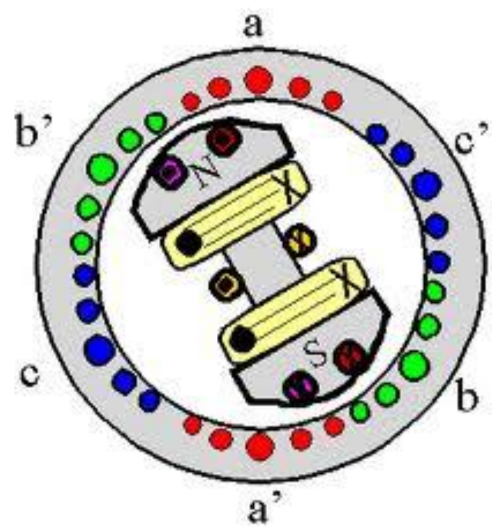
Construction of synchronous machines

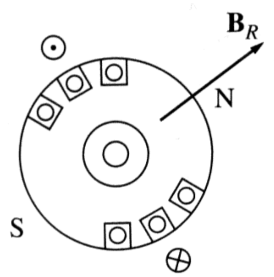
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.



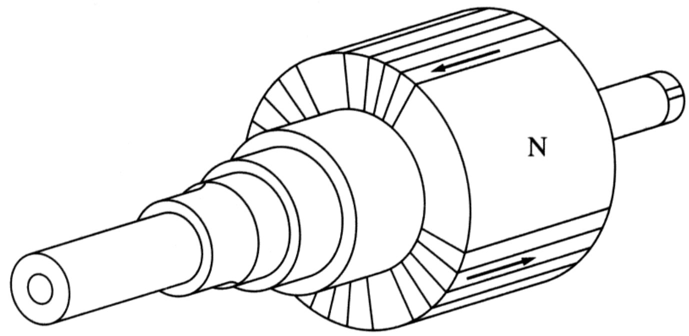
- Field windings are the windings producing the main magnetic field (rotor windings
- armature windings are the windings where the main voltage is induced (stator windings)

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.

