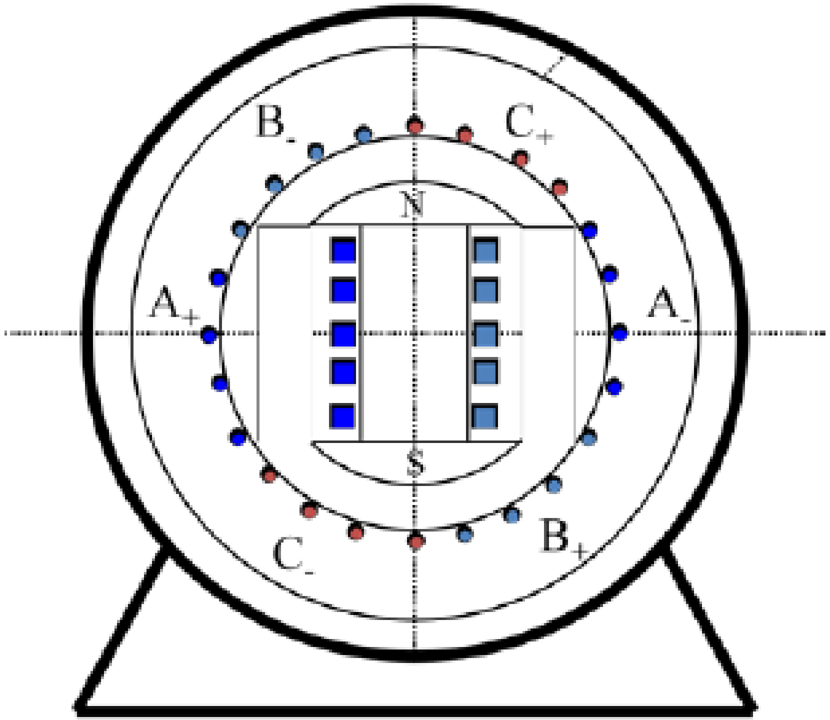
Salient Rotor Machine

- The stator has a laminated iron-core with slots and three phase windings placed in the slots.
- The rotor has salient poles excited by dc current.
- DC current is supplied to the rotor through slip-rings and brushes.
- The number of poles varies between 2 - 128.

- **Concept (two poles)**



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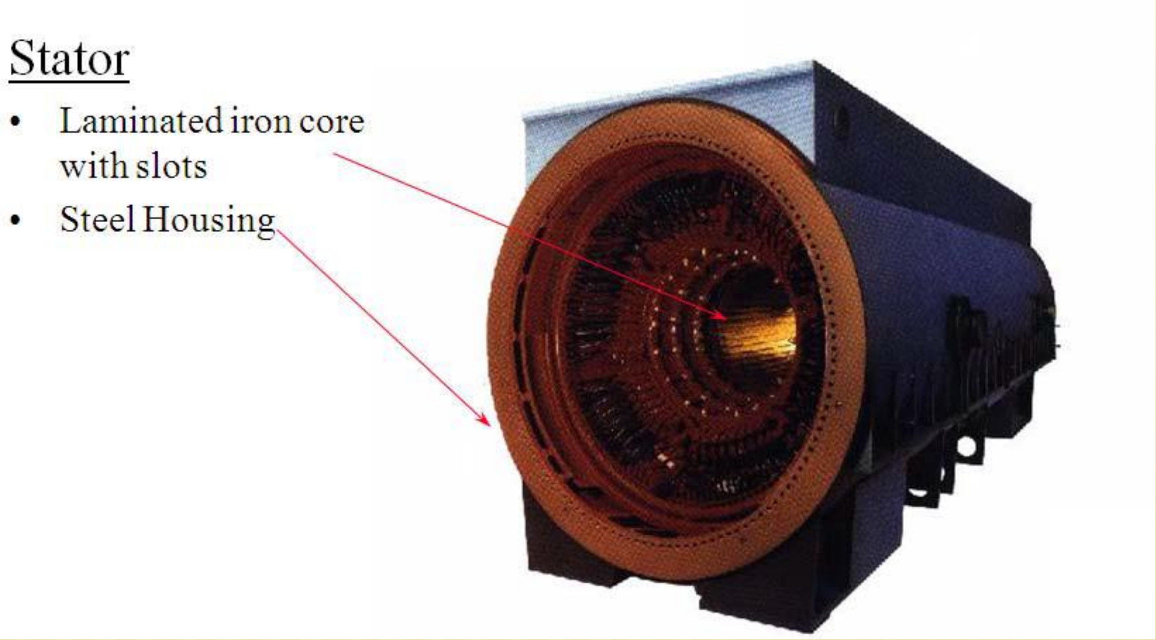
Construction

The winding consists of copper bars insulated with mica and epoxy resin.

The conductors are secured by steel wedges.

The iron core is supported by a steel housing.



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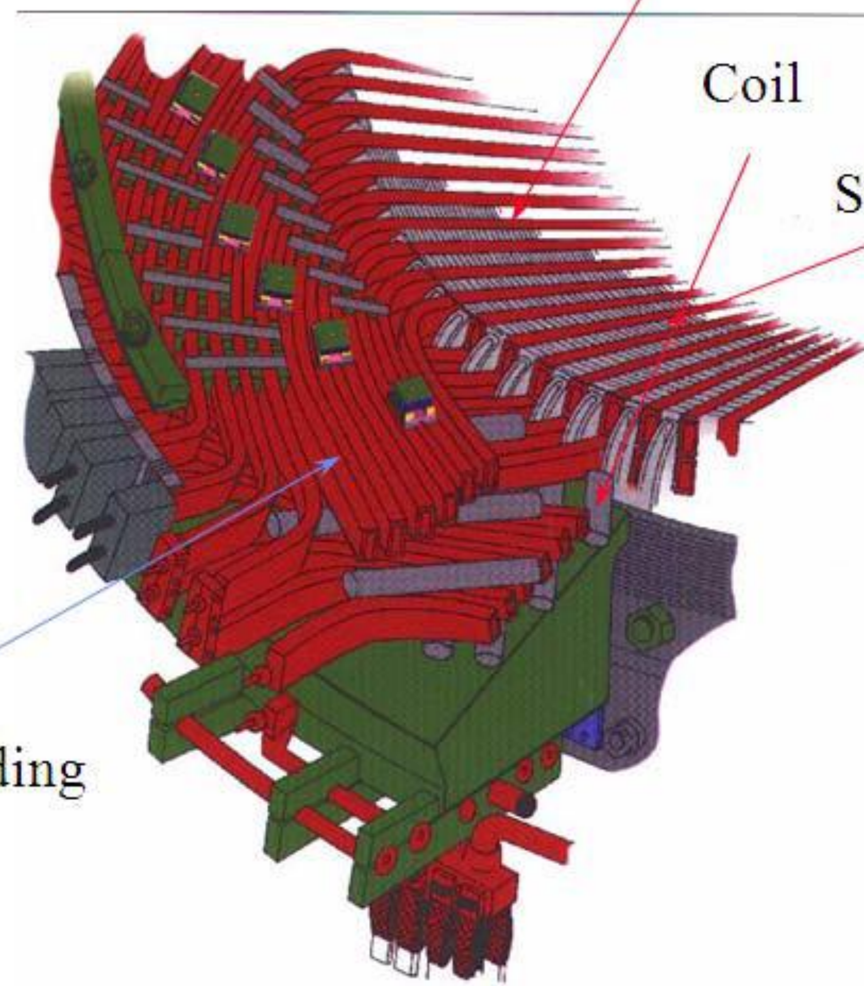
Stator details

- Coils are placed in slots
- Coil end windings are bent to form the armature winding.



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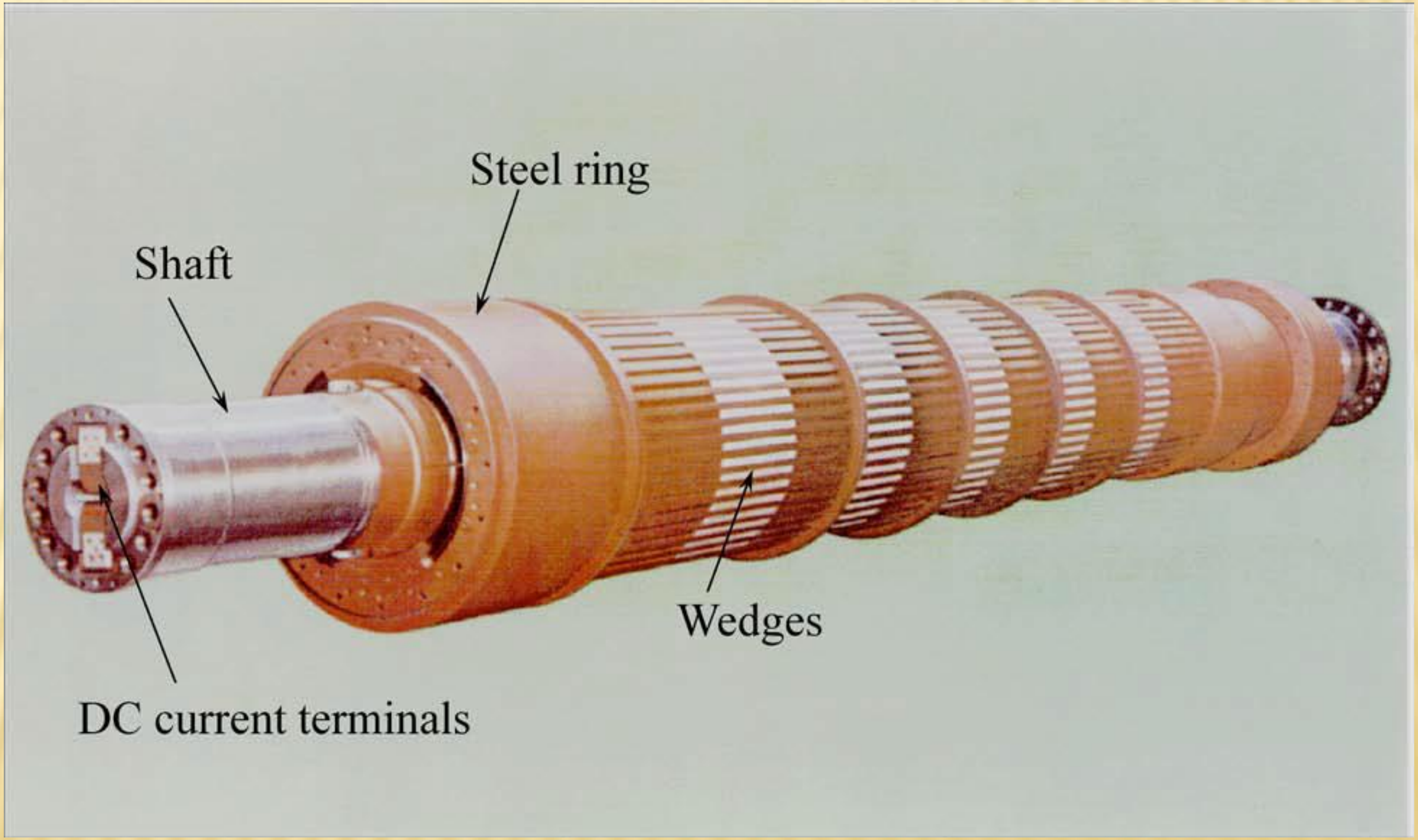
Round rotor

- **The round rotor is used for large high speed (3600rpm) machines.**
- **A forged iron core (not laminated,DC) is installed on the shaft.**
- **Slots are milled in the iron and insulated copper bars are placed in the slots.**
- The slots are closed by wedges and re-enforced with steel rings.

CONT…

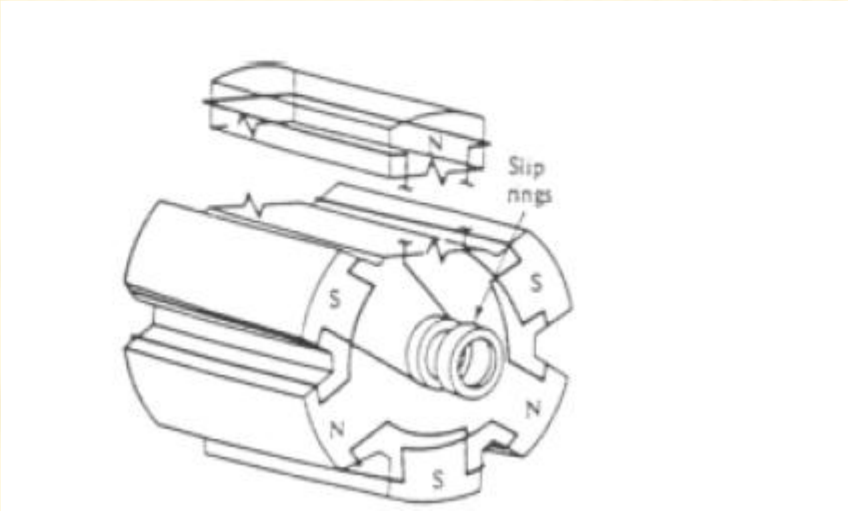
Round rotor



Salient pole rotor construction

- The poles are bolted to the shaft.
- Each pole has a DC winding.
- The DC winding is connected to the slip-rings (not shown).
- A DC source supplies the winding with DC through brushes pressed into the slip ring.
- A fan is installed on the shaft to assure air circulation and effective cooling.
- Low speed, large hydro-generators may have more than one hundred poles.
- These generators are frequently mounted vertically

Salient Rotor

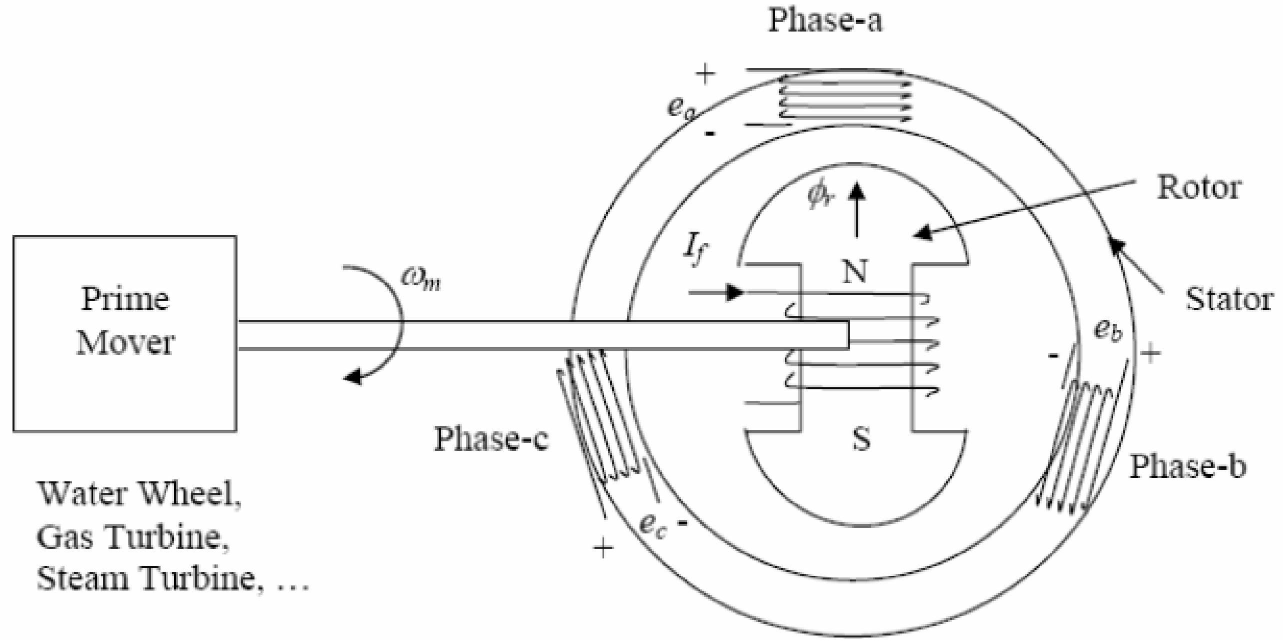


Principle of Operation

1) From an external source, the field winding is supplied with a DC current -> excitation.

