
Synchronous Machine Parameter Measurement

Introduction

Wound field synchronous machines are mostly used for power generation but also are well suited for motor applications where constant speed and leading power factor operation are desirable. In this experiment, classical tests will be performed to determine the synchronous machine parameters. Under generator operation, the standard open-circuit voltage and short-circuit current characteristics are obtained. This allows calculation of the synchronous reactance and Short Circuit Ratio (SCR).

The fundamental principle of the synchronous machine is that the electrical frequency (in Hz) is related to the mechanical speed (in RPM) through the number of poles by

$$n = \frac{120f}{\text{poles}} \quad (1)$$

The radian electrical frequency is given by

$$\omega_e = 2\pi f \quad (2)$$

The synchronous generator steady-state per-phase equivalent electric circuit is shown in Figure 1. Typically, the armature voltage is used as a reference and the internal generated voltage (or back-emf) and armature current are defined relative to this phasor by

$$\hat{V}_a = V_a \angle 0 \quad (3)$$

$$\hat{E}_{af} = E_{af} \angle \delta \quad (4)$$

$$\hat{I}_a = I_a \angle -\theta \quad (5)$$

In this model, the armature resistance is neglected and X_s represents the stator reactance. All electrical quantities are operating at the frequency ω_e with the exception of the dc field voltage and current.

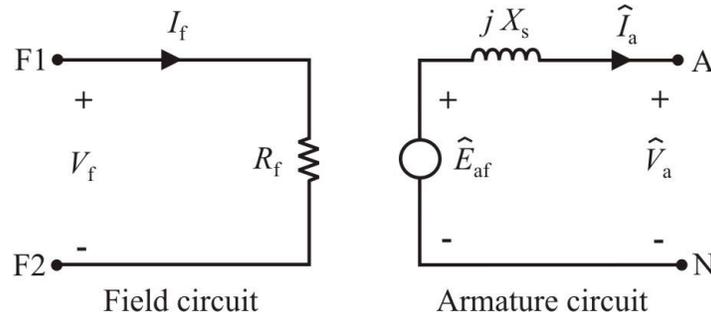


Figure 1. Synchronous generator equivalent circuit.

A standard test that is performed on the synchronous generator is to measure the synchronous reactance by measuring the open-circuit armature voltage and short-circuit armature current versus field current while the machine is driven at a constant mechanical speed. If the machine terminals are open-circuited, armature current will be zero and thus the magnitude of the open-circuit voltage will be

$$V_{a,OC} = E_{af} = \frac{\omega_e L_{af} I_f}{\sqrt{2}} \quad (6)$$

Since E_{af} is proportional to field current I_f , one would expect the open-circuit voltage to increase linearly with field current. However, as the field current is increased, the machine steel saturates and the open-circuit characteristic exhibits the characteristic shown in Figure 2.

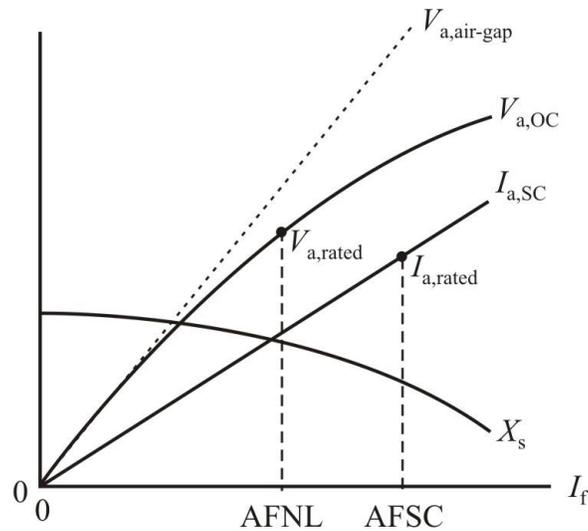


Figure 2. Synchronous generator open- and short-circuit characteristics.

In Figure 2, the short-circuit current and stator reactance are also plotted versus field current. From the equivalent circuit, the reactance can be defined as

$$X_s = \frac{V_{a,OC}}{I_{a,SC}} \quad (7)$$

It should be noted that $V_{a,OC}$ is a line-to-neutral voltage and if line-to-line voltage is measured, the measured voltage should be divided by $\sqrt{3}$.

It can be seen from Figure 2, that the synchronous reactance changes as the machine saturates. For low values of field current, the machine is unsaturated and the reactance value is referred to as the unsaturated reactance $X_{s,u}$. The saturated reactance is defined as the reactance calculated according to (7) at a field current which corresponds to rated armature voltage on the open-circuit curve.

