Synchronous Generator Line Synchronization

Introduction

One issue in power generation is synchronous generator starting. Typically, a synchronous generator is connected to the utility grid through the process of line-synchronization which amounts to generating voltages that match the grid so that the machine can be electrically connected. Once the machine is synchronized to the grid, the real power can be controlled through the shaft torque and the reactive power is controlled through the field current. In this experiment, the synchronous generator is connected to a fixed-voltage fixed-frequency source through line synchronization. The power generation levels are set and the reactive power is controlled to produce the generator "V-curves".

Line Synchronization

Figure 2 shows the set-up for line synchronization. The machine is first driven to synchronous speed mechanically using a "prime mover" which could be an electric motor or a turbine. A DC field current is established in the rotor so that the machine generates an open-circuit voltage that matches the three-phase source.
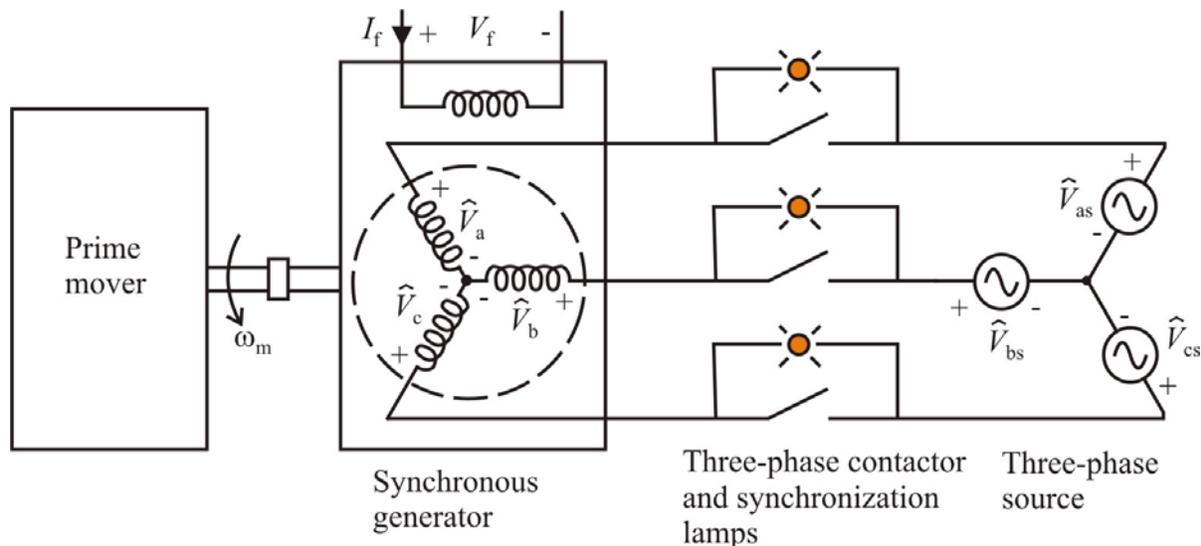

Figure 1. Line synchronization scheme.

Before closing the line contactors, a set of conditions must be met. Specifically, the generator and line voltage must match in terms of

1. Frequency of the voltages
2. Magnitude of the voltages
3. Phase of the voltage

Note that matching the phase in a three-phase system implies matching the phase sequence. Under the conditions above, the voltages across the contactors will be zero. The frequency of the generator is set by the prime mover mechanical speed ω_m. In particular, the mechanical speed is adjusted so to match the source frequency f_e according to

$$\omega_m = \left(\frac{2}{poles}\right) 2\pi f_e \tag{1}$$

After matching the frequency, the magnitude of the open-circuit armature voltages V_a, V_b, and V_c are set to match the magnitude of the line voltages V_{as}, V_{bs}, and V_{cs}. Since the open-circuit voltages are equal to the back-emf, the magnitude can be set using the field current. Assuming the frequency is matched according to (1) the a-phase back-emf is

$$E_{af} = \frac{\omega_e L_{af} I_f}{\sqrt{2}} \tag{2}$$

The final step is matching the phase of the generated voltage to the phase of the line voltages. The key to this is that the frequency is not matched exactly. Over a long time period, the phase of the generated voltages will shift and at some point be aligned with the line voltages. At this time, all conditions are matched and the synchronization lamps will go dark. When all three lamps are off, it is safe to close the contactor and connect the generator to the line. The phase sequence must also be matched. If the generator has a different phase sequence than the line, the lamps will blink one at a time. If this is the case, two phases of the line voltage (on the left side of the contactor in Figure 1) can be swapped.

