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EEN320 - Power Systems I (Συστήματα Ισχύος I)

Part 6: Synchronous machine

https://sps.cut.ac.cy/courses/een320/

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Today's learning objectives

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After this part of the lecture and additional reading, you should be able to . . .

1. . . . explain the basic principles of synchronous machines and motors;
2. . . . perform basic calculations concerning synchronous machines and motors.

Outline

1 Outline

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1. **Synchronous generator**
2. Synchronous motor

1 Field current

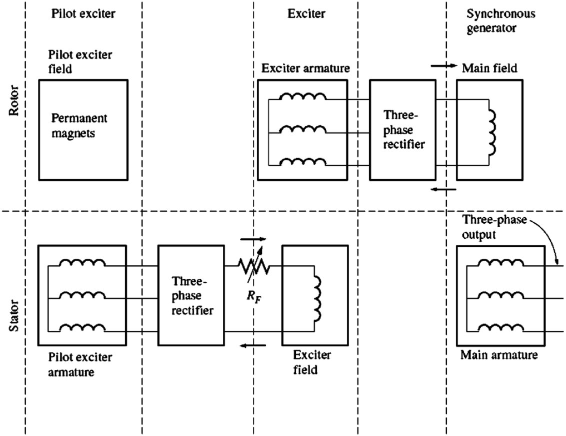
- To supply the rotor with DC current we:
  1. Supply from external DC source by means of slip rings and brushes.
  2. Supply from a special DC power source mounted on the shaft.
- We can make generator independent of external sources by including a small pilot exciter (usually, a small permanent magnet generator) mounted on the rotor shaft.
- It is reminded that:

$$\boxed{E_{RMS} = \sqrt{2} N_c \Phi_M \pi f}$$

with Φ_M depending on B_M which depends on the field current I_F. Thus, the generator output voltage E_{RMS} is proportional to I_F.

Chapman, S.J. (2012). Electric machinery fundamentals (5e). McGraw-Hill.

1 Field current example



A brushless excitation scheme that includes a pilot exciter. The permanent magnets of the pilot exciter produce the field current of the exciter. Which in turn produces the field current of the main machine.

Chapman, S.J. (2012). Electric machinery fundamentals (5e). McGraw-Hill.

1 (Simplified) equivalent circuit of synchronous generator

The induced voltage $\underline{E}_A$ is usually **different** from the real synchronous machine output $\underline{V}_A$:

1. There is a distortion in the magnetic field of the stator due to the current flowing in the windings, called *armature reaction*.
2. Self-inductance of the armature coils.
3. Resistance of the armature coils.
4. Effect of salient-pole rotor shape.

1. Armature reaction

- If the generator is feeding a load (inductive or capacitive), then the currents in the windings will generate their own field $\underline{B}_S$, distorting the rotor one. The net magnetic field will now be:

$$\underline{B}_{net} = \underline{B}_R + \underline{B}_S$$

- The rotor field $\underline{B}_R$ induces the voltage $\underline{E}_A$ as shown in the previous section. The stator field $\underline{B}_S$ induces a voltage $\underline{E}_S$ which lies 90° behind the current $\underline{I}_A$ in the stator[1].
- The stator induced voltage can then be modelled as $\underline{E}_S = -jX\underline{I}_A$, with X a proportional constant.

[1] Why? Use Faraday's law to explain.

2+3. Self-inductance and resistance of armature coils

As expected, the coils in the stator have a self-inductance L_A and a resistance R_A that create a voltage drop $-jX_A\underline{I}_A$ and $-R_A\underline{I}_A$, respectively.

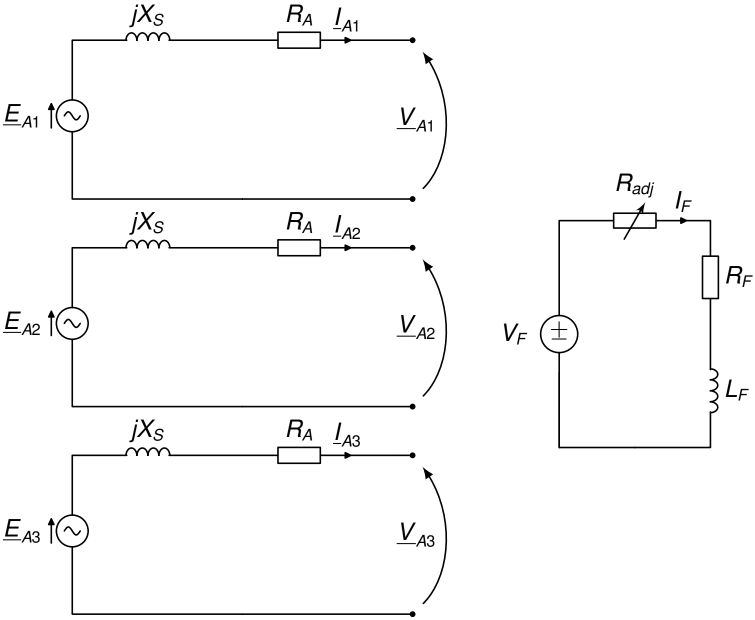
Equivalent model

Combining the above, the (simplified) equivalent model is given:

