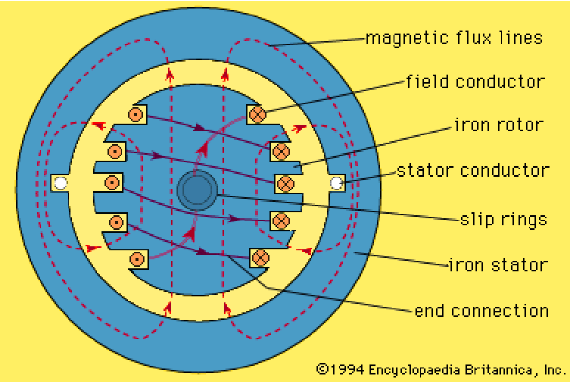
Introduction to Synchronous Machines

INTRODUCTION TO POLYPHASE SYNCHRONOUS MACHINES

Two types:

1-Cylindirical rotor: High speed, fuel or gas fired power plants

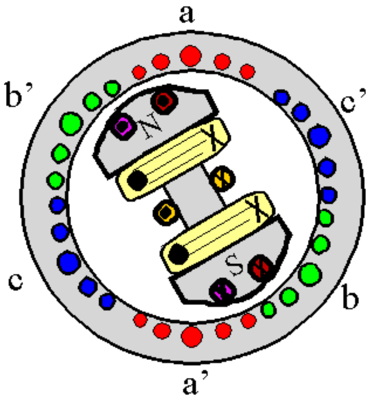
$$f_e = \frac{p}{2}\frac{n}{60} = \frac{p}{120}n$$

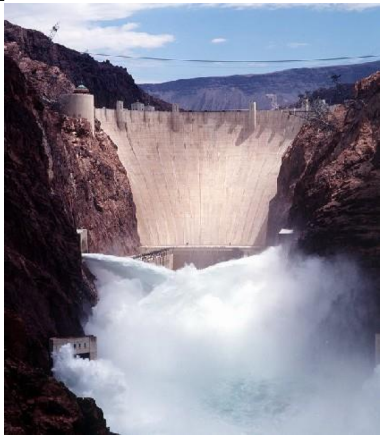


To produce 50 Hz electricity
***p*=2, *n*=3000 rpm**
***p*=4, *n*=1500 rpm**

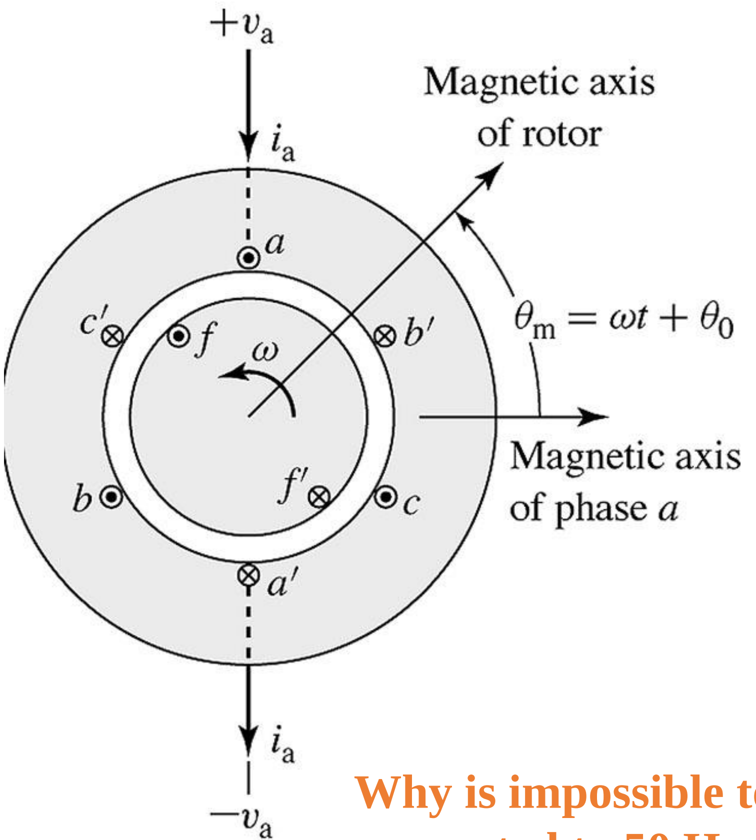
2-Salient-pole rotor: Low speed, hydroelectric power plants

To produce 50 Hz electricity
***p*=12, *n*=500 rpm**
***p*=24, *n*=250 rpm**





INTRODUCTION TO POLYPHASE SYNCHRONOUS MACHINES



How does a synchronous generator work?

1- Apply DC current to rotor winding (field winding)
2- Rotate the shaft (rotor) with constant speed.
3- Rotor magnetic field will create flux linkages in stator coils and as a result voltage will be produced because of Faraday's Law.

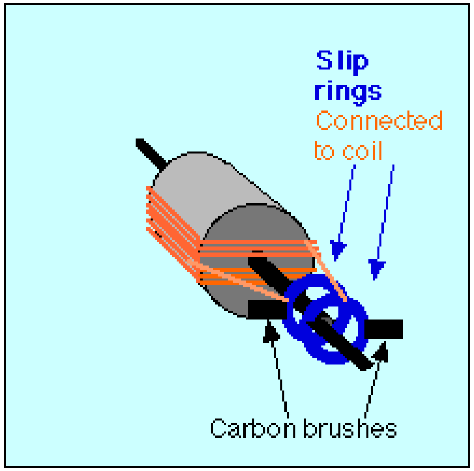
Why is impossible to rotate a synchronous motor when it is connected to 50 Hz electric power?

Because before connecting to supply, the shaft speed of rotor is zero. If the motor is two-pole, when it is connected to 50 Hz supply it suddenly needs to rotate 3000 rpm. This is impossible for large synchronous motors.

INTRODUCTION TO POLYPHASE SYNCHRONOUS MACHINES

How is DC current applied to the rotor?

1- Slip Rings



Note: **Magnetic field of rotor can also be produced by permanent magnets for small machine applications**

2- Brushless Excitation System:

Excitation supplied from ac exciter and solid rectifiers. The alternator of the ac exciter and the rectification system are on the rotor. The current is supplied directly to the field-winding without the need to slip rings.

Construction of synchronous machines

Synchronous machines are AC machines that have a field circuit supplied by an external DC source.

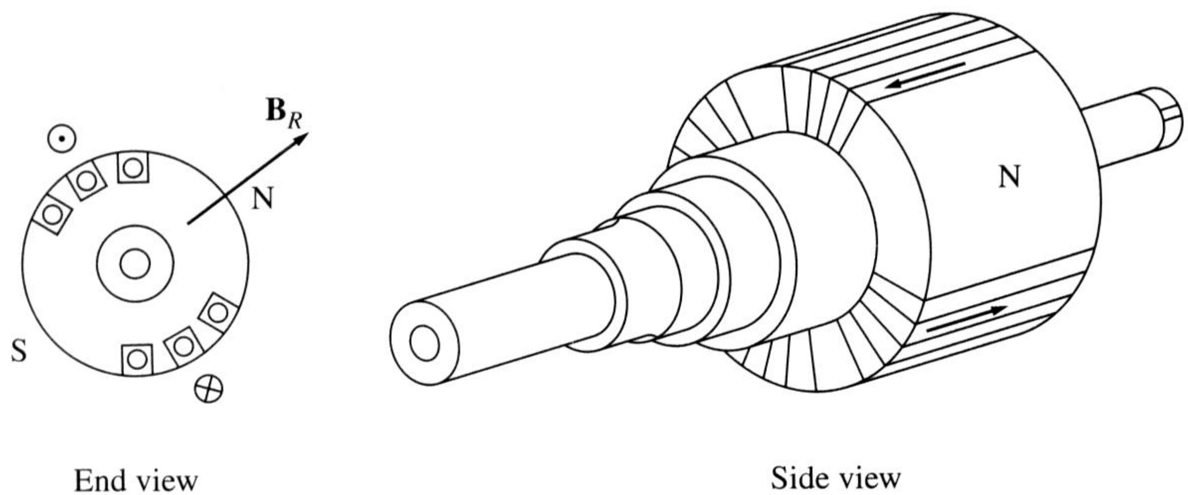
In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then turned by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

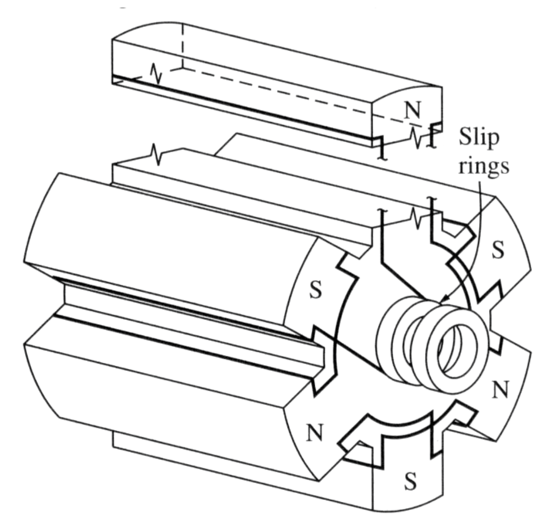
In a synchronous motor, a 3-phase set of stator currents produces a rotating magnetic field causing the rotor magnetic field to align with it. The rotor magnetic field is produced by a DC current applied to the rotor winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

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.





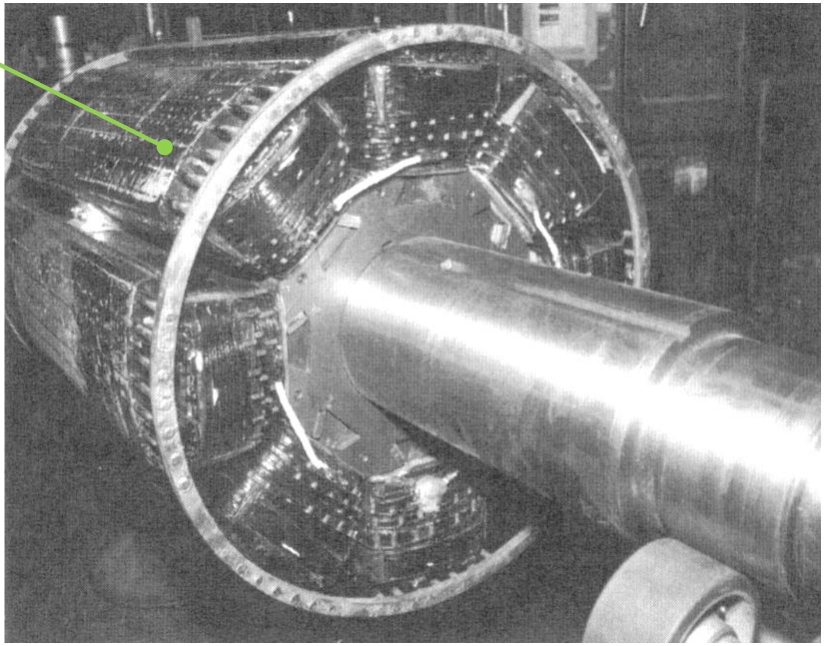
Non-salient-pole rotor: usually two- and four-pole rotors.

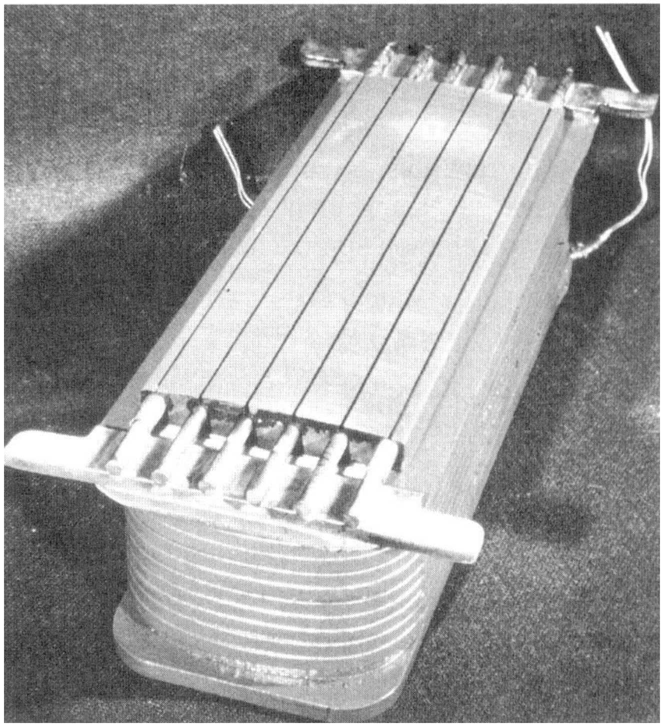
Salient-pole rotor: four and more poles.

Rotors are made laminated to reduce eddy current losses.