2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.

3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



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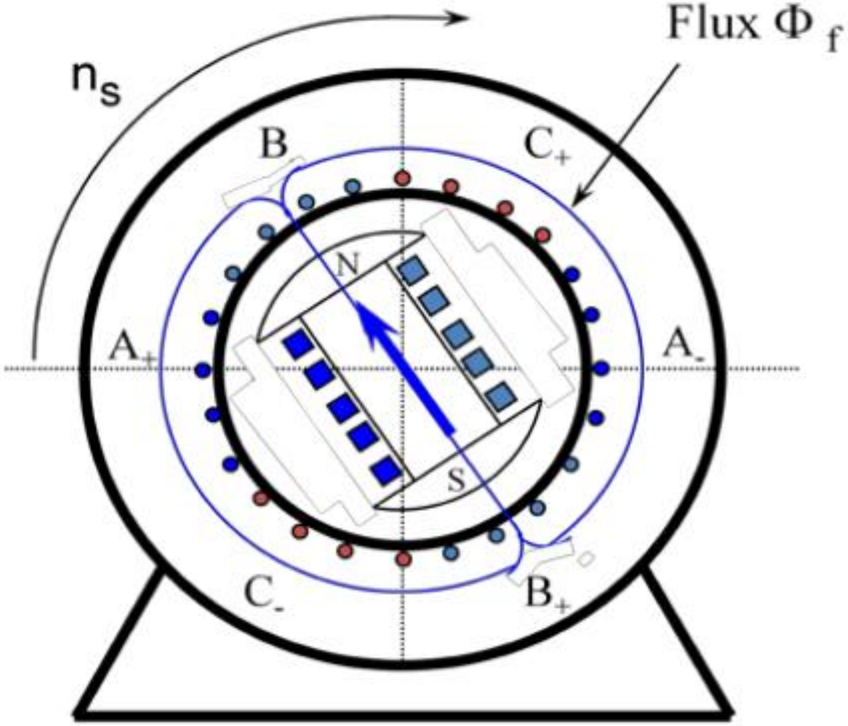
Operation concept

- The rotor is supplied by DC current I_f that generates a DC flux Φ_f.
- The rotor is driven by a turbine with a constant speed of n_s.
- The rotating field flux induces a voltage in the stator winding.
- The frequency of the induced voltage depends upon the speed.

Operation (two poles)



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- The frequency - speed relation is **$f = (p / 120)\ n = p\ n / 120$**
  p is the number of poles.

- Typical rotor speeds are 3600 rpm for 2-pole, 1800 rpm for 4 pole and 450 rpm for 16 poles.

- **The rms. value of the induced voltages are:**

$$E_{an} = E_{rms}\, e^{i\,0\deg} \qquad E_{bn} = E_{rms}\, e^{-i\,120\deg} \qquad E_{cn} = E_{rms}\, e^{-i\,240\deg}$$

- **where:** $E_{rms} = \dfrac{k_w\, \omega N_a\, \Phi_f}{\sqrt{2}} = 4.44\ f\ N_a\, \Phi_f\, k_w$

k_w = 0.85-0.95 is the winding factor.

EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

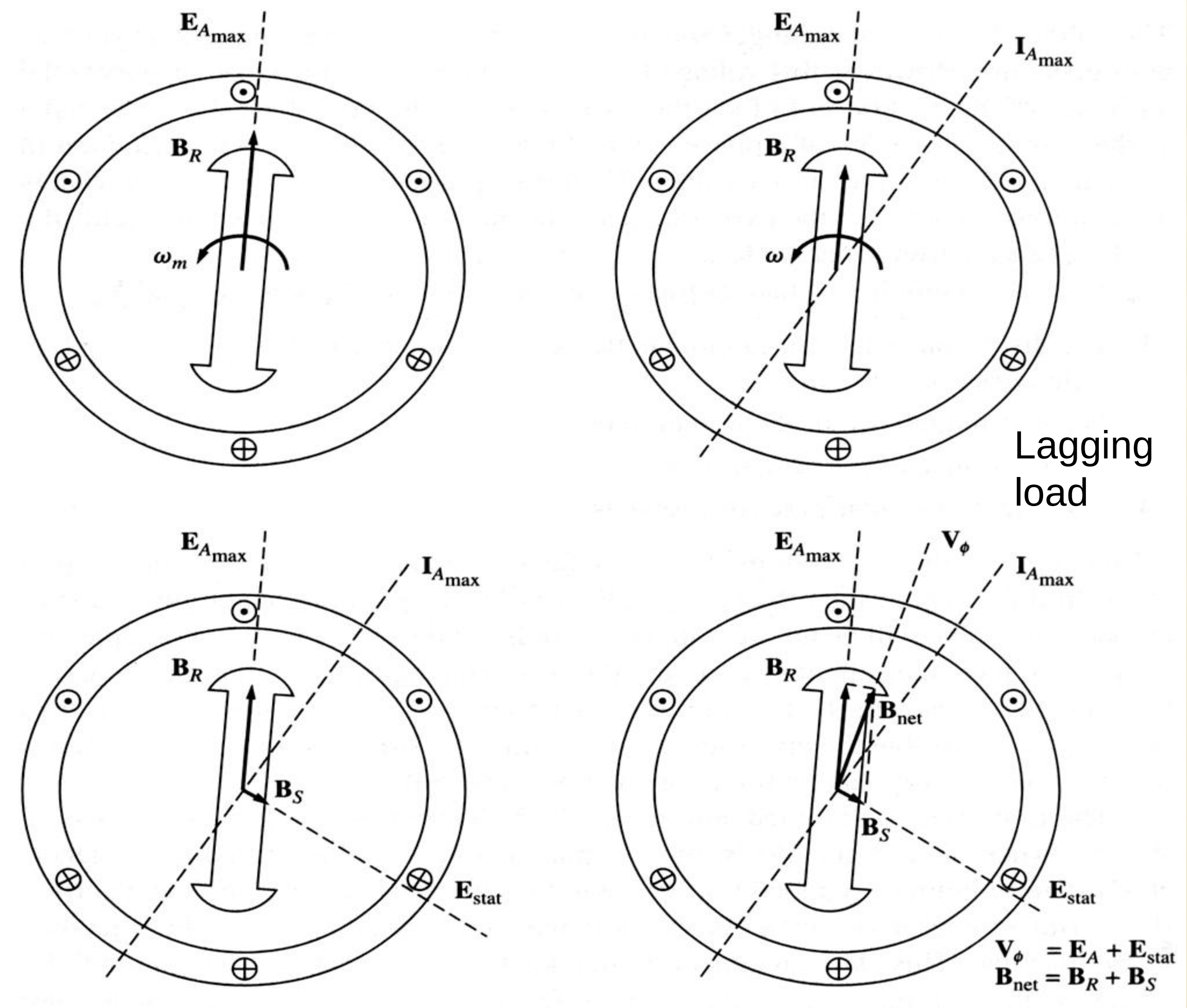
The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals. It equals to the output voltage V_ϕ only when there is no armature current in the machine. The reasons that the armature voltage E_A is not equal to the output voltage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

EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

Armature reaction (the largest effect):

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

Assuming that the generator is connected to a lagging load, 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

Note that the directions of the net magnetic flux and the phase voltage are the same.

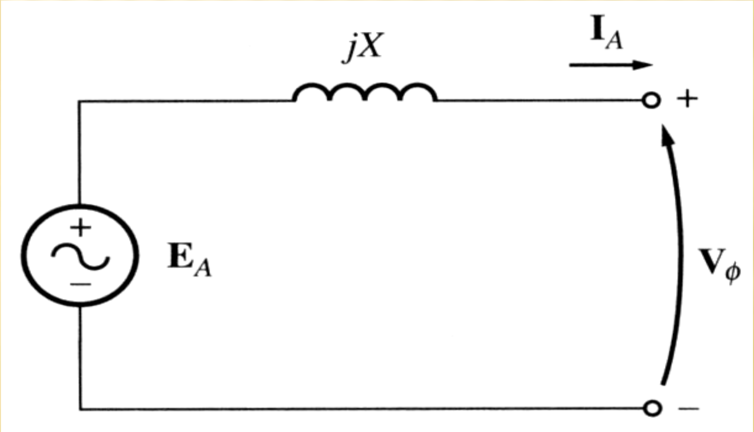
EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

Assuming that the load reactance is *X*, the armature reaction voltage is

$$E_{stat} = -jXI_A$$

The phase voltage is then $$V_\phi = E_A - jXI_A$$

Armature reactance can be modeled by the following circuit…



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

$$V_\phi = E_A - jXI_A - jX_AI_A - RI_A \quad (7.17.3)$$

EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

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

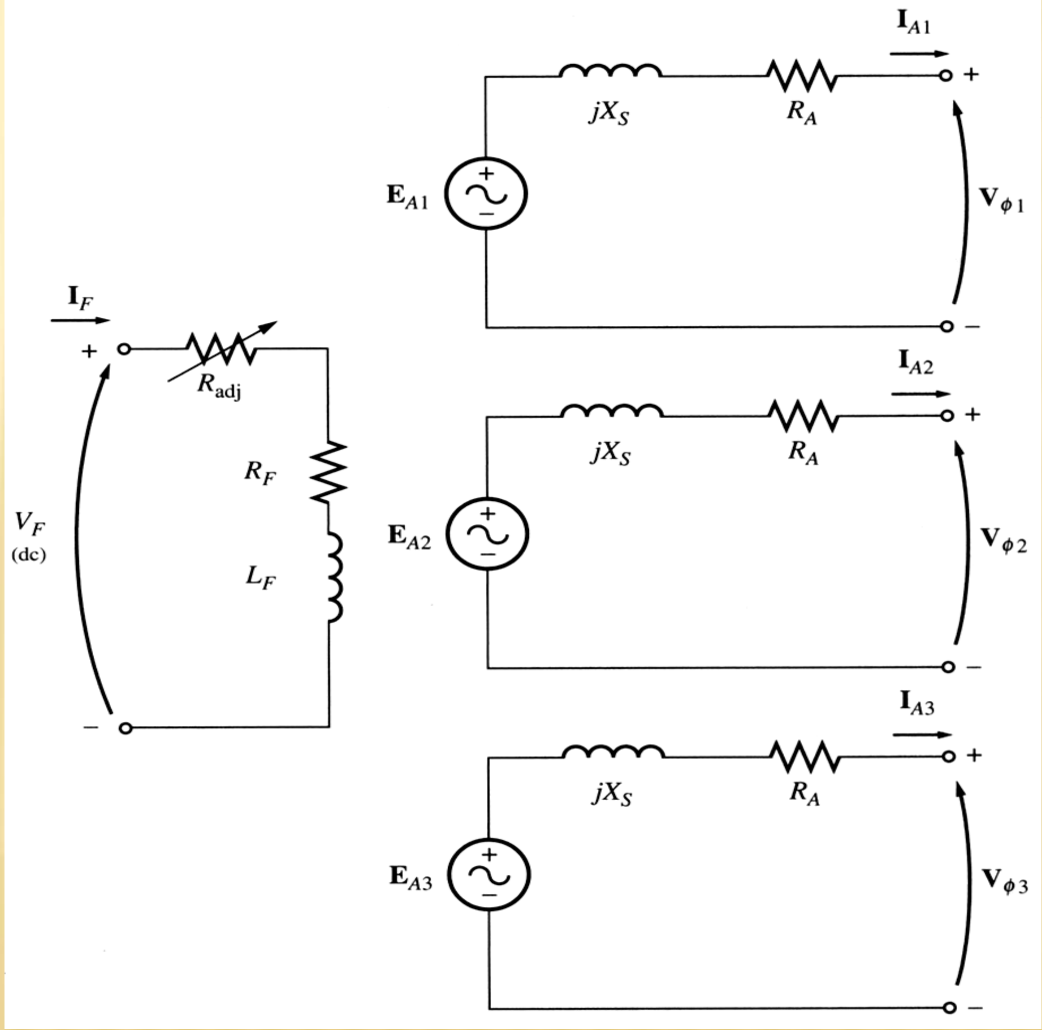
$$X_S = X + X_A$$

Therefore, the phase voltage is

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

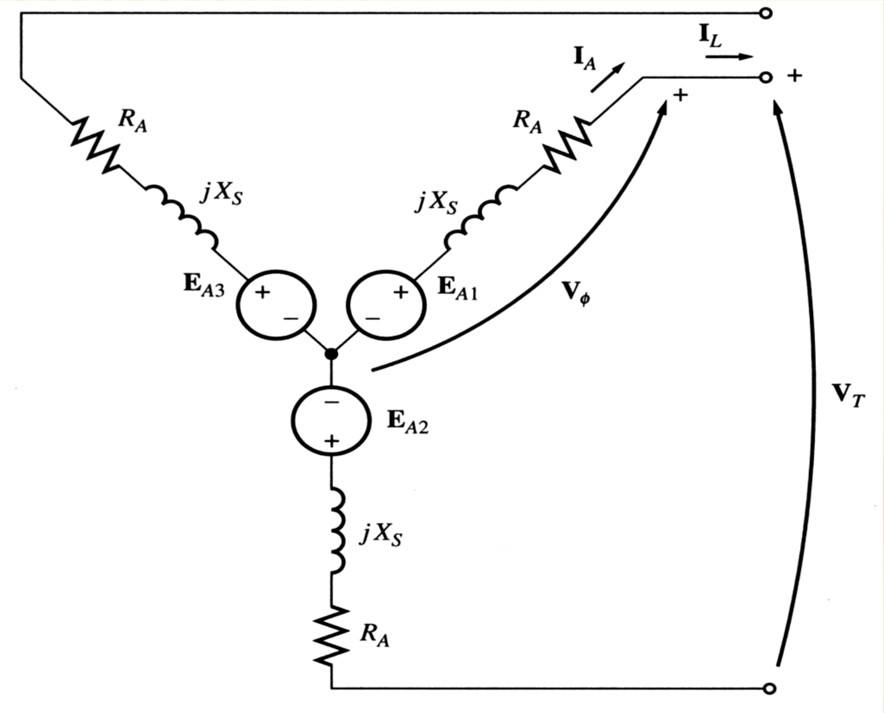
The equivalent circuit of a 3-phase synchronous generator is shown.