$$\boxed{\underline{V}_A = \underline{E}_A - jX\underline{I}_A - jX_A\underline{I}_A - R_A\underline{I}_A = \underline{E}_A - jX_S\underline{I}_A - R_A\underline{I}_A}$$

with $X_S = X + X_A$ the synchronous reactance of the generator.

1 (Simplified) equivalent circuit of synchronous generator



1 Synchronous generator phasor diagrams

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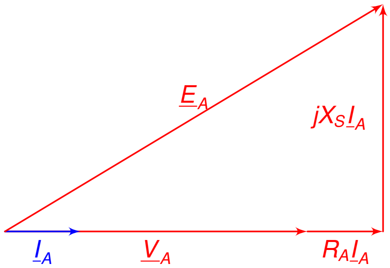
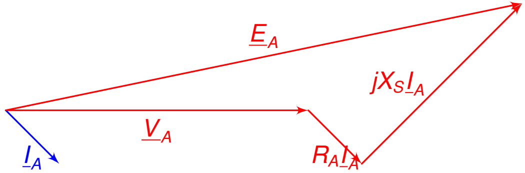
For a load current with unit power factor:



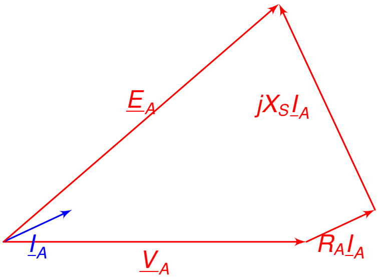
For a load current with lagging power factor:



To keep V_A constant for a lagging load, we need to increase E_A. How?

1 Synchronous generator phasor diagrams

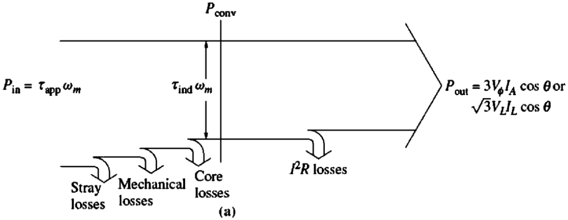
For a load current with leading power factor:



To keep V_A constant for a leading load, we need to decrease E_A. How?

1 Synchronous generator power and torque

Let's get back the power flow diagram of a generator:



The power converted from mechanical to electrical is:

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

where γ is the angle between $\underline{E}_A$ and $\underline{I}_A$.

Chapman, S.J. (2005). Electric machinery fundamentals (4e). McGraw-Hill.

1 Synchronous generator power and torque

The output power is:

$$P_{out} = 3V_A I_A \cos(\theta) \quad Q_{out} = 3V_A I_A \sin(\theta)$$

where θ is the angle between $\underline{V}_A$ and $\underline{I}_A$ and the power angle at the generator terminal.

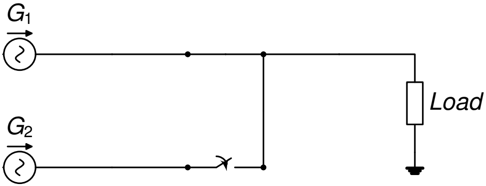
If we ignore the resistance R_A (since $R_A << X_S$), we can use the power flow equations over a reactance, derived in Part 6, to get the generator power output and torque:

$$\boxed{P = \frac{3V_A E_A}{X_S} \sin(\delta)} \quad \boxed{\tau = \frac{3V_A E_A}{\omega_m X_S} \sin(\delta)}$$

with δ the angle between $\underline{E}_A$ and $\underline{V}_A$, also called *torque angle*.

Q: What is the maximum power of the generator, if we keep E_A and V_A constant?

- Parallel operation of synchronous generators is necessary to increase security and reliability, minimise cost, and increase flexibility for dispatching and maintenance.
- When connecting a generator to the grid, if the switch is closed arbitrarily, the generators might be severely damaged, and the load may lose power.
- If the voltages are not **exactly** the same in each conductor being tied together, there will be a very large current flow when the switch is closed.



1 Conditions for connection

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1. The rms line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of the two α phases must be equal.
4. The frequency of the new generator, called the oncoming generator, must be slightly higher than the frequency of the running system.