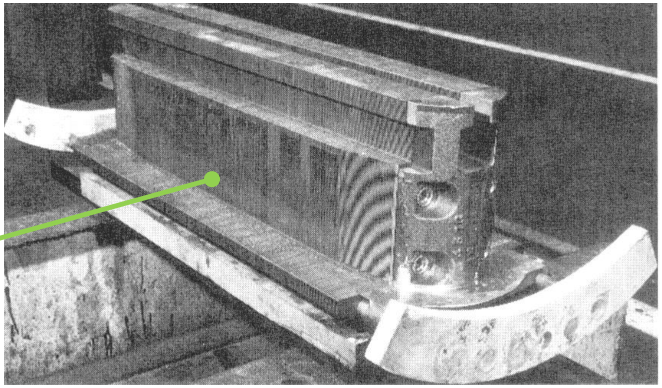
Construction of synchronous machines

A synchronous rotor with 8 salient poles





Salient pole with field windings



Salient pole without field windings – observe laminations

Construction of synchronous machines

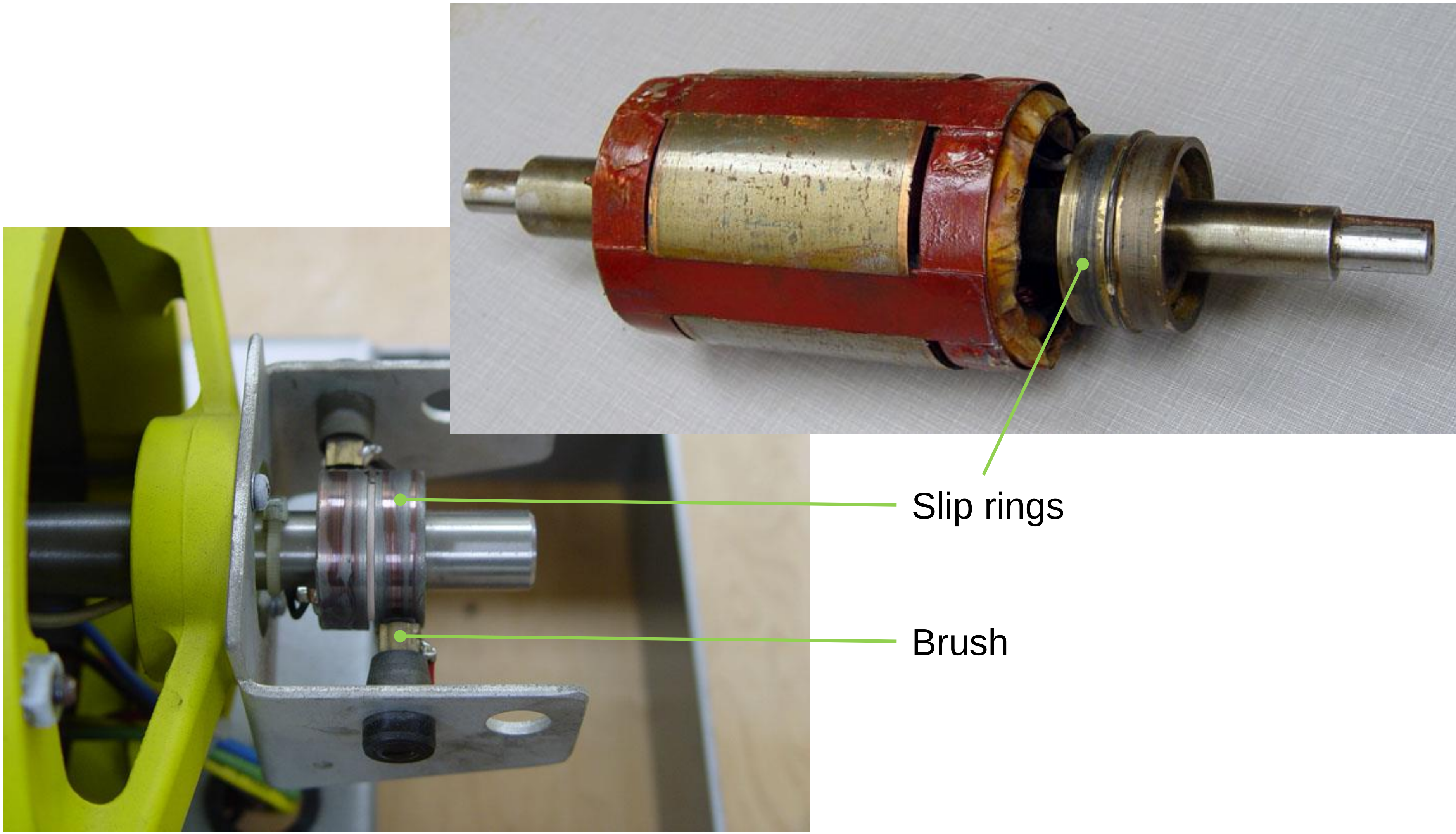
Two common approaches are used to supply a DC current to the field circuits on the rotating rotor:

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. One end of a DC rotor winding is connected to each of the two slip rings on the machine's shaft. Graphite-like carbon brushes connected to DC terminals ride on each slip ring supplying DC voltage to field windings regardless the position or speed of the rotor.

Construction of synchronous machines



Construction of synchronous machines

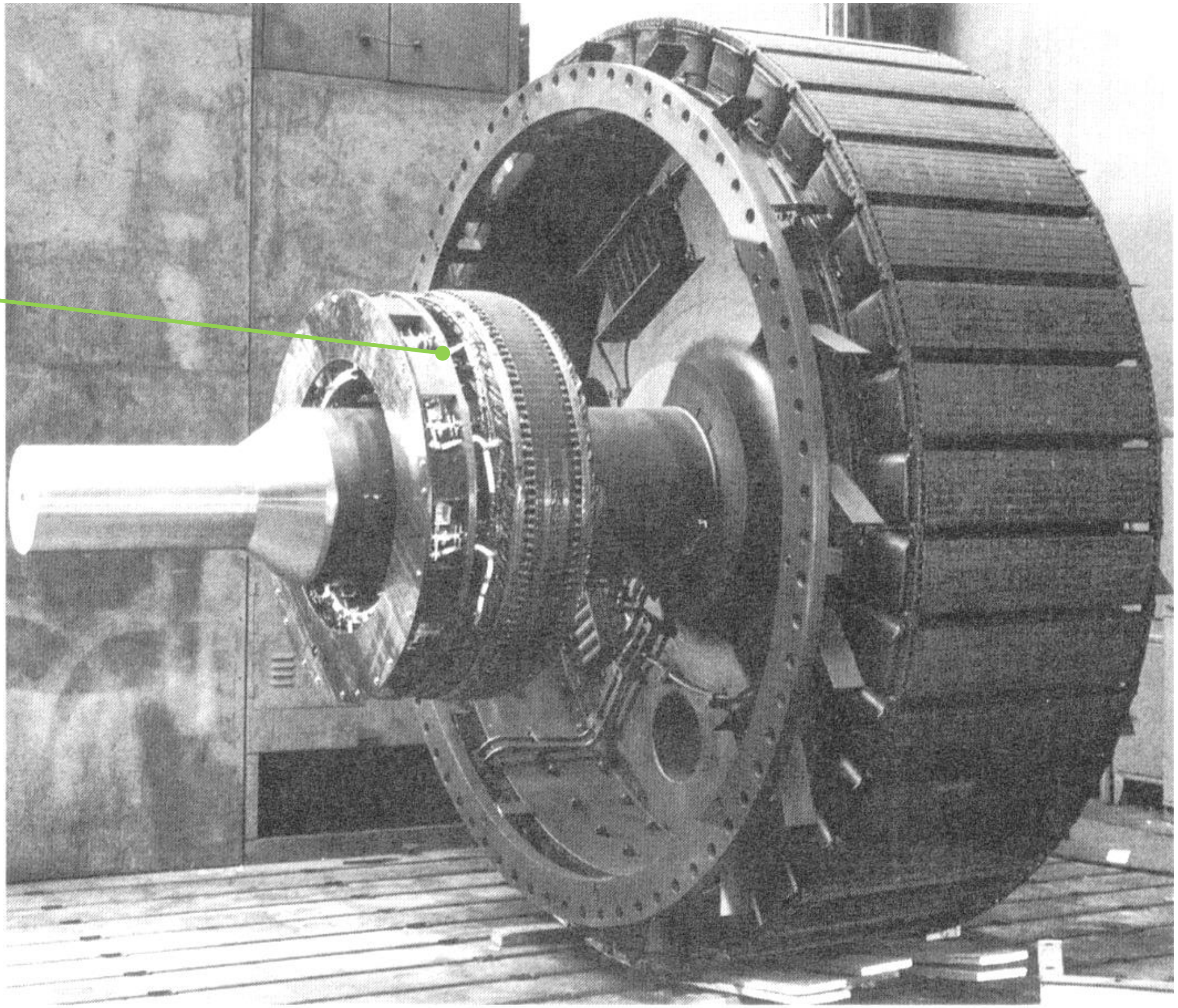
Slip rings and brushes have certain disadvantages: increased friction and wear (therefore, needed maintenance), brush voltage drop can introduce significant power losses. Still this approach is used in most *small* synchronous machines.

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).

Since no mechanical contact occurs between the rotor and the stator, exciters of this type require much less maintenance.

Construction of synchronous machines

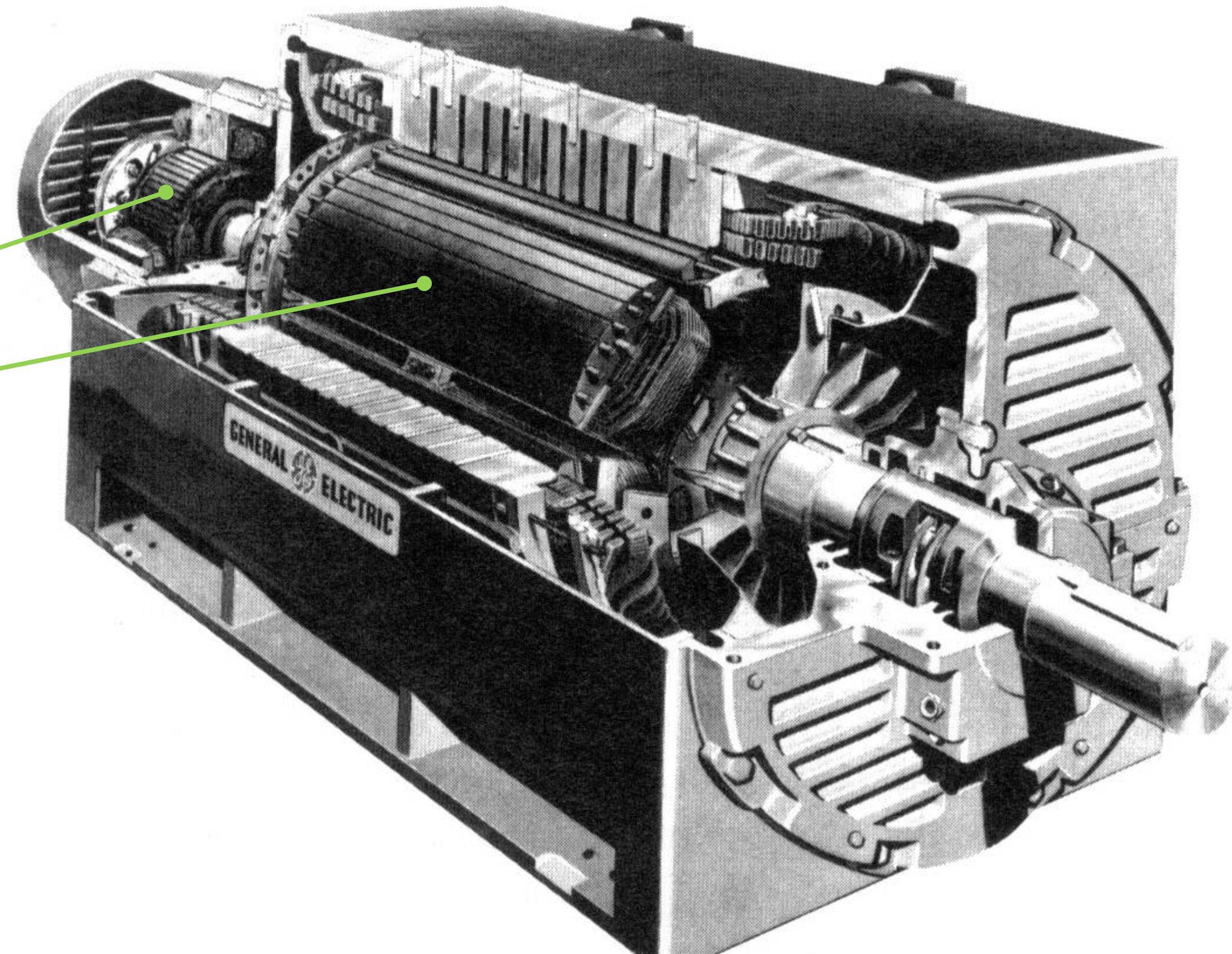
A rotor of large synchronous machine with a brushless exciter mounted on the same shaft.



Many synchronous generators having brushless exciters also include slip rings and brushes to provide emergency source of the field DC current.

Construction of synchronous machines

A large synchronous machine with the exciter and salient poles.



Rotation speed of synchronous generator

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

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

Where f_e is the electrical frequency, Hz;
n_m is mechanical speed of magnetic field (rotor speed for synchronous machine), rpm;
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 and turn 2-pole generators.
Water turbines are most efficient when rotating at low speeds (200-300 rpm); therefore, they usually turn generators with many poles.

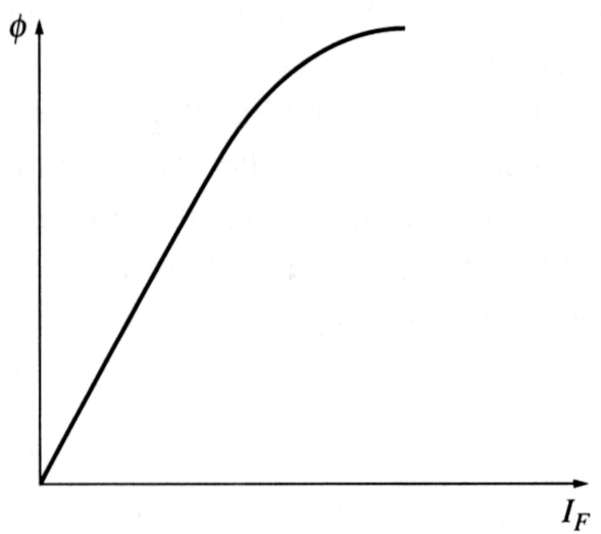
Internal generated voltage of a synchronous generator

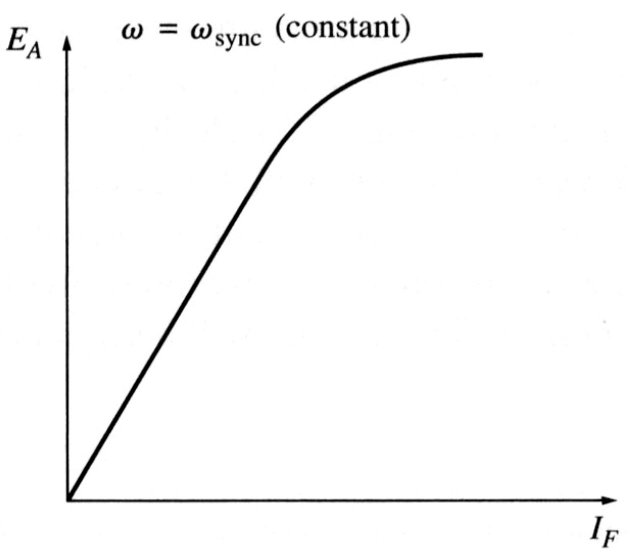
The magnitude of internal generated voltage induced in a given stator is