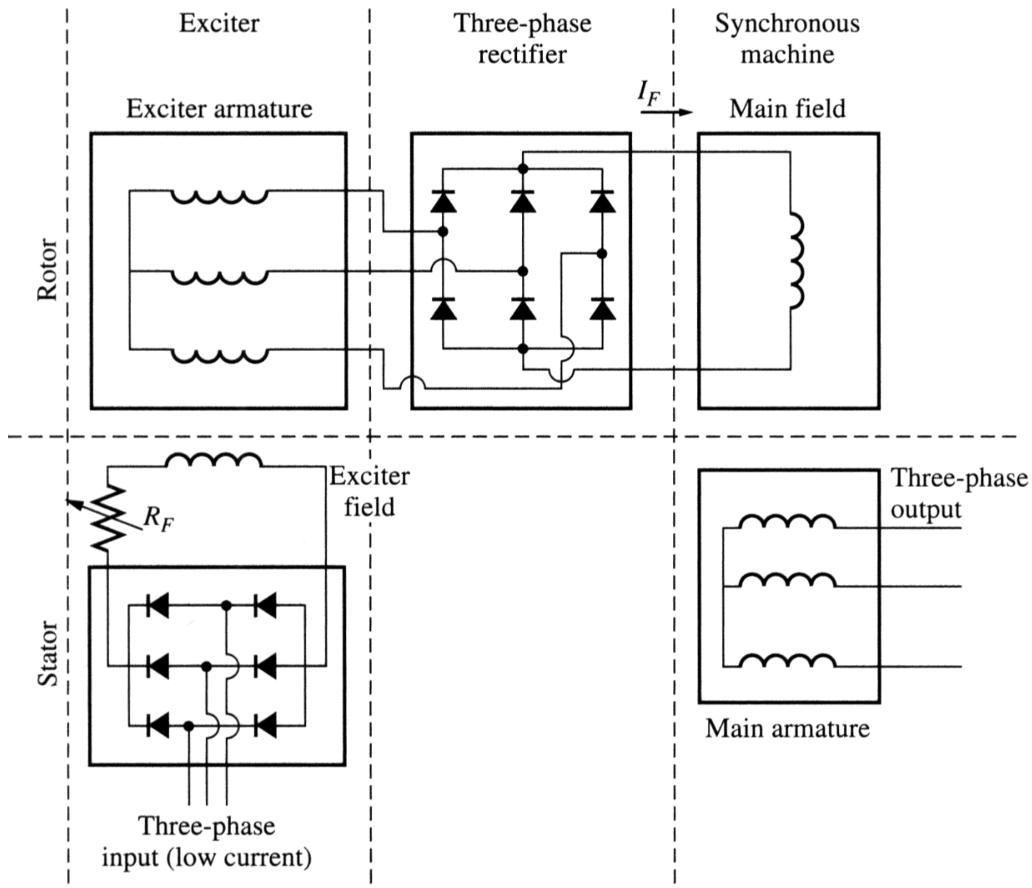
Construction of synchronous machines

- 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).

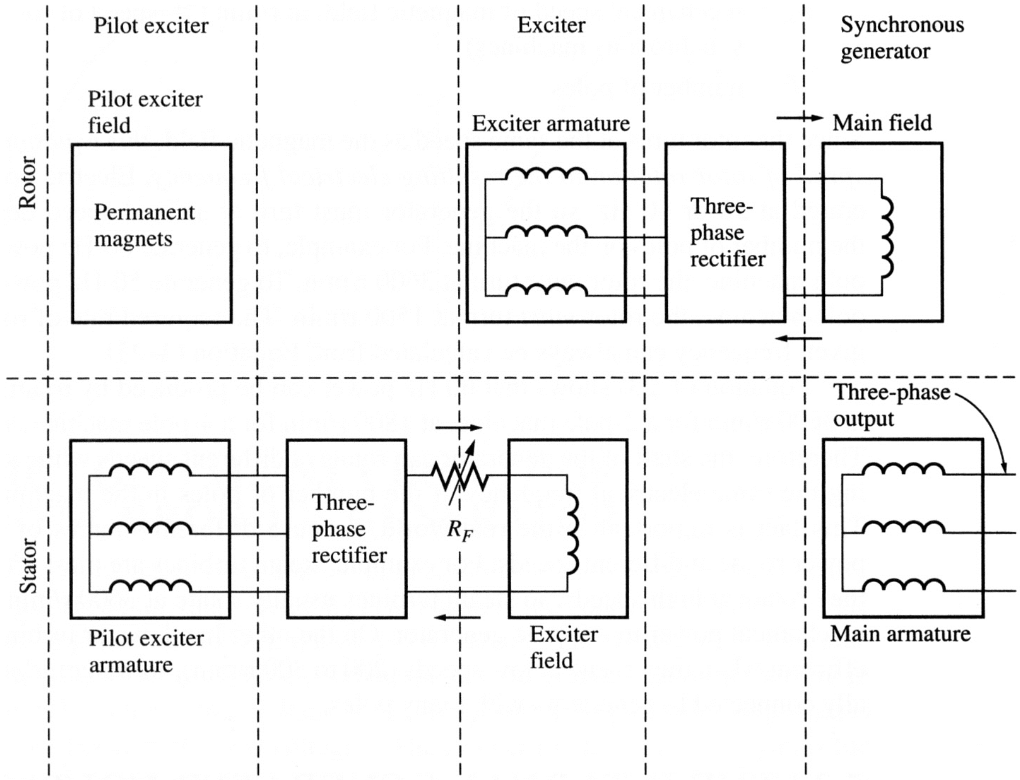
The output of the exciter's armature circuit (on the rotor) is rectified and used as the field current of the main machine.



