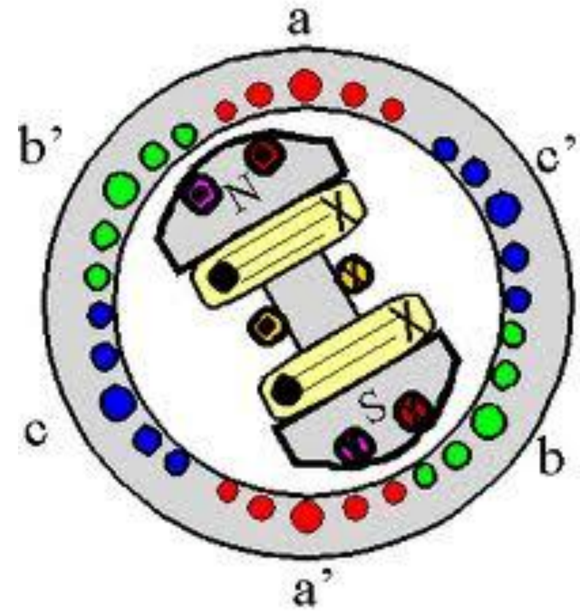
Synchronous Generators I

EE 340

Spring 2011

Construction of synchronous machines

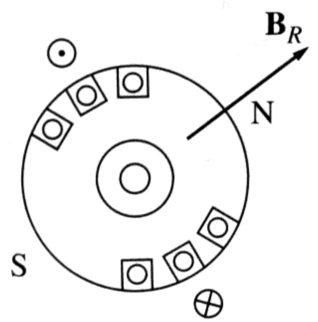
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.



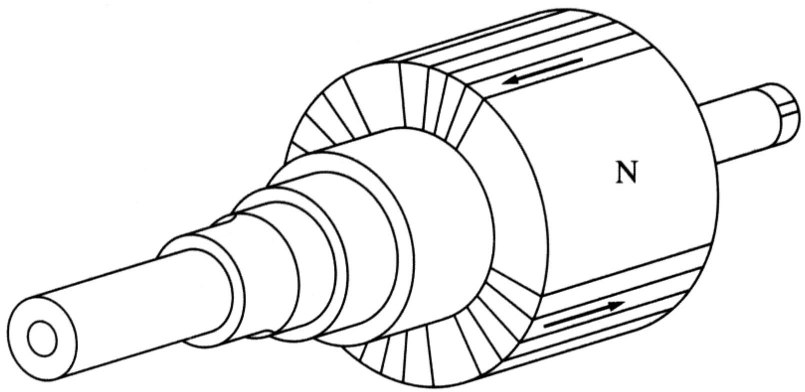
- Field windings are the windings producing the main magnetic field (rotor windings
- armature windings are the windings where the main voltage is induced (stator windings)

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: usually two- and four-pole rotors.

Salient-pole rotor: four and more poles.

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.

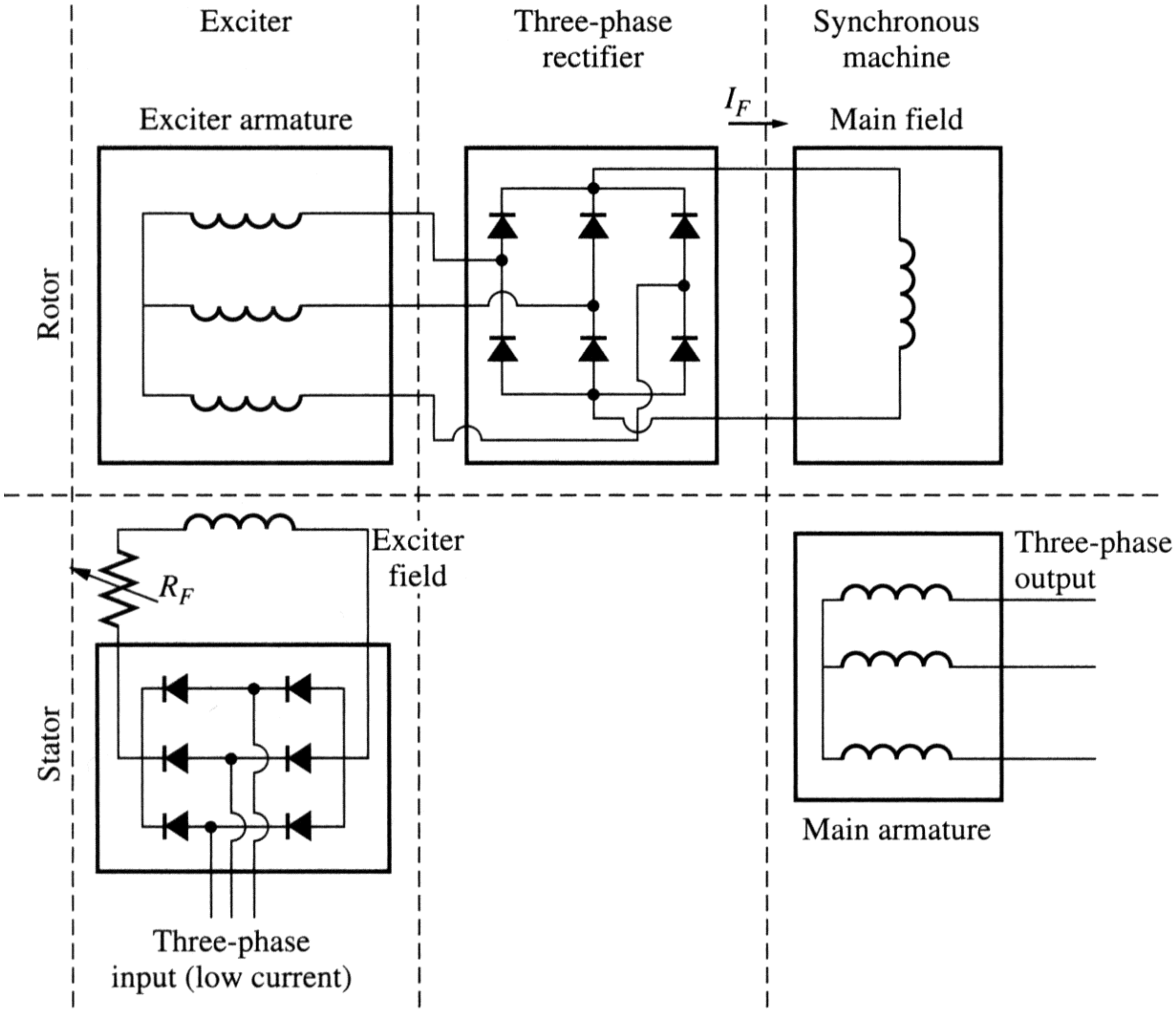
Construction of synchronous machines

- 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

A brushless exciter: a low 3-phase current is rectified and used to supply the field circuit of the exciter (located on the stator).