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

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

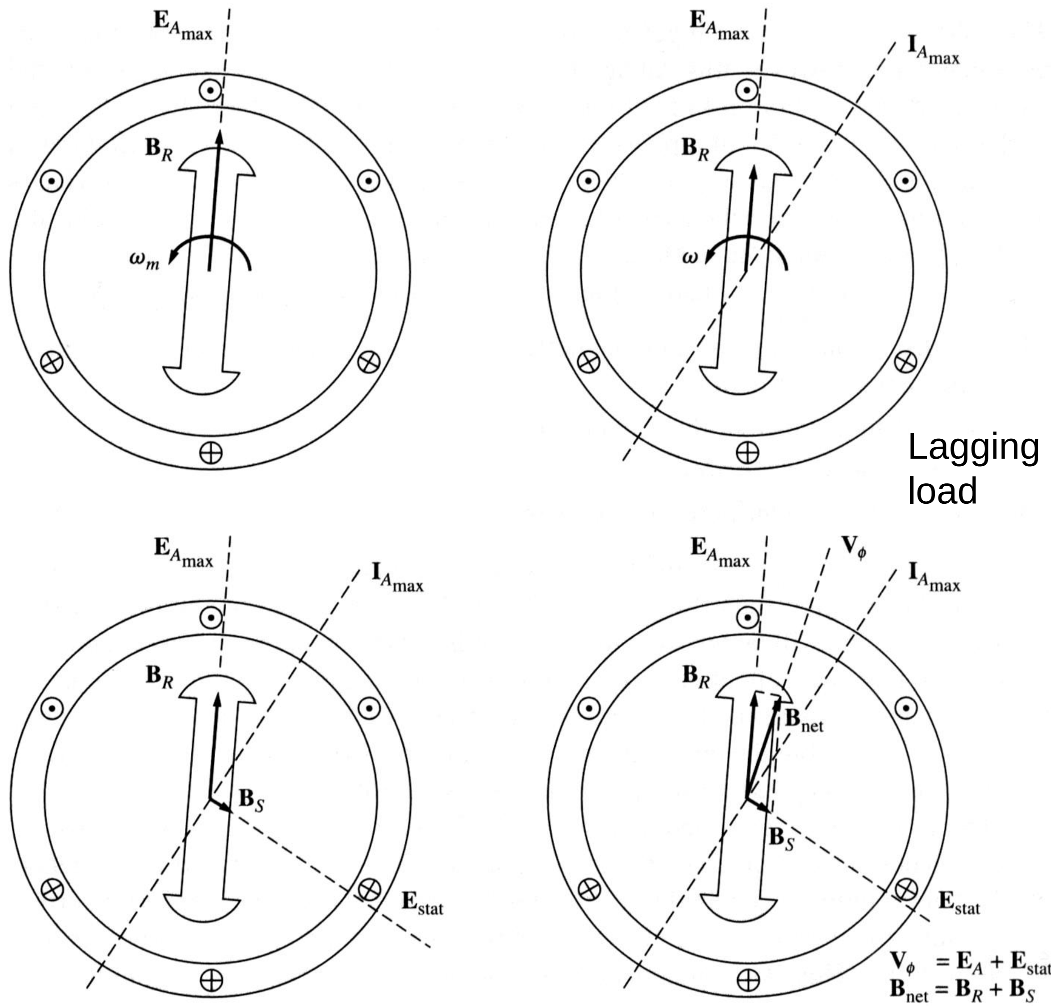
The internally generated voltage in a single phase of a synchronous machine E_A is not usually the voltage appearing at its terminals. It equals to the output voltage V_ϕ only when there is no armature current in the machine. The reasons that the armature voltage E_A is not equal to the output voltage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

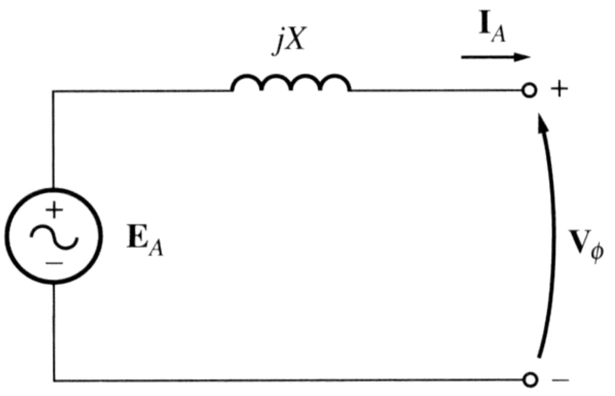
Equivalent circuit of a synchronous generator

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

$$E_{stat} = -jXI_A$$

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

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

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

Equivalent circuit of a synchronous generator

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

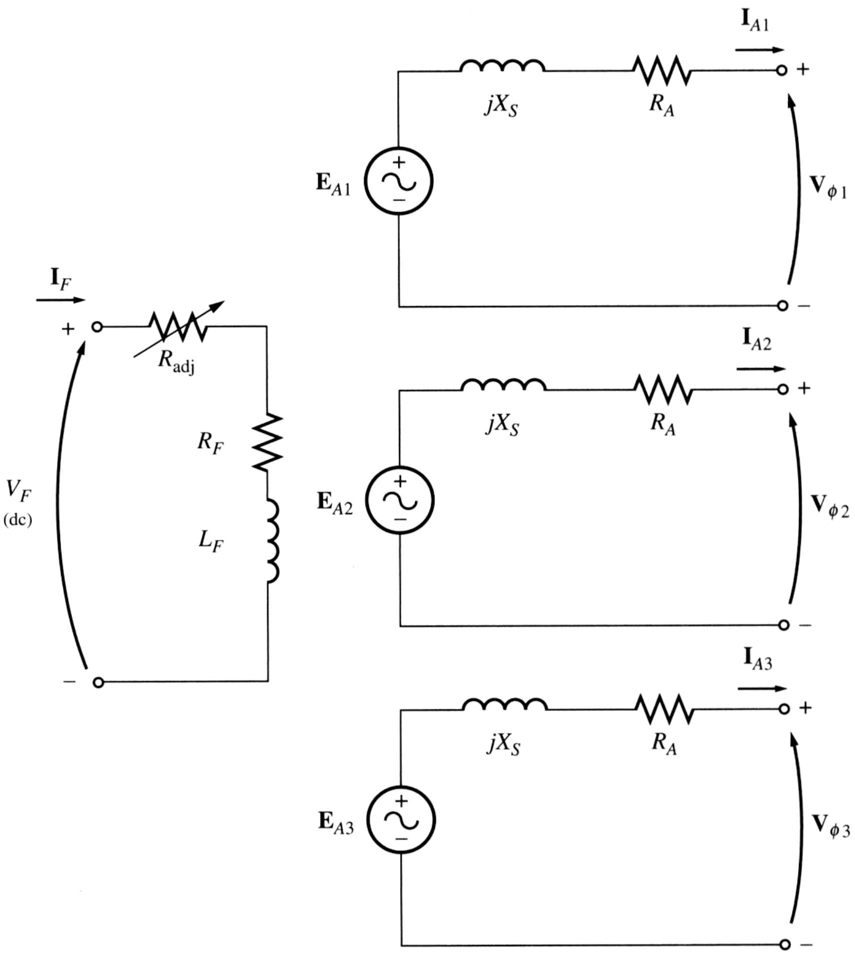
$$X_S = X + X_A \qquad (7.18.1)$$

Therefore, the phase voltage is

$$\boxed{V_\phi = E_A - jX_S I_A - RI_A} \qquad (7.18.2)$$

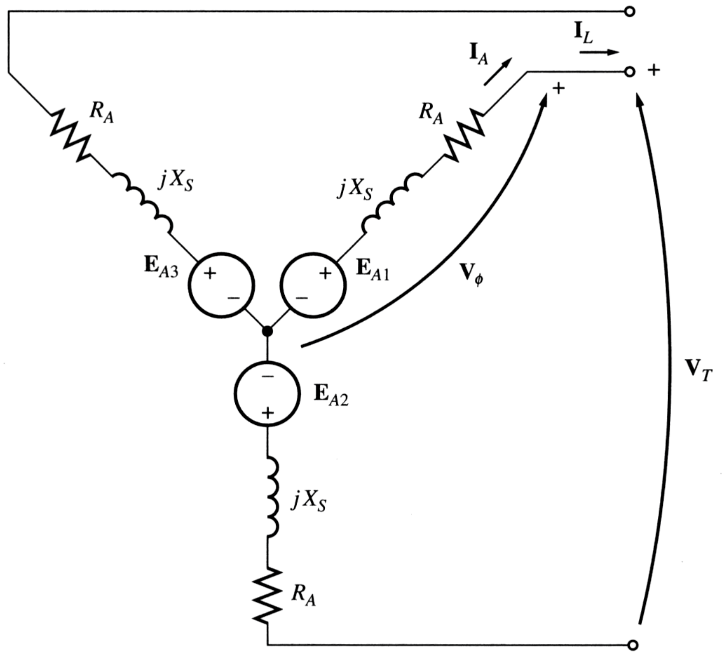
The equivalent circuit of a 3-phase synchronous generator is shown.

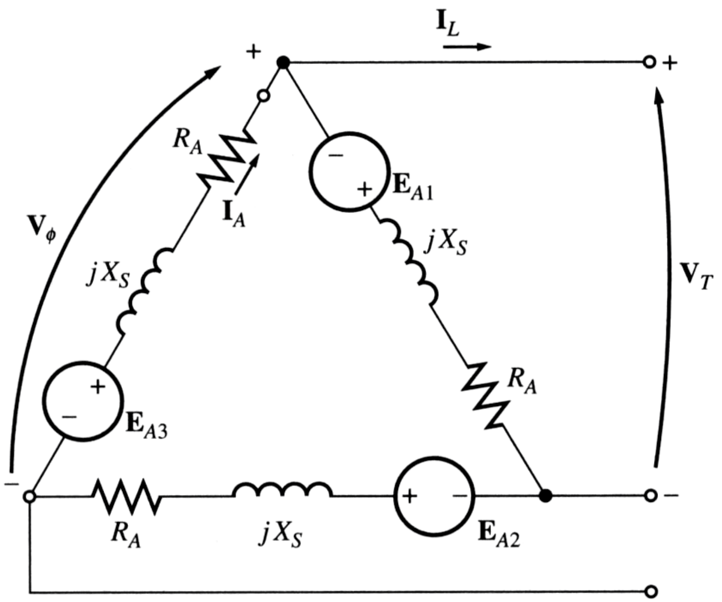
The adjustable resistor R_{adj} controls the field current and, therefore, the rotor magnetic field.



Equivalent circuit of a synchronous generator

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





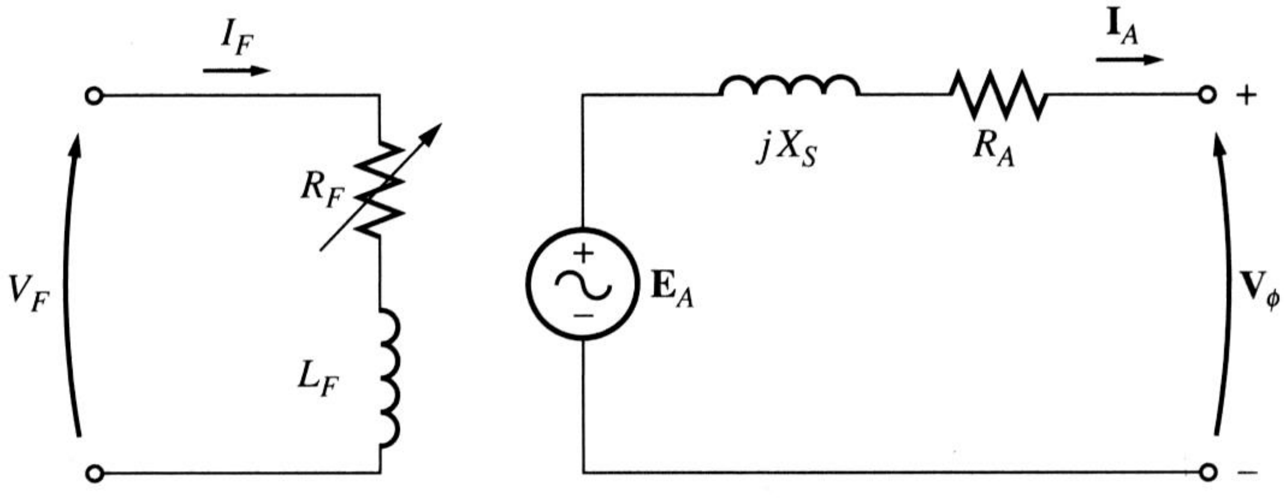
The terminal voltage will be

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

Equivalent circuit of a synchronous generator

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

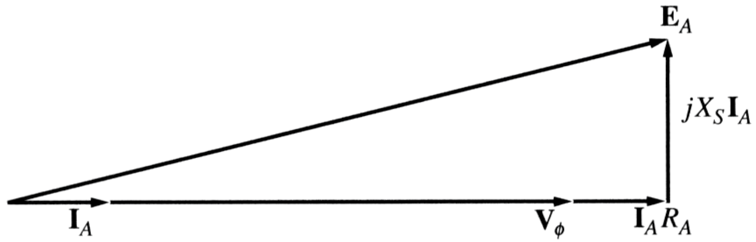
Since – for balanced loads – the three phases of a synchronous generator are identical except for phase angles, per-phase equivalent circuits are often used.



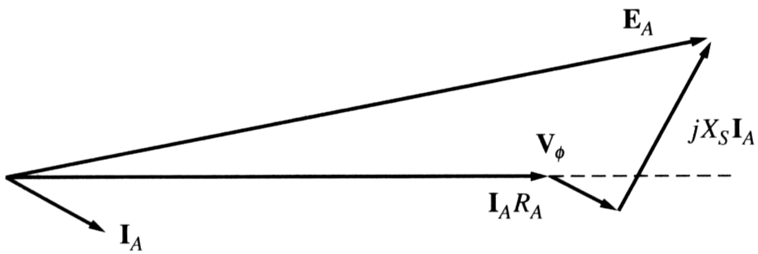
Phasor diagram of a synchronous generator

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.

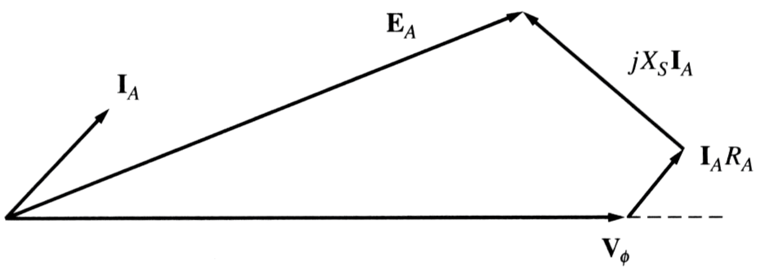
A phasor diagram of a synchronous generator with a unity power factor (resistive load)



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).