Construction of synchronous machines

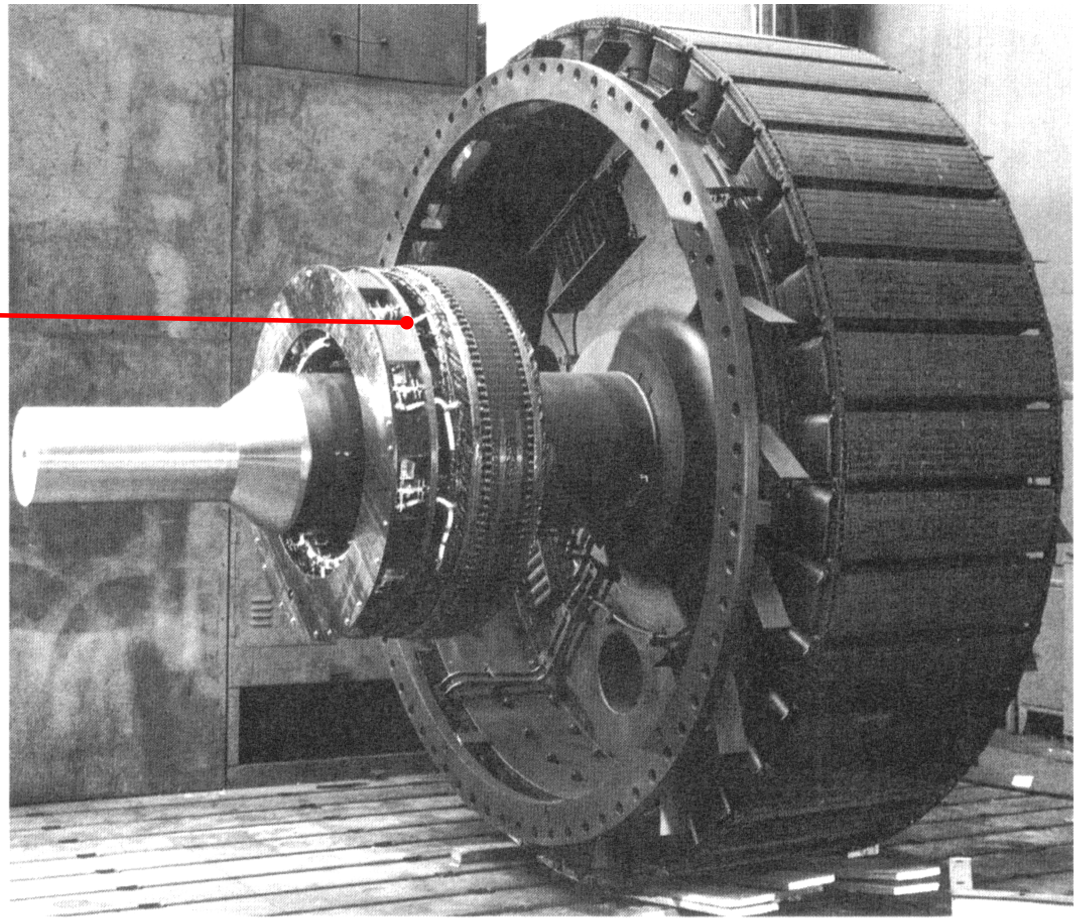
To make the excitation of a generator completely independent of any external power source, a small pilot exciter is often added to the circuit.