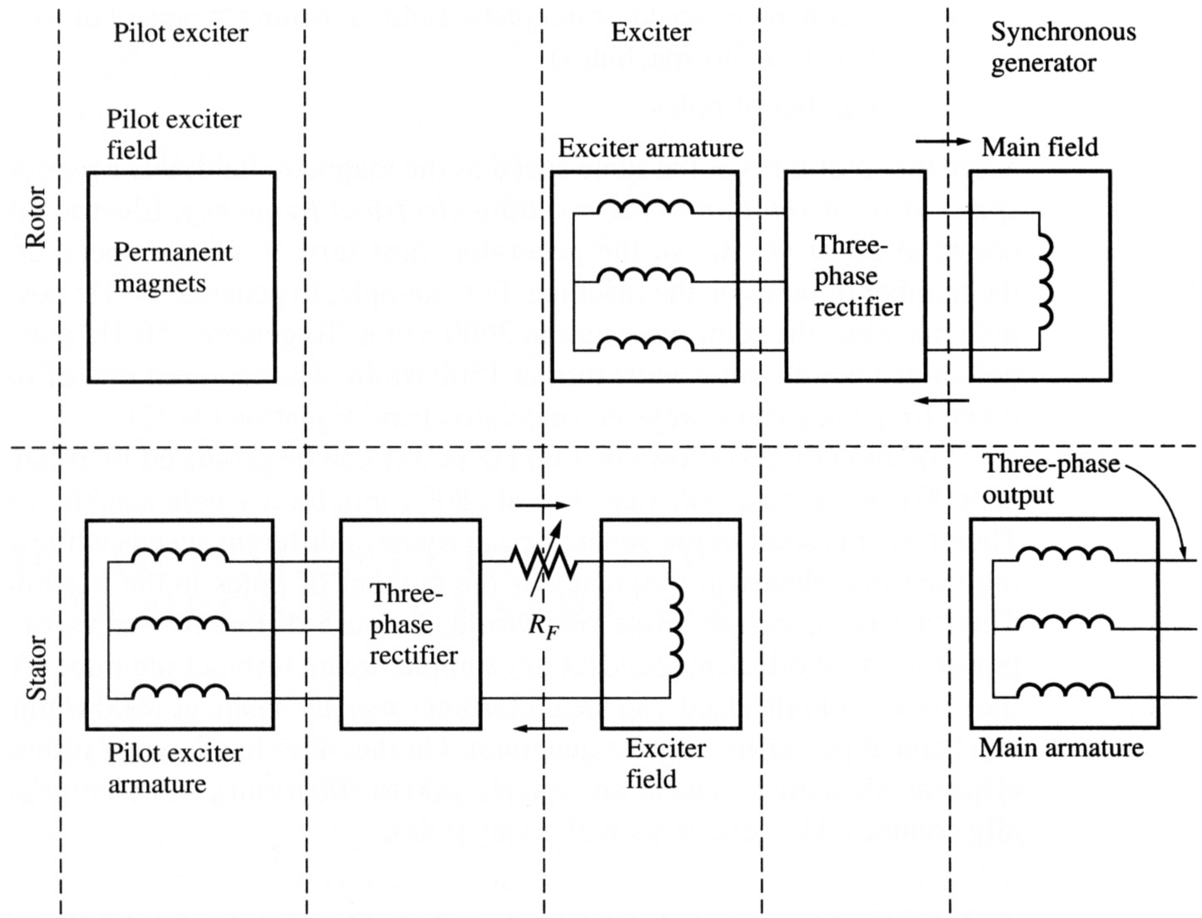
The output of the exciter's armature circuit (on the rotor) is rectified and used as the field current of the main machine.



Construction of synchronous machines

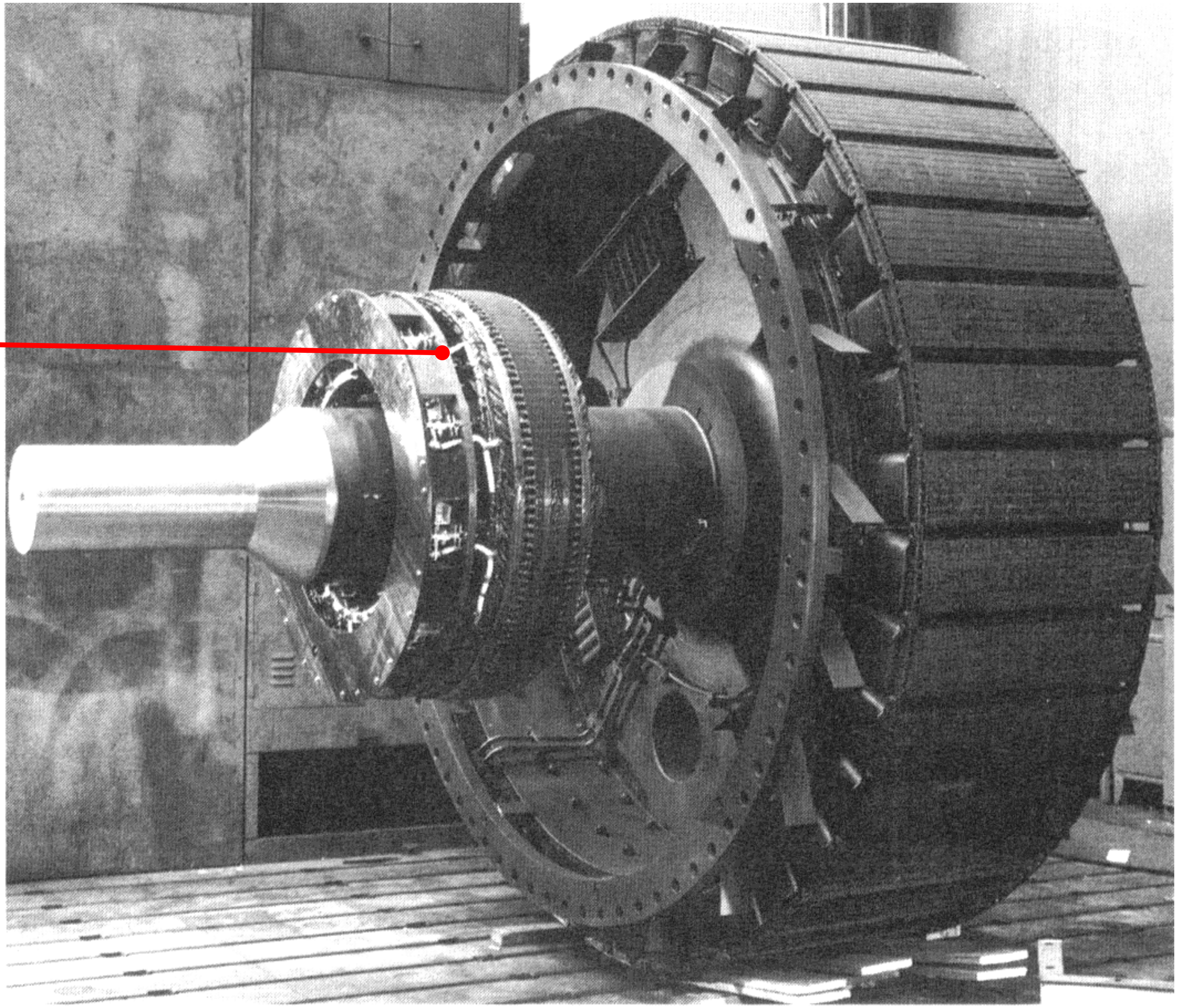
To make the excitation of a generator completely independent of any external power source, a small pilot exciter is often added to the circuit.