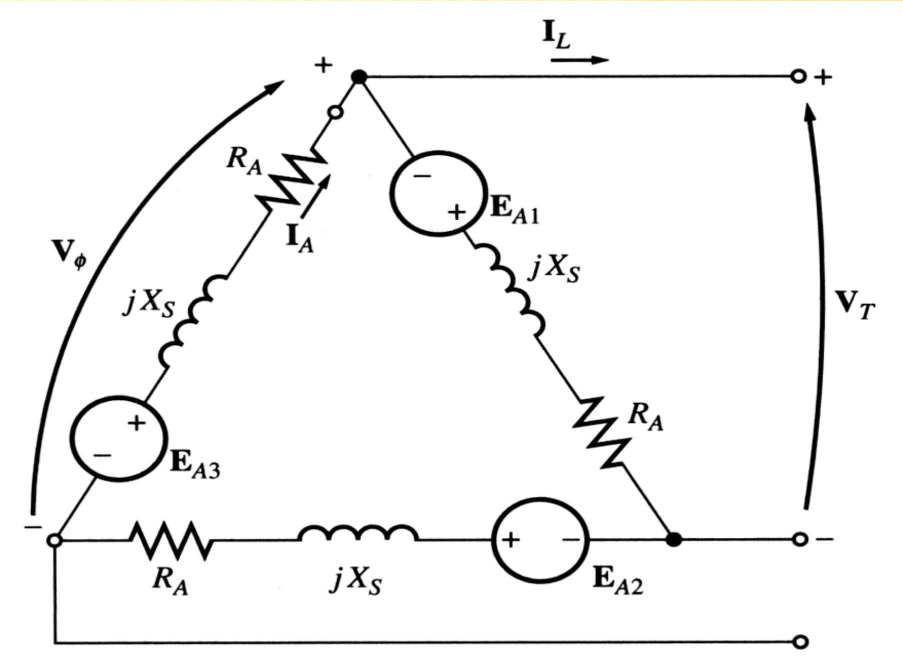
The adjustable resistor R_{adj} controls the field current and, therefore, the rotor magnetic field.



EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

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





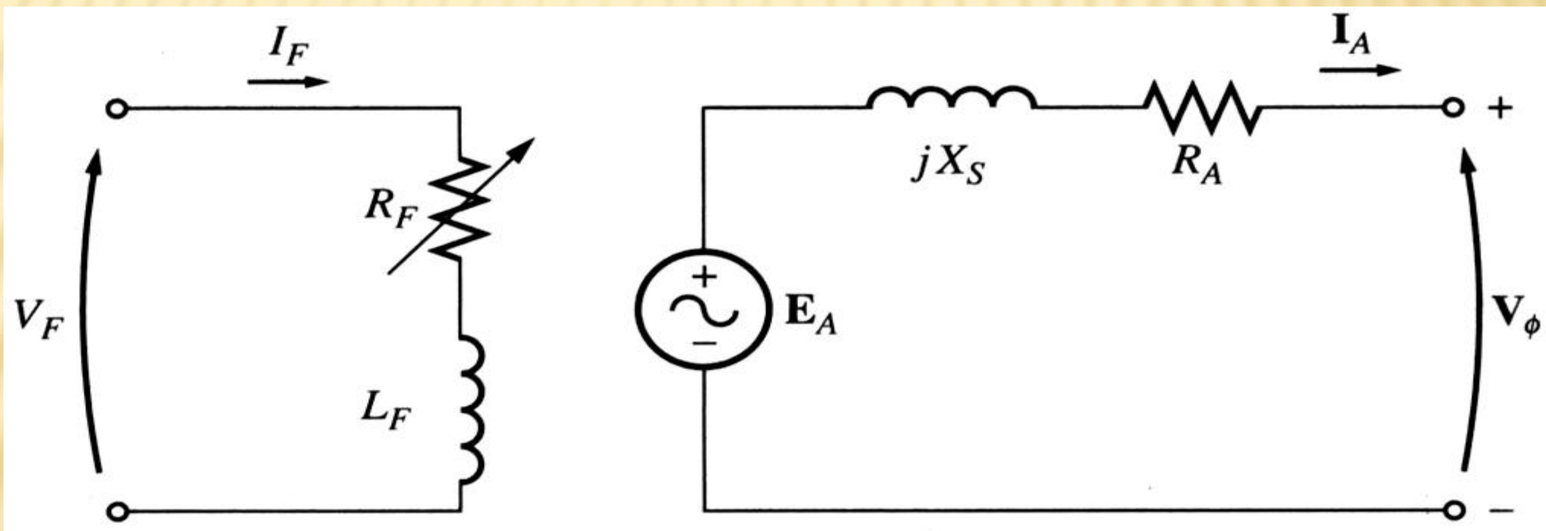
The terminal voltage will be

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

EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

Note: the discussion above assumed a balanced load on the generator!

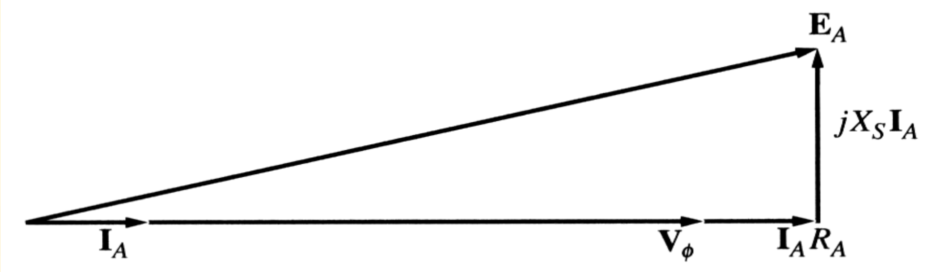
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



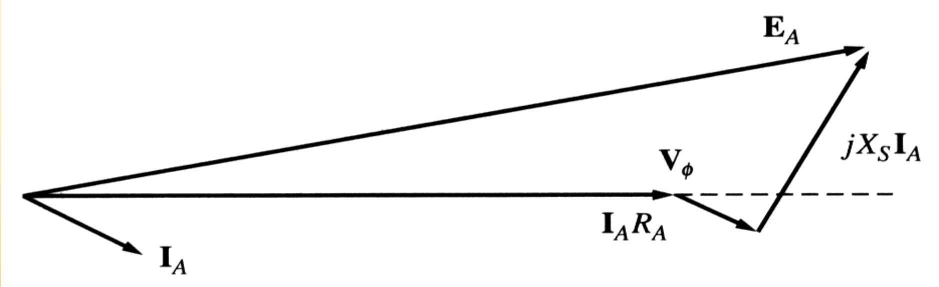
PHASOR DIAGRAM OF A SYNCHRONOUS GENERATOR

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.

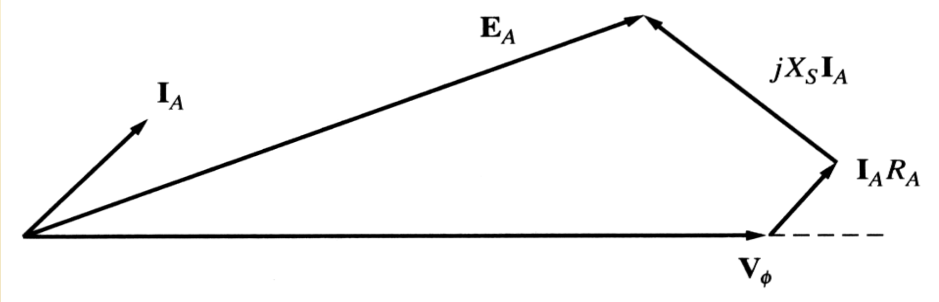
A phasor diagram of a synchronous generator with a unity power factor (resistive load)



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).



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

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

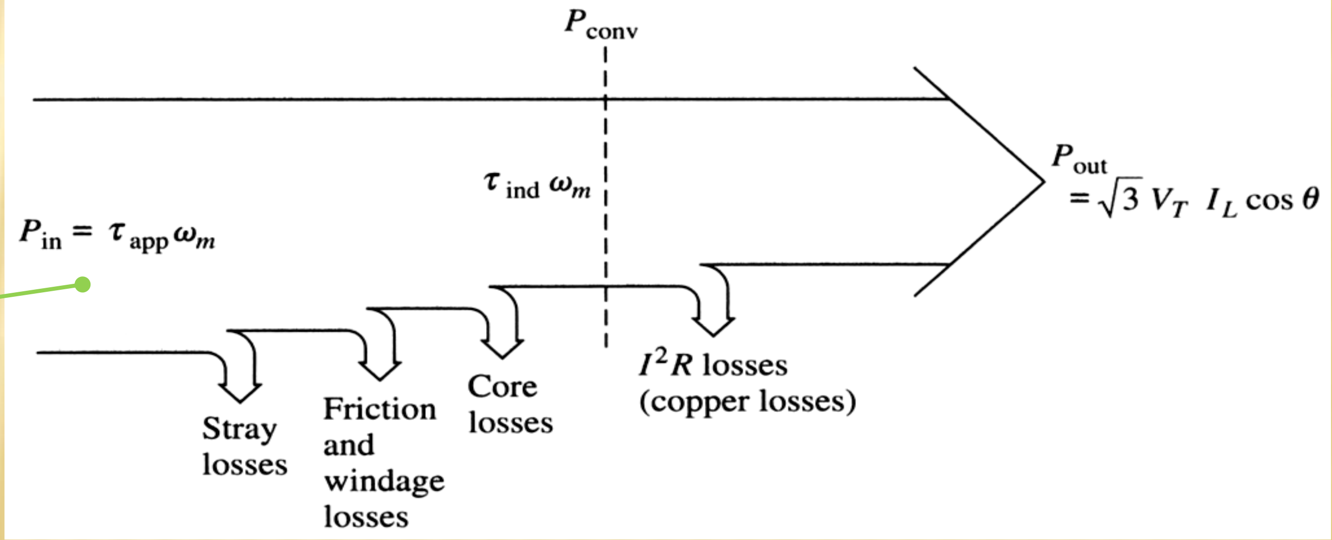
$$P_{in} = \tau_{app}\omega_m$$

is partially converted to electricity

$$P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma \quad (7.22.2)$$

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

The real output power of the synchronous generator is

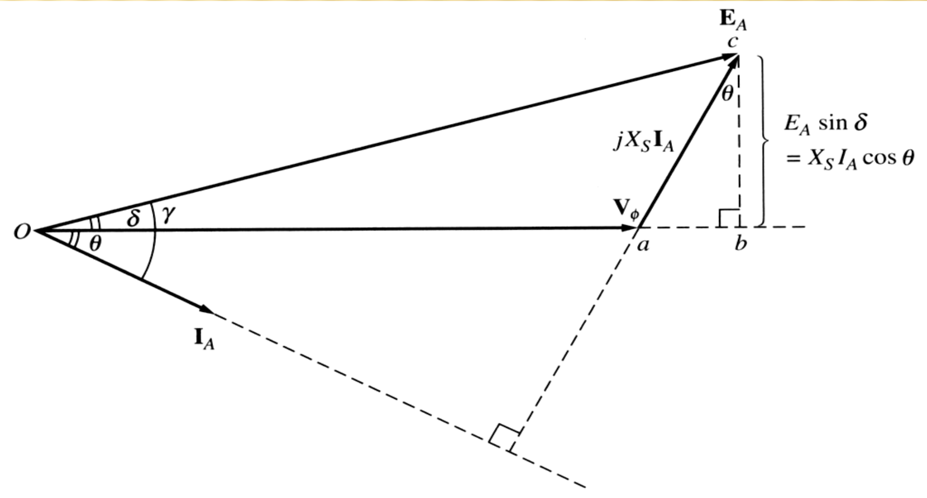
$$P_{out} = \sqrt{3} V_T I_L \cos\theta = 3 V_\phi I_A \cos\theta \qquad (7.23.1)$$

The reactive output power of the synchronous generator is

$$Q_{out} = \sqrt{3} V_T I_L \sin\theta = 3 V_\phi I_A \sin\theta \qquad (7.23.2)$$

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

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



$$I_A \cos\theta = \frac{E_A \sin\delta}{X_S} \qquad (7.23.3)$$

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 δ is the torque angle of the machine – the angle between V_{ϕ} and E_A.

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

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

POWER AND TORQUE IN SYNCHRONOUS GENERATORS

The maximum power specified in previous slide is called the static stability limit of the generator. Normally, real generators do not approach this limit: full-load torque angles are usually between 15° and 20°.

The induced torque is

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

Notice that the torque angle δ is also the angle between the rotor magnetic field B_R and the net magnetic field B_{net}.

Alternatively, the induced torque is

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

MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

The three quantities must be determined in order to describe the generator model:

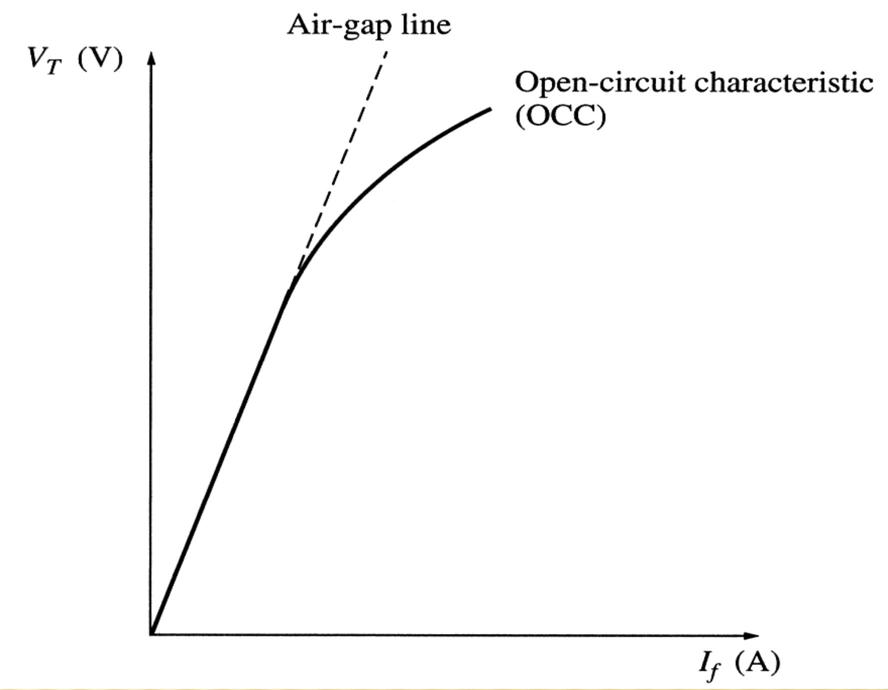
1. The relationship between field current and flux (and therefore between the field current I_F and the internal generated voltage E_A);
2. The synchronous reactance;
3. The armature resistance.

We conduct first the open-circuit test on the synchronous generator: the generator is rotated at the rated speed, all the terminals are disconnected from loads, the field current is set to zero first. Next, the field current is increased in steps and the phase voltage (whish is equal to the internal generated voltage E_A since the armature current is zero) is measured.

Therefore, it is possible to plot the dependence of the internal generated voltage on the field current – the open-circuit characteristic (OCC) of the generator.

MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

Since the unsaturated core of the machine has a reluctance thousands times lower than the reluctance of the air-gap, the resulting flux increases linearly first. When the saturation is reached, the core reluctance greatly increases causing the flux to increase much slower with the increase of the mmf.