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

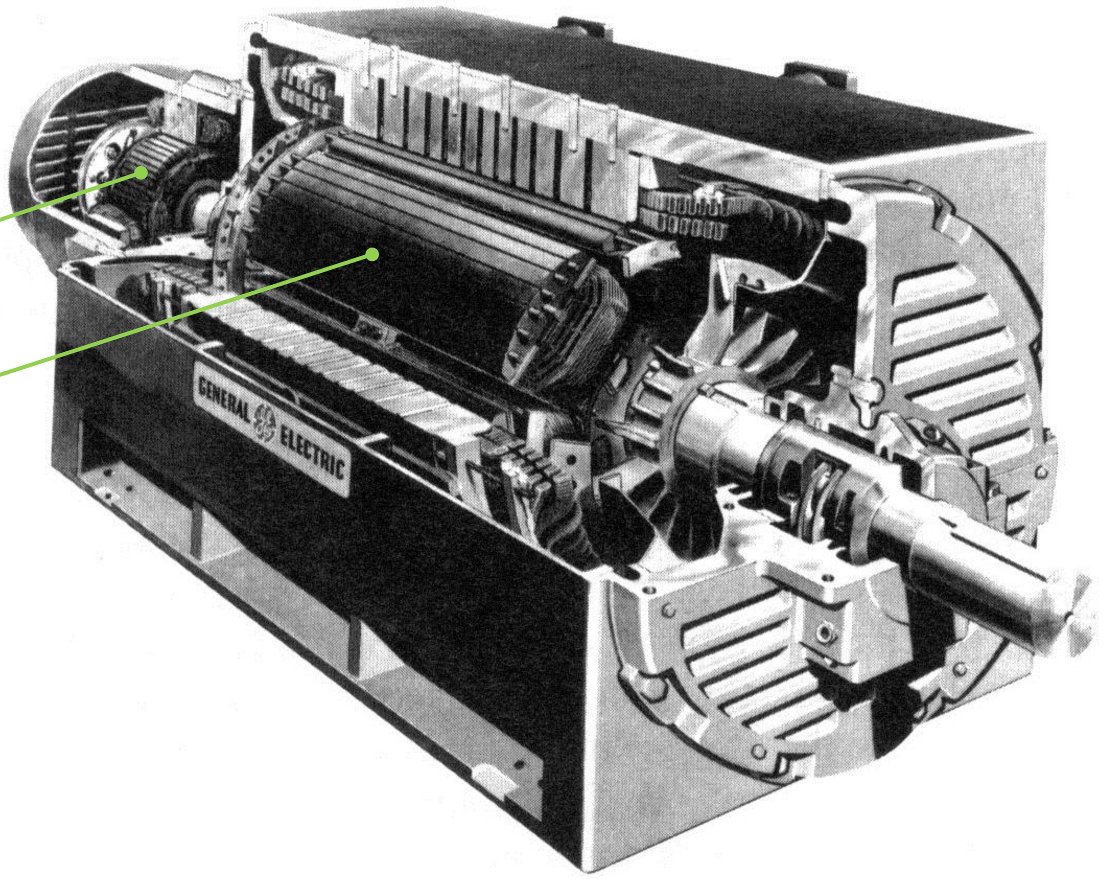
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.



Construction of synchronous machines

Exciter

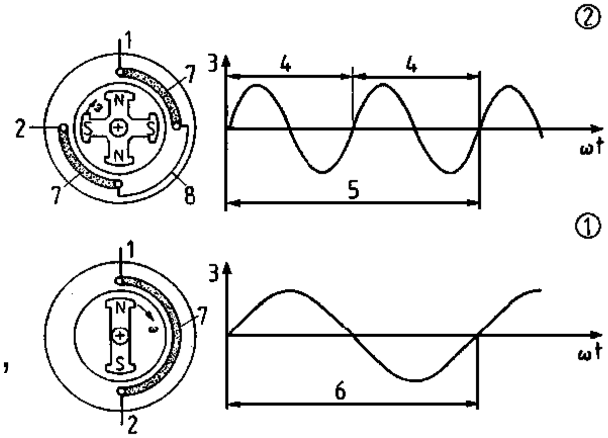
Salient poles.



Rotation speed of synchronous generator

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

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



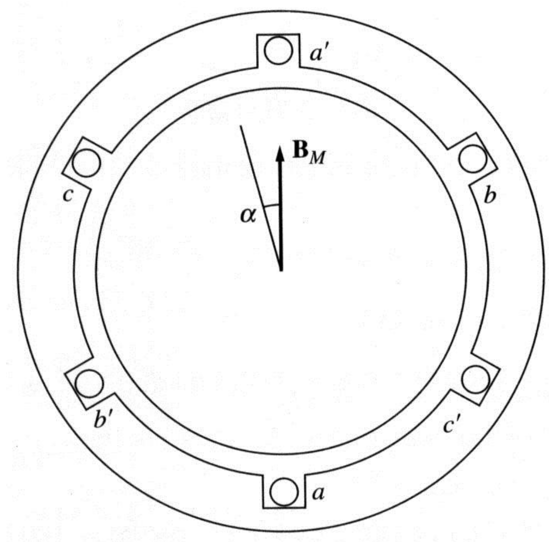
Where f_e is the electrical frequency, Hz;
n_m is the rotor speed of the machine,
p is the number of poles.