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

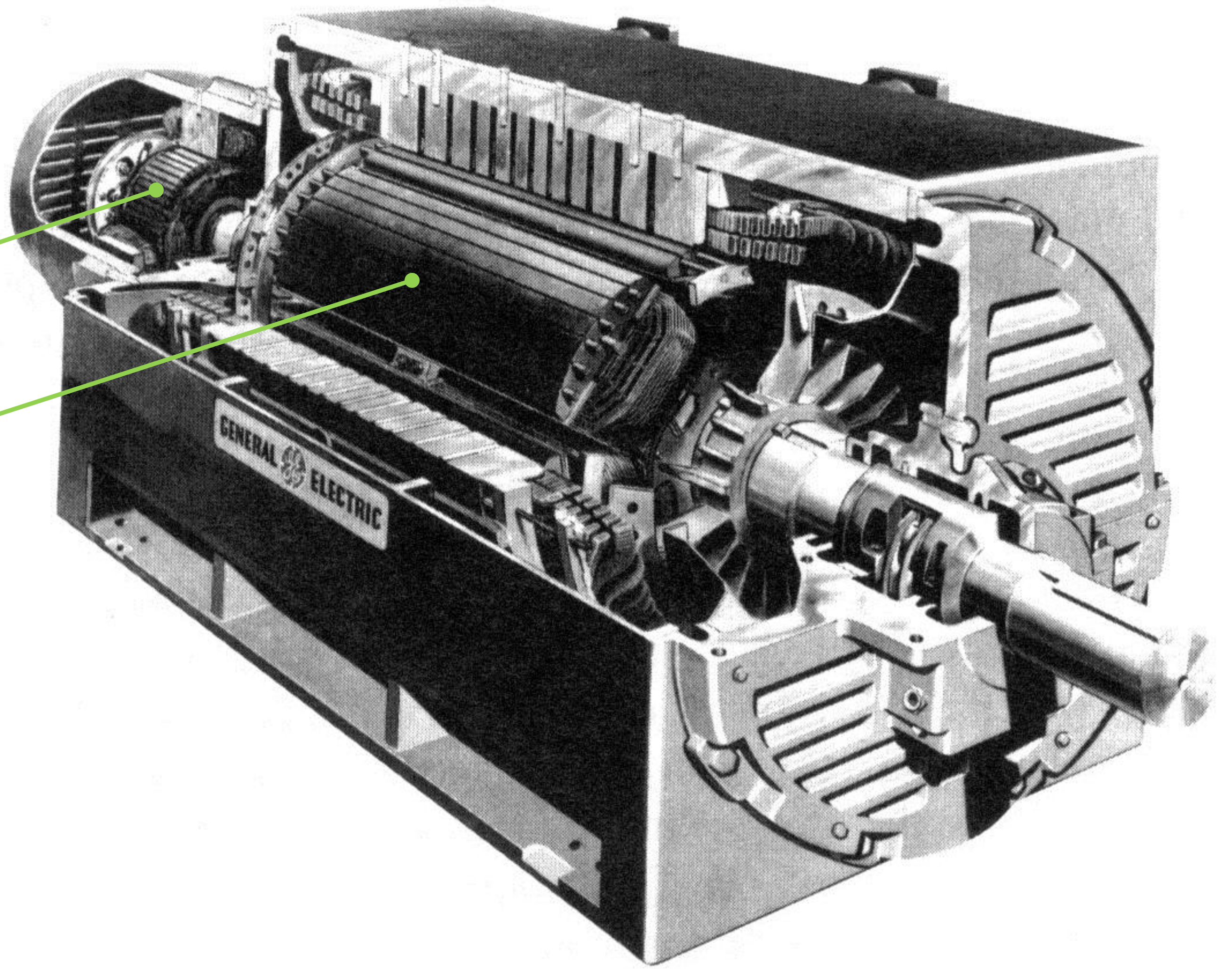
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.



Construction of synchronous machines

Exciter

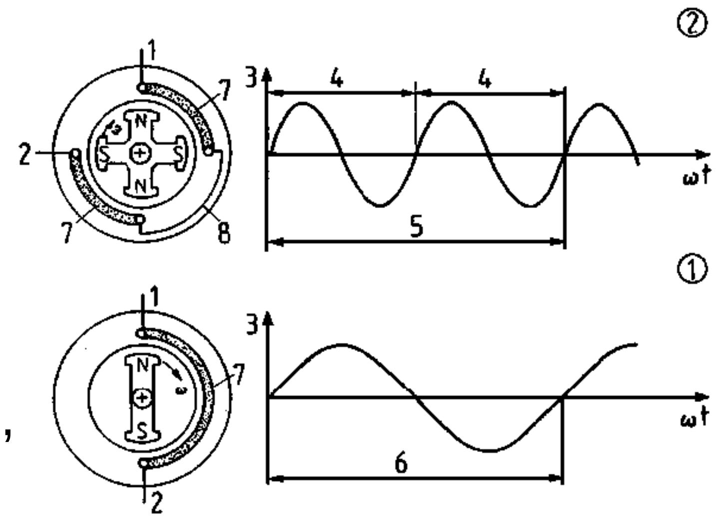
Salient poles.



Rotation speed of synchronous generator

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

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



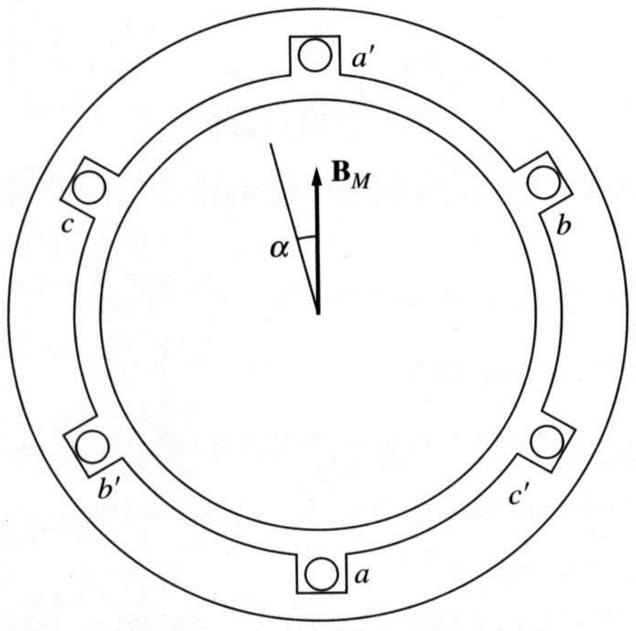
Where f_e is the electrical frequency, Hz;
n_m is the rotor speed of the machine,
p is the number of poles.