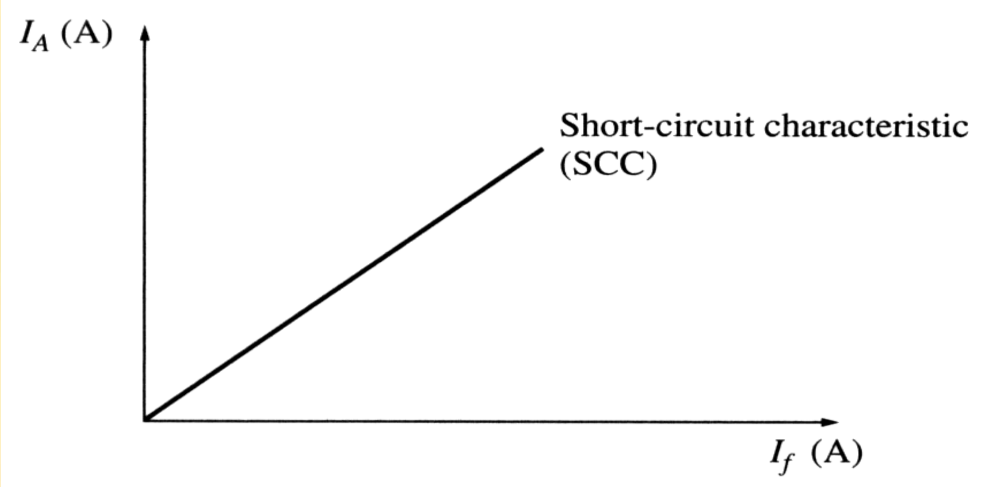
We conduct next the short-circuit test on the synchronous generator: the generator is rotated at the rated speed, all the terminals are short-circuited through ammeters, the field current is set to zero first. Next, the field current is increased in steps and the armature current I_A is measured as the field current is increased.

The plot of armature current (or line current) vs. the field current is the short-circuit characteristic (SCC) of the generator.

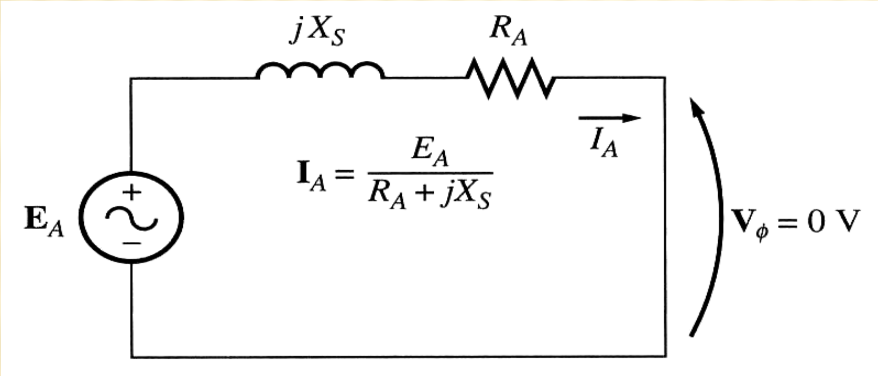
MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

The SCC is a straight line since, for the short-circuited terminals, the magnitude of the armature current is

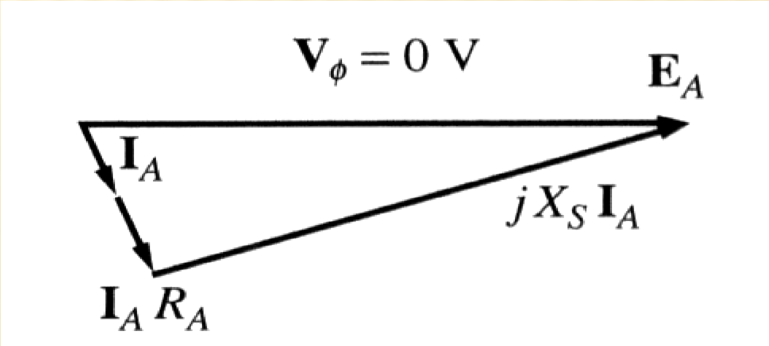
$$I_A = \frac{E_A}{\sqrt{R_A^2 + X_S^2}}$$



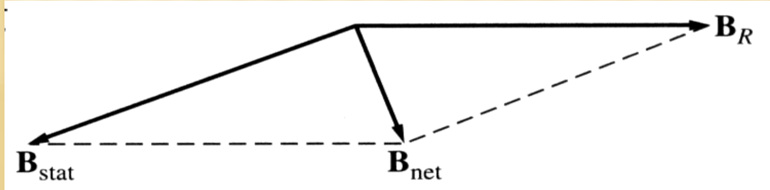
The equivalent generator's circuit during SC



The resulting phasor diagram



The magnetic fields during short-circuit test



Since B_S almost cancels B_R, the net field B_{net} is very small.

MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

An approximate method to determine the synchronous reactance X_S at a given field current:

1. Get the internal generated voltage E_A from the OCC at that field current.
2. Get the short-circuit current $I_{A,SC}$ at that field current from the SCC.
3. Find X_S from

$$X_S \approx \frac{E_A}{I_{A,SC}}$$

Since the internal machine impedance is

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_{A,SC}} \approx X_S \qquad \{\text{since } X_S \gg R_A\}$$

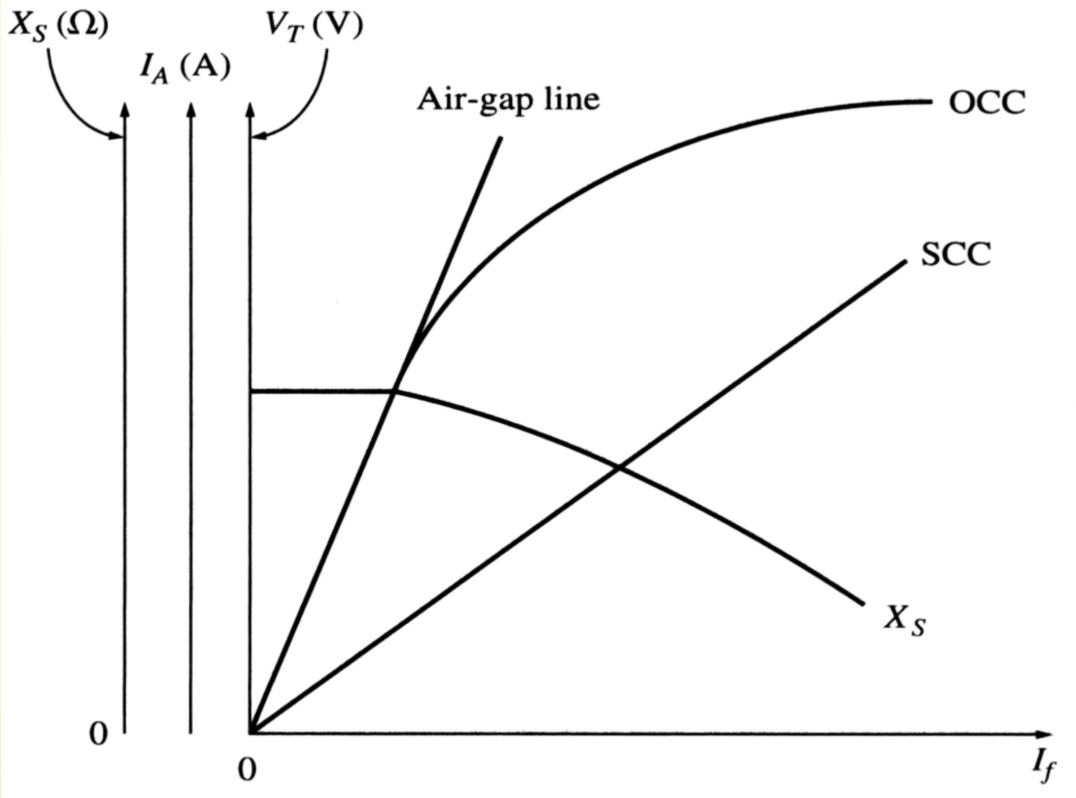
MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL

A drawback of this method is that the internal generated voltage E_A is measured during the OCC, where the machine can be saturated for large field currents, while the armature current is measured in SCC, where the core is unsaturated. Therefore, this approach is accurate for unsaturated cores only.

The approximate value of synchronous reactance varies with the degree of saturation of the OCC.

Therefore, the value of the synchronous reactance for a given problem should be estimated at the approximate load of the machine.

The winding's resistance can be approximated by applying a DC voltage to a stationary machine's winding and measuring the current. However, AC resistance is slightly larger than DC resistance (skin effect).



MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL: EX

Example 7.1: A 200 kVA, 480 V, 50 Hz, Y-connected synchronous generator with a rated field current of 5 A was tested and the following data were obtained:

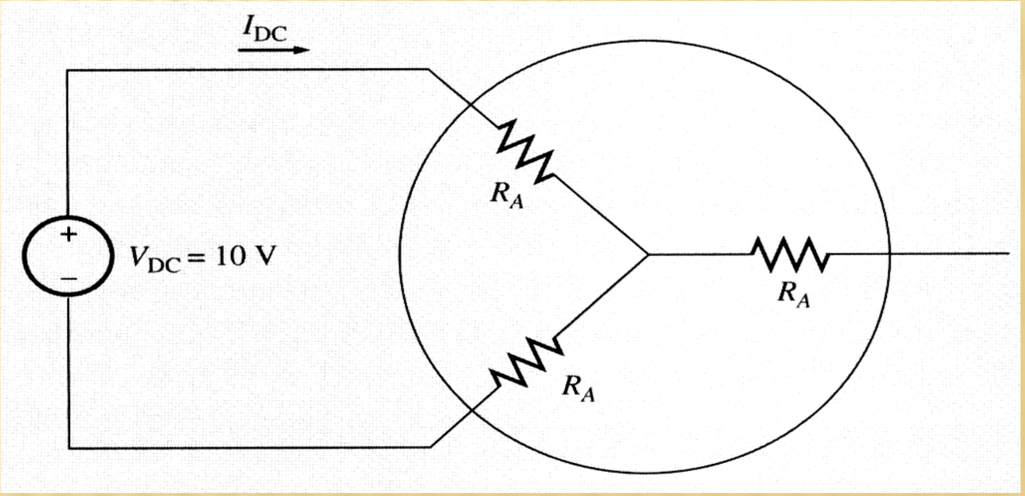
1. $V_{T,OC}$ = 540 V at the rated I_F.
2. $I_{L,SC}$ = 300 A at the rated I_F.
3. When a DC voltage of 10 V was applied to two of the terminals, a current of 25 A was measured.

Find the generator's model at the rated conditions (i.e., the armature resistance and the approximate synchronous reactance).

Since the generator is Y-connected, a DC voltage was applied between its ***two*** phases. Therefore:

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{V_{DC}}{2I_{DC}} = \frac{10}{2 \cdot 25} = 0.2\,\Omega$$



MEASURING PARAMETERS OF SYNCHRONOUS GENERATOR MODEL: EX

The internal generated voltage at the rated field current is

$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} = 311.8\,V$$

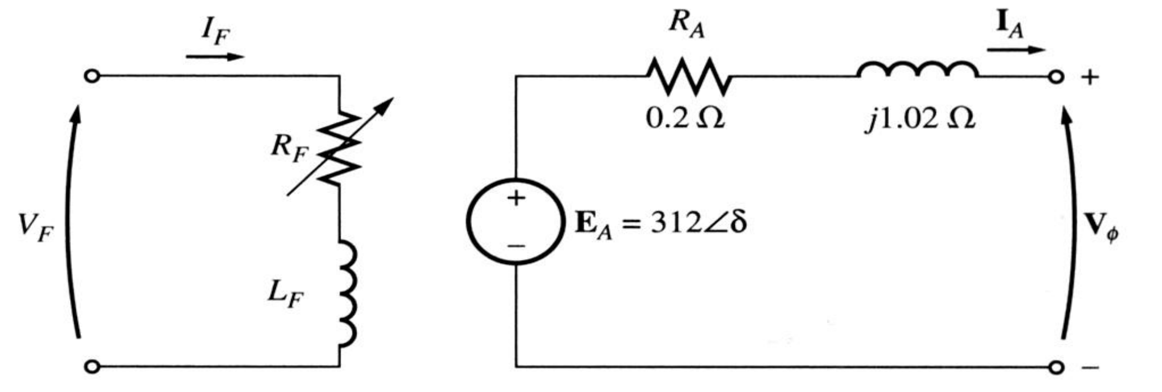
The synchronous reactance at the rated field current is precisely

$$X_S = \sqrt{Z_S^2 - R_A^2} = \sqrt{\frac{E_A^2}{I_{A,SC}^2} - R_A^2} = \sqrt{\frac{311.8^2}{300^2} - 0.2^2} = 1.02\,\Omega$$

We observe that if X_S was estimated via the approximate formula, the result would be:

$$X_S \approx \frac{E_A}{I_{A,SC}} = \frac{311.8}{300} = 1.04\,\Omega$$

Which is close to the previous result. The error ignoring R_A is much smaller than the error due to core saturation.



The equivalent circuit

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.

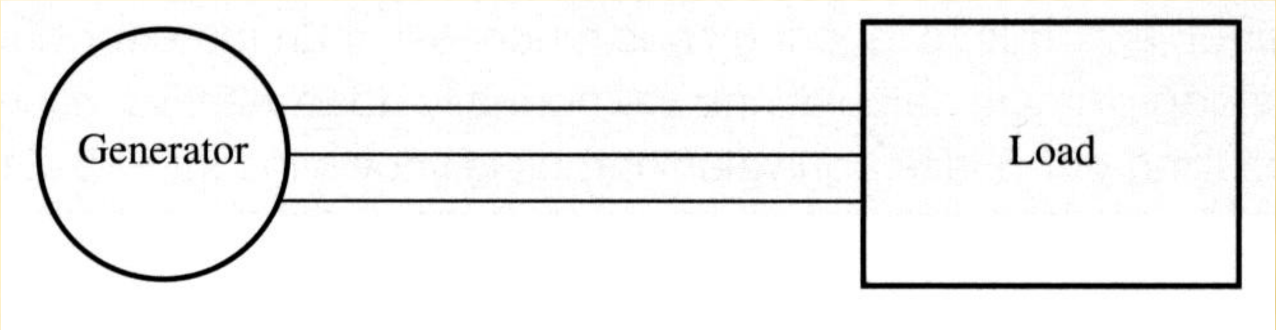
Although most of the synchronous generators in the world operate as parts of large power systems, we start our discussion assuming that the synchronous generator works alone.

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

THE SYNCHRONOUS GENERATOR OPERATING ALONE

Effects of load changes

A increase in the load is an increase in the real and/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.