The per-phase synchronous generator model is shown in Figure 2. Once the generator is connected to the line, the synchronous speed will be fixed to the frequency by

$$\omega_s = \left(\frac{2}{poles}\right) 2\pi f_e \tag{3}$$

In RPM, the synchronous speed may be calculated as

$$n_s = \frac{120 f_e}{poles} \tag{4}$$

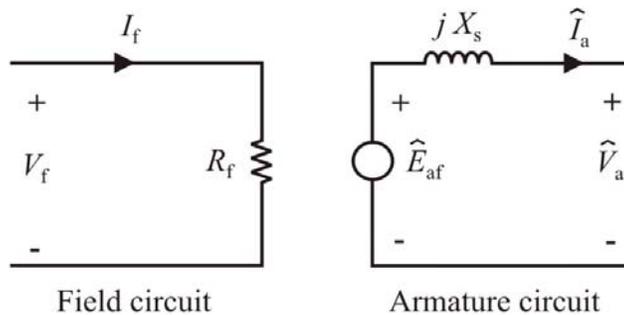Field circuit   Armature circuit
Figure 2. Synchronous generator equivalent circuit.

Generator V-curves

In steady-state operation, the real power flow can be controlled using the shaft torque of the prime mover. The reactive power can be controlled by adjusting the field current. From the machine per-phase model of Figure 2, it can be seen that the output power is

$$P = 3V_a I_a \cos(\theta) \tag{5}$$

If the armature resistance is neglected, it can be shown through power relationships that

$$X_s I_a \cos(\theta) = E_{af} \sin(\delta) \tag{6}$$

Therefore, for constant power operation

$$I_a \cos(\theta) = C_1 \tag{7}$$

$$E_{af} \sin(\delta) = C_2 \tag{8}$$

where C_1 and C_2 are constants.

From the KVL equation, the phase voltage is

$$\hat{E}_{af} = \hat{V}_a + j X_s \hat{I}_a \tag{9}$$

Using the information from (5-9), the circuit phasors can be plotted for constant power as the field current is varied. This is shown for three values of field current in Figure 3. Note that the synchronous generator can operate with a leading power factor, unity power factor, or lagging power factor. Since the magnitude of $\hat{E}_{af}$ is proportional to field current excitation, the leading power factor condition is sometimes referred to as under-excited operation and lagging power factor condition is referred to as over-excited operation for the synchronous generator. Note that the current $\hat{I}_a$ and the voltage $\hat{E}_{af}$ follow the lines of constant power given by (7-8). If the armature current magnitude is plotted versus field current for several power levels, the resultant plots are the generator V-curves shown in Figure 4. The points marked *a*, *b*, and *c* on the upper curve correspond to the operating conditions in Figure 3.

