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AC Synchronous Machine Synchronization

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Overview

Source: Ali Bazzi, Department of Electrical Engineering, University of Connecticut, Storrs, CT.

Three-phase wound-rotor synchronous generators are the main source of electrical power worldwide. They require a prime mover and an exciter in order to generate power. The prime mover can be a turbine spun by fluid (gas or liquid), thus the sources of the fluid can be water running off a dam through a long nozzle, steam from water evaporated using burned coal, etc. Most power plants including coal, nuclear, natural gas, fuel oil, and others utilize synchronous generators.

The objective of this experiment is to understand the concepts of adjusting the voltage and frequency outputs of a three-phase synchronous generator, followed by synchronizing it with the grid. The effects of field current and speed variations on the generator output power are also demonstrated.

Principles

Synchronous machines rely on the same rotating magnetic field concept that was introduced for AC induction machines. Three-phase currents, flowing in the machine's stator, produce a rotating magnetic field of constant magnitude at a desired frequency. The difference between the synchronous and asynchronous machines is that the latter has shorted windings or a "squirrel cage" on the rotor side, while synchronous machines have a fixed magnetic field on the rotor side. This magnetic field is either provided by an exciter or permanent magnets. Permanent magnet synchronous machines are becoming more common due to their high efficiency and compact size, but they typically utilize rare earth material, which is undesirable from a strategic material availability perspective. The term synchronous is used because the rotor magnetic field, which is independent from the stator, locks to the rotating magnetic field and causes the rotor to spin at the same speed (or synchronous speed) as the stator's rotating magnetic field.

Exciters provide the DC field for the generator and can be brushed or brushless. The setup utilized in this demonstration is a brushed exciter, where DC is applied to the rotor winding (field) of the synchronous machine through internal brushes and slip rings. Permanent magnet excitation is also possible but beyond the scope of this experiment.

In order to connect the generator at one plant to the electrical grid, three factors in the generator output voltages must match those of the grid: magnitude, frequency, and phase sequence. While automatic synchronizers are usually utilized in large power plants, a simple method is used in this video for manual synchronization. This method is the "three-lamp method." The method provides the visual inspection of having the three phases on the generator side and the grid side of the same magnitude, frequency, and phase sequence when all the lamps turn off due to the matching voltages, whose differential amount, seen by the lamps, is zero.

After synchronization, and once the generator is tied to the grid, speed control is no longer required for this demonstration, since the grid acts like an "infinite bus" where the generator dynamics have minimal effect on the grid. Thus, the frequency and voltage of the generator read exactly as those on the grid side. But there is still some effect of the prime mover: if the prime mover tries to speed up the generator, the generator speed does not change, but rather, the generator produces more power in the grid. For example, if the generator is assumed to be ideal, increasing the speed effectively increases the input mechanical power, but since the speed is fixed, the input torque increases, and thus, the output electrical power of the generator increases. However, if the prime mover tries to slow down the generator, the torque decreases and, at some point, reverses the sign, causing the generator to reduce its output power until power flow is reversed, and it acts like a motor.

Procedure

1. Prime-Mover Initialization

The prime-mover in this experiment is the dynamometer, which operates as a motor that spins the generator rotor (field).

1. Make sure the three-phase disconnect switch, synchronous motor switch, and DC motor switch are all off.
2. Check that the VARIAC is at 0%.
3. Wire the VARIAC to the three-phase outlet and connect the setup shown in Fig. 1.
 1. Use the three-phase switch on the synchronous machine side as "S₁."
 2. Note that "S₁" and the three-lamp setup are in parallel.
 3. Also note the polarities of the digital power meter probes.
 4. Check that the "Start/Run" switch is in the "Start" position.
4. Set "R_F" to maximum resistance.
5. Leave the VARIAC at 0% and leave "S₁" off.
6. Turn on the three-phase disconnect switch.
 1. Turn on the high voltage DC power supply.
 2. Make sure all connections are clear from the supply terminals.

3. Press the "V/I DIS" button on the supply to display the voltage and current operating points. Adjust the voltage knob to 15 V.
4. Press "Start" on the DC supply panel. The dynamometer should have a large transient current drawn from the DC supply. If its "OCT" light turns on, increase the over-current limit.
7. The machine should spin slowly.
 1. Increase the DC supply output voltage to around 160 V.
 2. Measure the shaft rotational speed.
 3. Adjust the supply voltage in order to achieve 1800 RPM rotational speed.
 4. Record the DC current and voltage on the supply display.
8. Leave the setup intact and do not turn off any of the equipment.