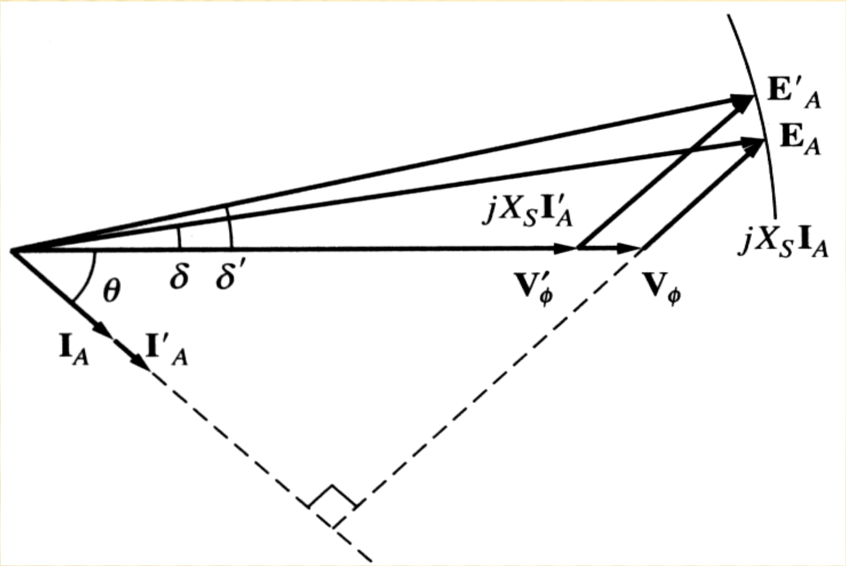
Assuming the same power factor of the load, change in load will change the magnitude of the armature current I_A. However, the angle will be the same (for a constant PF). Thus, the armature reaction voltage jX_SI_A will be larger for the increased load. Since the magnitude of the internal generated voltage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

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

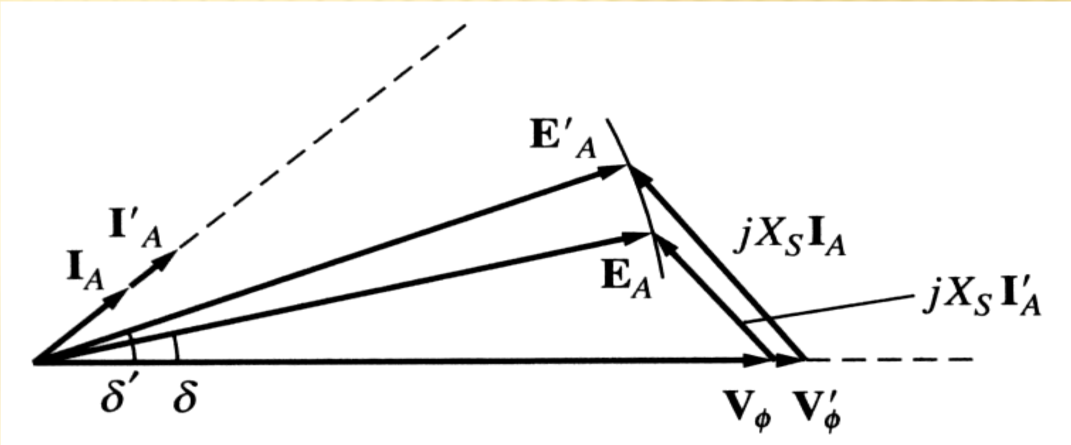
Armature reaction voltage vector will "move parallel" to its initial position.

THE SYNCHRONOUS GENERATOR OPERATING ALONE

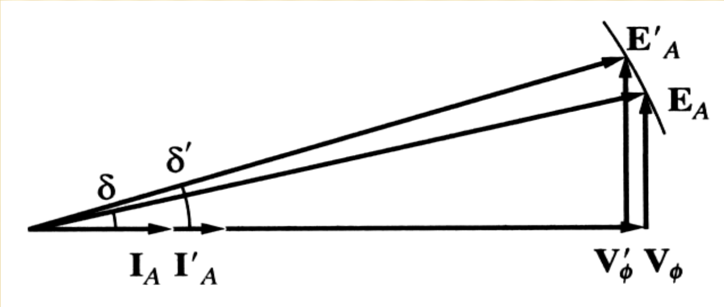
Increase load effect on generators with



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.

Therefore, the terminal voltage of the generator can be changed by adjusting the field resistance.

THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

Example 7.2: A 480 V, 60 Hz, Y-connected six-pole synchronous generator has a per-phase synchronous reactance of 1.0 Ω. Its full-load armature current is 60 A at 0.8 PF lagging. Its friction and windage losses are 1.5 kW and core losses are 1.0 kW at 60 Hz at full load. Assume that the armature resistance (and, therefore, the I^2R losses) can be ignored. The field current has been adjusted such that the no-load terminal voltage is 480 V.

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

THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

Since the generator is Y-connected, its phase voltage is

$$V_\phi = V_T / \sqrt{3} = 277\, V$$

At no load, the armature current I_A = 0 and the internal generated voltage is E_A = 277 V and it is constant since the field current was initially adjusted that way.

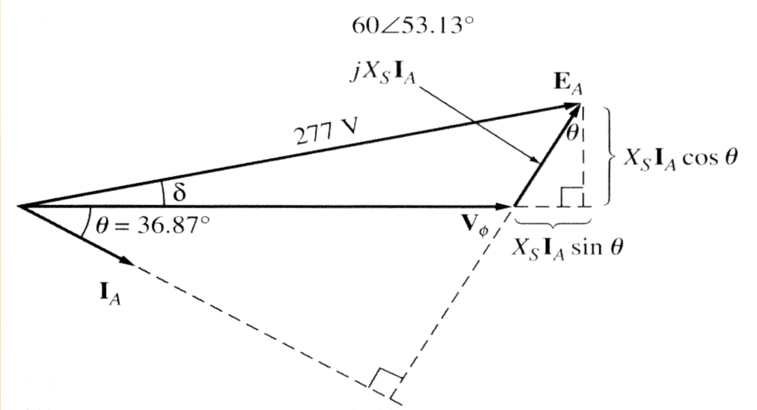
a. The speed of rotation of a synchronous generator is

$$n_m = \frac{120}{P} f_e = \frac{120}{6} 60 = 1200\, rpm$$

which is

$$\omega_m = \frac{1200}{60} 2\pi = 125.7\, rad/s$$

b.1. For the generator at the rated current and the 0.8 PF lagging, the phasor diagram is shown. The phase voltage is at 0°, the magnitude of E_A is 277 V,



THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

and that $jX_S I_A = j \cdot 1 \cdot 60\angle -36.87° = 60\angle 53.13°$

Two unknown quantities are the magnitude of V_ϕ and the angle δ of E_A. From the phasor diagram:

$$E_A^2 = \left(V_\phi + X_S I_A \sin\theta\right)^2 + \left(X_S I_A \cos\theta\right)^2$$

Then:

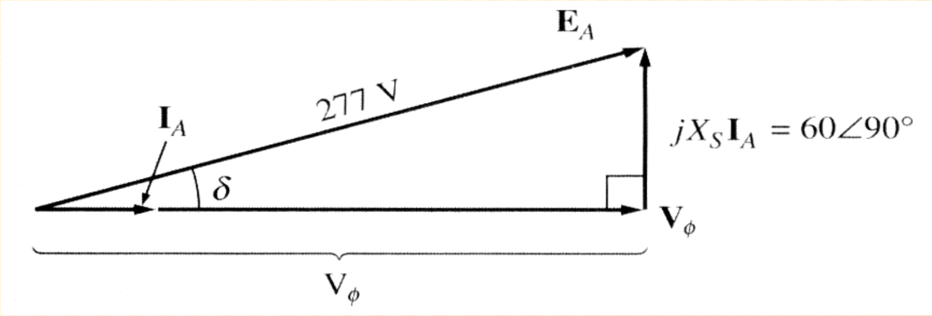
$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta\right)^2} - X_S I_A \sin\theta = 236.8\,V$$

Since the generator is Y-connected,

$$V_T = \sqrt{3}V_\phi = 410\,V$$

THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

b.2. For the generator at the rated current and the 1.0 PF, the phasor diagram is shown. Then:

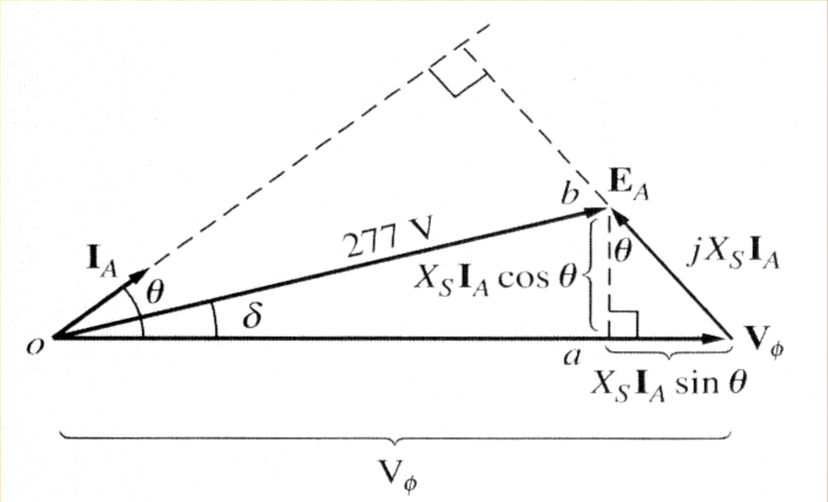


$$V_\phi = \sqrt{E_A^2 - (X_S I_A \cos\theta)^2} - X_S I_A \sin\theta = 270.4\,V$$

and

$$V_T = \sqrt{3}V_\phi = 468.4\,V$$

b.3. For the generator at the rated current and the 0.8 PF leading, the phasor diagram is shown. Then:



$$V_\phi = \sqrt{E_A^2 - (X_S I_A \cos\theta)^2} - X_S I_A \sin\theta = 308.8\,V$$

and

$$V_T = \sqrt{3}V_\phi = 535\,V$$

THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

c. The output power of the generator at 60 A and 0.8 PF lagging is

$$P_{out} = 3V_{\phi}I_A \cos\theta = 3 \cdot 236.8 \cdot 60 \cdot 0.8 = 34.1\,kW$$

The mechanical input power is given by

$$P_{in} = P_{out} + P_{elec\,loss} + P_{core\,loss} + P_{mech\,loss} = 34.1 + 0 + 1.0 + 1.5 = 36.6\,kW$$

The efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\,\% = \frac{34.1}{36.6} \cdot 100\% = 93.2\%$$

d. The input torque of the generator is

$$\tau_{app} = \frac{P_{in}}{\omega_m} = \frac{36.6}{125.7} = 291.2\ \ N\text{-}m$$

THE SYNCHRONOUS GENERATOR OPERATING ALONE: EXAMPLE

The induced counter torque of the generator is

$$\tau_{app} = \frac{P_{conv}}{\omega_m} = \frac{34.1}{125.7} = 271.3 \ \ N\text{-}m$$

e. The voltage regulation of the generator is

Lagging PF:

$$VR = \frac{480 - 410}{410} \cdot 100\% = 17.1\%$$

Unity PF:

$$VR = \frac{480 - 468}{468} \cdot 100\% = 2.6\%$$

Leading PF:

$$VR = \frac{480 - 535}{535} \cdot 100\% = -10.3\%$$

TERMINAL CHARACTERISTICS OF SYNCHRONOUS GENERATORS

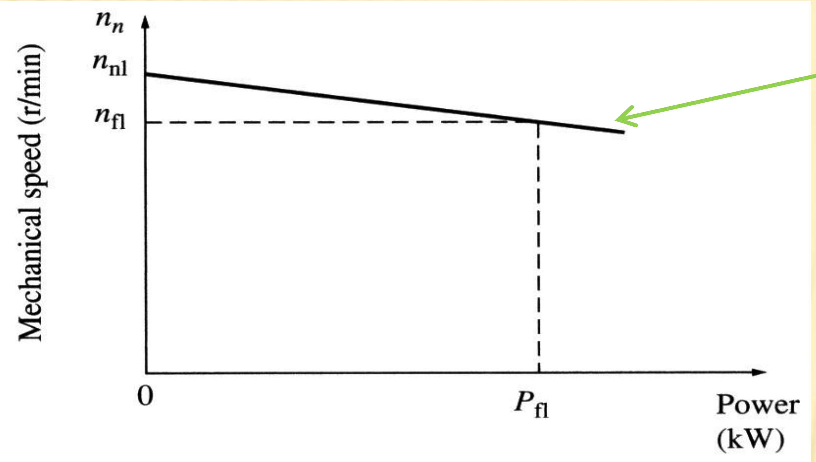
All generators are driven by a prime mover, such as a steam, gas, water, wind turbines, diesel engines, etc. Regardless the power source, most of prime movers tend to slow down with increasing the load. This decrease in speed is usually nonlinear but governor mechanisms of some type may be included to linearize this dependence.

The speed drop (SD) of a prime mover is defined as:

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

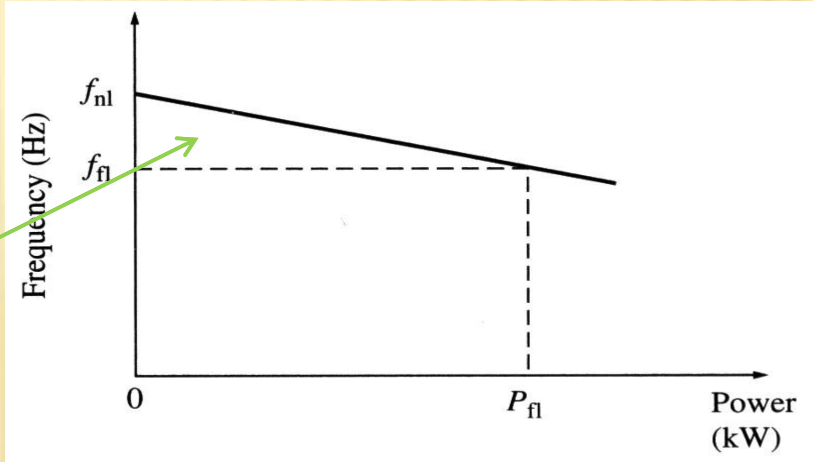
Most prime movers have a speed drop from 2% to 4%. Most governors have a mechanism to adjust the turbine's no-load speed (set-point adjustment).

TERMINAL CHARACTERISTICS OF SYNCHRONOUS GENERATORS



A typical speed vs. power plot

A typical frequency vs. power plot



Since the shaft speed is linked to the electrical frequency as

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

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

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

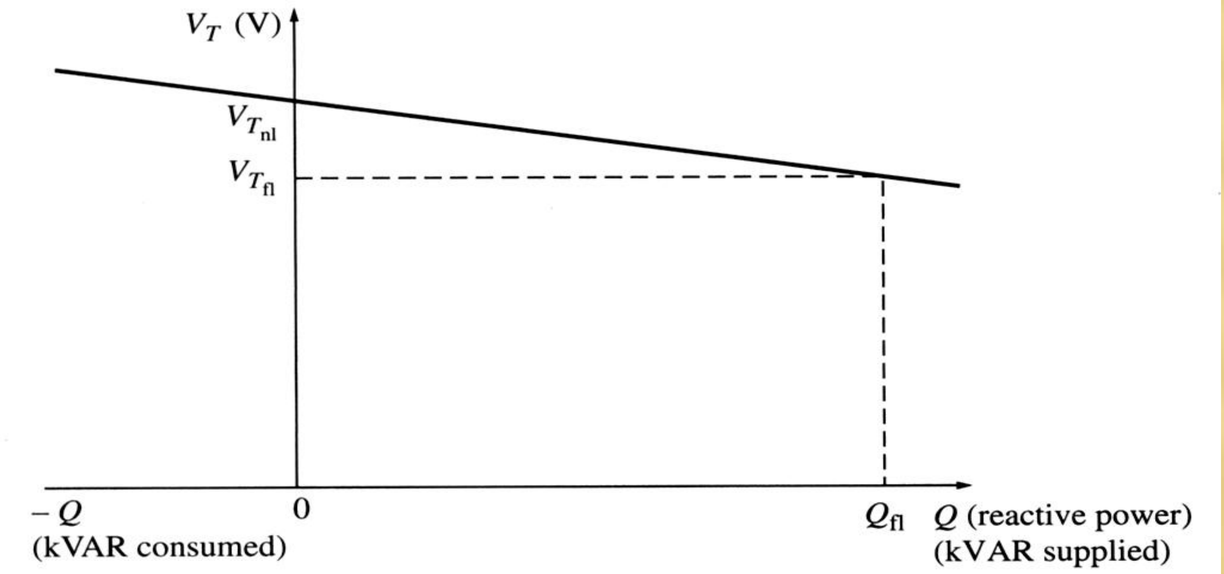
Slope of curve, W/Hz

Operating frequency of the system

TERMINAL CHARACTERISTICS OF SYNCHRONOUS GENERATORS

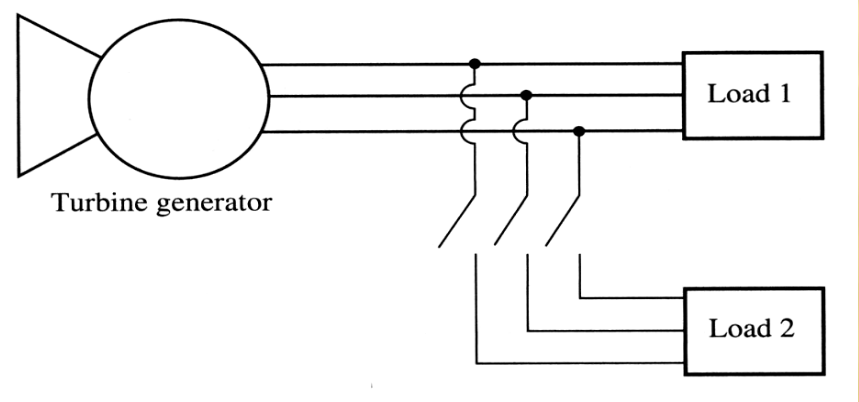
A similar relationship can be derived for the reactive power Q and terminal voltage V_T. When adding a lagging load to a synchronous generator, its terminal voltage decreases. When adding a leading load to a synchronous generator, its terminal voltage increases.