Note that for $P = 0$, the generator is supplying or absorbing only reactive power. For the under-excited case denoted by point d) in Figure 4, the generated reactive power is negative. This means that the machine is absorbing reactive power and is effectively operating as an inductor. For the over-excited case denoted by point e), the generated reactive power is positive meaning that the machine is supplying reactive power. For point e), the machine appears as a capacitor. This mode of operation is sometimes used for reactive power compensation on a power system. Operation at point e) is referred to as synchronous condenser operation; condenser being an old term for capacitor.
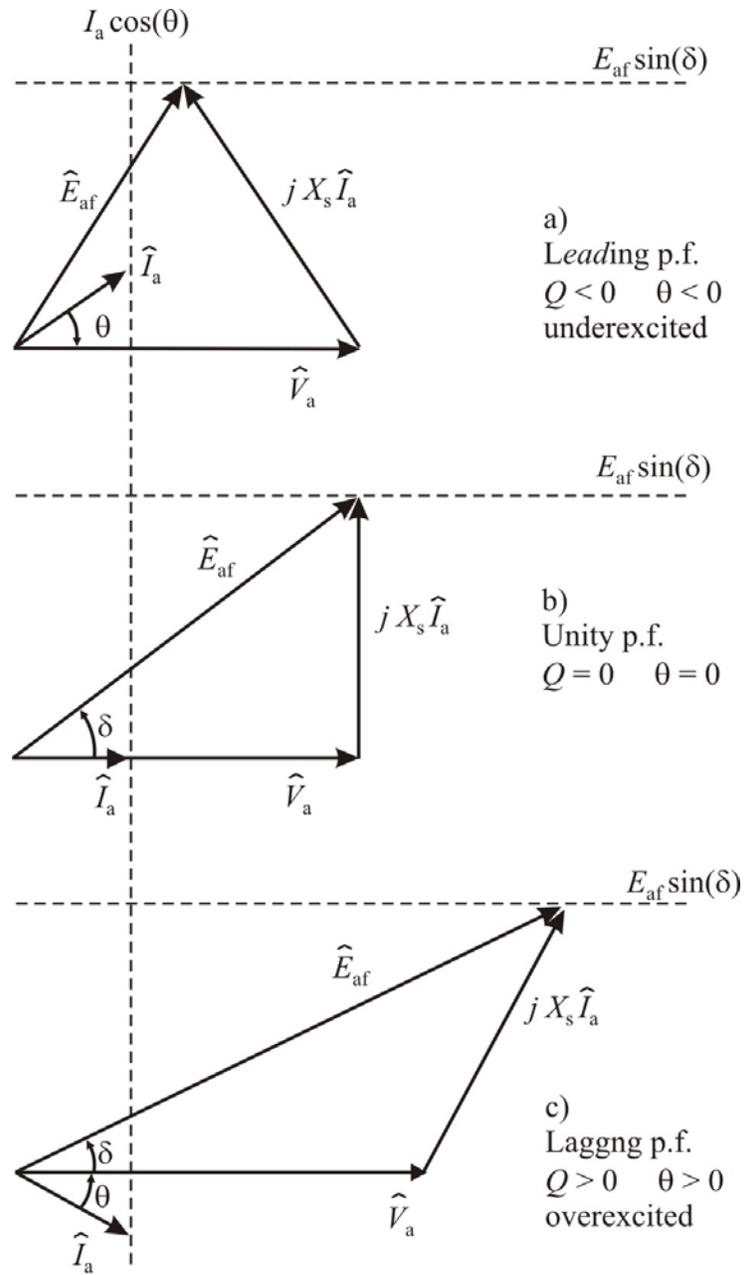
$I_a \cos(\theta)$

$E_{af} \sin(\delta)$

$\widehat{E}_{af}$ $j X_s \widehat{I}_a$

$\widehat{I}_a$

θ

$\widehat{V}_a$

a)
Leading p.f.
$Q < 0$ $\theta < 0$
underexcited

$E_{af} \sin(\delta)$

$\widehat{E}_{af}$

$j X_s \widehat{I}_a$

b)
Unity p.f.
$Q = 0$ $\theta = 0$

δ

$\widehat{I}_a$ $\widehat{V}_a$

$E_{af} \sin(\delta)$

$\widehat{E}_{af}$

$j X_s \widehat{I}_a$

c)
Laggng p.f.
$Q > 0$ $\theta > 0$
overexcited

δ

θ

$\widehat{V}_a$

$\widehat{I}_a$

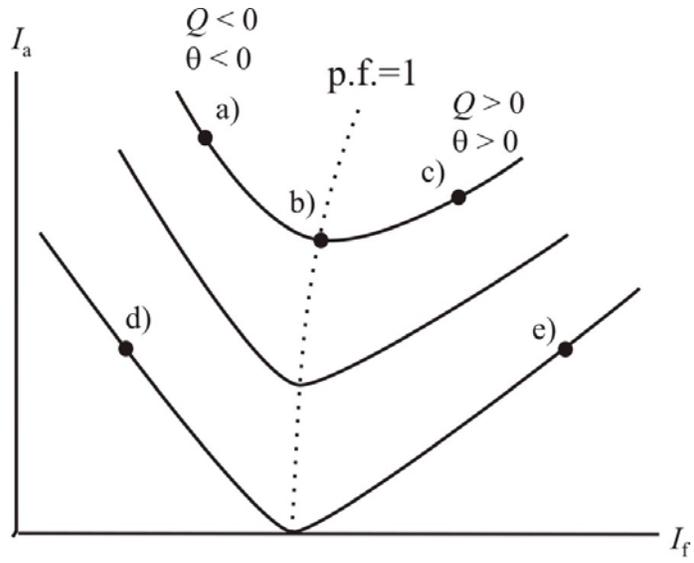Figure 3. Synchronous generator phasor diagrams.