If the armature resistance R_a is included in the model, an exact value for the stator reactance can be calculated using

$$X_{s,exact} = \sqrt{\left(\frac{V_{a,OC}}{I_{a,SC}}\right)^2 - R_a^2} \quad (8)$$

For practical machines R_a is much less than X_s and (7) gives a value of reactance with an error less than 0.05%.

Another parameter that is of interest in synchronous machines is the short-circuit ratio (SCR). This is defined as the amount of field current that results in rated armature voltage AFNL (amperes field no-load) from the open-circuit test divided by the field current that results rated armature current AFSC (amperes field short-circuit) from the short-circuit test. This can be expressed as

$$SCR = \frac{AFNL}{AFSC} \quad (9)$$

With this definition, SCR is a per-unit quantity. It can be shown that the reciprocal of SCR times the rated armature voltage $V_{a,rated}$ over the rated armature current $I_{a,rated}$ is equivalent to the stator reactance

$$X_s = \left(\frac{1}{SCR}\right) \left(\frac{V_{a,rated}}{I_{a,rated}}\right) \quad (10)$$

Equation (10) is valid for the saturated reactance as defined above.

Laboratory Software

Figure 3 shows a screen-shot of the laboratory software used in this experiment, “LabSynchronousMachineParametersTenma.” For creating the open-circuit voltage and short-circuit current plots, the primary variables of interest are the field current I_f , the armature voltage $V_{LL}(\text{rms})$, and the armature current $I_a(\text{rms})$. These variables are logged along with the frequency by clicking the **Add** button. The field current in the synchronous machine is controlled by the knob on the Tenma power supply. After adjusting the supply through all field currents and obtaining the open-circuit test, the **Test Type** can be changed to **Short-Circuit** for the short-circuit test.