- 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:

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



Peak voltage:

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

RMS voltage:

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

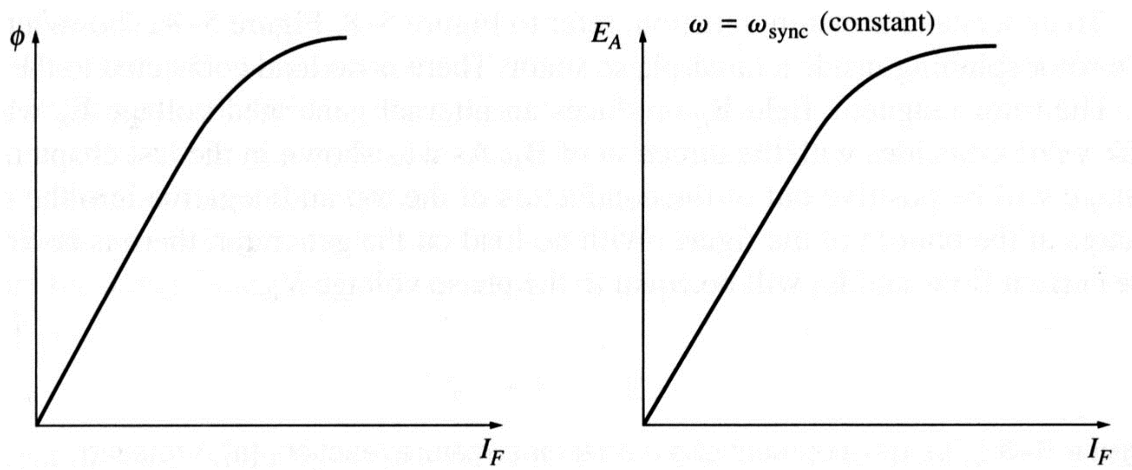
Internal generated voltage of a synchronous generator

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

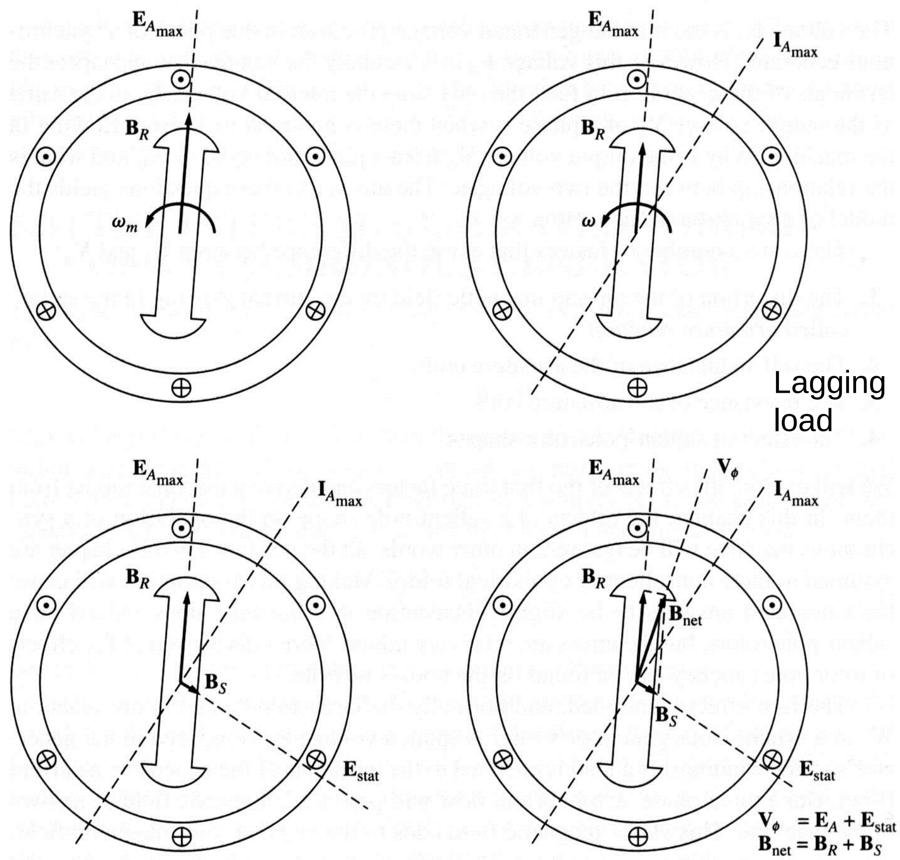
The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals. It equals to the output voltage V_ϕ only when there is no armature current in the machine. The reasons that the armature voltage E_A is not equal to the output voltage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