Figure 4. Synchronous generator V-curves.

Laboratory Software

Figure 5 shows a screen-shot of the software for this experiment. The synchronous machine armature voltage, armature current, real power, and reactive power are displayed as well as graphs of the armature voltage and armature current. The field quantities are also displayed and a control is built-in for adjustment of the field current.   After going through the line-synchronization procedure, the field current will be adjusted and the data is saved at each step for plotting the machine V-curves. The standard "Add", "Clear", "Print", and "Save" buttons are included. Three V-curves will be obtained in this experiment and can be marked by selecting power levels of "0W" (shown in Figure 5), "50W", or "100W".
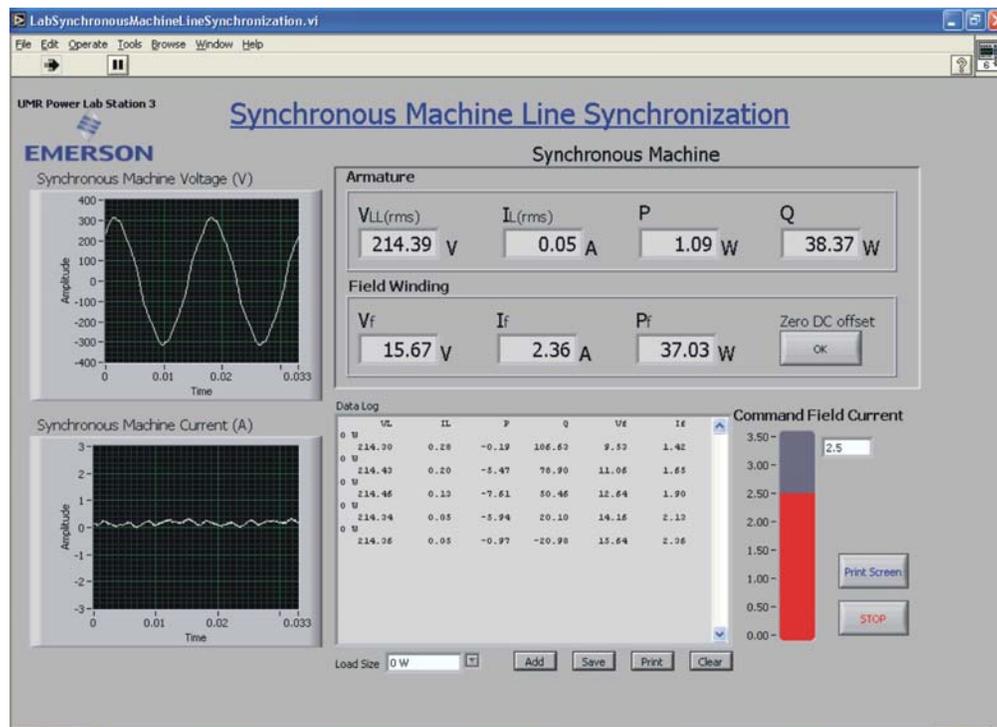

Figure 5. Laboratory software for the synchronous motor V-curve experiment.

Laboratory machines

Figure 6 shows the a 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 form 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, 250-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.
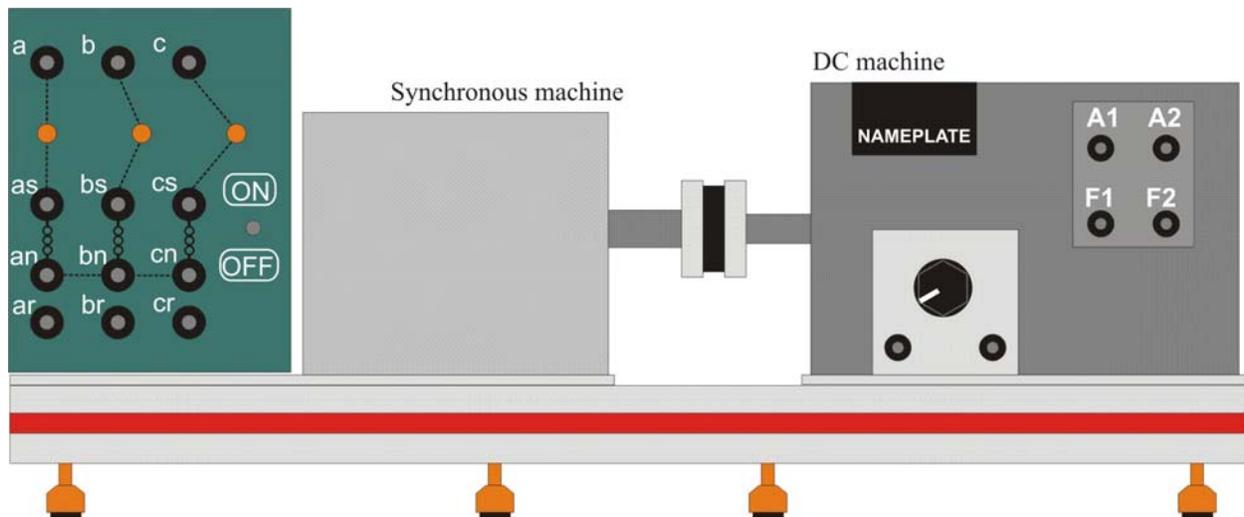

