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AC Synchronous Machine Synchronization

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Corresponding Author:	Ali Bazzi UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	
Corresponding Author's Secondary Institution:	
First Author:	Ali Bazzi
First Author Secondary Information:	
Order of Authors:	Ali Bazzi
Order of Authors Secondary Information:	

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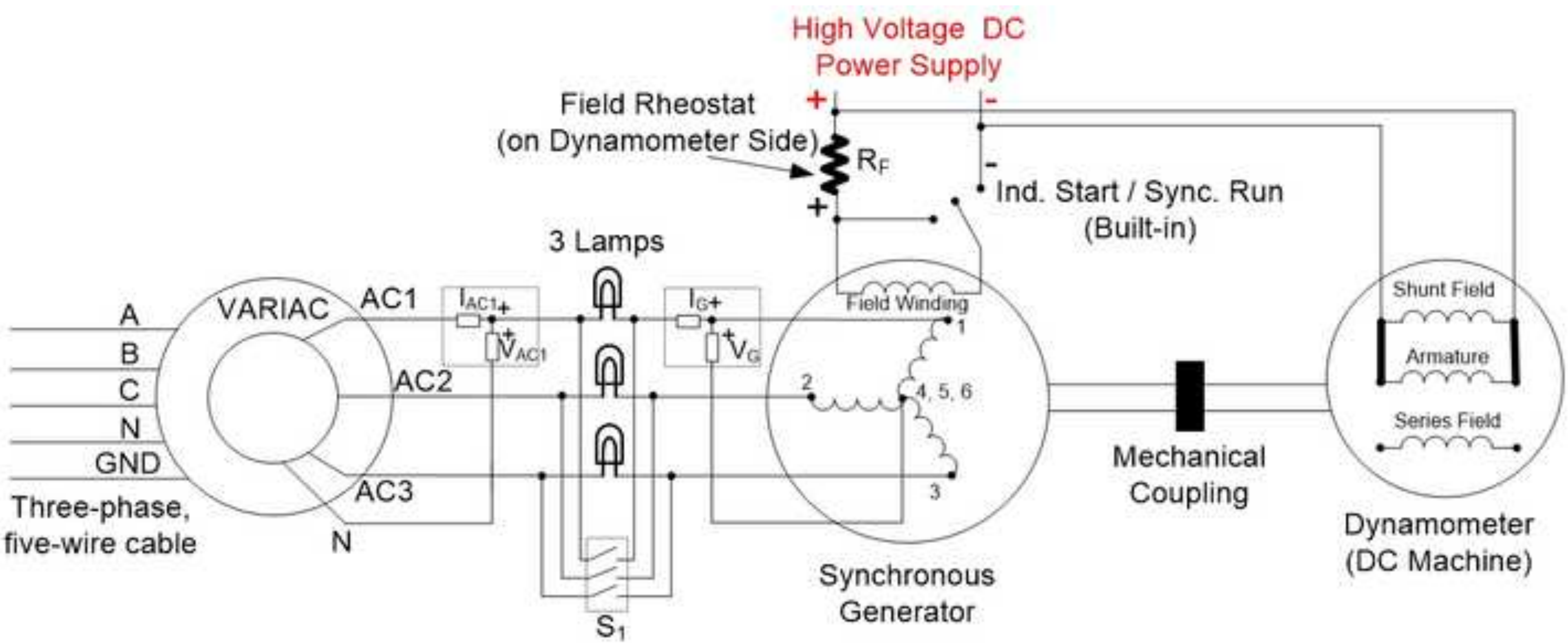

PI: Ali Bazzi – University of Connecticut

Electrical Engineering Science Education Title: AC Synchronous Machine Synchronization

Overview

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

Commented [AM1]: Please provide more theoretical background to how the AC Synchronous motor works. We want to teach the concepts around how the equipment works, as well as the appropriate tests that you have described here. It should be clear to the viewer how this machine differs from the AC induction motor, etc.

Ali: Further technical details are now provided under principles.

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.

Principles

Synchronous machines rely on the rotating magnetic field concept introduced for induction machines. Three-phase currents, flowing in the machine's stator, produce a ~~resulting~~ 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.

Commented [AM2]: Be sure to include information about how the generator works. The principles section should be included in all manuscripts in order to provide background on the inner workings of the equipment, as well as how to use it.