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

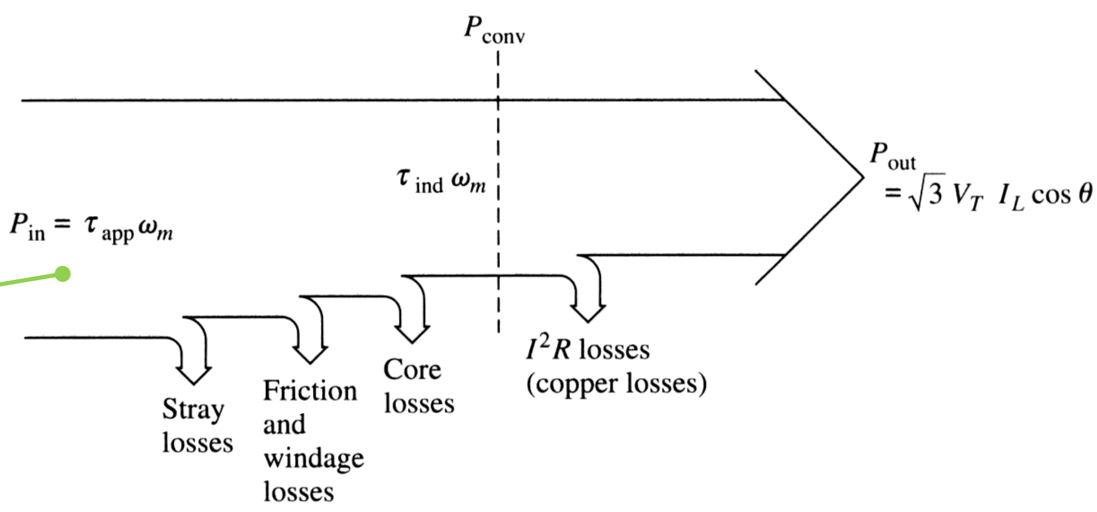
$$P_{in} = \tau_{app}\omega_m \tag{7.22.1}$$

is partially converted to electricity

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

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

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

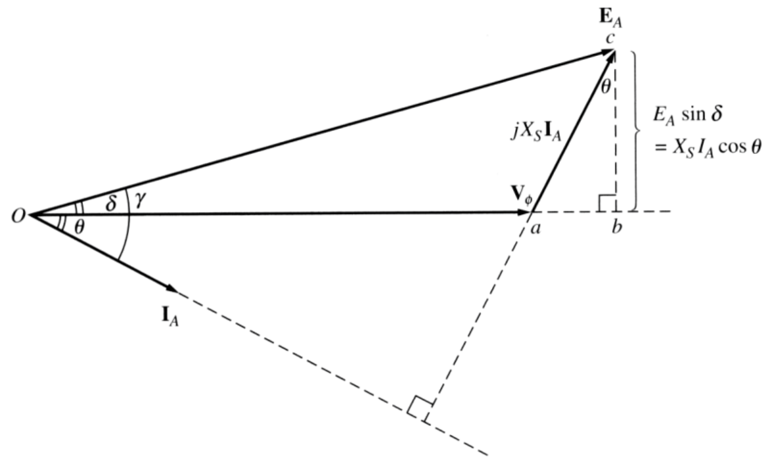
The reactive output power of the synchronous generator is

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

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

$$\boxed{P_{out} \approx \frac{3V_\phi E_A \sin\delta}{X_S}} \tag{7.24.1}$$

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

$$P_{conv} \approx P_{out} \tag{7.24.2}$$

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 $\delta = 90^0$:

$$P_{\max} = \frac{3V_\phi E_A}{X_S} \tag{7.24.3}$$

Power and torque in synchronous generators

The maximum power specified by (7.24.3) 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

$$\tau_{ind} = kB_R \times B_S = kB_R \times B_{net} = kB_R B_{net} \sin\delta \qquad (7.25.1)$$

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

$$\boxed{\tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_S}} \qquad (7.25.2)$$

Measuring parameters of synchronous generator model

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

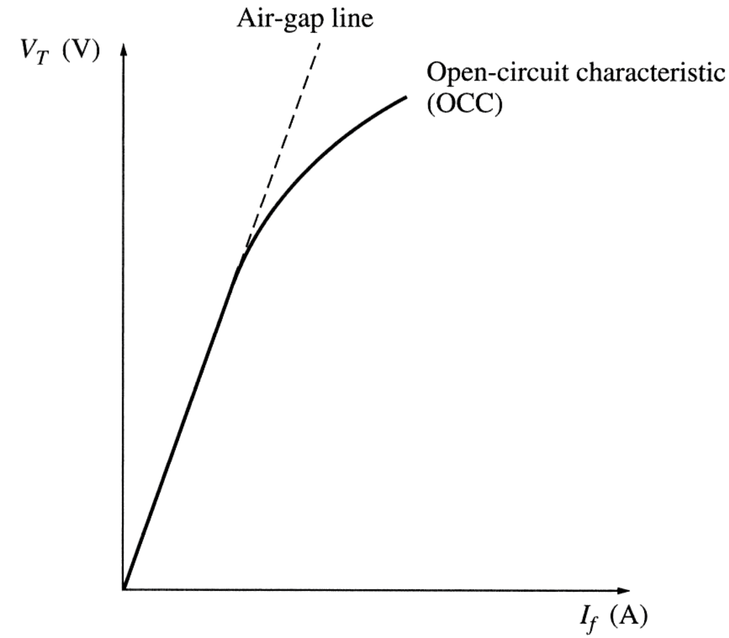
1. The relationship between field current and flux (and therefore between the field current I_F and the internal generated voltage E_A);
2. The synchronous reactance;
3. The armature resistance.

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.



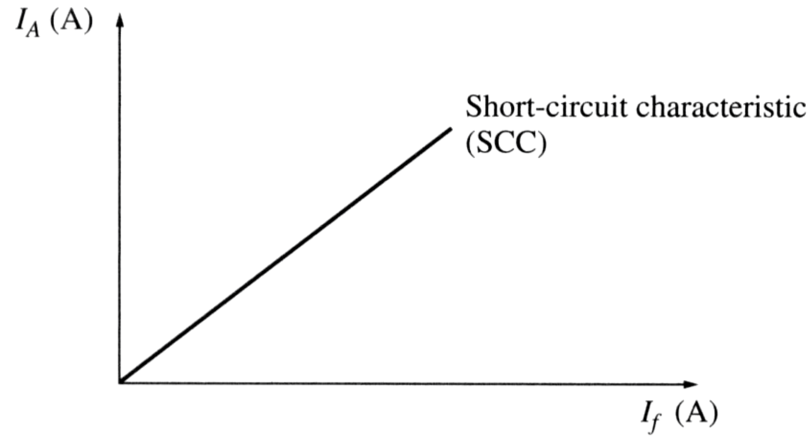
We conduct next the short-circuit test on the synchronous generator: the generator is rotated at the rated speed, all the terminals are short-circuited through ammeters, the field current is set to zero first. Next, the field current is increased in steps and the armature current I_A is measured as the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

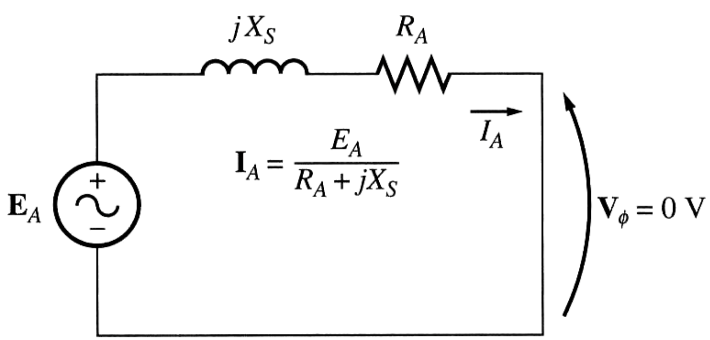
Measuring parameters of synchronous generator model

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

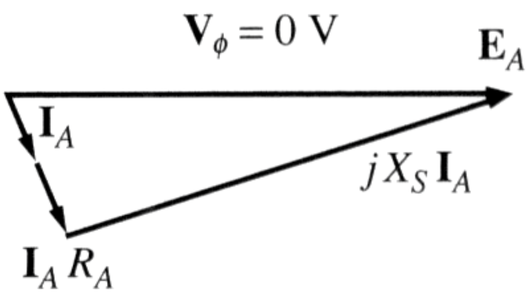
$$I_A = \frac{E_A}{\sqrt{R_A^2 + X_S^2}} \qquad (7.28.1)$$



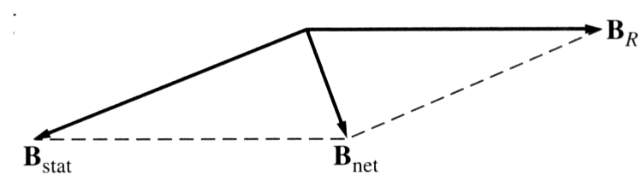
The equivalent generator's circuit during SC



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

$$X_S \approx \frac{E_A}{I_{A,SC}} \tag{7.29.1}$$

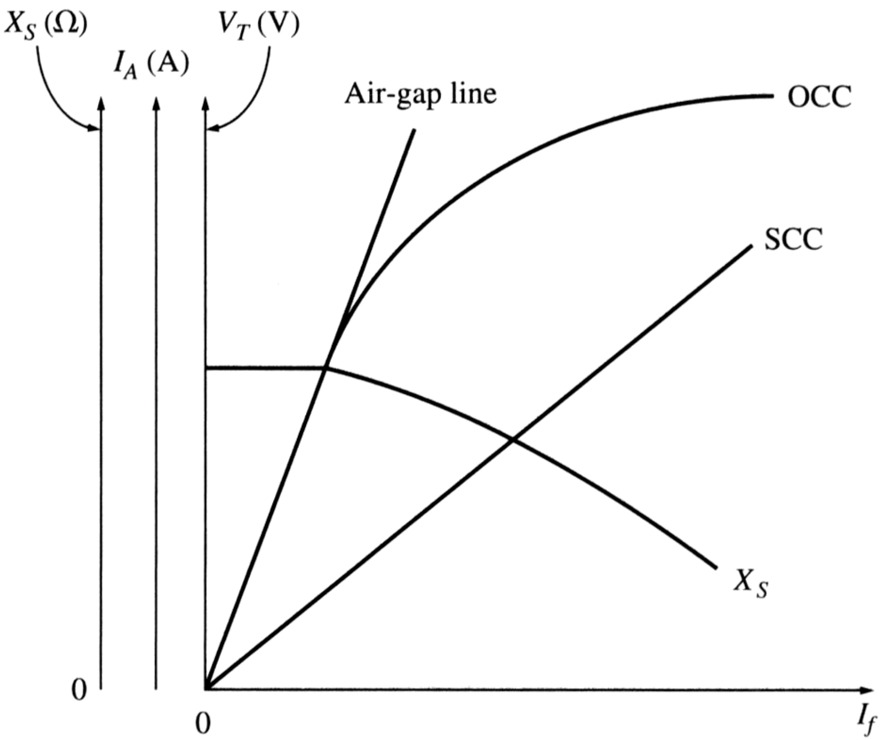
Since the internal machine impedance is

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_{A,SC}} \approx X_S \qquad \{\text{since } X_S \gg R_A\} \tag{7.29.2}$$

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.

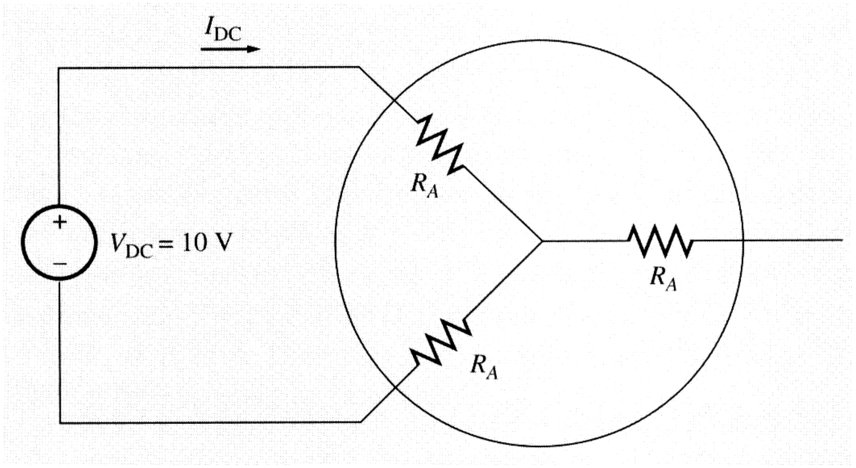
Find the generator's model at the rated conditions (i.e., the armature resistance and the approximate synchronous reactance).

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

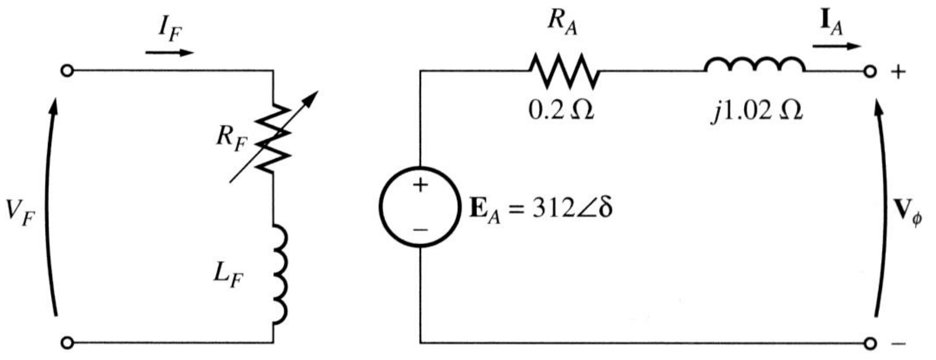
$$E_A = V_{\phi,OC} = \frac{V_T}{\sqrt{3}} = \frac{540}{\sqrt{3}} = 311.8\ V$$

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 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 countertorque?
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

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

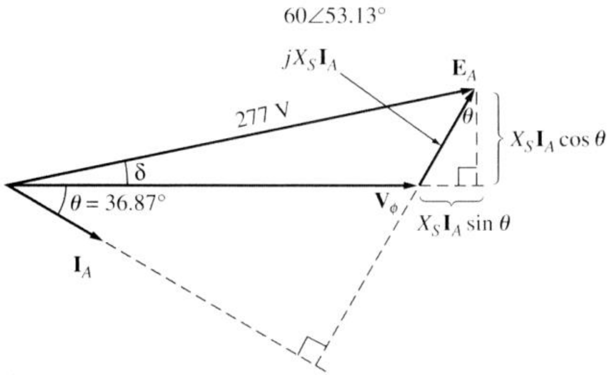
At no load, the armature current I_A = 0 and the internal generated voltage is E_A = 277 V and it is constant since the field current was initially adjusted that way.