Figure 6. Synchronous and dc machine motor-generator set.

Laboratory Work

Figure 7 shows the wiring diagram for this experiment. Start by connecting the dc machine as a shunt-wound motor through a meter channel. Note that the rheostat is connected in series with the field. The rheostat should be turned all the way counter-clockwise as shown in Figure 7. Next, connect the Sorenson DC output to the synchronous machine through a meter channel as shown in Figure 7.

Lastly, connect the synchronous machine armature (terminals a, b, and c) to the meter box as shown in Figure 7. **Make sure the switch on the connection box is in the OFF position.** As a last step, connect the meter box to the 208-V line voltage. This is the terminals A, B, and C directly below the Sorenson DC supply. Adapter plugs will be necessary to make this connection. Keep in mind that you are connecting into an energized source. For this reason, the switch on the synchronous machine connection box must be OFF. After connecting into this source, the synchronization lamps on the connection box will light up.

The next step is to establish a field current. Start the **Line Synchronization** experiment on the computer and switch on the Sorenson power supply. Increase the commanded field current to 2.5-A using the software interface. Make sure that the field supply is working by noting the current on the computer screen.

Next, switch on the source panel and increase the variac to 15%. At this point, the DC motor should start. If it does not, reduce the variac to zero, switch off the source panel. Swap the field terminals F1 and F2 and try starting the motor again. Once the motor is running, increase the voltage until the speed is very close to 1800-RPM (as measured with the hand-held tachometer). This will be about 55% on the variac setting.

At this point, all three lamps should be blinking in synchronism at a very low frequency. If the lamps are blinking one at a time, then the phase sequence is incorrect. If this is the case, reduce the motor speed to zero, switch off the source panel, and swap the "b" and "c" terminals of the synchronous machine. When you bring the motor up to 1800-RPM again, all lamps should blink at the same time.

With the lamps blinking slowly, throw the synchronous machine switch at an instant when all of the lamps go off. This will bypass the lamps and connect the synchronous machine to the line.

At this point, the synchronous generator is running with no load as evidenced by the power reading of nearly zero. Reduce the field current to 1.5-A. Set the **Load Size** to **0W** in the software and obtain a set of V-curves by increasing the field current from 1.5-A to 3.5-A and logging the data for each point (by clicking **Add**). Reduce the field back current to 1.5-A.

The next step is to generate some power and send it into the line by changing the DC motor torque. Increase the rheostat setting until the synchronous generator power reads -50 W on the computer screen. Set the **Load Size** to **50W** in the software and record another set of V-curves.

Increase the rheostat again so that the generator power reads -100 W. Set the **Load Size** to **100W** in the software and record another set of V-curves.