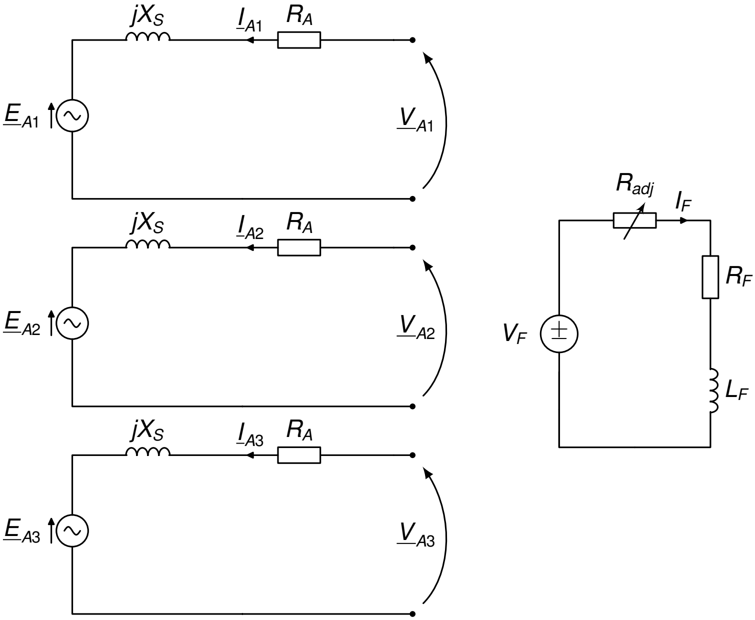
2 Outline

2 Synchronous motor equivalent model

The operation is inverted:

- Three-phase voltage is applied on the stator, creating a **rotating** magnetic field $\underline{B}_S$.
- The DC field current generates a magnetic field $\underline{B}_R$.
- Since the stator magnetic field is rotating, the rotor magnetic field (and hence the rotor itself) will constantly try to catch up. The larger the angle between th e two magnetic fields (up to a certain maximum), the greater the **torque** on the rotor of the machine.
- The basic principle of synchronous motor operation is that the rotor ”chases” the rotating stator magnetic field around in a circle, never quite catching up with it.
- Most of the characteristics of the motor are the same as the generator seen before.

2 Synchronous motor equivalent model



2 Synchronous motor equivalent model

With the equivalent model equation inverted to:

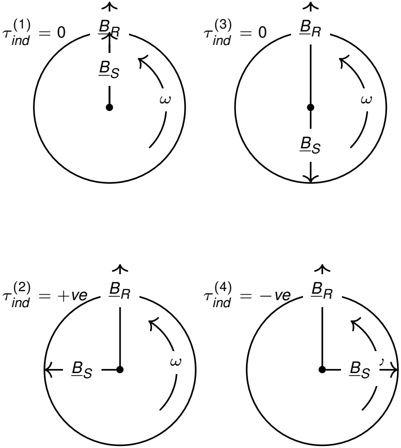
$$\boxed{\underline{E}_A = \underline{V}_A - jX_S\underline{I}_A - R_A\underline{I}_A}$$

- In a generator, $\underline{E}_A$, lies ahead of $\underline{V}_A$
- In a motor, $\underline{E}_A$ lies behind $\underline{V}_A$
- The angle between them is δ, also called torque angle
- The torque and power, similar to the generator case, is given by:

$$\boxed{P = \frac{3V_AE_A}{X_S}\sin(\delta)} \quad \boxed{\tau = \frac{3V_AE_A}{\omega_mX_S}\sin(\delta)}$$

Q: At which angle do we get the maximum or ”pull-out” torque?

If we try to start a motor by simply supplying voltages to the stator, it just vibrates and fails as the average torque is zero. Assume a 50 Hz two-pole generator:



1. At $t = 0$, the two magnetic fields are in the same direction, so the torque is $\tau_{ind} = k\underline{B}_R \times \underline{B}_S = 0$.
2. A quarter of a period later ($t = 1/200\ s$), the two fields are in 90° angle and the torque is clockwise.
3. Half a period later ($t = 2/200\ s$), the two fields are in 180° angle and the torque is again zero.
4. 3/4 of a period later ($t = 3/200\ s$), the two fields are in 270° angle and the torque is anti-clockwise.

2 Starting a synchronous motor

To start a motor, the most popular methods are:

1. Reduce the speed of the stator magnetic field to a low enough value that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field 's rotation. This can be done by reducing the frequency of the applied electric power. Power electronics are used through AC-DC-AC conversion that can vary the frequency at the motor side.
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. Then, turning off or disconnecting the prime mover will make the synchronous machine a motor.
3. Use damper windings or amortisseur windings.