The plot of terminal voltage vs. reactive power is not necessarily linear.
Both the frequency-power and terminal voltage vs. reactive power characteristics are important for parallel operations of generators.



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

TERMINAL CHARACTERISTICS OF SYNCHRONOUS GENERATORS: EXAMPLE



Example 7.3: A generator with no-load frequency of 61.0 Hz and a slope s_p of 1 MW/Hz is connected to Load 1 consuming 1 MW of real power at 0.8 PF lagging. Load 2 (that is to be connected to the generator) consumes a real power of 0.8 MW at 0.707 PF lagging.

a. Find the operating frequency of the system before the switch is closed.
b. Find the operating frequency of the system after the switch is closed.
c. What action could an operator take to restore the system frequency to 60 Hz after both loads are connected to the generator?

The power produced by the generator is

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

Therefore:

$$f_{sys} = f_{nl} - \frac{P}{s_p}$$

TERMINAL CHARACTERISTICS OF SYNCHRONOUS GENERATORS: EXAMPLE

a. The frequency of the system with one load is

$$f_{sys} = f_{nl} - \frac{P}{s_p} = 61 - \frac{1}{1} = 60\ Hz$$

b. The frequency of the system with two loads is

$$f_{sys} = f_{nl} - \frac{P}{s_p} = 61 - \frac{1.8}{1} = 59.2\ Hz$$

c. To restore the system to the proper operating frequency, the operator should increase the governor no-load set point by 0.8 Hz, to 61.8 Hz. This will restore the system frequency of 60 Hz.

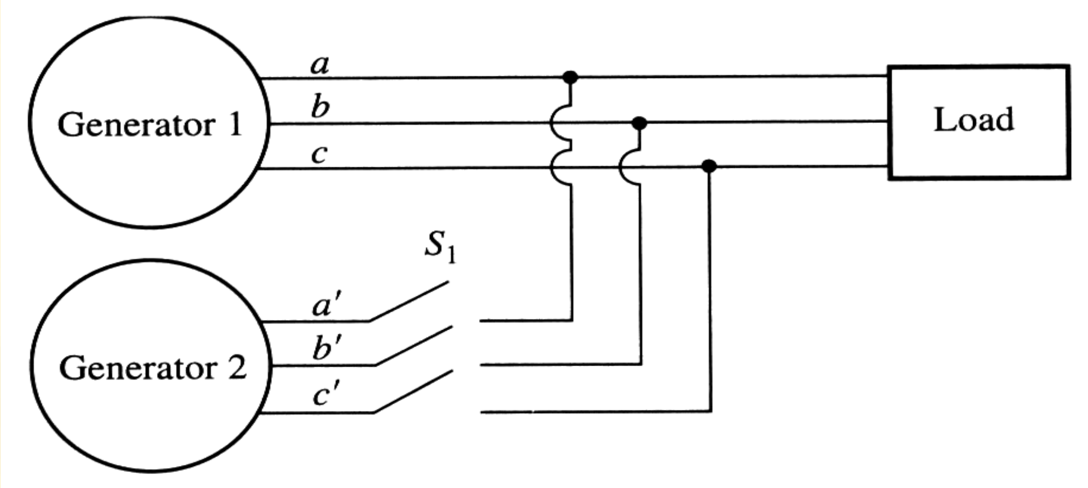
PARALLEL OPERATION OF SYNCHRONOUS GENERATORS

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:

1. Several generators can supply a bigger load;
2. A failure of a single generator does not result in a total power loss to the load increasing reliability of the power system;
3. Individual generators may be removed from the power system for maintenance without shutting down the load;
4. 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 of them when operating the rest at near full-load condition.

CONDITIONS REQUIRED FOR PARALLELING

A diagram shows that Generator 2 (oncoming generator) will be connected in parallel when the switch S_1 is closed.
However, closing the switch **at an arbitrary moment** can severely damage both generators!

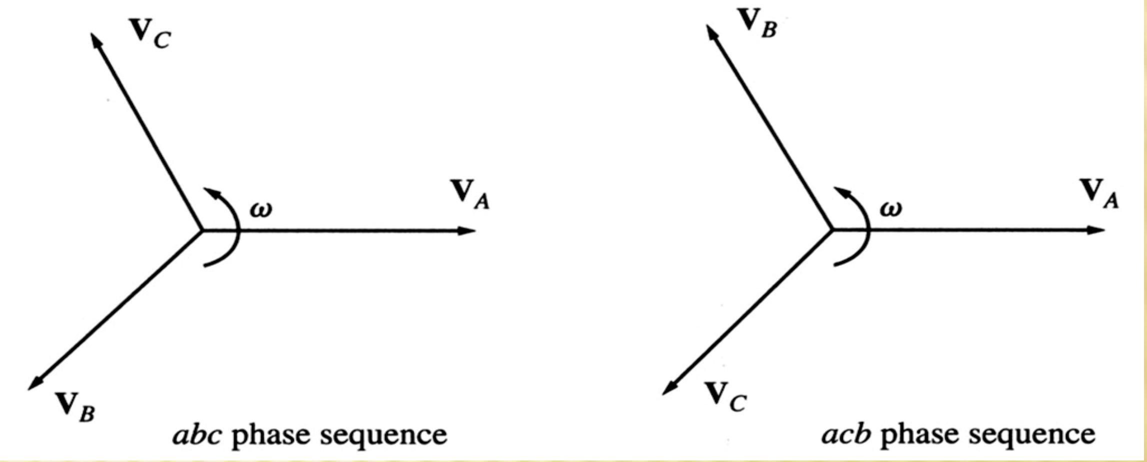


If voltages are not exactly the same in both lines (i.e. in *a* and *a'*, *b* and *b'* etc.), a very large current will flow when the switch is closed. Therefore, to avoid this, voltages coming from both generators must be exactly the same. Therefore, the following conditions must be met:

1. The rms line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of two *a* phases must be equal.
4. The frequency of the oncoming generator must be slightly higher than the frequency of the running system.

CONDITIONS REQUIRED FOR PARALLELING

If the phase sequences are different, then even if one pair of voltages (phases *a*) are in phase, the other two pairs will be 120° out of phase creating huge currents in these phases.

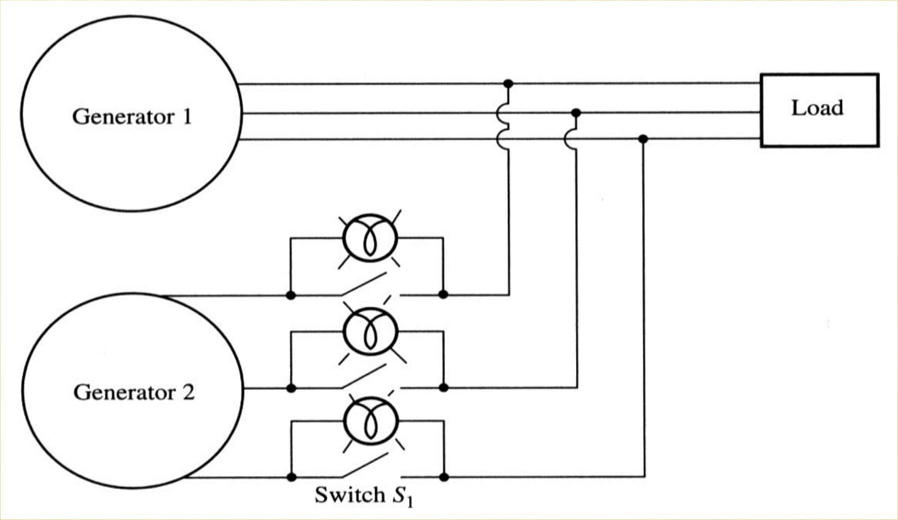


If the frequencies of the generators are different, a large power transient may occur until the generators stabilize at a common frequency. The frequencies of two machines must be very close to each other but not exactly equal. If frequencies differ by a small amount, the phase angles of the oncoming generator will change slowly with respect to the phase angles of the running system.
If the angles between the voltages can be observed, it is possible to close the switch S_1 when the machines are in phase.

GENERAL PROCEDURE FOR PARALLELING GENERATORS

When connecting the generator G_2 to the running system, the following steps should be taken:

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. This can be done by different ways:
   1) Connect a small induction motor to the terminals of the oncoming generator and then to the terminals of the running system. If the motor rotates in the same direction, the phase sequence is the same;
   2) Connect three light bulbs across the open terminals of the switch. As the phase changes between the two generators, light bulbs get brighter (large phase difference) or dimmer (small phase difference). If all three bulbs get bright and dark together, both generators have the same phase sequences.



GENERAL PROCEDURE FOR PARALLELING GENERATORS

If phase sequences are different, two of the conductors on the oncoming generator must be reversed.

3. The frequency of the oncoming generator is adjusted to be slightly higher than the system's frequency.
4. Turn on the switch connecting G_2 to the system when phase angles are equal.

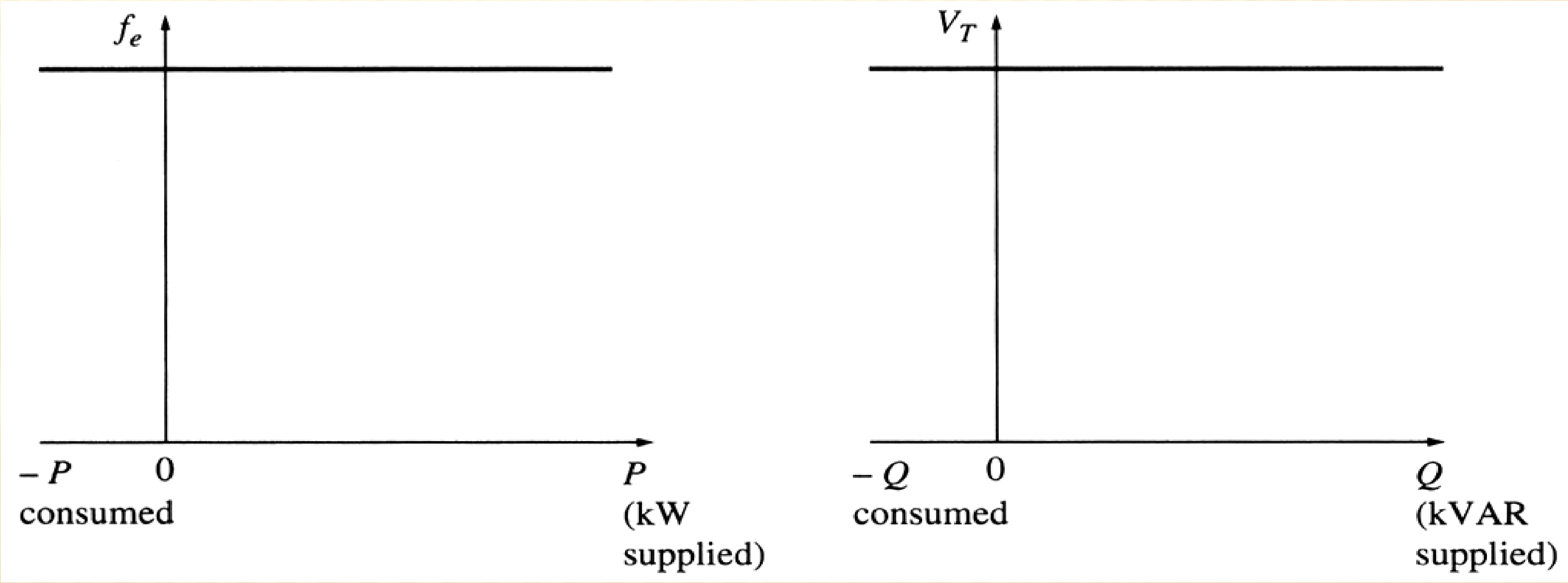
The simplest way to determine the moment when two generators are in phase is by observing the same three light bulbs. When all three lights go out, the voltage across them is zero and, therefore, machines are in phase.

A more accurate way is to use a synchroscope – a meter measuring the difference in phase angles between two *a* phases. However, a synchroscope does not check the phase sequence since it only measures the phase difference in one phase.

The whole process is usually automated…

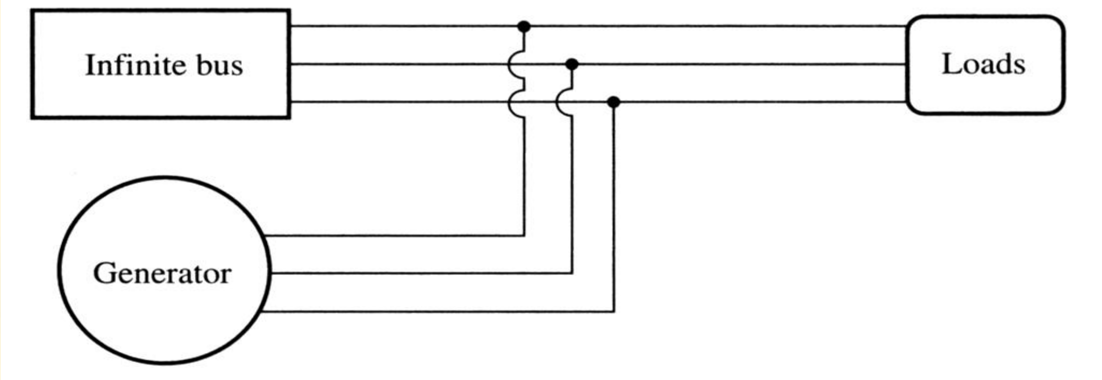
OPERATION OF GENERATORS IN PARALLEL WITH LARGE POWER SYSTEMS

Often, 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. A concept of an infinite bus is used to characterize such power systems.
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. The power-frequency and reactive power-voltage characteristics are:

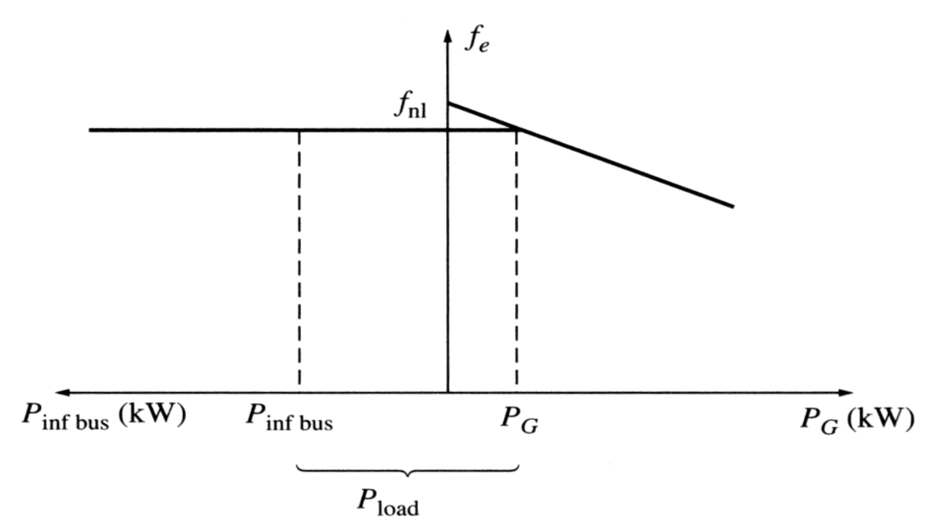


OPERATION OF GENERATORS IN PARALLEL WITH LARGE POWER SYSTEMS

Consider adding a generator to an infinite bus supplying a load.



