Synchronous Machines

- Gas/Steam Turbines
- Diesel
- Hydro
- Special Applications
Synchronous generators or alternators are used to convert mechanical power derived from steam, gas, or hydraulic-turbine to ac electric power.

Synchronous generators are the primary source of electrical energy we consume today.

Large ac power networks rely almost exclusively on synchronous generators.
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 for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).
Basic parts of a synchronous generator:

- Rotor - dc excited winding
- Stator - 3-phase winding in which the ac emf is generated

The manner in which the active parts of a synchronous machine are cooled determines its overall physical size and structure.
Various Types

- Salient-pole synchronous machine
- Cylindrical or round-rotor synchronous machine
5.1 INTRODUCTION TO POLYPHASE SYNCHRONOUS MACHINES

Two types:

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

\[ f_e = \frac{p \cdot n}{2 \cdot 60} = \frac{p}{120} n \]

To produce 50 Hz electricity
\[ p=2, \; n=3000 \text{ rpm} \]
\[ p=4, \; n=1500 \text{ rpm} \]

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

To produce 50 Hz electricity
\[ p=12, \; n=500 \text{ rpm} \]
\[ p=24, \; n=250 \text{ rpm} \]
1. Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min)

2. A large number of poles are required on the rotor
Stator

Salient-Pole Synchronous Generator

Many salient poles offer compact overall unit dimensions, easy pole design and magnetic flux optimized, providing superior characteristics well suited for communication applications. 4 to 12 pole is available to match lower speed.
Cylindrical-Rotor Synchronous Generator

- High speed
- 3600 r/min ⇒ 2-pole
- 1800 r/min ⇒ 4-pole
- Direct-conductor cooling (using hydrogen or water as coolant)
- Rating up to 2000 MVA
Cylindrical-Rotor Synchronous Generator

Stator

Cylindrical rotor
Construction of synchronous machines

[Image of a synchronous machine with labeled parts: Slip rings and Brush]
The rotor of the generator is driven by a prime-mover

A dc current is flowing in the rotor winding which produces a rotating magnetic field within the machine

The rotating magnetic field induces a three-phase voltage in the stator winding of the generator
Electrical frequency produced is locked or synchronized to the mechanical speed of rotation of a synchronous generator:

\[ f_e = \frac{P n_m}{120} \]

where

- \( f_e \) = electrical frequency in Hz
- \( P \) = number of poles
- \( n_m \) = mechanical speed of the rotor, in r/min
By the definition, synchronous generators produce electricity whose frequency is synchronized with the mechanical rotational speed.

- 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.
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, \( \phi \) is flux in it and \( \omega \) 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
The internal voltage $E_f$ produced in a machine is not usually the voltage that appears at the terminals of the generator. The only time $E_f$ is same as the output voltage of a phase is when there is no armature current flowing in the machine. There are a number of factors that cause the difference between $E_f$ and $V_t$:

- The distortion of the air-gap magnetic field by the current flowing in the stator, called the armature reaction.
- The self-inductance of the armature coils.
- The resistance of the armature coils.
- The effect of salient-pole rotor shapes.
Equivalent circuit of a cylindrical-rotor synchronous machine
5.2.4 EQUIVALENT CIRCUITS

Motor:

\[ \hat{V}_a = R_a \hat{I}_a + j X_s \hat{I}_a + \hat{E}_{af} \]

Generator:

\[ \hat{V}_a = \hat{E}_{af} - R_a \hat{I}_a - j X_s \hat{I}_a \]

Synchronous Reactance

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

\[ X_S = X + X_A \]  

(7.18.1)

Therefore, the phase voltage is

\[ V_\phi = E_A - jX_S I_A - RI_A \]  

(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.
The voltages and currents of the three phases are 120° apart in angle, but otherwise the three phases are identical.
Since the voltages in a synchronous generator are AC voltages, they are usually expressed as phasors. A vector plot of voltages and currents within one phase is called a phasor diagram.

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

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

Leading power factor (capacitive load).

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

\[ P_{in} = \tau_{app} \omega_m \]  

(7.22.1)

is partially converted to electricity

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

(7.22.2)

Where \( \gamma \) is the angle between \( E_A \) and \( I_A \).

The power-flow diagram of a synchronous generator.
The real output power of the synchronous generator is

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

The reactive output power of the synchronous generator is

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

Recall that the power factor angle \( \theta \) is the angle between \( V_\phi \) 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

\[ I_A \cos \theta = \frac{E_A \sin \delta}{X_S} \]  
(7.23.3)
Then the real output power of the synchronous generator can be approximated as

\[ P_{\text{out}} \approx \frac{3V_\phi E_A \sin \delta}{X_S} \]  

(7.24.1)

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

\[ P_{\text{conv}} \approx P_{\text{out}} \]  

(7.24.2)

Here \( \delta \) is the torque angle of the machine – the angle between \( V_\phi \) and \( E_A \).