- 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 120^0:

$$e_{aa'}(t) = N_C \phi \omega_m \cos \omega_m t$$
$$e_{bb'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 120^\circ\right)$$
$$e_{cc'}(t) = N_C \phi \omega_m \cos\left(\omega_m t - 240^\circ\right)$$



Peak voltage:

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

RMS voltage:

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

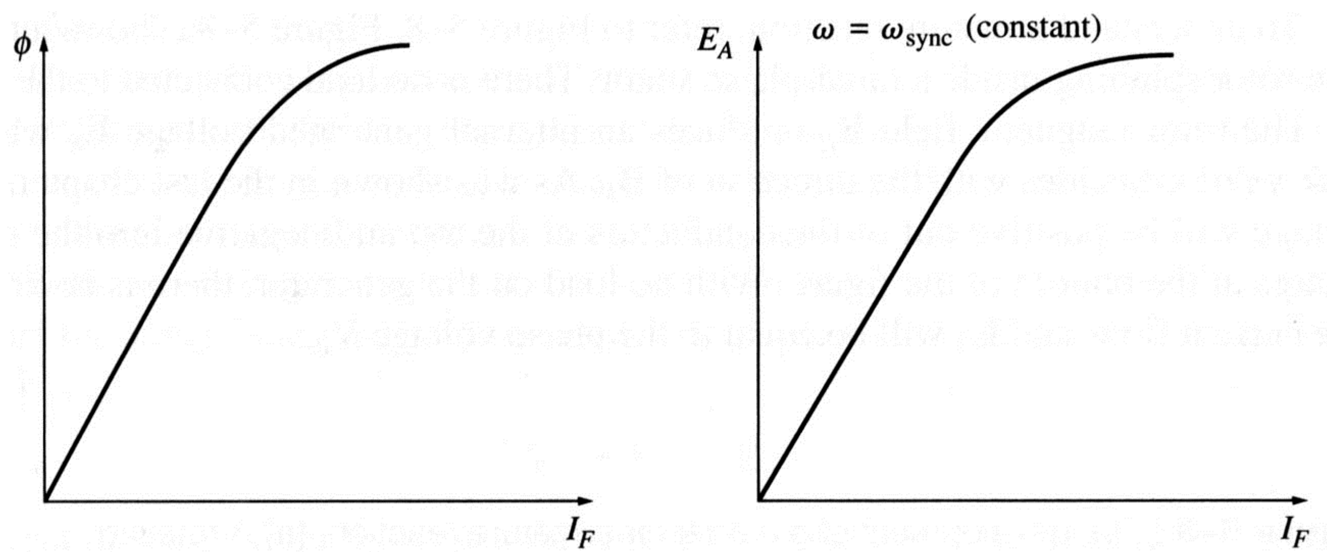
Internal generated voltage of a synchronous generator

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

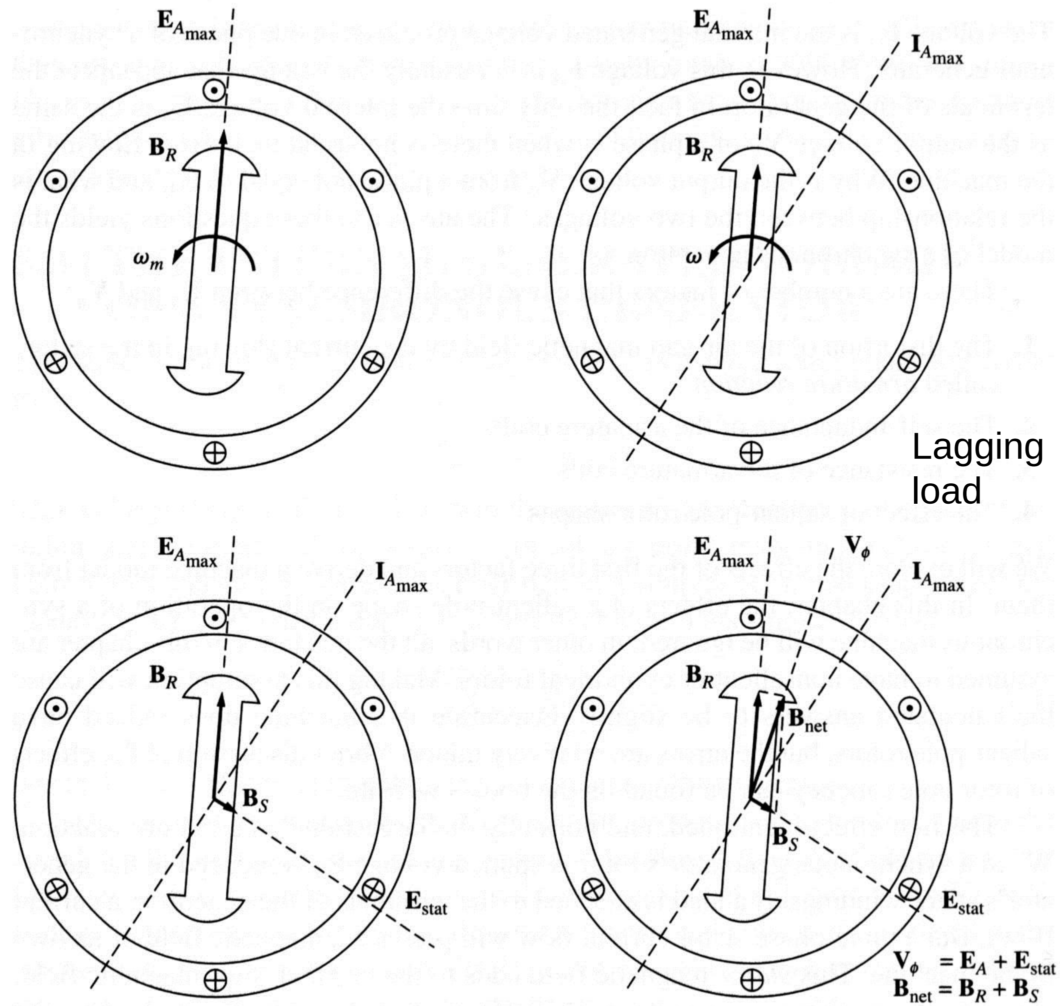
The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals. It equals to the output voltage V_ϕ only when there is no armature current in the machine. The reasons that the armature voltage E_A is not equal to the output voltage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