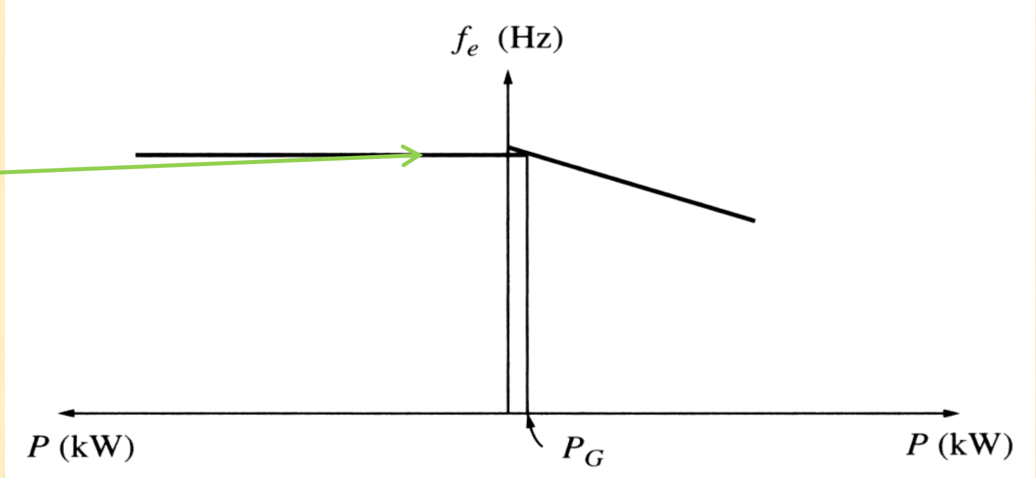
The frequency and terminal voltage of all machines must be the same. Therefore, their power-frequency and reactive power-voltage characteristics can be plotted with a common vertical axis.



Such plots are called sometimes as house diagrams.

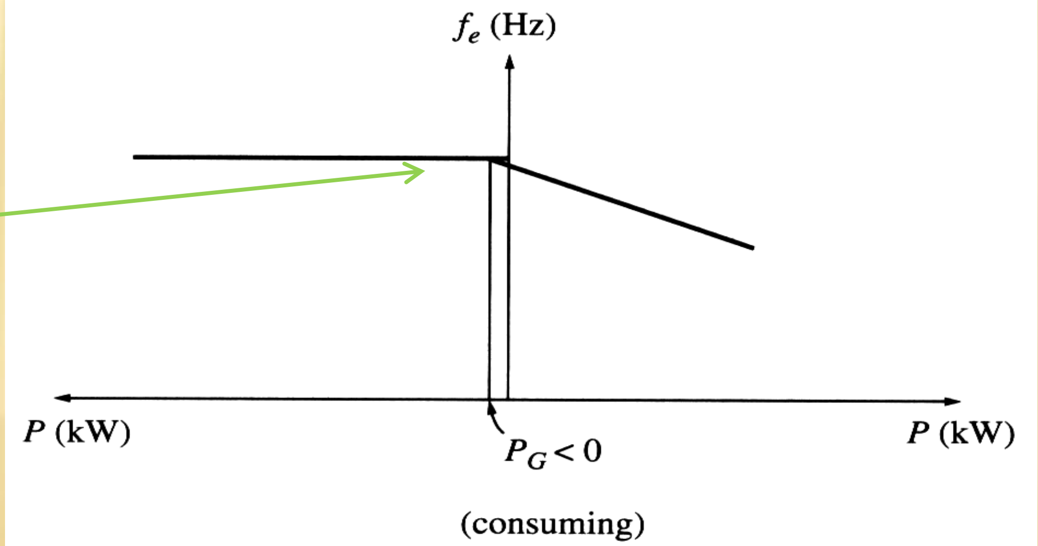
OPERATION OF GENERATORS IN PARALLEL WITH LARGE POWER SYSTEMS

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.



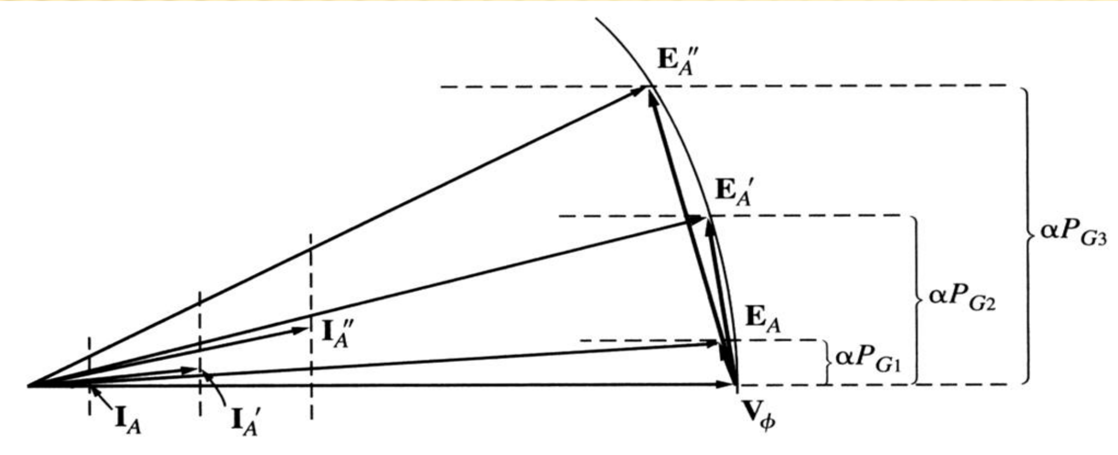
If the no-load frequency of the oncoming generator is slightly lower than the system's frequency, the generator will supply a negative power to the system: the generator actually consumes energy acting as a motor!

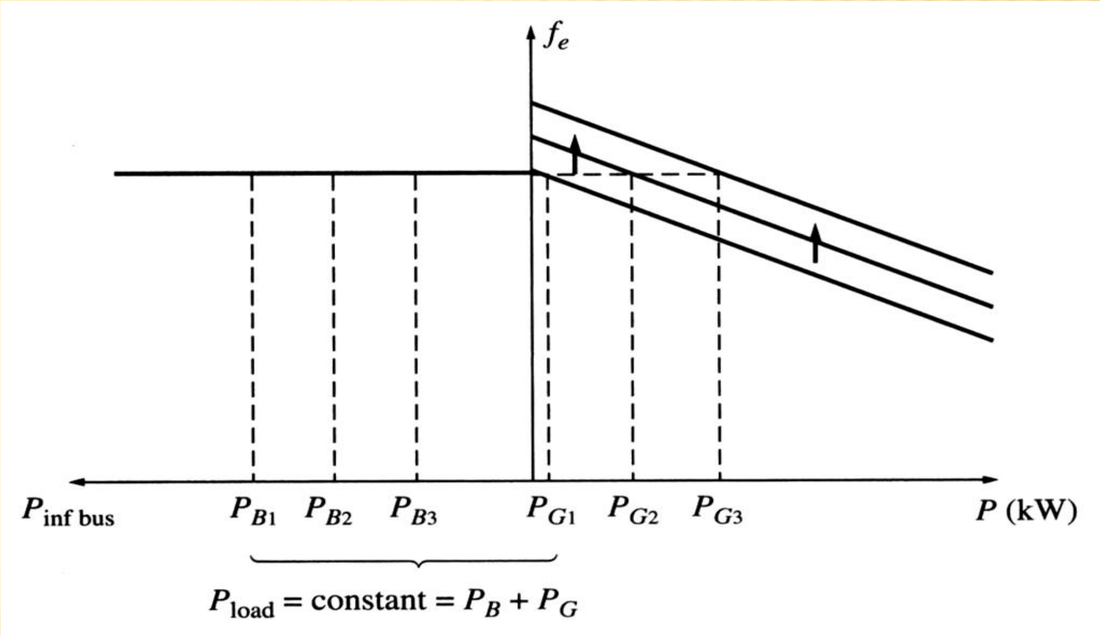
Many generators have circuitry automatically disconnecting them from the line when they start consuming energy.



OPERATION OF GENERATORS IN PARALLEL WITH LARGE POWER SYSTEMS

If the frequency of the generator is increased after it is connected to the infinite bus, the system frequency cannot change and the power supplied by the generator increases.





Notice that when E_A stays constant (field current and speed are the same), $E_A \sin\delta$ (which is proportional to the output power if V_T is constant) increases.

If the frequency of the generator is further increased, power output from the generator will be increased and at some point it may exceed the power consumed by the load. This extra power will be consumed by the load.

OPERATION OF GENERATORS IN PARALLEL WITH LARGE POWER SYSTEMS

After the real power of the generator is adjusted to the desired value, the generator will be operating at a slightly leading PF acting as a capacitor that consumes reactive power. Adjusting the field current of the machine, it is possible to make it to supply reactive power Q to the system.

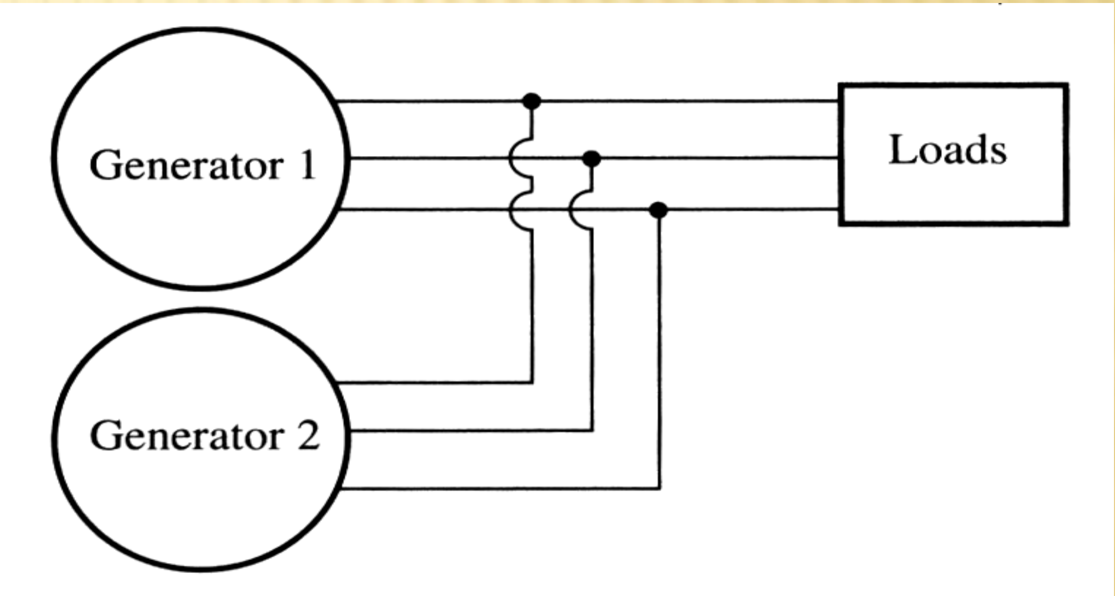
Summarizing, when the generator is operating in parallel to an infinite bus:

1. The frequency and terminal voltage of the generator are controlled by the system to which it is connected.
2. The governor set points of the generator control the real power supplied by the generator to the system.
3. The generator's field current controls the reactive power supplied by the generator to the system.

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

When a generator is working alone, its real and reactive power are fixed and determined by the load.
When a generator is connected to an infinite bus, its frequency and the terminal voltage are constant and determined by a bus.

When two generators of the same size are connected to the same load, the sum of the real and reactive powers supplied by the two generators must equal the real and reactive powers demanded by the load:



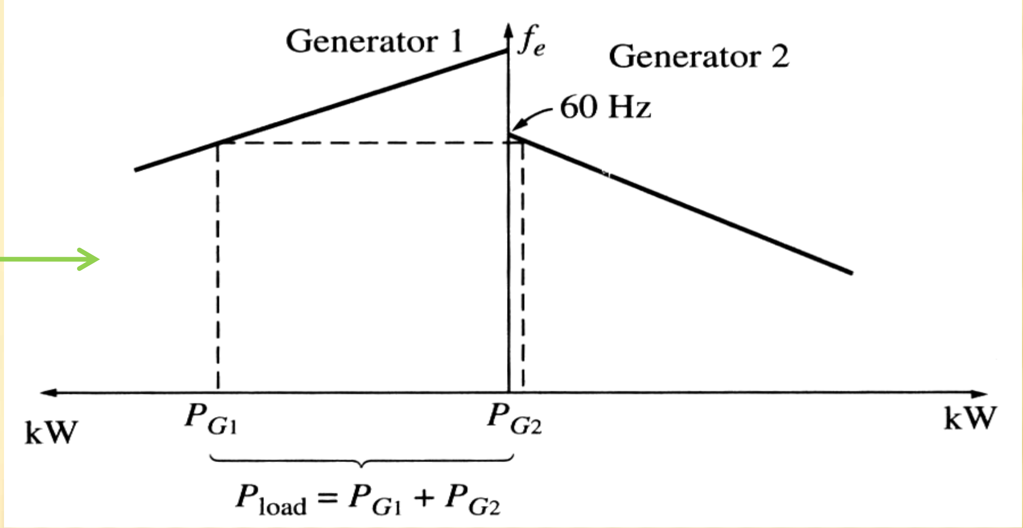
$$P_{tot} = P_{load} = P_{G1} + P_{G2}$$

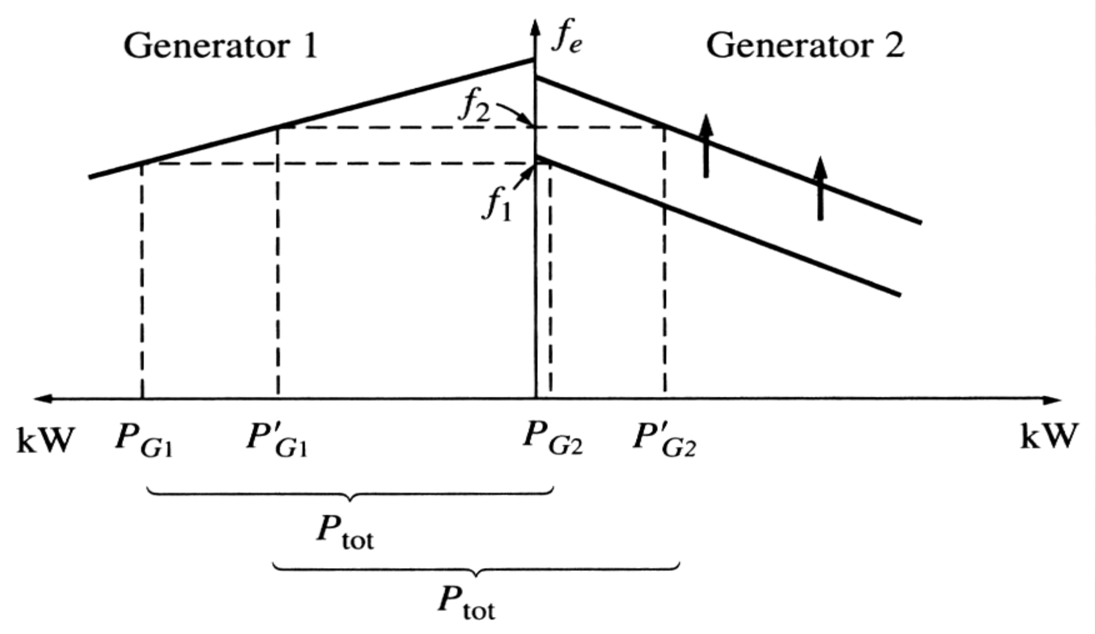
$$Q_{tot} = Q_{load} = Q_{G1} + Q_{G2}$$

(7.59.2)

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

Since the frequency of G_2 must be slightly higher than the system's frequency, the power-frequency diagram right after G_2 is connected to the system is shown.