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

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 0^0, 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:

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

Then:

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

Since the generator is Y-connected,

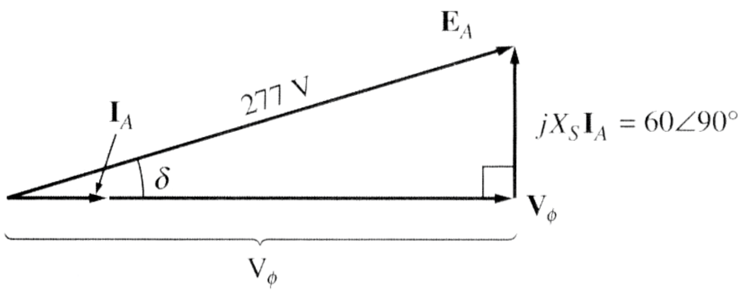
$$V_T = \sqrt{3} V_\phi = 410\, V$$

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:

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

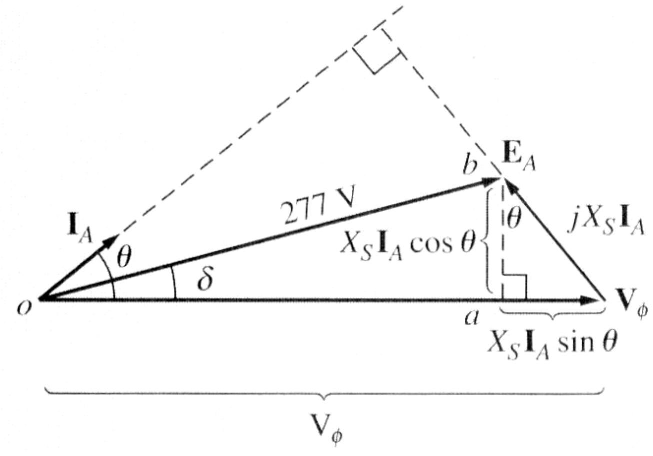
and $$V_T = \sqrt{3} V_\phi = 468.4\ V$$



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

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

The Synchronous generator operating alone: Example

The induced countertorque of the generator is

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

e. The voltage regulation of the generator is

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

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

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

Terminal characteristics of synchronous generators

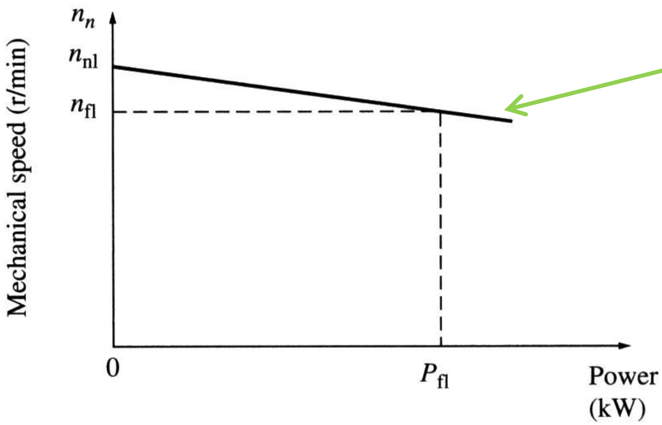
All generators are driven by a prime mover, such as a steam, gas, water, wind turbines, diesel engines, etc. Regardless the power source, most of prime movers tend to slow down with increasing the load. This decrease in speed is usually nonlinear but governor mechanisms of some type may be included to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

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

$$\boxed{SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \cdot 100\%} \tag{7.44.1}$$

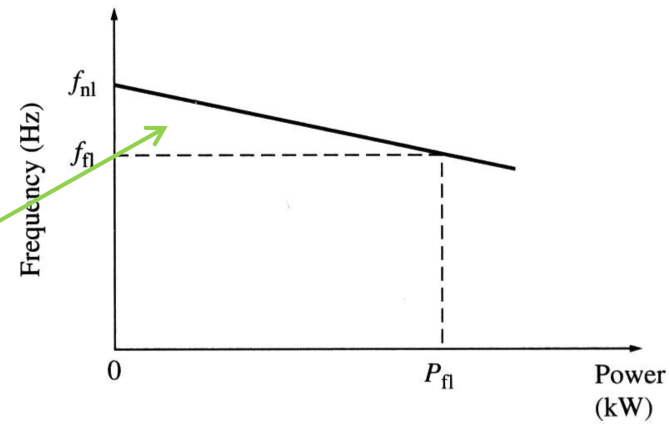
Most prime movers have a speed drop from 2% to 4%. Most governors have a mechanism to adjust the turbine's no-load speed (set-point adjustment).

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

$$f_e = \frac{n_m P}{120} \tag{7.45.1}$$

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

$$\boxed{P = s_p\left(f_{nl} - f_{sys}\right)} \tag{7.45.2}$$

Slope of curve, W/Hz

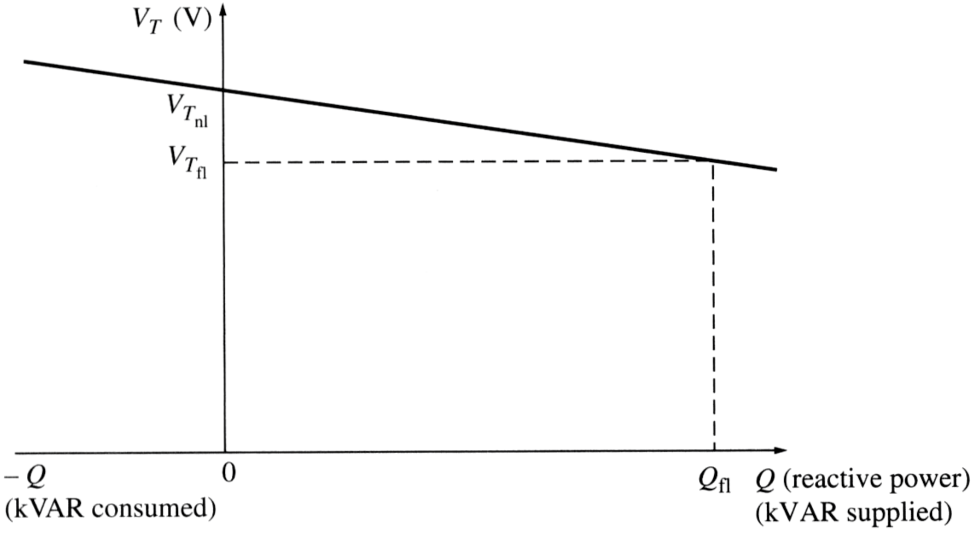
Operating frequency of the system

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.

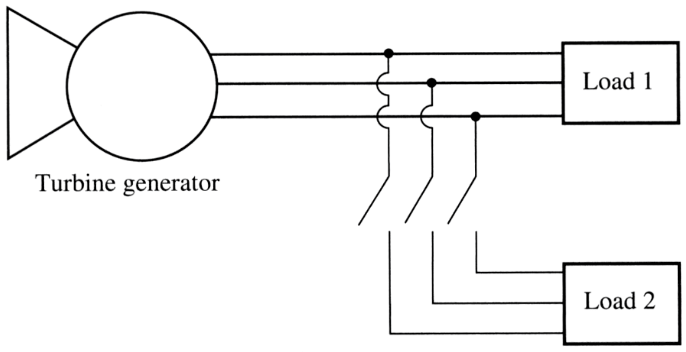


When a generator is operating alone supplying the load:

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

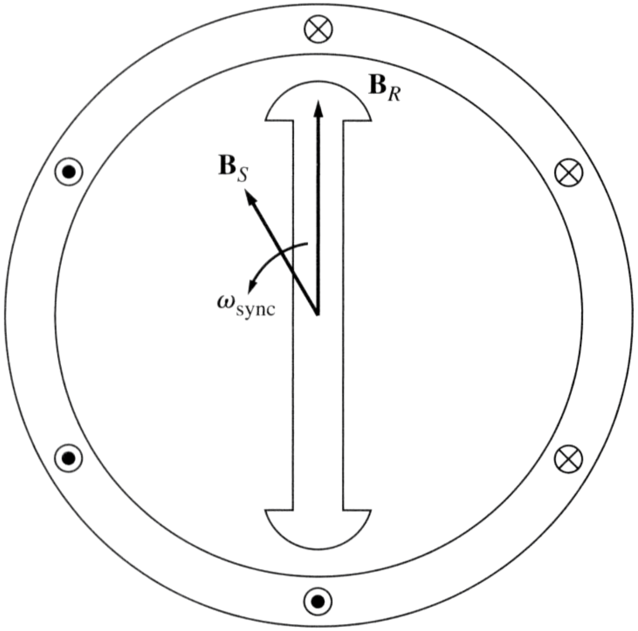
$$f_{sys} = f_{nl} - \frac{P}{s_p} = 61 - \frac{1.8}{1} = 59.2\ Hz$$

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.

Synchronous motors

The field current I_F of the motor produces a steady-state rotor magnetic field B_R. A 3-phase set of voltages applied to the stator produces a 3-phase current flow in the windings.

A 3-phase set of currents in an armature winding produces a uniform rotating magnetic field B_s.



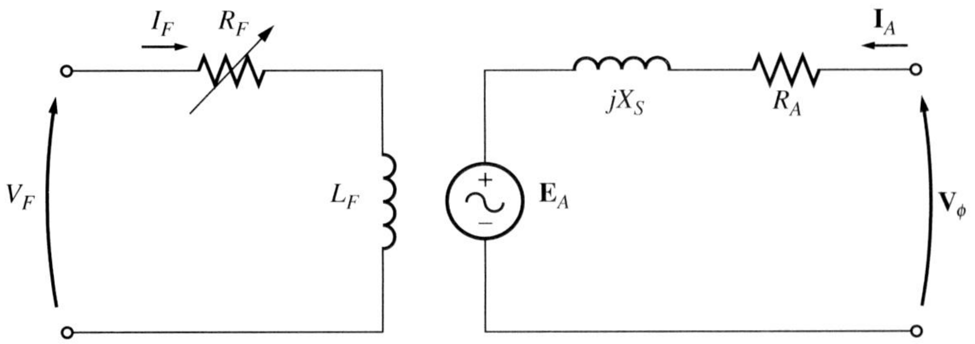
$$\tau_{\text{ind}} = k\,\mathbf{B}_R \times \mathbf{B}_S$$
$$= \text{counterclockwise}$$

Two magnetic fields are present in the machine, and the rotor field tends to align with the stator magnetic field. Since the stator magnetic field is rotating, the rotor magnetic field will try to catch up pulling the rotor.

The larger the angle between two magnetic fields (up to a certain maximum), the greater the torque on the rotor of the machine.

Synchronous motor equivalent circuit

A synchronous motor has the same equivalent circuit as synchronous generator, except that the direction of power flow (and the direction of I_A) is reversed. Per-phase circuit is shown:



A change in direction of I_A changes the Kirchhoff's voltage law equation:

$$V_\phi = E_A + jX_S I_A + R_A I_A \qquad (7.69.1)$$

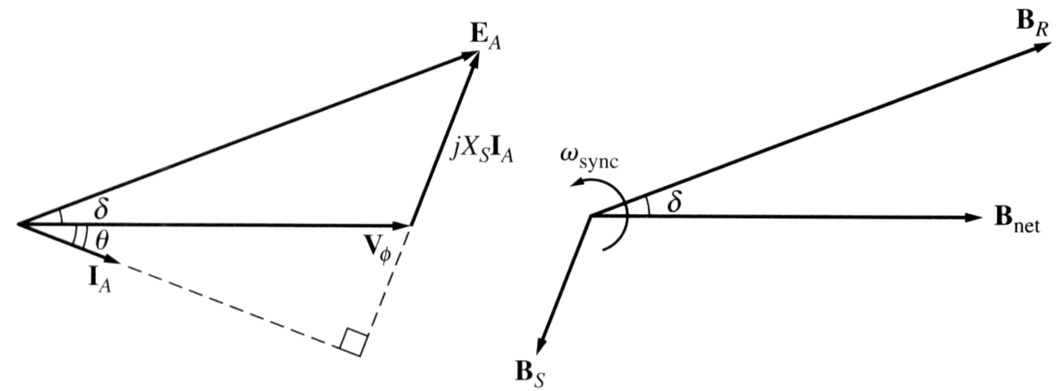
Therefore, the internal generated voltage is

$$\boxed{E_A = V_\phi - jX_S I_A - R_A I_A} \qquad (7.69.2)$$

We observe that this is exactly the same equation as the equation for the generator, except that the sign on the current terms is reversed.

Synchronous motor vs. synchronous generator

Let us suppose that a phasor diagram of synchronous generator is shown. B_R produces E_A, B_{net} produces V_ϕ, and B_S produces $E_{stat} = -jX_S I_A$. The rotation on both diagrams is counterclockwise and the induced torque is



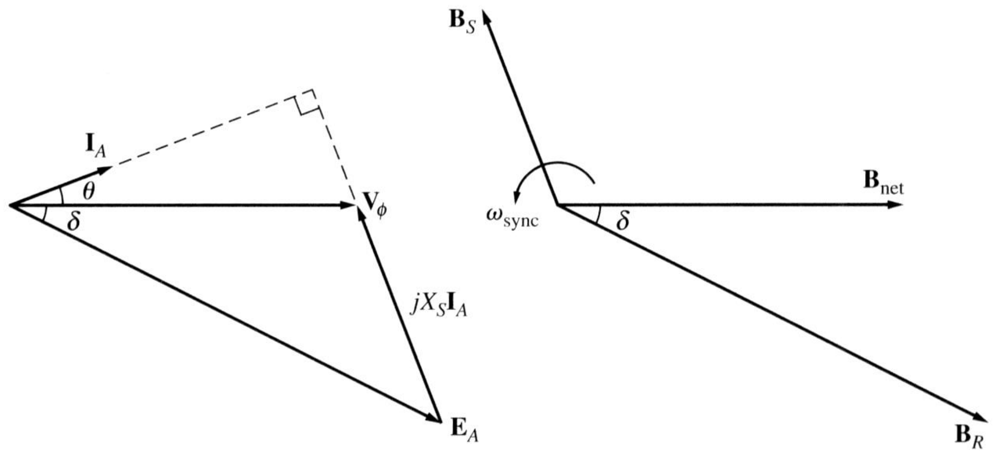
$$\tau_{ind} = kB_R \times B_{net} \qquad (7.70.1)$$

clockwise, opposing the direction of rotation. In other words, the induced torque in generators is a counter-torque that opposes the rotation caused by external torque.

If the prime mover loses power, the rotor will slow down and the rotor field B_R will fall behind the magnetic field in the machine B_{net}. Therefore, the operation of the machine changes…

Synchronous motor vs. synchronous generator

The induced torque becomes counter-clockwise, being now in the direction of rotation. The machine starts acting as a motor.
The increasing torque angle δ results in an increasing torque in the direction of rotation until it equals to the load torque.



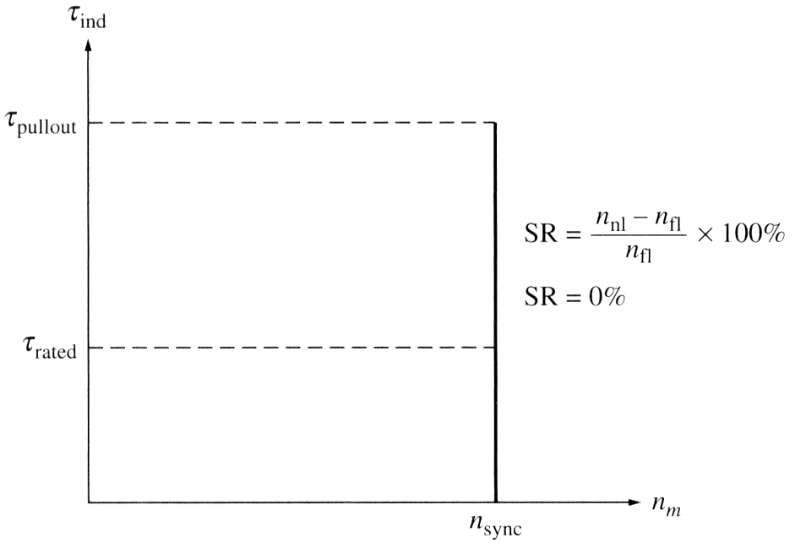
At this point, the machine operates at steady state and synchronous speed but as a motor.

Notice that, since the direction of I_A is changed between the generator and motor actions, the polarity of stator voltage ($-jX_SI_A$) also changes.

In a summary: in a generator, E_A lies ahead of V_ϕ, while in a motor, E_A lies behind V_ϕ.

Steady-state operation of motor: Torque-speed curve

Usually, synchronous motors are connected to large power systems (infinite bus); therefore, their terminal voltage and system frequency are constant regardless the motor load. Since the motor speed is locked to the electrical frequency, the speed should be constant regardless the load.



The steady-state speed of the motor is constant from no-load to the maximum torque that motor can supply (pullout torque). Therefore, the speed regulation of synchronous motor is 0%.