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

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

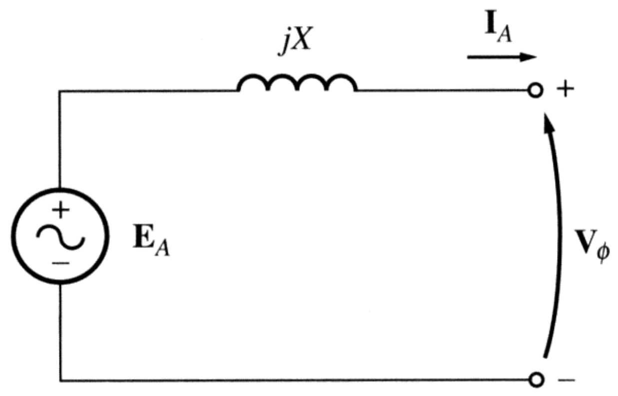
Rotor field

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

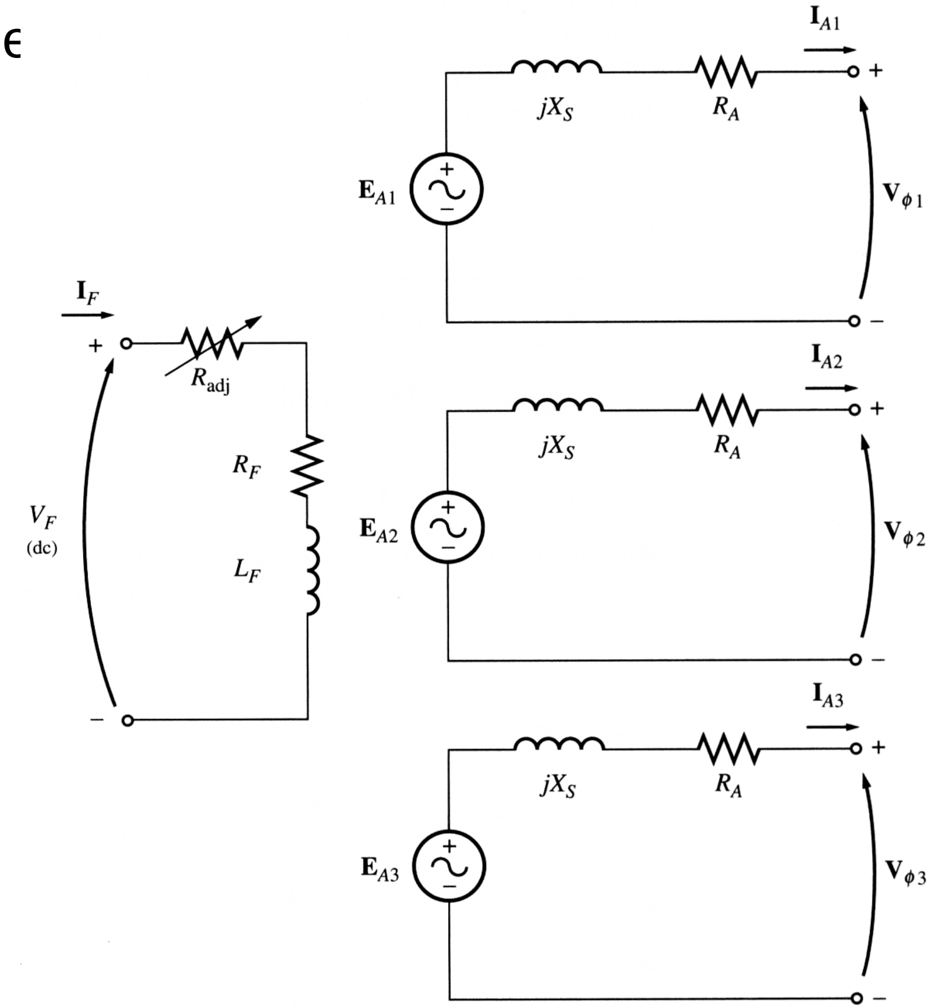
$$X_S = X + X_A$$

Therefore, the phase voltage is

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

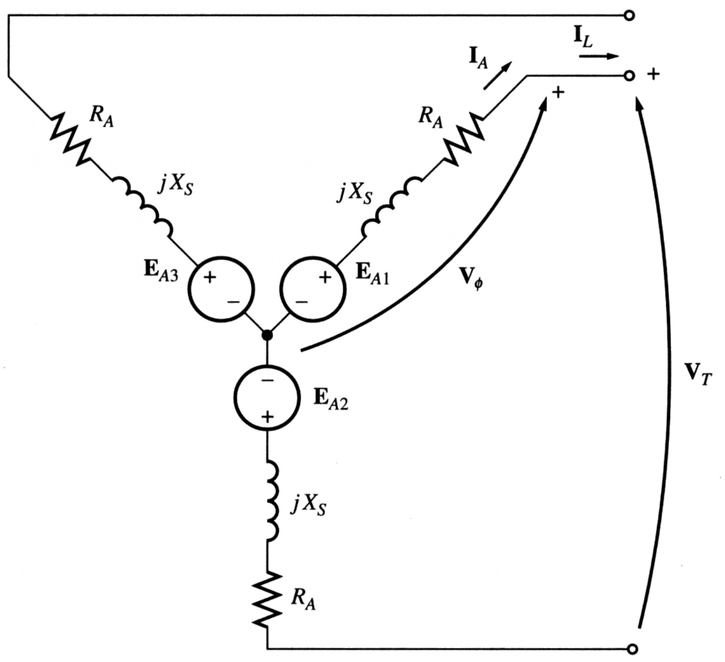
The equivalent circuit of a 3-phase synchronous generator is shown.

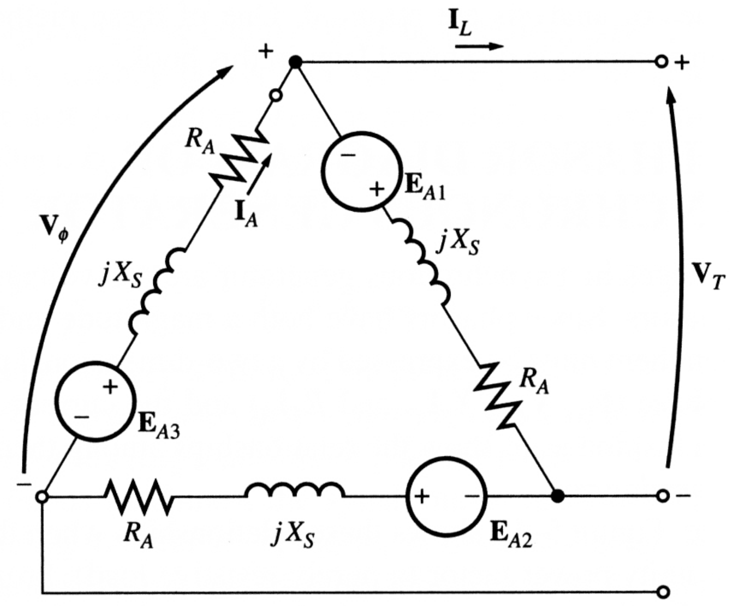
The adjustable resistor R_{adj} controls the field current and, therefore, the rotor magnetic field.