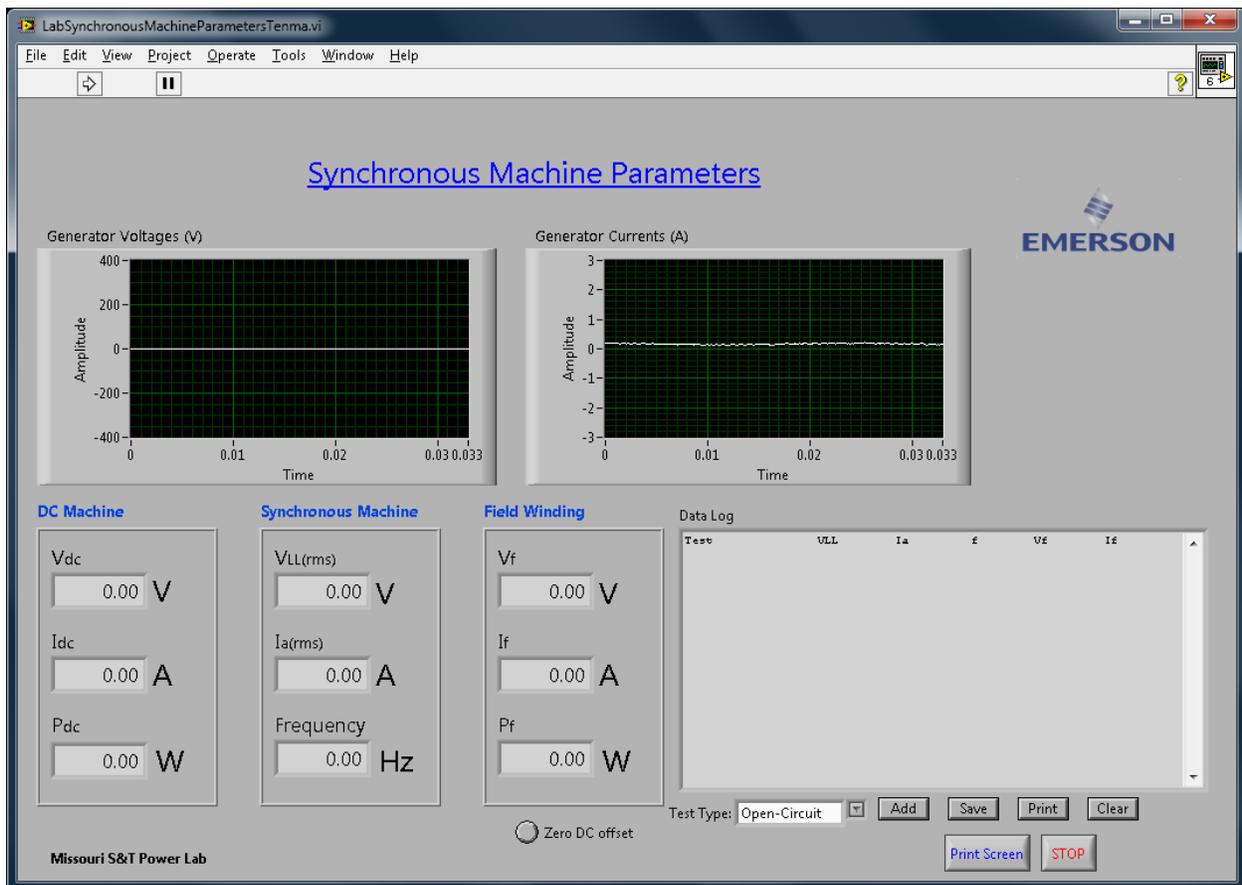


Figure 5. Screen shot of LabView software used for this experiment.

Laboratory Synchronous Machines

Figure 7 shows the diagram of the motor test stand used for this experiment. The synchronous machine is actually a wound-rotor induction machine. It will operate as a synchronous machine when a dc current is supplied to the rotor. Besides the rotor windings accessible from the connector box, the machine also has short-circuited damper windings on the rotor. Both sides of each stator winding (as, bs, cs, an, bn, and cn terminals) are brought out on the connector box for connection in wye or delta. However, in this experiment, the machine will be connected in wye. The rotor is wye-connected internally, and the three terminals are brought out (ar, br, and cr). Synchronization lamps are connected in-between the stator windings and the line connection (terminals a, b, and c). A three-phase switch bypasses these lamps when switched on. This set-up can be used for synchronizing the generator to the line or for synchronous motor starting. The synchronous machine is rated at 208 V (line-to-line rms), 60 Hz, 200 W. It is a 4-pole machine and thus has a synchronous speed of 1800 RPM.

The dc machine armature and field terminals are available for connection (A1, A2, F1, and F2). The machine is designed to be shunt-connected (armature and field in parallel) and is used to drive the synchronous machine as a generator or absorb a mechanical load when the synchronous machine is operating as a motor.

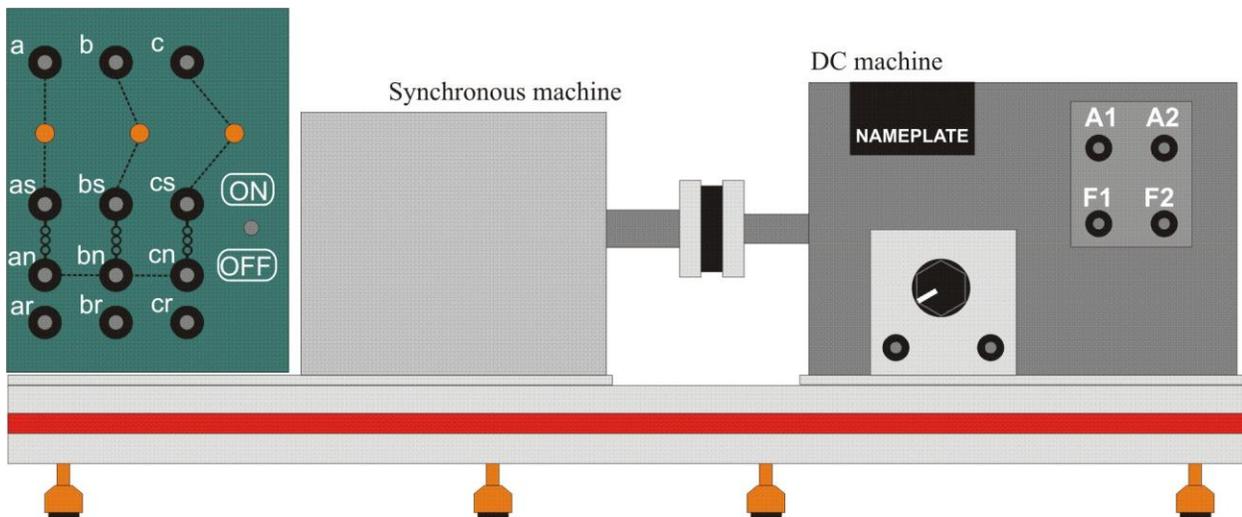


Figure 4. Laboratory experiment connection diagram.

