SYNCHRONOUS MACHINE

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February 2014

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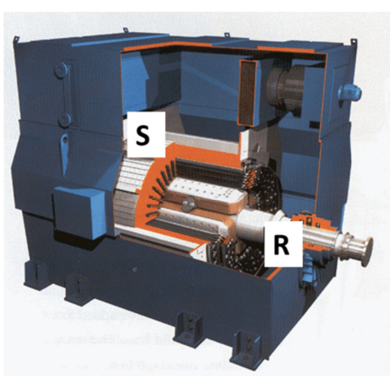
Synchronous machine is the most used solution for electric energy generation. The range of power rating of these generators is very large. One can underline, for instance, the small units (1kW) that are equipping the cars vehicles and the large ones used in nuclear power plants (1200MW). However, all these generators work with the same basic principles.

1.1 Typical Layouts

In their design there are two main components, the rotor and the stator. The rotor is the mobile component of the machine and it is usually located in its inner side. It is made of ferromagnetic material. Figure 1 shows the rotor of salient poles design. In this component there is the excitation system of the machine. In the case presented in the figure, the induced magnetic distribution is generated by current flowing in the field winding. In some cases the field circuit is not used and instead it is used a permanent magnet material to generate the excitation field distribution. This solution is proposed for off-shore wind generators (10 MW). In these cases the rotor is located in the outer side of the machine.



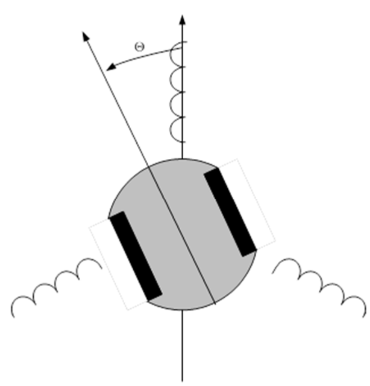


Figure 1 – Synchronous generator and its schematic representation.

The other main machine component is the stator which is also made of ferromagnetic material. In usual design, the stator is the fixed part of the machine and is in its outer side. In the inner part of the stator there are put coils whose active conductors are in slots and forming three independent and equal circuits that are in different angular positions of the stator, but with a regular distribution (120º).

1.2 Modeling the Steady State Regime

Consider the no load operation that is the machine has no currents in the stator windings, and the rotor runs at a constant angular speed ω / p. In these operation mode if the field winding is supplied, at the terminals of each stator circuits appears a sinusoidal waveform voltage that is equal to the *emf* - electromotive force[1]. Note there is a motion of conductors relative to magnetic field distribution. These voltages have frequency ω and a RMS value which depends on the angular speed of the rotor – it is proportional to it - and also depends on the value of the field current. Of course the *emfs* in the three circuits of the stator are similar and only their phases have a phase shift of 120º.

$$E_{RMS} \propto \omega\phi(i_f) \tag{1}$$

When the circuits of the stator are close to each other, electric current flows in them and each phase can be represented by an equivalent circuit like the one presented in Figure 2 and represented by equations (2), where X_S is the equivalent self-reactance of the single phase of the stator circuit.

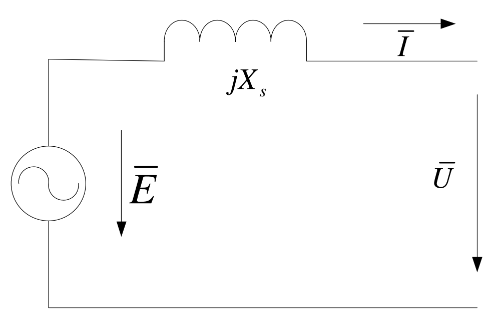


Figure 2 – Equivalent single phase circuit of synchronous generator.

$$\overline{E} = jX_s\overline{I} + \overline{U} \qquad \overline{E} = j\omega\overline{\phi}(I_f) \qquad X_s = \omega L_s \tag{2}$$

One must note that the frequency ω is constant in steady state regime when the generator is directly connected to the mains. However, in renewable energy production, the frequency may change, because the speed of the resource, wind or waves for instance, also changes.

[1] Note this *emf* is a result of Lorentz forces *(Blv).*

1. **Problem**

Consider a permanent magnet three phase synchronous generator supplying a load represented by a resistor $R = 3\Omega$. The equivalent self-inductance is equal to *100 mH*. At no load the voltage at the terminals of the stator circuit is equal to *70 V* when the rotor speed is equal to *300 rpm*.

a) Determine the voltage at no load if the speed becomes equal to *100 rpm*.
b) Determine the short-circuit current when speed is equal to *300* and *100 rpm*.
c) Determine power delivery to the load at the two speeds referred before.

Hints: The permanent magnet can be represented by a constant field current.

1.3 The Synchronous Generator Directly Connected to the Mains

Equation (2) can also be represented by the phasor diagram of Figure 3 where it is signalized the load angle δ, variable that represents the relative position of the rotor .

The value of complex power is determined by equations (3) where the load angle is used. The multiplication by three is used to calculate the global power delivery by the generator. Note that the equivalent circuit represents only one phase of the stator.