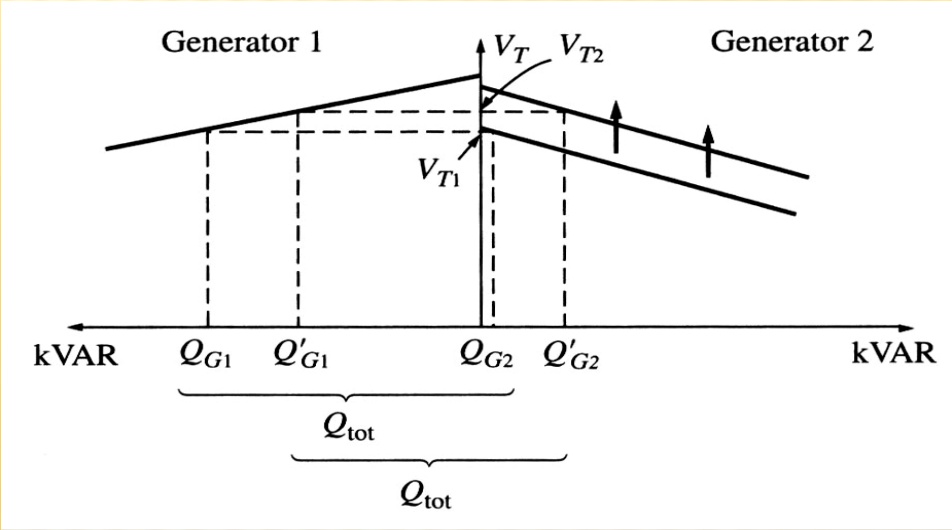
If the frequency of G_2 is next increased, its power-frequency diagram shifts upwards. Since the total power supplied to the load is constant, G_2 starts supplying more power and G_1 starts supplying less power and the system's frequency increases.

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

Therefore, when two generators are operating together, an increase in frequency (governor set point) on one of them:

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

When two generators are operating together, an increase in the field current on one of them:

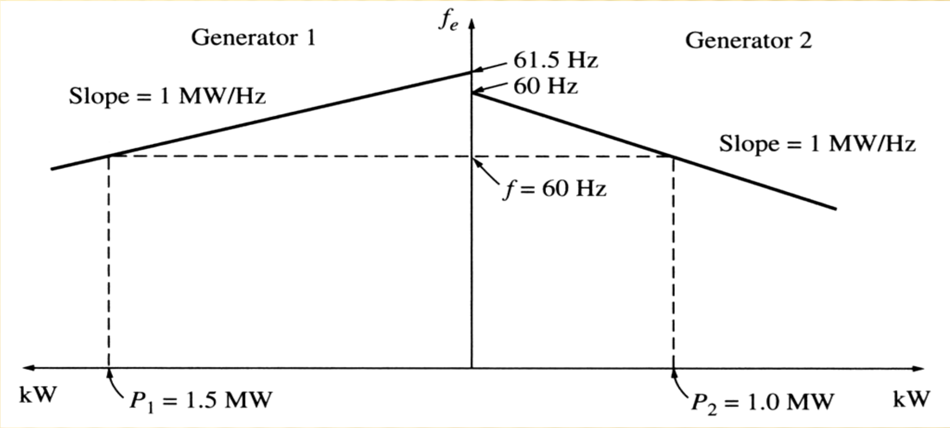


1. Increases the system terminal voltage.
2. Increases the reactive power supplied by that generator, while reducing the reactive power supplied by the other.

If the frequency-power curves of both generators are known, the powers supplied by each generator and the resulting system frequency can be determined.

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE: EX

Example 7.4: Two generators are set to supply the same load. Generator 1 has a no-load frequency of 61.5 Hz and a slope s_{p1} of 1 MW/Hz. Generator 2 has a no-load frequency of 61.0 Hz and a slope s_{p2} of 1 MW/Hz. The two generators are supplying a real load of 2.5 MW at 0.8 PF lagging.



a. Find the system frequency and power supplied by each generator.
b. Assuming that an additional 1 MW load is attached to the power system, find the new system frequency and powers supplied by each generator.
c. With the additional load attached (total load of 3.5 MW), find the system frequency and the generator powers, if the no-load frequency of G_2 is increased by 0.5 Hz.

The power produced by a synchronous generator with a given slope and a no-load frequency is

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

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE: EX

The total power supplied by the generators equals to the power consumed by the load:

$$P_{load} = P_1 + P_2$$

a. The system frequency can be found from:

$$P_{load} = P_1 + P_2 = s_{p1}\left(f_{nl,1} - f_{sys}\right) + s_{p2}\left(f_{nl,2} - f_{sys}\right)$$

as

$$f_{sys} = \frac{s_{p1} f_{nl,1} + s_{p2} f_{nl,2} - P_{load}}{s_{p1} + s_{p2}} = \frac{1 \cdot 61.5 + 1 \cdot 61.0 - 2.5}{1+1} = 60.0\ Hz$$

The powers supplied by each generator are:

$$P_1 = s_{p1}\left(f_{nl,1} - f_{sys}\right) = 1 \cdot \left(61.5 - 60\right) = 1.5\ MW$$

$$P_2 = s_{p2}\left(f_{nl,2} - f_{sys}\right) = 1 \cdot \left(61.0 - 60\right) = 1\ MW$$

GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE: EX

b. For the new load of 3.5 MW, the system frequency is

$$f_{sys} = \frac{s_{p1} f_{nl,1} + s_{p2} f_{nl,2} - P_{load}}{s_{p1} + s_{p2}} = \frac{1 \cdot 61.5 + 1 \cdot 61.0 - 3.5}{1+1} = 59.5\ Hz$$

The powers are:

$$P_1 = s_{p1}\left(f_{nl,1} - f_{sys}\right) = 1 \cdot (61.5 - 59.5) = 2.0\ MW$$

$$P_2 = s_{p2}\left(f_{nl,2} - f_{sys}\right) = 1 \cdot (61.0 - 59.5) = 1.5\ MW$$

c. If the no-load frequency of G_2 increases, the system frequency is

$$f_{sys} = \frac{s_{p1} f_{nl,1} + s_{p2} f_{nl,2} - P_{load}}{s_{p1} + s_{p2}} = \frac{1 \cdot 61.5 + 1 \cdot 61.5 - 3.5}{1+1} = 59.75\ Hz$$

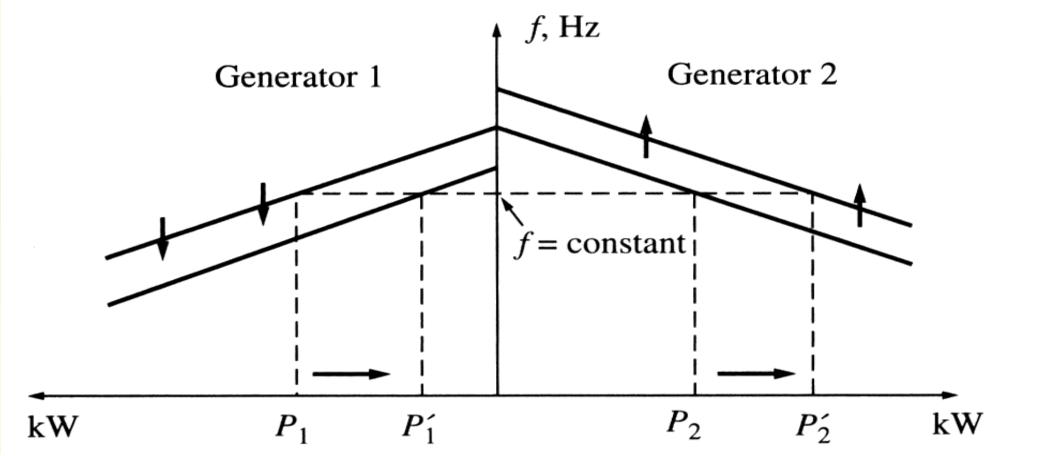
The powers are:

$$P_1 = P_2 = s_{p1}\left(f_{nl,1} - f_{sys}\right) = 1 \cdot (61.5 - 59.75) = 1.75\ MW$$

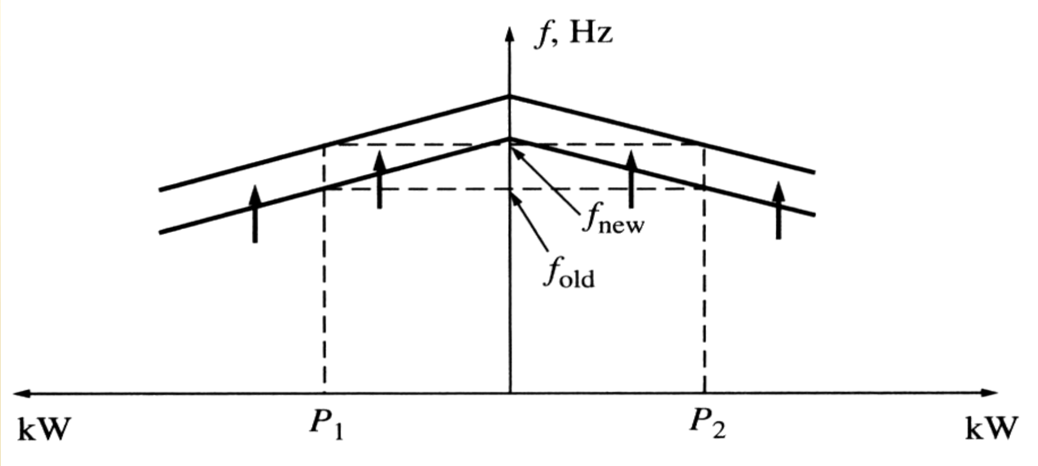
GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

When two generators of the same size are working in parallel, a change in frequency (governor set points) of one of them changes both the system frequency and power supplied by each generator.

To adjust power sharing without changing the system frequency, we need to increase the frequency (governor set points) of one generator and simultaneously decrease the frequency of the other generator.

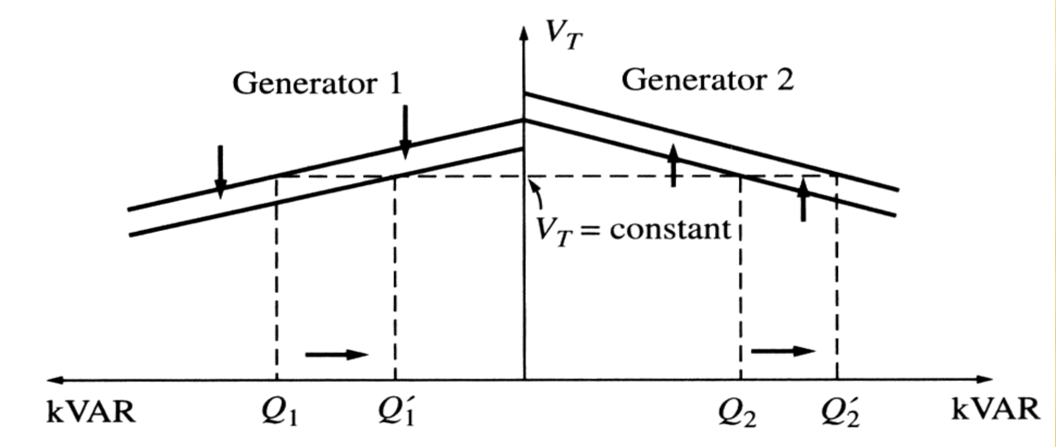


To adjust the system frequency without changing power sharing, we need to simultaneously increase or decrease the frequency (governor set points) of both generators.

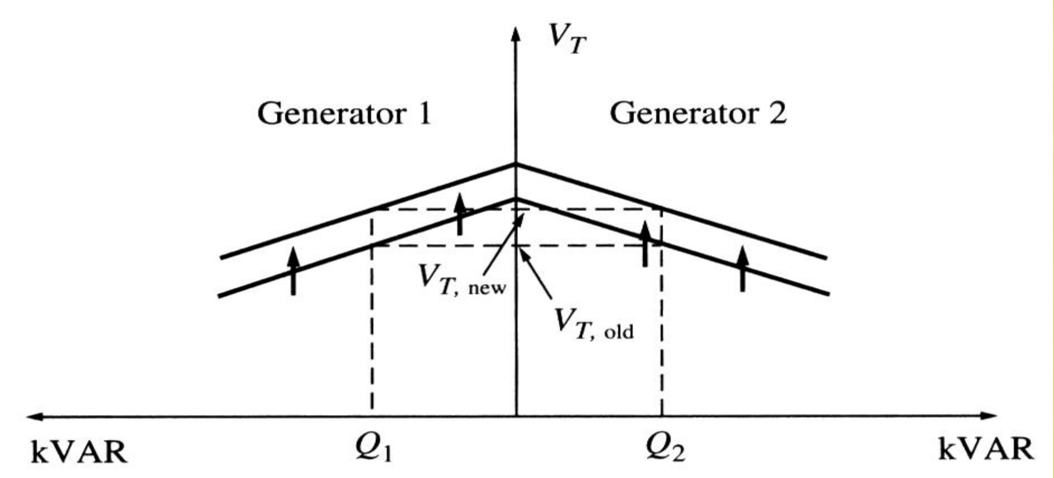


GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

Similarly, to adjust the reactive power sharing without changing the terminal voltage, we need to increase simultaneously the field current of one generator and decrease the field current of the other generator.



To adjust the terminal voltage without changing the reactive power sharing, we need to simultaneously increase or decrease the field currents of both generators.



GENERATORS IN PARALLEL WITH OTHER GENERATORS OF THE SAME SIZE

It is important that both generators being paralleled have dropping frequency-power characteristics.

If two generators have flat or almost flat frequency-power characteristics, the power sharing between them can vary widely with only finest changes in no-load speed. For good of power sharing between generators, they should have speed drops of 2% to 5%.