Laboratory Work

Connect the dc and synchronous machines to the sources as shown in Figure 5. The dc motor will be connected to the dc supply on the source panel through the meter box so that the voltage, current and power can be displayed. The synchronous machine field is connected to the Tenma benchtop dc supply through a meter box channel as shown. In future experiments, you will use the Magna-Power supply instead. However, for this experiment, we need to operate at very low current levels where the Magna-Power is unstable. Throughout this experiment, some variation is allowable in the setting, ± 0.05 A. Connect the synchronous machine armature terminals to the first and second channels of the meter box as shown. **Make sure the switch on the connection box is in the ON position.**

Open and run the correct parameter measurement program, "LabSynchronousMachineParametersTenma." Click **Zero DC offset** on the laboratory software to zero the offset in the dc channels. After zeroing these channels, remove the short circuit wires.

The benchtop supply should be set for its maximum output voltage (about 20 V) and minimum possible current limit. Unfortunately, the current limit is not indicated unless the power supply is active. Switch on the supply at the back, but do not enable it on the front. Adjust the voltage to its maximum and turn the current down using the knobs on the front of the supply. Install a short (the dotted line in Figure 5, on the low side of the third channel of the meter box, the synchronous machine field connection) and enable the benchtop supply. Verify that the display on the LabView program is similar to the display on the benchtop supply, and turn the current down as low as possible. Disable the supply and remove the short.

Switch on the source panel and increase the voltage to 20%. At this time, the dc motor should start. However, the machine may not start since the armature and field are being increased simultaneously. If this is the case, reduce the voltage to zero and switch off the source panel circuit breaker then connect the motor using the alternate connection shown in Figure 5. This reverses the field flux and the machine should start the next time the source panel is switched on and adjusted to 15%.

If the dc motor is running smoothly, increase the source panel voltage to 50%. This should correspond to a dc voltage of about 150 V as seen on the computer screen. At this point, the speed will be nearly 1800 RPM. Also, the armature voltage will have a small value even though the synchronous machine field current is zero. This is because the rotor field poles are slightly magnetized from previous use. This small voltage can be used to determine the number of poles. Write down the frequency displayed on the computer screen. Use the hand-held tachometer at your station to measure the shaft speed. From this information, the number of poles can be computed from equation (1) above. The number of poles should be an even integer number.

Make sure the **Test Type** is set to **Open-Circuit** and log a data point by clicking **Add**. Increase the commanded field current to 0.25 A (using the current knob on the front of the Tenma supply) and log another data point. Some deviation is acceptable, ± 0.05 A. Continue to increase the field current in increments of 0.25 A and log each data point for the entire range (up to 2.5 A). You should notice from the waveforms and rms readings that the armature voltage increases and the armature current is zero. Decrease the commanded field current to zero.

At this point, the machine should still be running and the field current should be zero. The armature voltage should be very small. Add the short circuit wires (dashed wires in Figure 5, on the high side of the first two channels, the synchronous machine stator connections). Change the **Test Type** to **Short-Circuit**. Log a data point by clicking **Add**. Increase the commanded field current to 0.25 A and log another data point. Continue to increase the field current in increments of 0.25 A and log each data point for the entire range (up to 2.5 A). You should notice the armature voltage is nearly zero and the armature current will increase (linearly with field current). Decrease the commanded field current to zero.

Turn the source panel voltage to zero and switch off the source panel. Switch off the Sorenson power supply. Click **Save** and save the test data to a file.