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

\[ P_{\text{max}} = \frac{3V_\phi E_A}{X_S} \]  

(7.24.3)
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

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

(7.25.1)

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

Alternatively, the induced torque is

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

(7.25.2)
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 (which 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.
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.
The SCC is a straight line since, for the short-circuited terminals, the magnitude of the armature current is

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

(7.28.1)

The equivalent generator’s circuit during SC

The resulting phasor diagram

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

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_{A,SC}} \approx X_S \quad \{\text{since } X_S \ll R_A\} \tag{7.29.2}$$
A 200 kVA, 480-V, 60-Hz, 4-pole, Y-Connected synchronous generator with a rated field current of 5 A was tested and the following data was taken.

a) from OC test – terminal voltage = 540 V at rated field current
b) from SC test – line current = 300A at rated field current
c) from Dc test – DC voltage of 10 V applied to two terminals, a current of 25 A was measured.

1. Calculate the speed of rotation in r/min
2. Calculate the generated emf and saturated equivalent circuit parameters (armature resistance and synchronous reactance)
1. 
\[ f_e = \text{electrical frequency} = \frac{Pn_m}{120} \]
\[ f_e = 60\text{Hz} \]
\[ P = \text{number of poles} = 4 \]
\[ n_m = \text{mechanical speed of rotation in r/min} \]
So, speed of rotation \[ n_m = 120 \frac{f_e}{P} \]
\[ = (120 \times 60)/4 = 1800 \text{ r/min} \]

2. In open-circuit test, \( I_a = 0 \) and \( E_f = V_t \)
\[ E_f = \frac{540}{1.732} \]
\[ = 311.8 \text{ V} \] (as the machine is Y-connected)
In short-circuit test, terminals are shorted, \( V_t = 0 \)
\[ E_f = I_a Z_s \text{ or } Z_s = \frac{E_f}{I_a} = \frac{311.8}{300} = 1.04 \text{ ohm} \]
From the DC test, \( R_a = V_{DC}/(2I_{DC}) \)
\[ = 10/(2 \times 25) = 0.2 \text{ ohm} \]

Synchronous reactance
\[ Z_{s,sat} = \sqrt{R_a^2 + X_{s,sat}^2} \]
\[ X_{s,sat} = \sqrt{Z_{s,sat}^2 - R_a^2} = \sqrt{1.04^2 - 0.2^2} = 1.02 \]
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 FR 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?
Since the generator is Y-connected, its phase voltage is

\[ V_\phi = V_T / \sqrt{3} = 277 \text{ V} \]

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

a. The speed of rotation of a synchronous generator is

\[ n_m = \frac{120}{P} f_e = \frac{120}{6} 60 = 1200 \text{ rpm} \]

which is

\[ \omega_m = \frac{1200}{60} 2\pi = 125.7 \text{ rad/s} \]

b.1. For the generator at the rated current and the 0.8 PF lagging, the phasor diagram is shown. The phase voltage is at 0°, the magnitude of \( E_A \) is 277 V,
The Synchronous generator operating alone: Example

and that \[ jX_s I_A = j \cdot 1 \cdot 60 \angle -36.87^\circ = 60 \angle 53.13^\circ \]

Two unknown quantities are the magnitude of \( V_\phi \) and the angle \( \delta \) of \( E_A \). From the phasor diagram:

\[
E_A^2 = (V_\phi + X_s I_A \sin \theta)^2 + (X_s I_A \cos \theta)^2
\]

Then:

\[
V_\phi = \sqrt{E_A^2 - (X_s I_A \cos \theta)^2 - X_s I_A \sin \theta} = 236.8 \text{ V}
\]

Since the generator is Y-connected,

\[
V_T = \sqrt{3} V_\phi = 410 \text{ V}
\]
b.2. For the generator at the rated current and the 1.0 PF, the phasor diagram is shown.

Then:

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

and

\[ V_T = \sqrt{3V_\phi} = 468.4 \text{ V} \]

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

Then:

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

and

\[ V_T = \sqrt{3V_\phi} = 535 \text{ V} \]
c. The output power of the generator at 60 A and 0.8 PF lagging is

\[
P_{out} = 3V \phi I_A \cos \theta = 3 \cdot 236.8 \cdot 60 \cdot 0.8 = 34.1 \text{ kW}
\]

The mechanical input power is given by

\[
P_{in} = P_{out} + P_{elec\ loss} + P_{core\ loss} + P_{mech\ loss} = 34.1 + 0 + 1.0 + 1.5 = 36.6 \text{ kW}
\]

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

\[
\tau_{app} = \frac{P_{in}}{\omega_m} = \frac{36.6}{125.7} = 291.2 \text{ N \cdot m}
\]
The induced countertorque of the generator is

\[ \tau_{app} = \frac{P_{conv}}{\omega_m} = \frac{34.1}{125.7} = 271.3 \text{ N} \cdot \text{m} \]

e. The voltage regulation of the generator is

Lagging PF:

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

Unity PF:

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

Lagging PF:

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