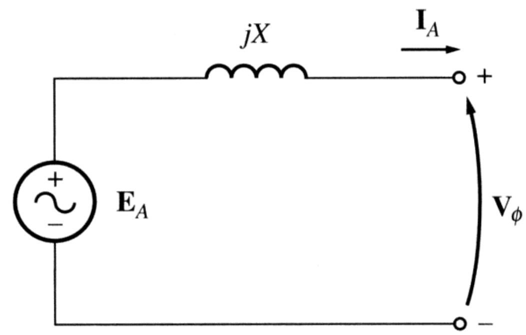
$$B_{net} = B_R + B_S$$

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

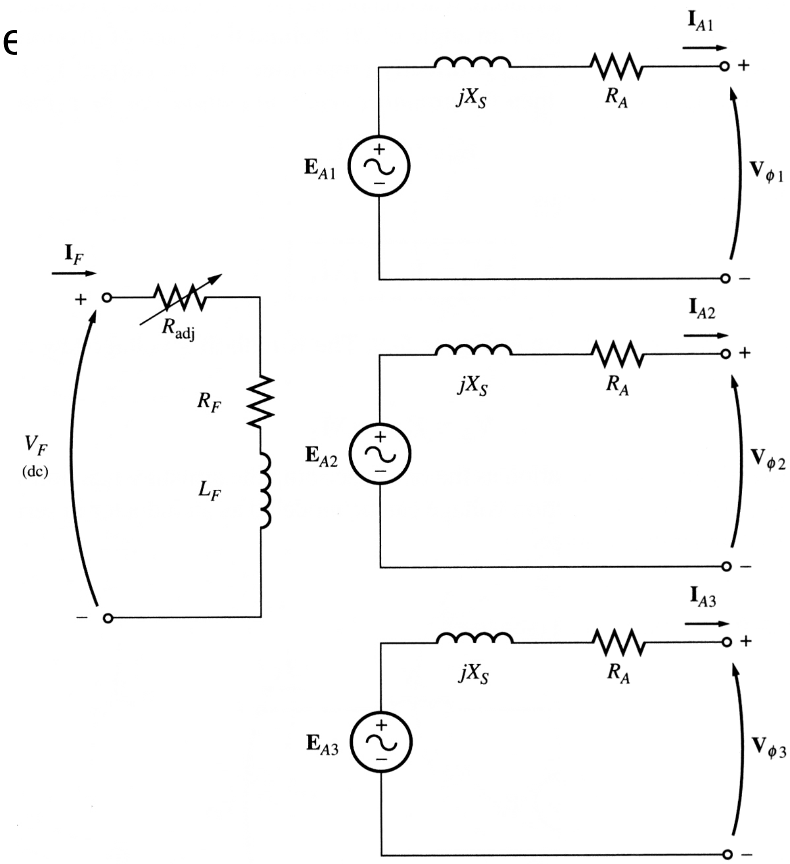
$$X_S = X + X_A$$

Therefore, the phase voltage is

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

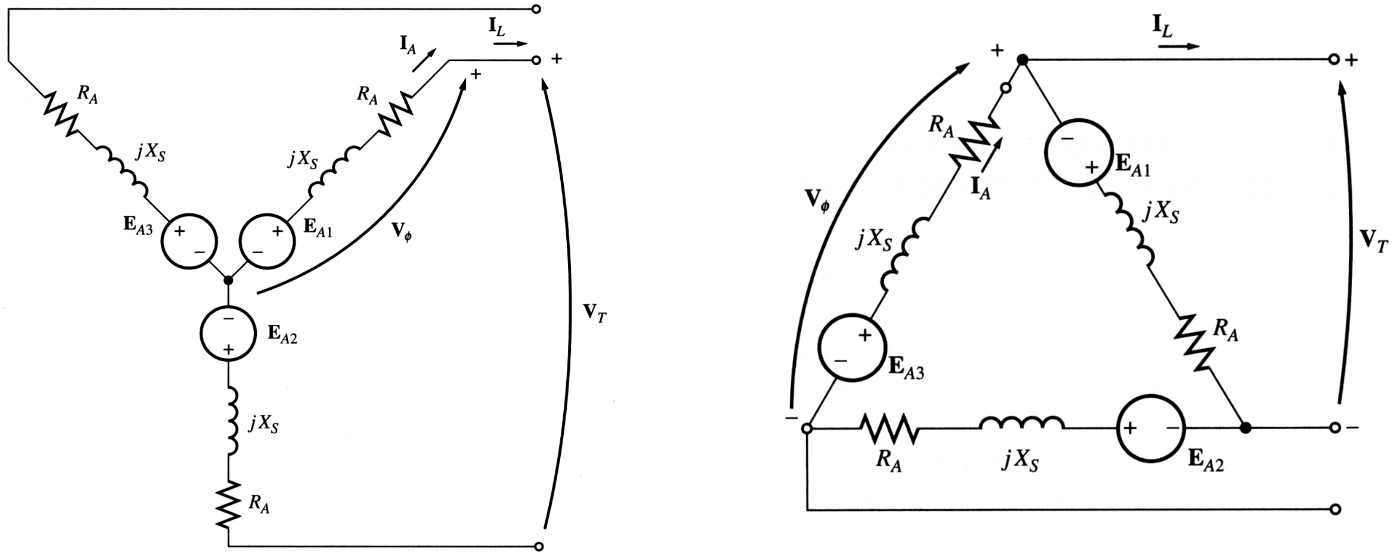
The equivalent circuit of a 3-phase synchronous generator is shown.

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:

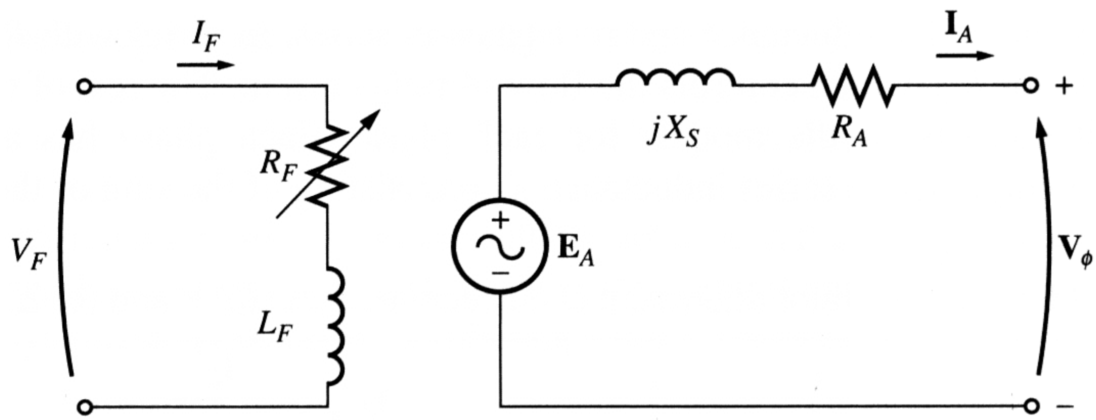


The terminal voltage will be

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

Equivalent circuit of a synchronous generator

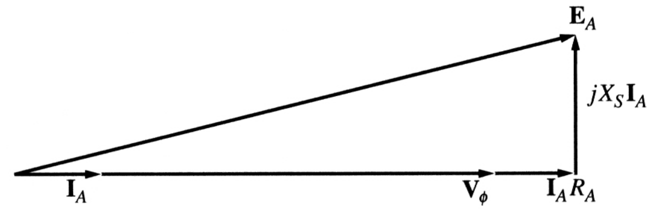
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



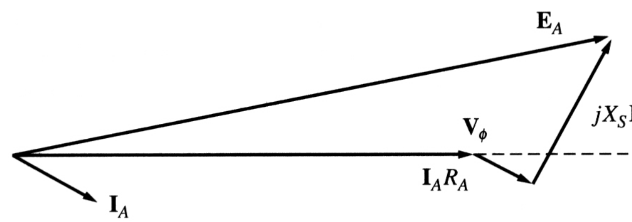
Phasor diagram of a synchronous generator (similar to that of a transformer)

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

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



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



Leading power factor (capacitive load).