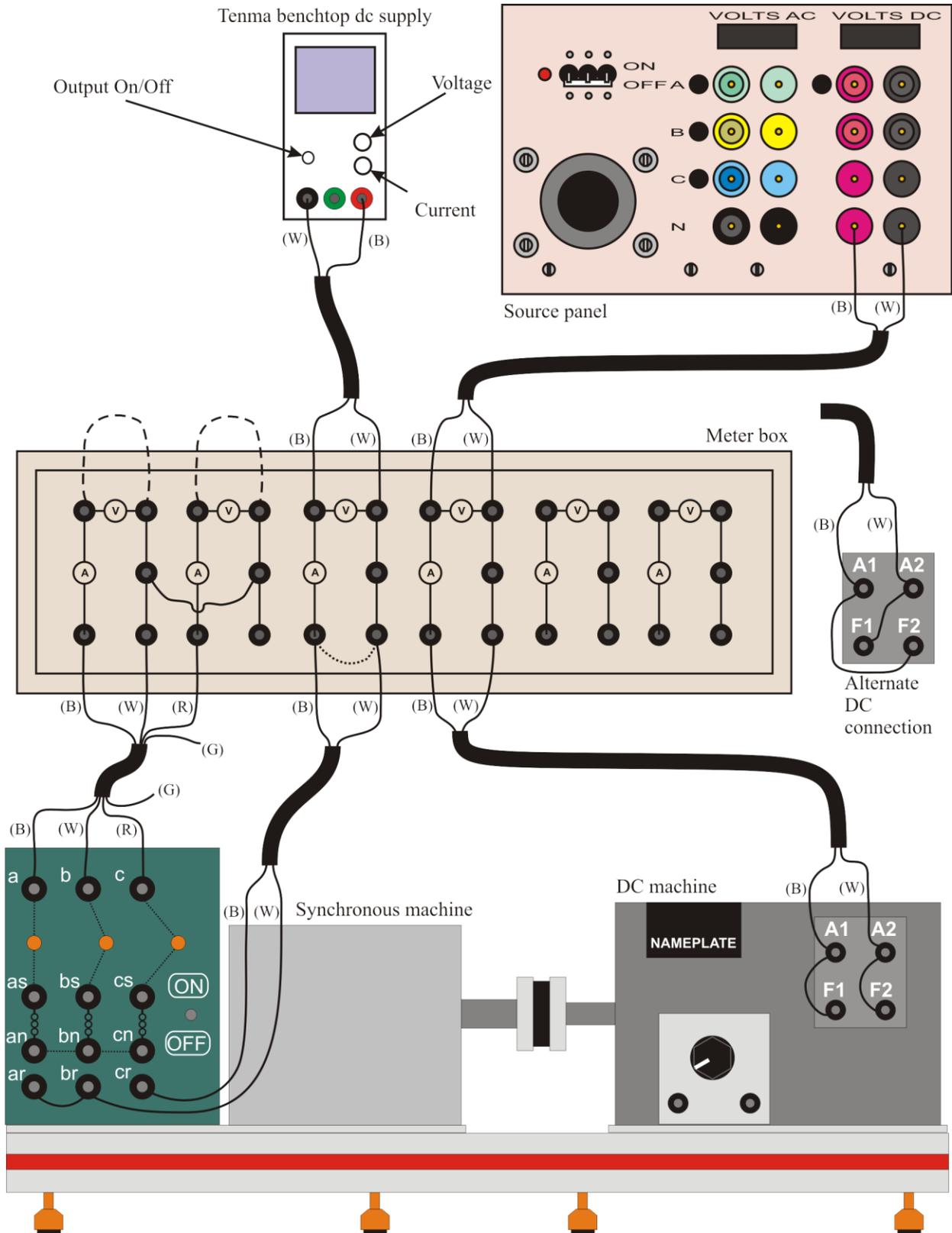


Figure 5. Laboratory experiment connection diagram.

Calculations and Questions

1. Plot the open-circuit voltage and short-circuit current versus field current from the test data. The measured open-circuit voltage is in line-to-line, so must be converted to line-to-neutral before plotting. Also plot the air-gap line $V_{a,\text{air-gap}}$ as shown in Figure 2. This can be computed as a straight line using some of the points with lower values of field current.
2. Use one of the open-circuit data points in the linear region (low field current) to compute the unsaturated synchronous reactance using (7). The 0.25 A or 0.5 A field current points are probably best for this.
3. Based on the rated armature voltage of $V_{a,\text{rated}} = 120\text{ V}$ and rated armature current of $I_{a,\text{rated}} = 0.7\text{ A}$, determine the AFNL and AFSC for this machine. Note that the measured data may not contain these exact values and linear interpolation should be used for accuracy. Using AFNL and AFSC compute the short-circuit ratio using equation (9).
4. Compute the saturated synchronous reactance using equation (7) for the data which corresponds to rated voltage. Compute a corresponding field constant that provides the generated voltage given a field current, using this same data point. Also compute the saturated synchronous reactance using the short-circuit ratio as in equation (10).
5. The armature resistance for this machine is given in the table below. Compute the exact saturated synchronous reactance using (8) and compare it to the calculation using (7).
6. Compute the field resistance R_f at each data point by dividing the field voltage V_f by the field current I_f . Average the values for all data points to obtain a value for field resistance.
7. Compile the machine parameters in a table similar to the one below.

Synchronous Machine Parameters	
Rated armature voltage	$V_{a,\text{rated}} = 120\text{ V}$
Rated armature current	$I_{a,\text{rated}} = 0.7\text{ A}$
Armature resistance	$R_a = 12.5\ \Omega$
Field resistance	$R_f =$
Unsaturated synchronous reactance	$X_{s,u} =$
Saturated synchronous reactance	$X_s =$
Short-circuit ratio	$SCR =$
Saturated Field Constant, E_{af}/I_f	$K_f =$