Ali: Done

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.

Commented [AM3]: Provide some context to this method. A brief introduction to what the test is would be beneficial to the viewer/reader who will then be seeing the method later on.

Ali: Done

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).

   1.1 Make sure the three-phase disconnect switch, synchronous motor switch, and DC motor switch are all off.

      1.1.1 Check that the VARIAC is at 0%.

   1.2 Wire the VARIAC to the three-phase outlet and connect the setup shown in **Figure 1**.

      1.2.1 Use the three-phase switch on the synchronous machine side as S_1.

      1.2.2 Note that S_1 and the three-lamp setup are in parallel.

      1.2.3 Also note the polarities of the digital power meter probes.

      1.2.4 Check that the Start/Run switch is in the Start position.

   1.3 Set R_F to maximum resistance.

   1.4 Leave the VARIAC at 0% and leave S_1 off.

   1.5 Turn on the three-phase disconnect switch.

      1.5.1 Turn on the high voltage DC power supply.

      1.5.2 Make sure all connections are clear from the supply terminals.

      1.5.3 Press the V/I DIS button on the supply to display the voltage and current operating points. Adjust the voltage knob to 15 V.

      1.5.4 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.

1.6 The machine should spin slowly.

1.6.1 Increase the DC supply output voltage to around 160 V.

1.6.2 Measure the shaft rotational speed.

1.6.3 Adjust the supply voltage in order to achieve 1800 RPM rotational speed.

1.6.4 Record the DC current and voltage on the supply display.

1.7 Leave the setup intact and do not turn off any of the equipment.

2. Synchronizing the Synchronous Generator with the Grid

2.1 Switch the Start/Run switch on the synchronous machine side to "Run". The three lamps should now turn on.

2.1.1 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 +/- 2% are acceptable.

2.1.2 Slightly increase the VARIAC output to achieve V_{AC1}=120 V.

2.2 At this stage, the grid is providing 120 V at a frequency of 60 Hz.

2.2.1 Record voltage, current, and power readings on both power meters. Do not ignore +/- signs in front of any number on the~~your~~ meters.

2.3 The lamps should change their lighting pattern.

2.3.1 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.

2.3.2 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.

2.3.2.1 In this case, turn the VARIAC back to 0%.

2.3.2.2 Press "Stop" on the power supply panel.

2.3.2.3 Reduce the DC voltage setting back to 15 V.

2.3.2.4 Switch phases b and c on the VARIAC side.

Commented [AM4]: What signs?

Ali: +/- signs

Commented [AM5]: If this is the case, would this be the stopping point? Or you would skip to 2.4 correct?

Ali: This is desired to see. 2.3.2 is a stopping point and 2.3.2.1 to 2.3.2.5 are the corrective actions

Commented [AM6]: Are these the labels of each lamp?

Ali: This is for the three phases

Commented [AM7]: Again, can you explain the labeling scheme?

2.3.2.5 Repeat all the above steps, starting at Step 1.

2.4 *This step requires quick action*: At the instant 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.

2.5 The generator is now synchronized with the grid. Record voltage, current, and power readings on both power meters. Do not ignore signs.

2.6 Leave the setup intact.

3. Effect of Field Current variation

Commented [AM8]: Perhaps we film this section as an application?

Ali: I think that the synchronization part as a whole is an excellent application, and it is very visual in terms of lights shining and dimming.

3.1 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.

3.2 If this R_F variation provides the same sign for all power readings:

3.2.1 Slightly adjust the DC supply output to achieve a reverse power flow from/into the synchronous machine.

3.2.2 Remember that negative power means the machine is generating electrical power.

3.3 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.

3.4 Keep the setup intact.

4. Disassembling the Setup

The following sequence should be followed before disassembling the setup:

4.1 Turn the VARIAC back to 0%.

4.2 Turn off the power supply output by pressing “Stop”.

4.3 When the machines stop rotating, flip the Start/Run switch to the “Start” position, and switch off S_1.

4.4 Turn off the three-phase disconnect switch.

4.5 Disassemble the setup.

Representative 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 $120f/P$=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 120V=170/sqrt(2) and a frequency of 60 Hz (2π*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 $170\cos(120\pi t+\varphi)$ 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

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."

Legend

Figure 1: A schematic setup for the three-phase synchronous generator experiment.