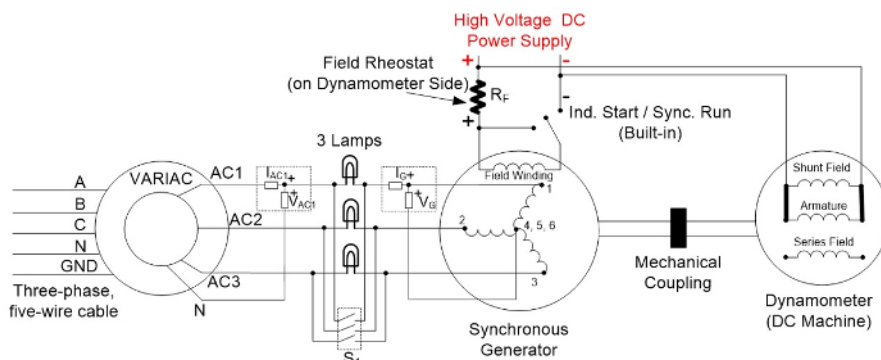


Figure 1: A schematic setup for the three-phase synchronous generator experiment. [Please click here to view a larger version of this figure.](#)

2. Synchronizing the Synchronous Generator with the Grid

1. Switch the Start/Run switch on the synchronous machine side to "Run". The three lamps should now turn on.
 1. Adjust " R_F " and the supply voltage iteratively to achieve $V_G=120$ V, and adjust the frequency of the V_G on the digital power meter to 60 Hz. Values within $\pm 2\%$ are acceptable.
 2. Slightly increase the VARIAC output to achieve $V_{AC1}=120$ V.
2. At this stage, the grid is providing 120 V at a frequency of 60 Hz.
 1. Record voltage, current, and power readings on both power meters. Do not ignore $\pm$ signs in front of any number on the meters.
3. The lamps should change their lighting pattern.
 1. If the lamps all go bright and dim at the same time, then the generator and the grid have the same phase sequence. Call it a-b-c for the three-phase sequence in use.
 2. If the lamps cycle, like Christmas tree lights, then the generator and the grid have different phase sequences, where one is a-b-c and the other is a-c-b across the set of lamps.
 1. In this case, turn the VARIAC back to 0%.
 2. Press "Stop" on the power supply panel.
 3. Reduce the DC voltage setting back to 15 V.
 4. Switch phases "b" and "c" on the VARIAC side.
 5. Repeat all the above steps, starting at Step 2.1.
4. *This step requires quick action:* At the instant that all the lights turn off, turn on " S_1 ." The lights should all remain off, since " S_1 " is now acting as a short circuit across their terminals.
5. The generator is now synchronized with the grid. Record the voltage, current, and power readings on both power meters. Do not ignore signs.
6. Leave the setup intact.

3. Effect of Field Current variation

1. Adjust " R_F " in about five steps from its maximum position to minimum position, and record the following for each step: Shaft speed; Shaft torque and sign; Voltage, current, and power readings on both power meters; Voltage and current readings on the DC supply.
2. If this " R_F " variation provides the same sign for all power readings:
 1. Slightly adjust the DC supply output to achieve a reverse power flow from/into the synchronous machine.
 2. Remember that negative power means the machine is generating electrical power.
3. Adjust the DC power supply voltage in five steps without exceeding a total DC current on the supply display of 3.5 A. Record the following for each step: Shaft speed; Shaft torque and sign; Voltage, current, and power readings on both power meters; Voltage and current readings on the DC supply.
4. Keep the setup intact.

4. Disassembling the Setup

The following sequence should be followed before disassembling the setup:

1. Turn the VARIAC back to 0%.
2. Turn off the power supply output by pressing "Stop".
3. When the machines stop rotating, flip the "Start/Run" switch to the "Start" position, and switch off "S₁".
4. Turn off the three-phase disconnect switch.
5. Disassemble the setup.

Results

The desired speed of the prime-mover is set at 1,800 RPM since the synchronous machine has four poles (P) and operates at a frequency $f = 60$ Hz, thus synchronous speed is $120/P = 1,800$ RPM.

When synchronizing the synchronous machine (generator) to the grid, the machine's prime-mover provides rotation, but a magnetic field on the machine's rotor should be provided. This is achieved using the DC power supply, which supplies the rotor coil and builds the rotor magnetic field. AC voltage is induced on the stator side by the rotating DC magnetic field on the rotor, and the strength of the rotor magnetic field is set by the DC power supply. In order to gradually increase the stator-side AC output voltage, the DC power supply is ramped up slowly.

Once the desired AC voltage is achieved, the lamps cycle. Using phase "a" as an example, it's assumed that the grid-side voltage is $170\cos(120\pi t)$ V which has an RMS voltage of $120\text{ V} = 170/\sqrt{2}$ and a frequency of 60 Hz ($2\pi \cdot 60$ rad/s). Once the machine's phase "a" arrives at $170\cos(120\pi t)$ V, the voltage across the lamp terminals becomes zero and the lamp turns off. However, it is very difficult to have both voltages at the same phase, and the machine's voltage is most likely $170\cos(120\pi t + \phi)$ V where ϕ is a non-zero phase difference. By adjusting the voltage magnitude, using the DC rotor field, and the frequency, using the prime-mover's speed, the voltages on each of the machine's phases and their corresponding grid-side voltages should match due to minor voltage and frequency disturbances.

If the phase sequence of a-b-c from the grid is met with another sequence a-c-b from the machine, the lamps cycle as the voltages across the lamps never add up to zero on all three phases at the same time.

The machine operates as a generator when the power readings show power flow into the grid versus into the machine. This can be noted on the power meters.

Applications and Summary

Synchronous generators are the backbone of electricity generation in power plants worldwide. Synchronizing a generator to the grid has become standard practice and is typically automated by matching the phase sequences, voltage magnitudes, and frequencies of the generator to the grid. Voltage control using the rotor magnetic field is achieved using "exciters," while frequency control is achieved using the speed control of a turbine or prime-mover, providing rotation using steam, wind, water, or other fluids. Frequency controls are usually achieved using "governors."