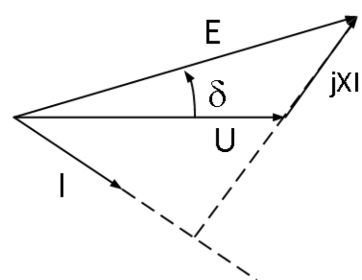


Figure 3 – Phasor diagram of synchronous machine.

$$\overline{S} = 3\overline{U}\,\overline{I}^* = 3\overline{U}\,\frac{\overline{E}^* - \overline{U}^*}{-jX_s}$$

$$\overline{S} = 3e^{j\pi/2}\,\frac{UEe^{-j\delta} - U^2}{X_s} = 3\frac{UE}{X_s}\sin(\delta) + j3\left(\frac{UE}{X_s}\cos(\delta) - \frac{U^2}{X_s}\right) \quad (3)$$

The most common use of the synchronous machine is the generator mode directly connected to the mains. In this operation mode the voltage and the frequency are fixed by the mains. From the generator it is possible to control the delivery of the active and reactive powers. The active power depends on the command of the driving machine, for instance the turbine, and the delivery of the reactive power depends on the field current intensity.

Figure 4 shows the so called V- curves of the synchronous generator. This curves show how the apparent power or the electric current - in this situation is the same – depends on the field current, for different values of active power. The minimum value of each curve corresponds to a situation where only active power is supplied to the mains. The right end side of these curves – large field currents side- is called the over exciting zone of the machine, and the generator supplies reactive power to the mains. The left side is called the under exciting zone of the machine, and the generator receives reactive power.

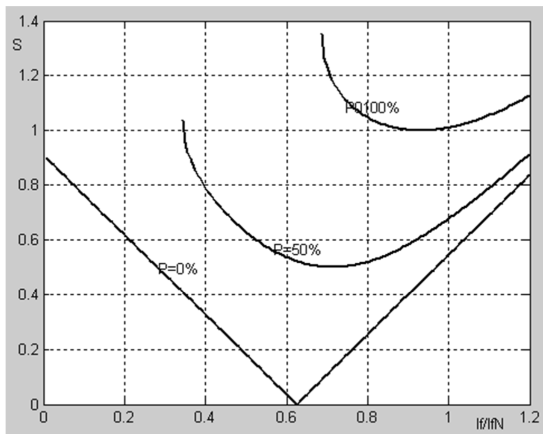


Figure 4 – V-curves of a synchronous generator connected to the main network.

2. Problem

Represent qualitatively on the Argand plane the phasors of voltage, current and *emf* representing each one of the cases reported on Figure 4.
Hints: Consider the expression of power using load angle and power factor - $\cos(\varphi)$.

3. Problem

Consider a 3 poles pairs, three phase, 100MVA, 15kV, 50Hz synchronous generator whose self-reactance is equal to 1.8 Ω. The generator is connected to the mains.

a) Determine the speed of the generator when it is synchronized with the mains.
b) Determine the *emf*, the torque, the active and the reactive power supplied by the generator when it delivery 80MVA to the mains with a power factor equal to 0.85.
c) If the generator is in the condition of precedent question when the field current increase 10%, determine the new values of active and reactive power delivery by the generator to the mains.

Hints: Consider a linear relation between field current and the *emf* in relation (2). Note that no changes are made to the drive motor of the generator.

1.4 Hints on Using Synchronous Generator on Renewable Energy Plants

When the synchronous generator is used in renewable energy power plants and the system does not include storage of energy, the connection of the synchronous generator to the utility grid is made in asynchronous mode due to large variations expected in speed and therefore in frequency. In these cases the connection is made using power electronics converters as shown on Figure 5. The voltages of the stator circuits are rectified and the power is delivered to a DC link. A second power electronics converter receives the power from the DC link and converts the DC voltage to a three phase balanced voltage with fixed frequency and equal to the voltage of the grid.

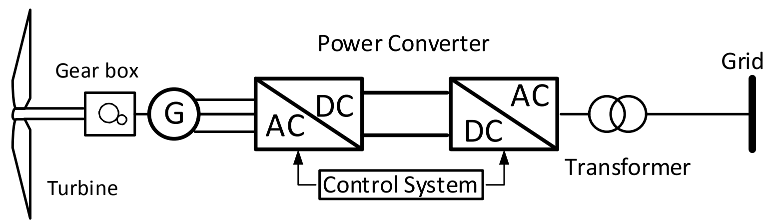


Figure 5 – Wind power plant.

In these applications, the design of the synchronous machines is modified to adapt itself to specific conditions characterized by low speed and large forces operation and maintenance problems. The modifications consist in the use of permanent magnet materials instead of a field circuit and recent design proposals put the rotor in the outside of the machine. These modifications try to eliminate the use of a gearbox usually present in these applications and reduce maintenance costs. Modular design and embedded power electronics are other expected future modifications.

Synchronous machine can also be used in motor mode. In spite of the problems of the starting of a synchronous motor, this is a good solution in some situations, as for instance when it is necessary to pump water in hydraulic power plants.