Switch off the source panel circuit breaker and then reduce the source panel variac to zero. Switch off the synchronous generator and the machine will come to a stop. Switch off the Sorenson power supply.
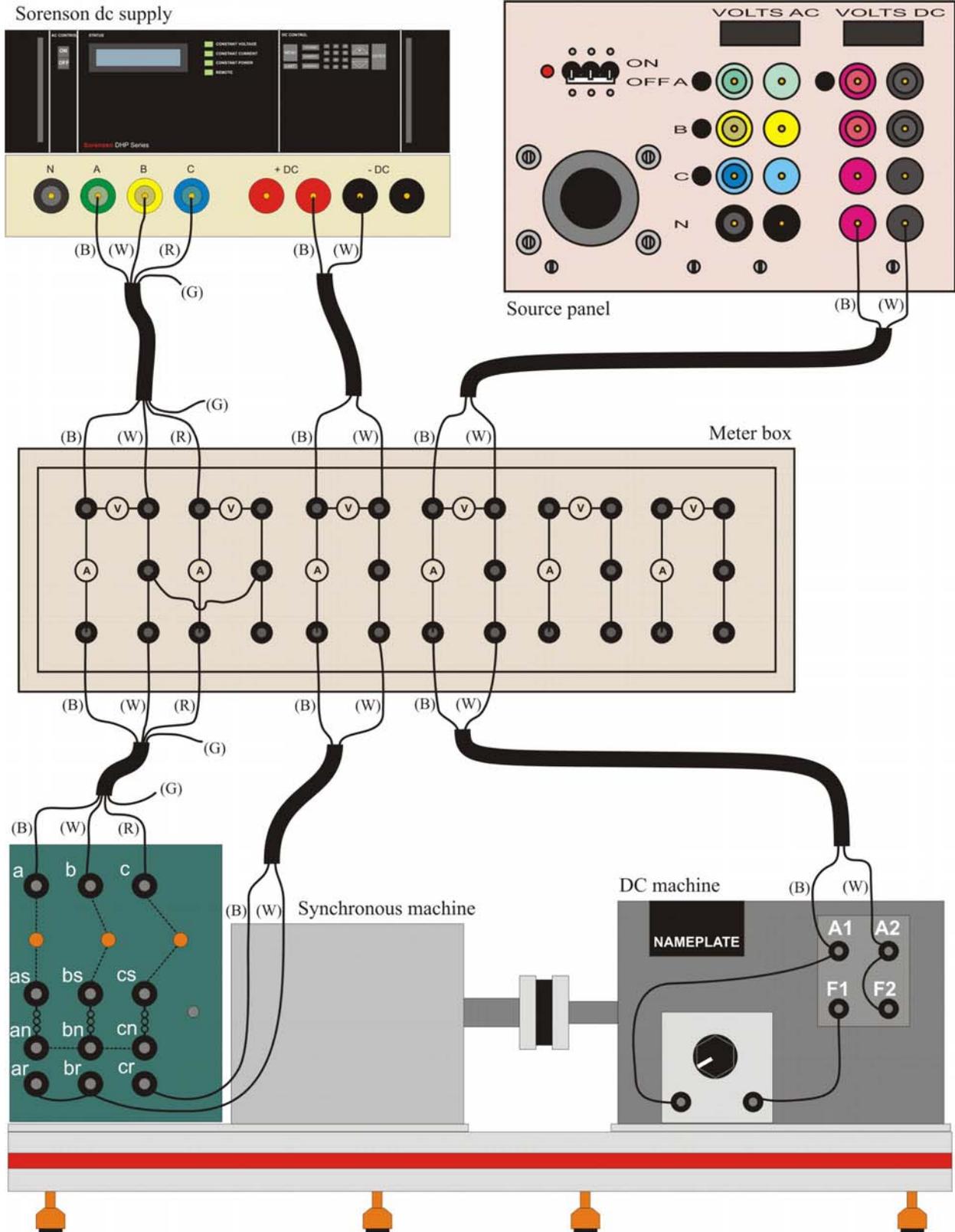
Figure 7. Laboratory experiment connection diagram.

Calculations and Questions

1. Create a plot of real power and reactive power versus field current for all three levels of loading. Make a separate plot for each load level, but use the same axes scales for each plot. The real power remains constant and the reactive power transitions from negative to positive. **Note that the measured real and reactive power are positive going into the machine which is opposite of the way it is defined in the model. For this reason, it is best to first multiply the measured real and reactive powers by -1 before doing the calculations.**

2. Create the V-curve plots for this motor by plotting the armature current magnitude versus field current. This should be one plot with all power levels.

3. Sketch the phasor diagrams for three operating points logged in the 100W test; one for leading power factor, one for unity power factor, and one for lagging power factor. For synchronous reactance use a value of $X_s = 152\,\Omega$.

4. For the 0-W V-curve data, compute the effective values of inductance and capacitance for the lowest and highest values of field current respectively.