The induced torque is

$$\tau_{ind} = kB_R B_{net} \sin\delta \qquad (7.72.1)$$

or

$$\boxed{\tau_{ind} = \frac{3V_\phi E_A}{\omega_m X_S} \sin\delta} \qquad (7.72.2)$$

Steady-state operation of motor: Torque-speed curve

The maximum pullout torque occurs when $\delta = 90^0$:

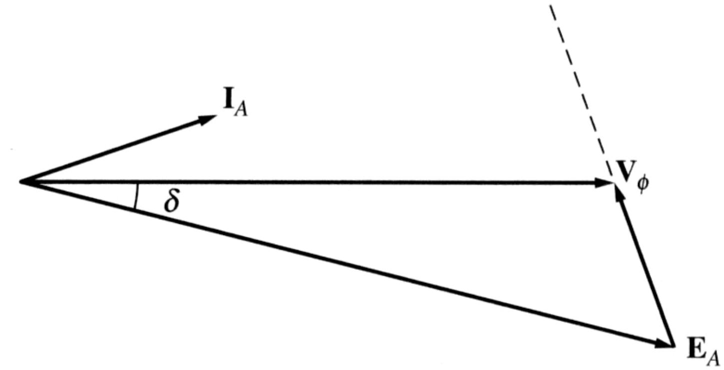
$$\tau_{\max} = kB_R B_{net} = \frac{3V_\phi E_A}{\omega_m X_S} \quad (7.73.1)$$

Normal full-load torques are much less than that (usually, about 3 times smaller).

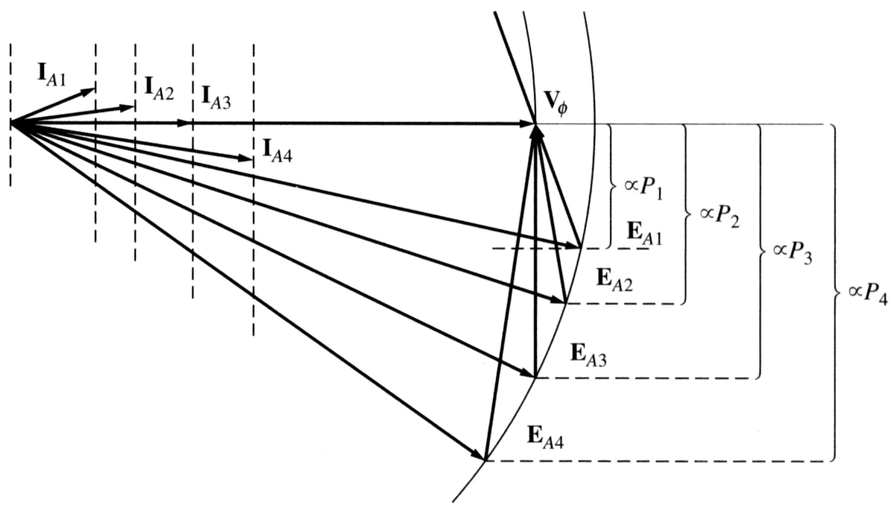
When the torque on the shaft of a synchronous motor exceeds the pullout torque, the rotor can no longer remain locked to the stator and net magnetic fields. It starts to slip behind them. As the motor slows down, the stator magnetic field “laps” it repeatedly, and the direction of the induced torque in the rotor reverses with each pass. As a result, huge torque surges of alternating direction cause the motor vibrate severely. The loss of synchronization after the pullout torque is exceeded is known as slipping poles.

Steady-state operation of motor: Effect of torque changes

Assuming that a synchronous motor operates initially with a leading PF.
If the load on the motor increases, the rotor initially slows down increasing the torque angle δ. As a result, the induced torque increases speeding up the rotor up to the synchronous speed with a larger torque angle δ.



Since the terminal voltage and frequency supplied to the motor are constant, the magnitude of internal generated voltage must be constant at the load changes ($E_A = K\phi\omega$ and field current is constant).



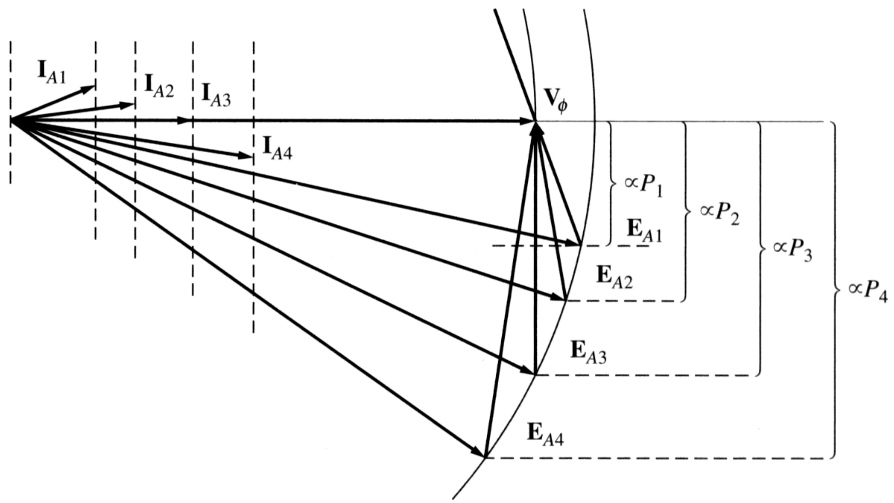
Steady-state operation of motor: Effect of torque changes

Assuming that the armature resistance is negligible, the power converted from electrical to mechanical form in the motor will be the same as its input power:

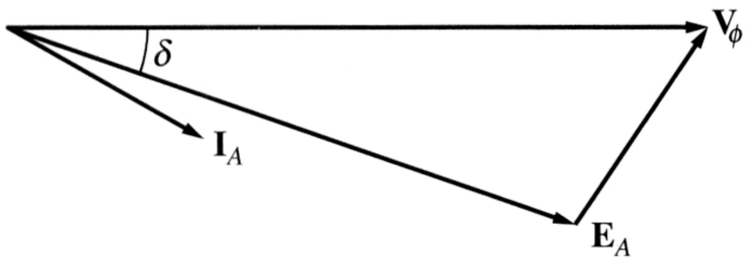
$$P = 3V_\phi I_A \cos\theta = \frac{3V_\phi E_A}{X_S}\sin\delta \qquad (7.73.1)$$

Since the phase voltage is constant, the quantities $I_A cos\theta$ and $E_A sin\delta$ are directly proportional to the power supplied by (and to) the motor. When the power supplied by the motor increases, the distance proportional to power increases.

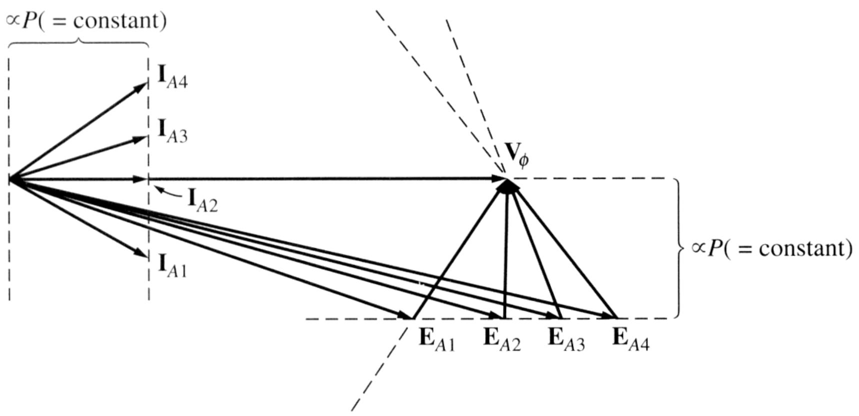
Since the internal generated voltage is constant, its phasor “swings down” as load increases. The quantity $jX_S I_A$ has to increase; therefore, the armature current I_A increases too.



Steady-state operation of motor: Effect of field current changes



Assuming that a synchronous motor operates initially with a lagging PF.
If, for the constant load, the field current on the motor increases, the magnitude of the internal generated voltage E_A increases.

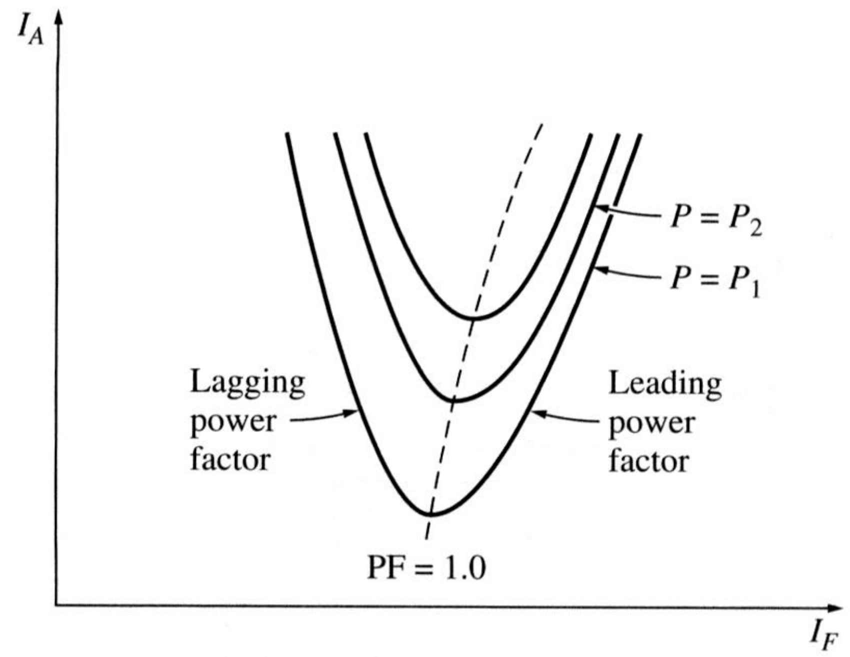


Since changes in I_A do not affect the shaft speed and the motor load is constant, the real power supplied by the motor is unchanged. Therefore, the distances proportional to power on the phasor diagram ($E_A sin\delta$ and $I_A cos\theta$) must be constant.

Notice that as E_A increases, the magnitude of the armature current I_A first decreases and then increases again. At low E_A, the armature current is lagging and the motor is an inductive load that consumes reactive power Q. As the field current increases , I_A eventually lines up with V_ϕ, and the motor is purely resistive. As the field current further increases, I_A becomes leading and the motor is a capacitive load that supplies reactive power Q to the system (consumes $-Q$).

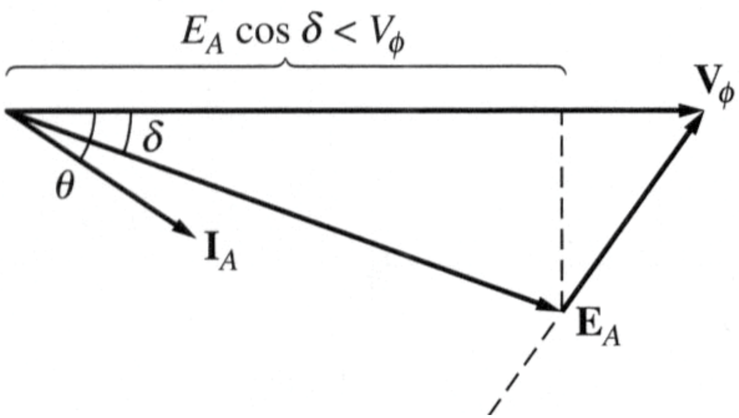
Steady-state operation of motor: Effect of field current changes

A plot of armature current vs. field current is called a synchronous motor V curve. V curves for different levels of real power have their minimum at unity PF, when only real power is supplied to the motor. For field currents less than the one giving the minimum I_A, the armature current is lagging and the motor consumes reactive power. For field currents greater than the one giving the minimum I_A, the armature current is leading and the motor supplies reactive power to the system.

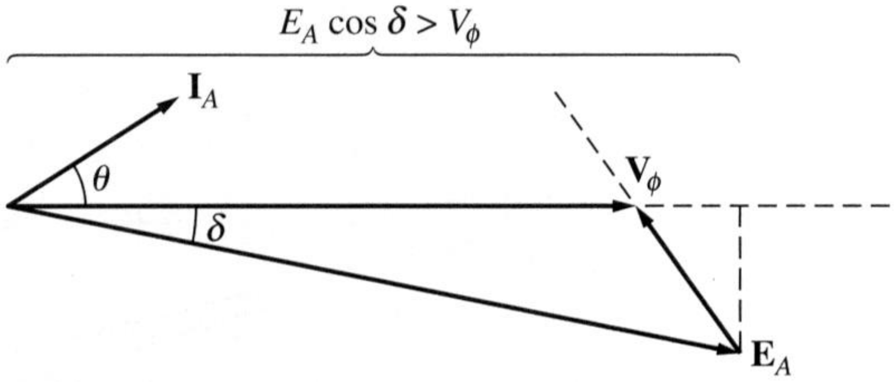


Steady-state operation of motor: Effect of field current changes

When the projection of the phasor E_A onto V_ϕ ($E_A \cos\delta$) is shorter than V_ϕ, a synchronous motor has a lagging current and consumes Q. Since the field current is small in this situation, the motor is sais to be **under-excited**.

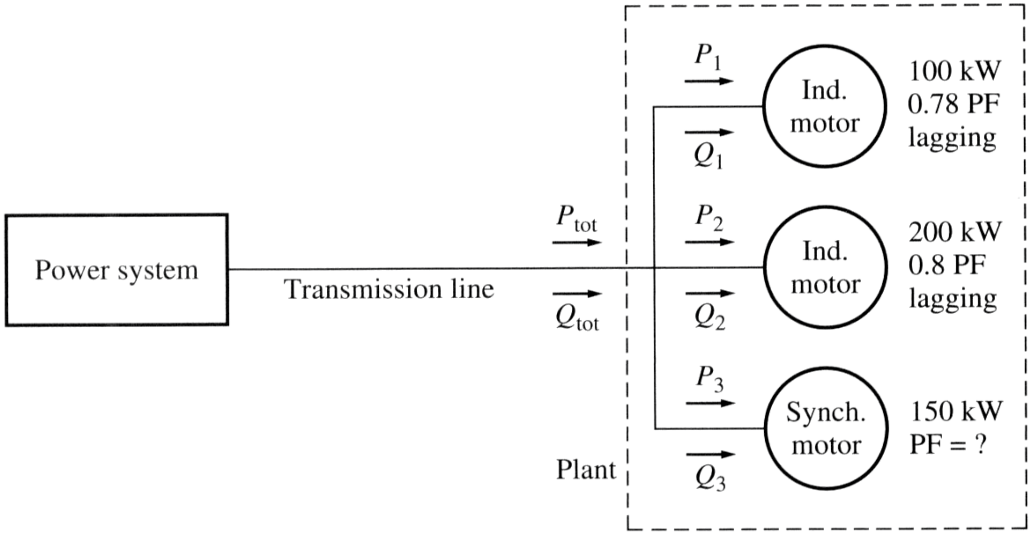


When the projection of the phasor E_A onto V_ϕ ($E_A \cos\delta$) is longer than V_ϕ, a synchronous motor has a leading current and supplies Q to the system. Since the field current is large in this situation, the motor is sais to be **over-excited**.