Equivalent circuit of a synchronous generator

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



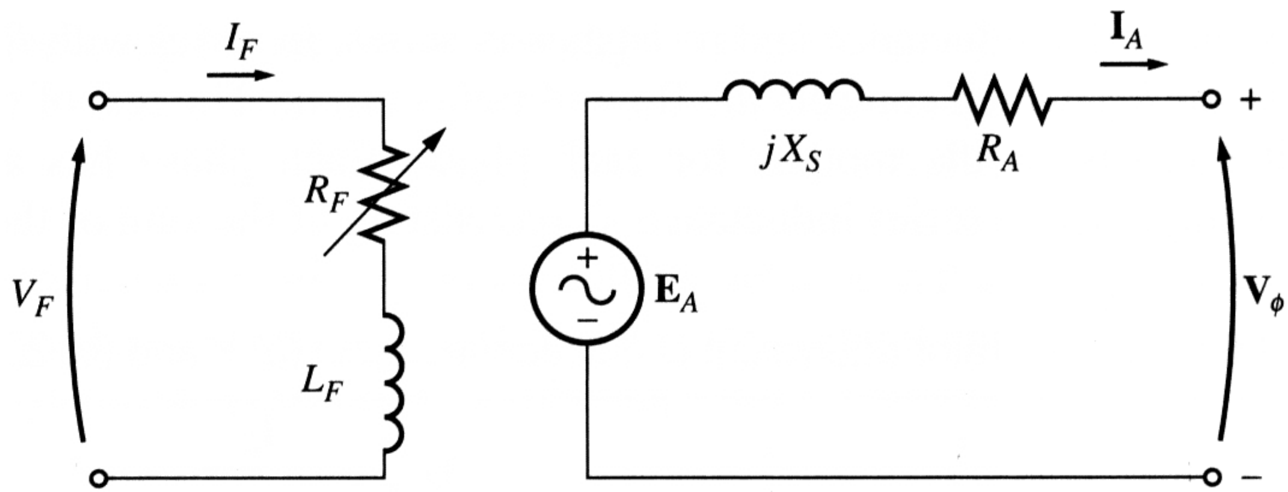


The terminal voltage will be

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

Equivalent circuit of a synchronous generator

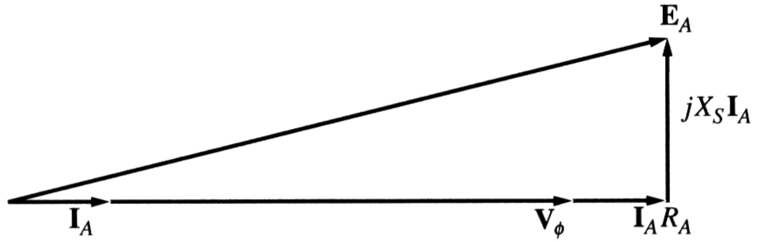
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



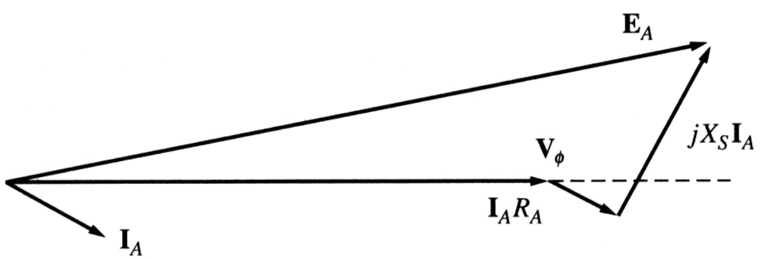
Phasor diagram of a synchronous generator (similar to that of a transformer)

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.

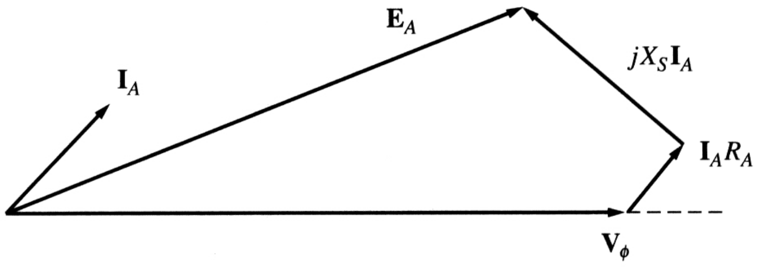
A phasor diagram of a synchronous generator with a unity power factor (resistive load)



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).



Measuring parameters of synchronous generator model

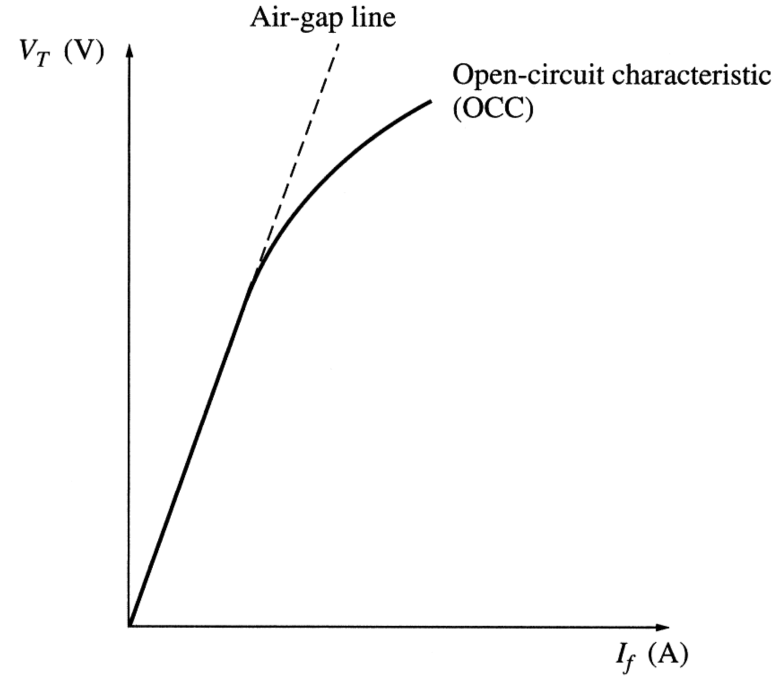
The three quantities must be determined in order to describe the generator model:

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.

Open circuit Test

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.



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.

Short Circuit Test

In here,

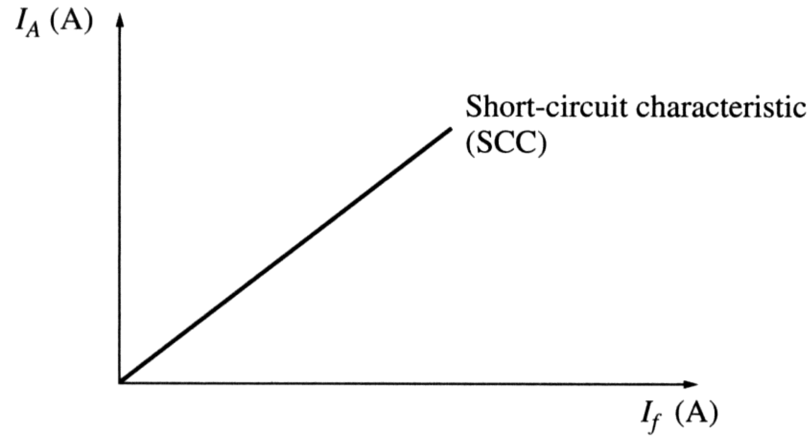
- the generator is rotated at the rated speed, with the field current is set to zero first, and all the terminals are short-circuited through ammeters.
- Next, the field current is increased in steps and the armature current I_A is measured as the field current is increased.

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

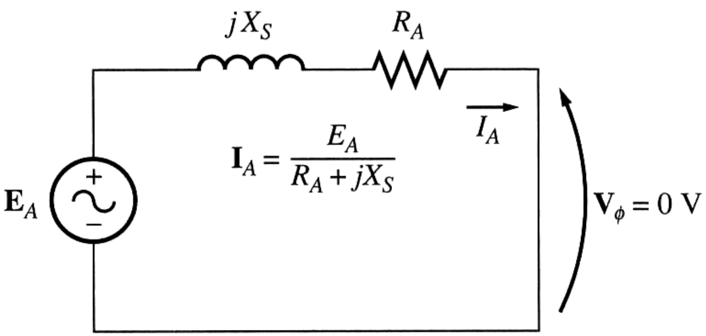
Short Circuit Test

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

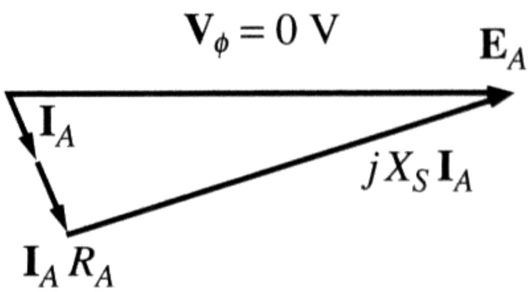
$$I_A = \frac{E_A}{\sqrt{R_A^2 + X_S^2}}$$



The equivalent generator's circuit during SC



The resulting phasor diagram



Short circuit test

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

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

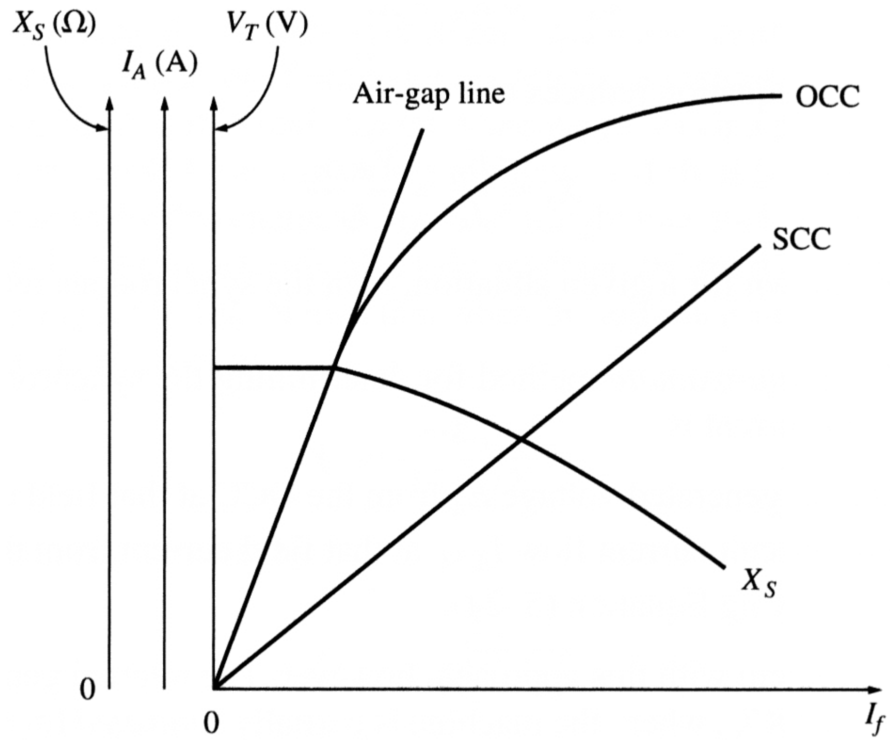
Since the internal machine impedance is

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

OCC and SCC

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).

Example

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:

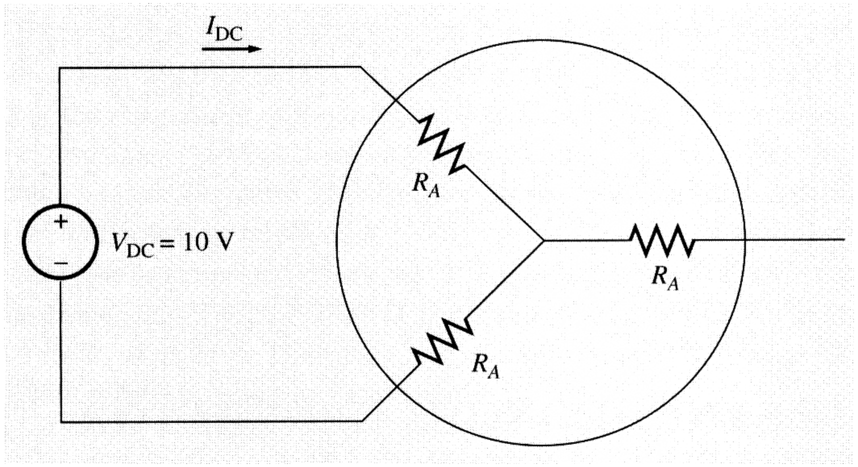
1. $V_{T,OC}$ = 540 V at the rated I_F.
2. $I_{L,SC}$ = 300 A at the rated I_F.
3. When a DC voltage of 10 V was applied to two of the terminals, a current of 25 A was measured.

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:

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

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



Example (cont.)

The internal generated voltage at the rated field current is

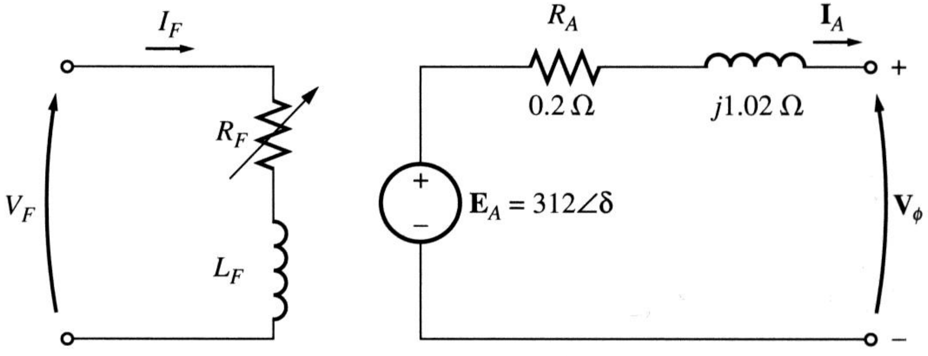
$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} = 311.8\,V$$

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 Synchronous generator operating alone

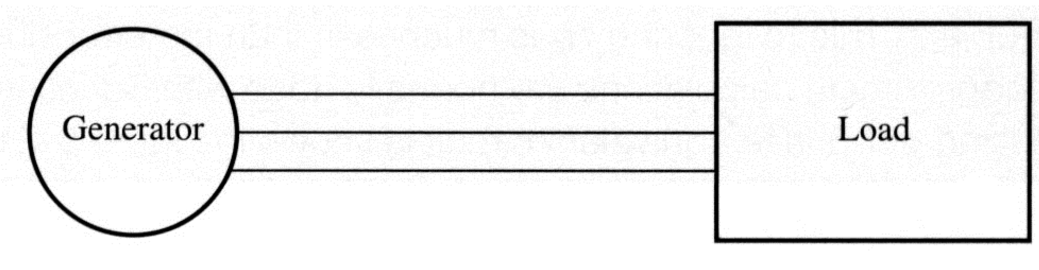
The behavior of a synchronous generator varies greatly under load depending on the power factor of the load and on whether the generator is working alone or in parallel with other synchronous generators.