Steady-state operation of motor: power factor correction

Assuming that a load contains a synchronous motor (whose PF can be adjusted) in addition to motors of other types. What does the ability to set the PF of one of the loads do for the power system?



Let us consider a large power system operating at 480 V. Load 1 is an induction motor consuming 100 kW at 0.78 PF lagging, and load 2 is an induction motor consuming 200 kW at 0.8 PF lagging. Load 3 is a synchronous motor whose real power consumption is 150 kW.

a. If the synchronous motor is adjusted to 0.85 PF lagging, what is the line current?
b. If the synchronous motor is adjusted to 0.85 PF leading, what is the line current?
c. Assuming that the line losses are $P_{LL} = 3I_L^2R_L$, how du these losses compare in the two cases?

Steady-state operation of motor: power factor correction

a. The real power of load 1 is 100 kW, and the reactive power of load 1 is

$$Q_1 = P_1 \tan\theta = 100 \tan(\cos^{-1} 0.78) = 80.2\ kVAR$$

The real power of load 2 is 200 kW, and the reactive power of load 2 is

$$Q_2 = P_2 \tan\theta = 200 \tan(\cos^{-1} 0.8) = 150\ kVAR$$

The real power of load 3 is 150 kW, and the reactive power of load 3 is

$$Q_3 = P_3 \tan\theta = 150 \tan(\cos^{-1} 0.85) = 93\ kVAR$$

The total real load is $P_{tot} = P_1 + P_2 + P_3 = 100 + 200 + 150 = 450\ kW$

The total reactive load is $Q_{tot} = Q_1 + Q_2 + Q_3 = 80.2 + 150 + 93 = 323.2\ kVAR$

The equivalent system PF is

$$PF = \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{323.2}{450}\right) = 0.812\ \ lagging$$

The line current is

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L\cos\theta} = \frac{450\ 000}{\sqrt{3}\cdot 480\cdot 0.812} = 667\ A$$

Steady-state operation of motor: power factor correction

b. The real and reactive powers of loads 1 and 2 are the same. The reactive power of load 3 is

$$Q_3 = P_3 \tan\theta = 150\tan(-\cos^{-1} 0.85) = -93\ kVAR$$

The total real load is $$P_{tot} = P_1 + P_2 + P_3 = 100 + 200 + 150 = 450\ kW$$

The total reactive load is $$Q_{tot} = Q_1 + Q_2 + Q_3 = 80.2 + 150 - 93 = 137.2\ kVAR$$

The equivalent system PF is

$$PF = \cos\theta = \cos\left(\tan^{-1}\frac{Q}{P}\right) = \cos\left(\tan^{-1}\frac{137.2}{450}\right) = 0.957\ \ lagging$$

The line current is

$$I_L = \frac{P_{tot}}{\sqrt{3}V_L\cos\theta} = \frac{450\ 000}{\sqrt{3}\cdot 480\cdot 0.957} = 566\ A$$

Steady-state operation of motor: power factor correction

c. The transmission line losses in the first case are

$$P_{LL} = 3I_L^2 R_L = 1\,344\,700\ R_L$$

The transmission line losses in the second case are

$$P_{LL} = 3I_L^2 R_L = 961\,070\ R_L$$

We notice that the transmission power losses are 28% less in the second case, while the real power supplied to the loads is the same.

Steady-state operation of motor: power factor correction

The ability to adjust the power factor of one or more loads in a power system can significantly affect the efficiency of the power system: the lower the PF, the greater the losses in the power lines. Since most loads in a typical power system are induction motors, having one or more over-excided synchronous motors (leading loads) in the system is useful for the following reasons:

1. A leading load supplies some reactive power to lagging loads in the system. Since this reactive power does not travel along the transmission line, transmission line current is reduced reducing power losses.
2. Since the transmission line carries less current, the line can be smaller for a given power flow reducing system cost.
3. The over-excited mode of synchronous motor increases the motor's maximum torque.

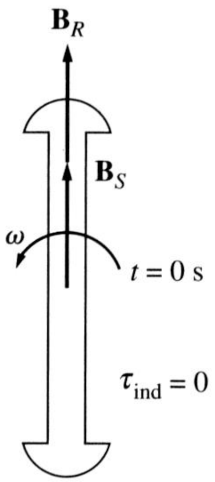
Usage of synchronous motors or other equipment increasing the overall system's PF is called power-factor correction. Since a synchronous motor can provide PF correction, many loads that can accept constant speed are driven by over-excited synchronous motors.

Starting synchronous motors

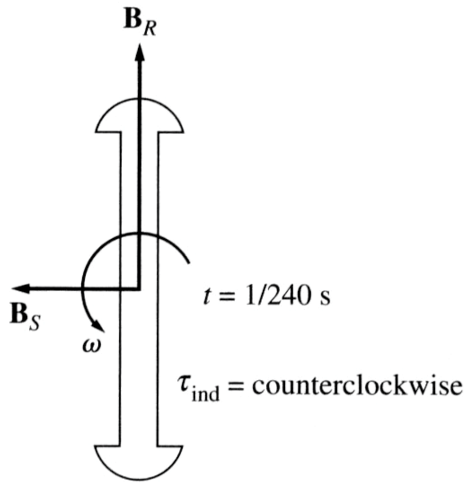
Consider a 60 Hz synchronous motor.
When the power is applied to the stator windings, the rotor (and, therefore its magnetic field B_R) is stationary. The stator magnetic field B_S starts sweeping around the motor at synchronous speed.
Note that the induced torque on the shaft

$$\tau_{ind} = kB_R \times B_S \qquad (7.84.1)$$

is zero at $t = 0$ since both magnetic fields are aligned.

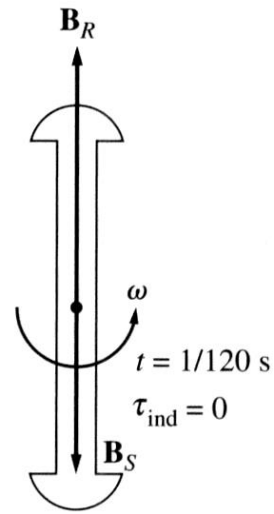


At $t = 1/240$ s the rotor has barely moved but the stator magnetic field B_S has rotated by 90^0. Therefore, the torque on the shaft is non-zero and counter-clockwise.

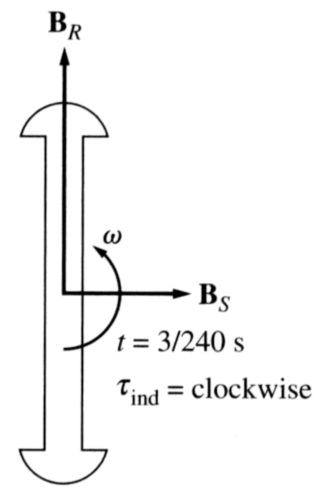


Starting synchronous motors

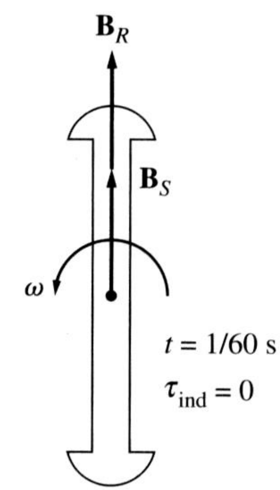
At t = 1/120 s the rotor and stator magnetic fields point in opposite directions, and the induced torque on the shaft is zero again.



At t = 3/240 s the stator magnetic fields point to the right, and the induced torque on the shaft is non-zero but clockwise.



Finally, at t = 1/60 s the rotor and stator magnetic fields are aligned again, and the induced torque on the shaft is zero.



During one electrical cycle, the torque was counter-clockwise and then clockwise, and the average torque is zero. The motor will vibrate heavily and finally overheats!

Starting synchronous motors

Three basic approaches can be used to safely start a synchronous motor:

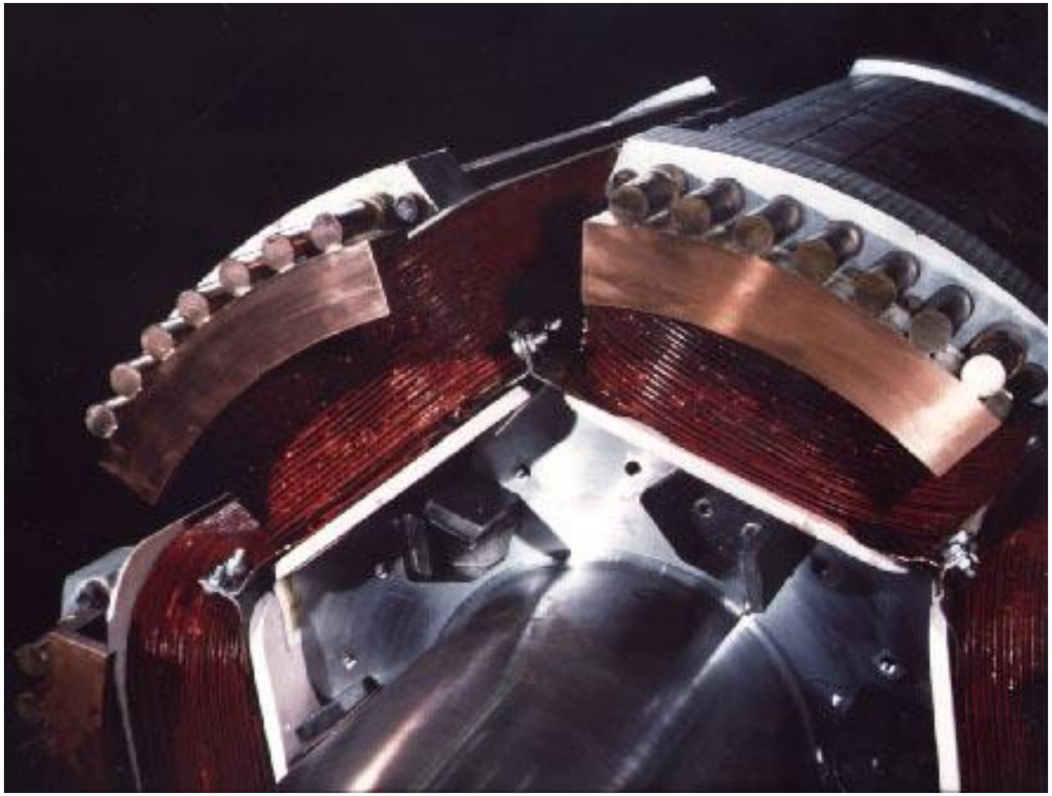
1. Reduce the speed of the stator magnetic field to a low enough value that the rotor can accelerate and two magnetic fields lock in during one half-cycle of field rotation. This can be achieved by reducing the frequency of the applied electric power (which used to be difficult but can be done now).

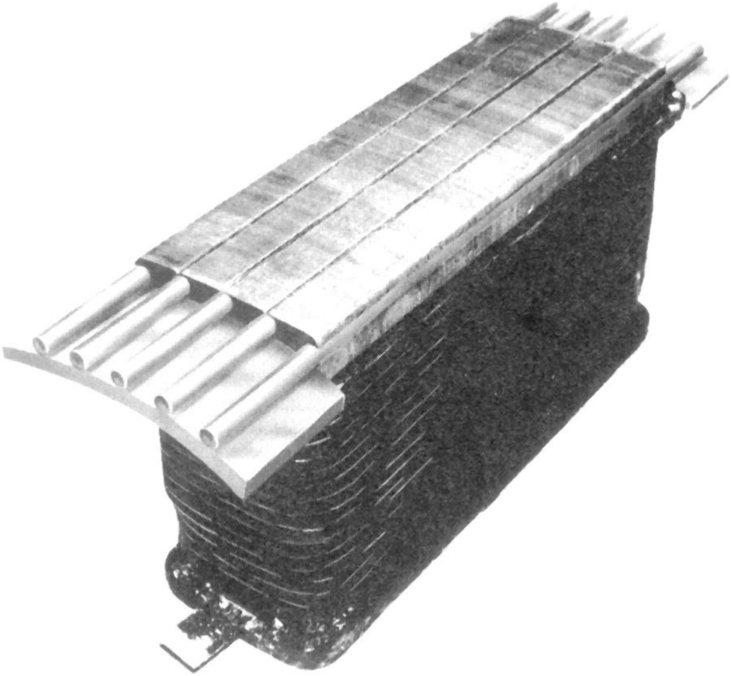
2. Use an external prime mover to accelerate the synchronous motor up to synchronous speed, go through the paralleling procedure, and bring the machine on the line as a generator. Next, turning off the prime mover will make the synchronous machine a motor.

3. Use damper windings or amortisseur windings – the most popular.

Motor starting by amortisseur or damper windings

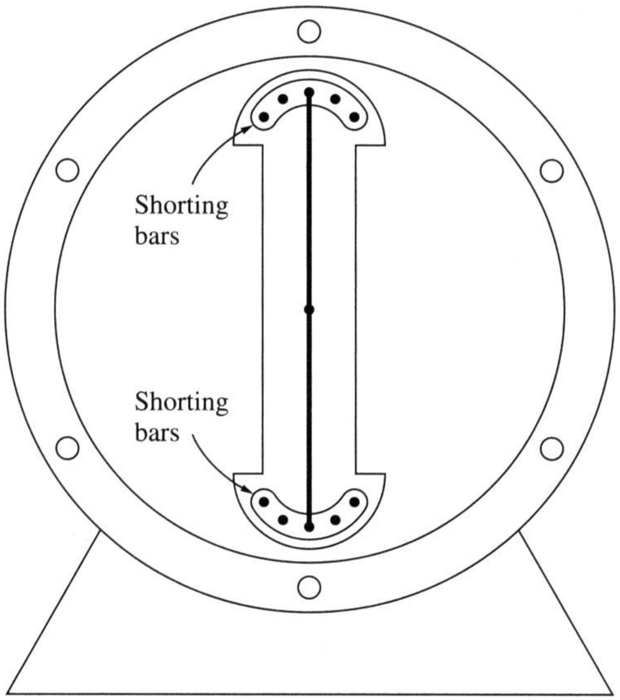
Amortisseur (damper) windings are special bars laid into notches carved in the rotor face and then shorted out on each end by a large shorting ring.

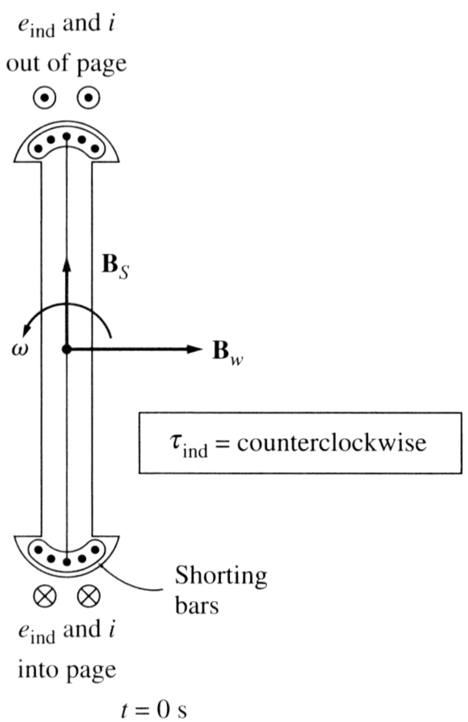




Motor starting by amortisseur or damper windings

A diagram of a salient 2-pole rotor with an amortisseur winding, with the shorting bars on the ends of the two rotor pole faces connected by wires (not quite the design of actual machines).