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.



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.

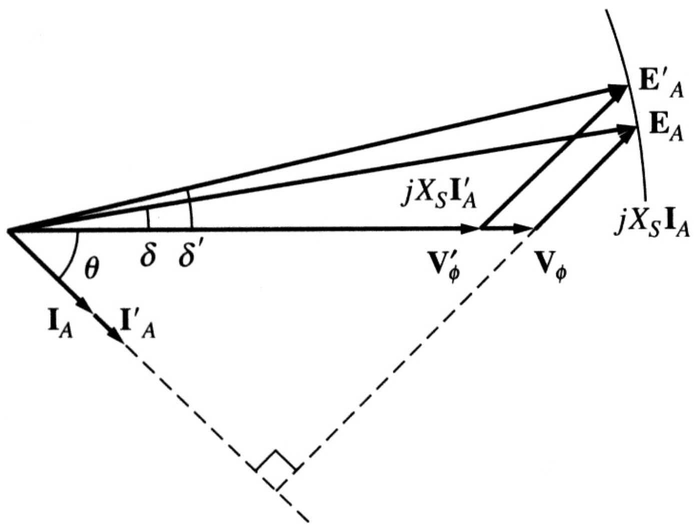
Assuming the same power factor of the load, change in load will change the magnitude of the armature current I_A. However, the angle will be the same (for a constant PF). Thus, the armature reaction voltage $jX_S I_A$ will be larger for the increased load. Since the magnitude of the internal generated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

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

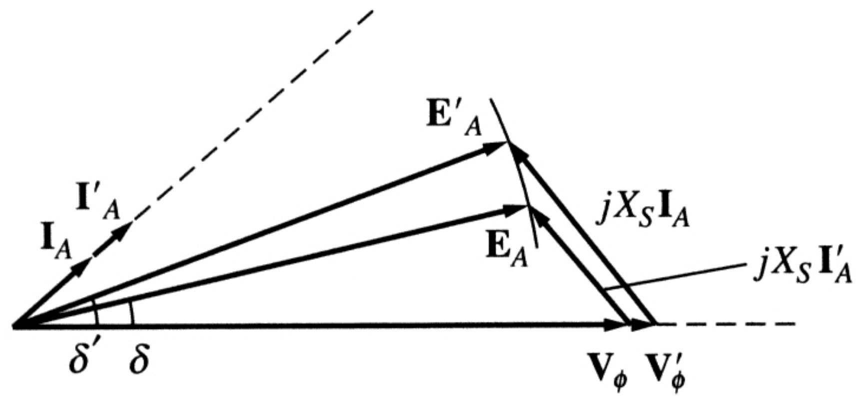
Armature reaction voltage vector will "move parallel" to its initial position.

The Synchronous generator operating alone

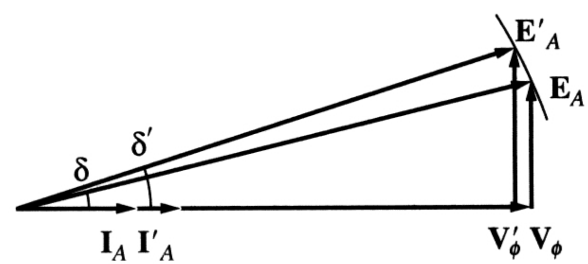
Increase load effect on generators with



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

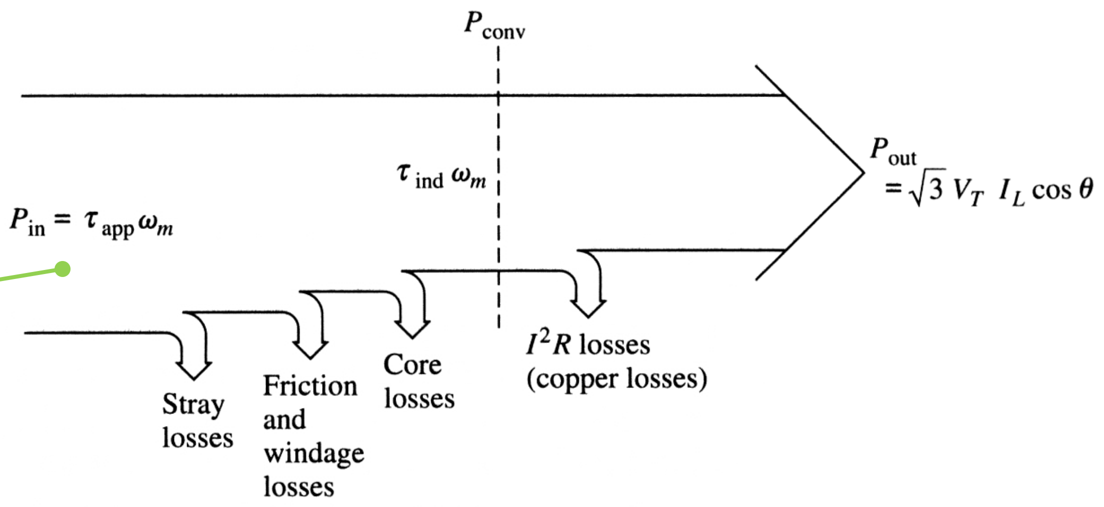
$$P_{in} = \tau_{app}\omega_m$$

is partially converted to electricity

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

Where 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

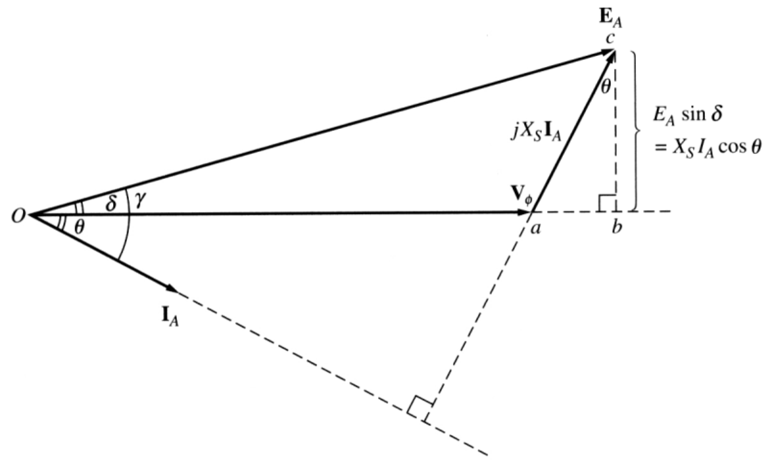
$$P_{out} = \sqrt{3} V_T I_L \cos\theta = 3 V_\phi I_A \cos\theta$$

The reactive output power of the synchronous generator is

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

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 $R_A \ll X_S$ 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 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 $\delta = 90^0$:

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

Power and torque in synchronous generators

The maximum power specified is called the static stability limit of the generator. Normally, real generators do not approach this limit: full-load torque angles are usually between 15^0 and 20^0.

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

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

Problems

- 5.1 through 5.17