We assume initially that the rotor windings are disconnected and only a 3-phase set of voltages are applied to the stator.

At t = 0, assume that B_S (stator field) is vertical.

As B_S sweeps along in s counter-clockwise direction, it induces a voltage in bars of the amortisseur winding:

$$e_{ind} = (v \times B) \cdot l \tag{7.88.1}$$

Motor starting by amortisseur or damper windings

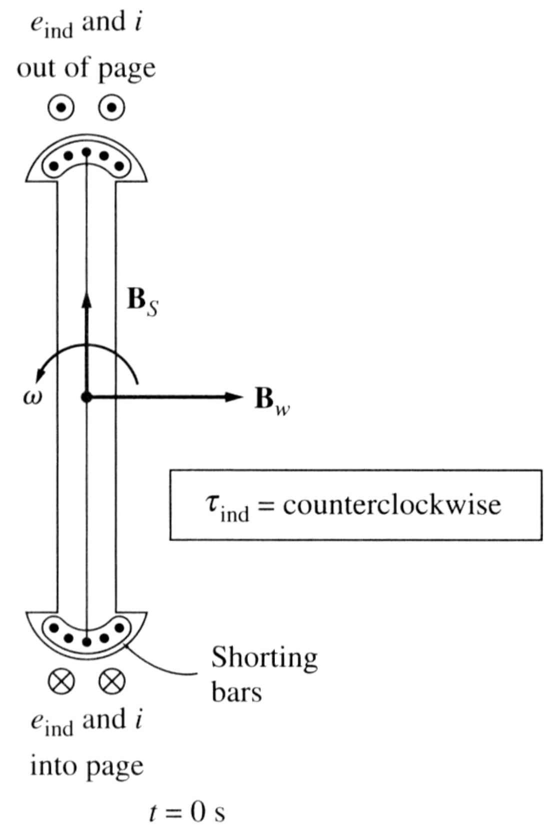
Here v – the velocity of the bar relative to the magnetic field;

B – magnetic flux density vector;

l – length of conductor in the magnetic field.

The bars at the top of the rotor are moving to the right relative to the magnetic field: a voltage, with direction out of page, will be induced. Similarly, the induced voltage is into the page in the bottom bars. These voltages produce a current flow out of the top bars and into the bottom bars generating a winding magnetic field B_w to the right. Two magnetic fields will create a torque

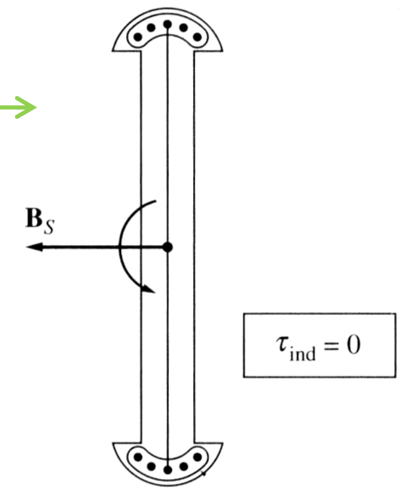
$$\tau_{ind} = kB_W \times B_S \quad (7.89.1)$$



The resulting induced torque will be counter-clockwise.

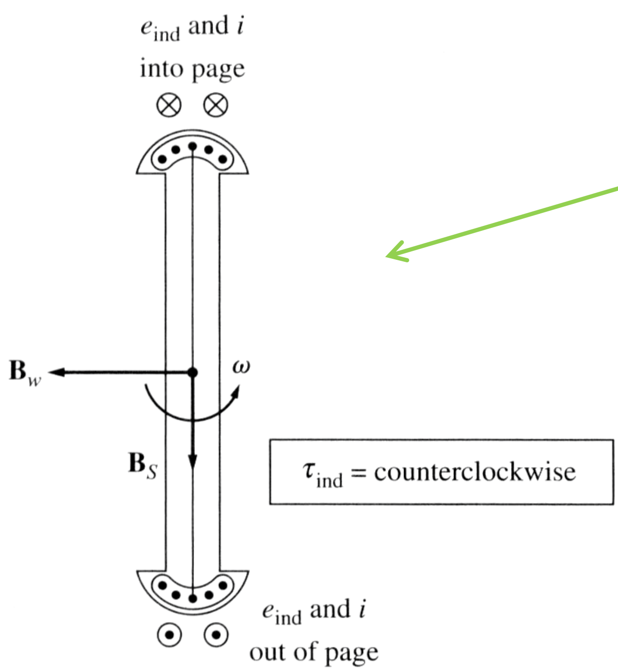
Motor starting by amortisseur or damper windings

At t = 1/240 s, B_S has rotated 90^0 while the rotor has barely moved. Since v is parallel to B_S, the voltage induced in the amortisseur windings is zero, therefore, no current in wires create a zero-torque.



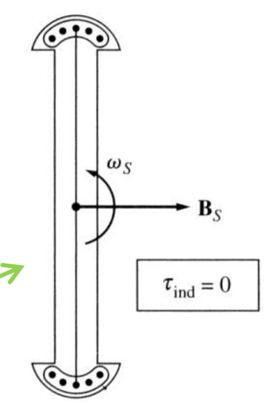
t = 1/240 s

At t = 1/120 s, B_S has rotated another 90^0 and the rotor is still. The voltages induced in the bars create a current inducing a magnetic field pointing to the left. The torque is counter-clockwise.



t = 1/120 s

Finally, at t = 3/240 s, no voltage is induced in the amortisseur windings and, therefore, the torque will be zero.



t = 3/240 s

Motor starting by amortisseur or damper windings

We observe that the torque is either counter-clockwise or zero, but it is always unidirectional. Since the net torque is nonzero, the motor will speed up.

However, the rotor will never reach the synchronous speed! If a rotor was running at the synchronous speed, the speed of stator magnetic field B_S would be the same as the speed of the rotor and, therefore, no relative motion between the rotor and the stator magnetic field. If there is no relative motion, no voltage is induced and, therefore, the torque will be zero.

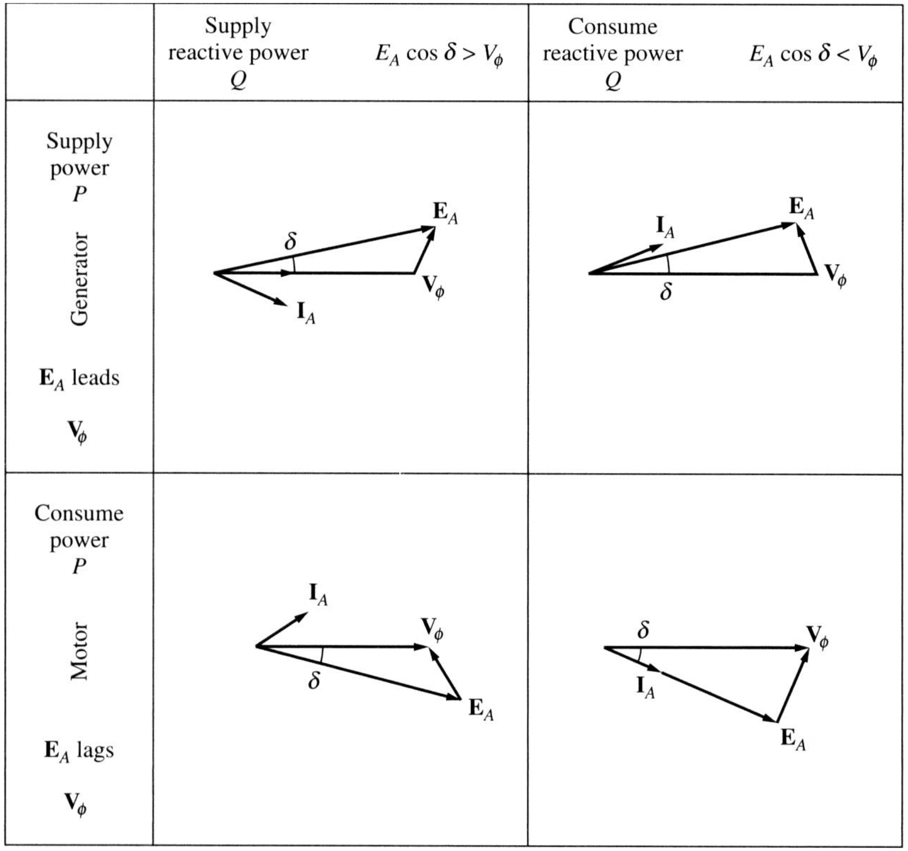
Instead, when the rotor's speed is close to synchronous, the regular field current can be turned on and the motor will operate normally. In real machines, field circuit are shorted during starting. Therefore, if a machine has damper winding:

1. Disconnect the field windings from their DC power source and short them out;
2. Apply a 3-phase voltage to the stator and let the rotor to accelerate up to near-synchronous speed. The motor should have no load on its shaft to enable motor speed to approach the synchronous speed as closely as possible;
3. Connect the DC field circuit to its power source: the motor will lock at synchronous speed and loads may be added to the shaft.

Relationship between synchronous generators and motors

Synchronous generator and synchronous motor are physically the same machines! A synchronous machine can supply real power to (generator) or consume real power (motor) from a power system. It can also either consume or supply reactive power to the system.

1. The distinguishing characteristic of a synchronous generator (supplying *P*) is that E_A lies ahead of V_ϕ while for a motor E_A lies behind V_ϕ.
2. The distinguishing characteristic of a machine supplying reactive power *Q* is that $E_a cos\delta > V_\phi$ (regardless whether it is a motor or generator). The machine consuming reactive power *Q* has $E_a cos\delta < V_\phi$.



Synchronous machine ratings

The speed and power that can be obtained from a synchronous motor or generator are limited. These limited values are called ratings of the machine. 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. The commonly used frequencies are 50 Hz (Europe, Asia), 60 Hz (Americas), and 400 Hz (special applications: aircraft, spacecraft, etc.). Once the operation frequency is determined, only one rotational speed in possible for the given number of poles:

$$n_m = \frac{120 f_e}{P} \qquad (7.93.1)$$

Synchronous machine ratings

A generator's voltage depends on the flux, the rotational speed, and the mechanical construction of the machine. For a given design and speed, the higher the desired voltage, the higher the flux should be. However, the flux is limited by the field current.

The rated voltage is also limited by the windings insulation breakdown limit, which should not be approached closely.

Is it possible to operate a synchronous machine at a frequency other than the machine is rated for? For instance, can a 60 Hz generator operate at 50 Hz?

The change in frequency would change the speed. Since $E_A = K\phi\omega$, the maximum allowed armature voltage changes when frequency changes. Specifically, if a 60 Hz generator will be operating at 50 Hz, its operating voltage must be derated to 50/60 or 83.3 %.

Synchronous machine ratings

Two factors limiting the power of electric machines are

1) Mechanical torque on its shaft (usually, shaft can handle much more torque)
2) Heating of the machine's winding

The practical steady-state limits are set by heating in the windings.
The maximum acceptable armature current sets the apparent power rating for a generator:

$$S = 3V_{\phi} I_A \tag{7.95.1}$$

If the rated voltage is known, the maximum accepted armature current determines the apparent power rating of the generator:

$$S = 3V_{\phi,rated} I_{A,\max} \quad = \sqrt{3} V_{L,rated} I_{L,\max} \tag{7.95.2}$$

Synchronous machine ratings

The stator cupper losses also do not depend on the current angle:

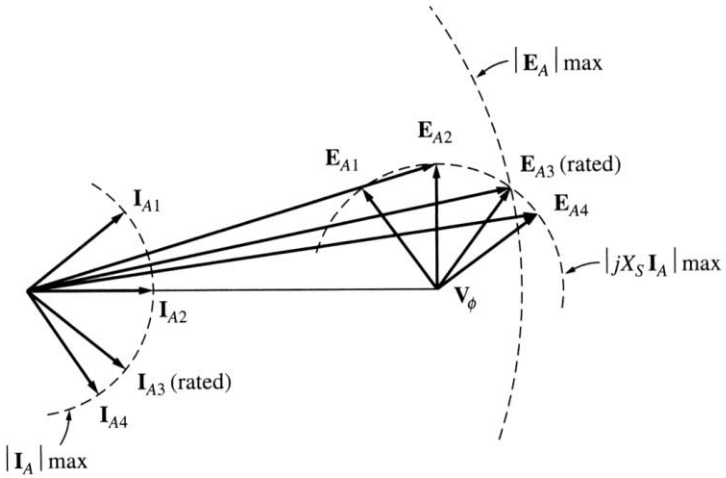
$$P_{SCL} = 3I_A^2 R_A \tag{7.96.1}$$

Since the current angle is irrelevant to the armature heating, synchronous generators are rated in kVA rather than in KW.

The rotor (field winding) cupper losses are:

$$P_{RCL} = I_F^2 R_F \tag{7.96.2}$$

Allowable heating sets the maximum field current, which determines the maximum acceptable armature voltage E_A. These translate to restrictions on the lowest acceptable power factor: The current I_A can have different angles (that depends on PF). E_A is a sum of V_ϕ and $jX_S I_A$. We see that, (for a constant V_ϕ) for some angles the required E_A exceeds its maximum value.



Synchronous machine ratings

If the armature voltage exceeds its maximum allowed value, the windings could be damaged. The angle of I_A that requires maximum possible E_A specifies the rated power factor of the generator. It is possible to operate the generator at a lower (more lagging) PF than the rated value, but **only** by decreasing the apparent power supplied by the generator.

Synchronous motors are usually rated in terms of real output power and the lowest PF at full-load conditions.

3. Short-time operation and service factor

A typical synchronous machine is often able to supply up to 300% of its rated power for a while (until its windings burn up). This ability to supply power above the rated values is used to supply momentary power surges during motor starts.

It is also possible to use synchronous machine at powers exceeding the rated values for longer periods of time, as long as windings do not have time to hit up too much before the excess load is removed. For instance, a generator that could supply 1 MW indefinitely, would be able to supply 1.5 MW for 1 minute without serious harm and for longer periods at lower power levels.

Synchronous machine ratings

The maximum temperature rise that a machine can stand depends on the insulation class of its windings. The four standard insulation classes with they temperature ratings are:

A – 60^0C above the ambient temperature
B – 80^0C above the ambient temperature
F – 105^0C above the ambient temperature
H – 125^0C above the ambient temperature

The higher the insulation class of a given machine, the greater the power that can be drawn out of it without overheating its windings.

The overheating is a serious problem and synchronous machines should not be overheated unless absolutely necessary. However, power requirements of the machine not always known exactly prior its installation. Because of this, general-purpose machines usually have their service factor defined as the ratio of the actual maximum power of the machine to the rating on its plate.
For instance, a machine with a service factor of 1.15 can actually be operated at 115% of the rated load indefinitely without harm.