ECE 5671/6671 – LAB 4

PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

1. Introduction

1.1 Objectives

The objective of this lab is to measure the power produced by a PMSG under various conditions. Data captured from the machine will be analyzed in order to compare the results of experiments with computations. Three-phase voltages and currents will be analyzed along with the active and reactive powers produced by the generator. Variations in the resistive and capacitive loads will produce changes in frequency output, active power output, and reactive power output. Curves similar to the droop curves of DC generators will be measured.

The procedures discussed for the remainder of this lab require correct execution of the instructions presented. Upon careful reading and comprehension of directions, proceed with the experiments. Headings throughout this handout will help distinguish whether a procedure is to be completed on the computer (Matlab, Simulink, or dSPACE) or on the actual equipment.

Equipment needed:

- PM Synchronous Generator (PMSG)
- DC generator (DCG), frame mounted, with coupler
- Digital multimeter
- dSPACE I/O box
- PEDB with ribbon cable and +12V supply
- Three-phase resistor box
- Three-phase capacitor box
- Current sensor board
- Grid connection box
- Rack of cables

1.2 Simulink functions and dSPACE layout

For the experiment, a new Simulink model must be created in order to compile a c-file that creates a **.sdf file** for dSPACE to load. Refer back to the tutorial of Lab 1 if questions arise about this process.

<u>>>Simulink Blocks</u>

Download, open, and examine the provided preliminary model (lab_4.mdl) to gain a sense of how this system will work. Included in this skeleton model is the controller for the prime mover (DC motor), which will be controlled by an input voltage. Also included are the encoder initialization block, position output, speed output, and frequency output. Figure 1 shows the controller for the prime mover (DC motor). The encoder setup for capturing position and angular velocity are displayed in figure 2.

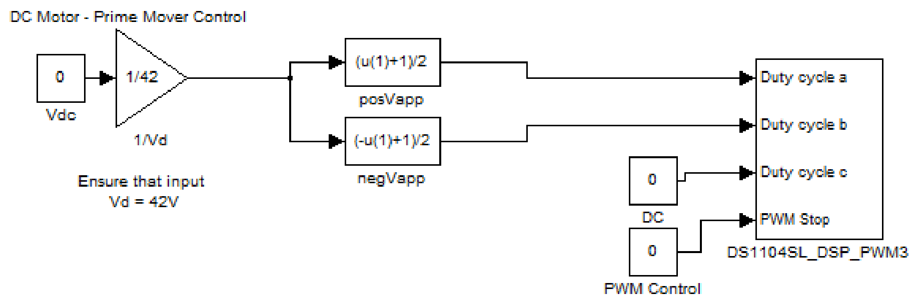

Figure 1: Prime mover controller

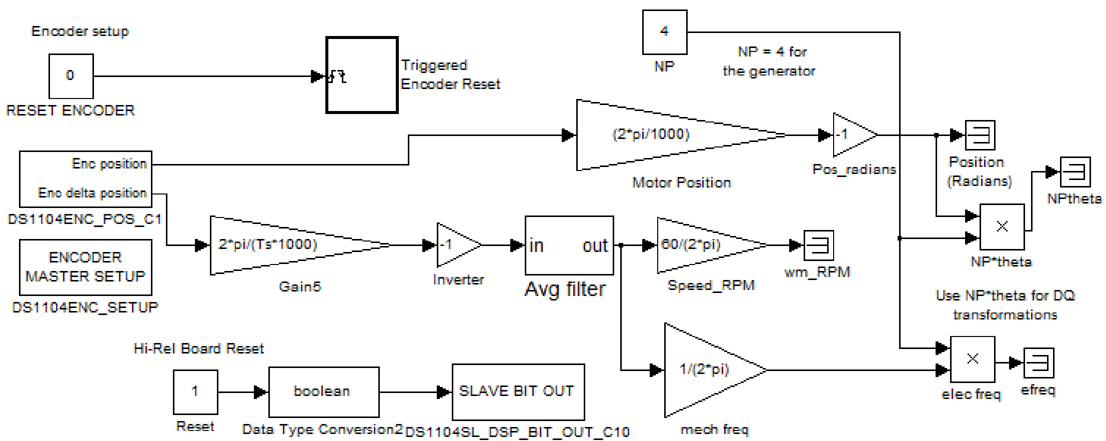

Figure 2: Encoder initialization, reset, and output of position and speed

Four Analog-to-digital channels (ADCH) will be used to capture data (voltage and current). Two channels will be used for measuring output voltage, and the other two will be used for measuring output current. Figure 3 displays the data capture blocks necessary for the experiments.

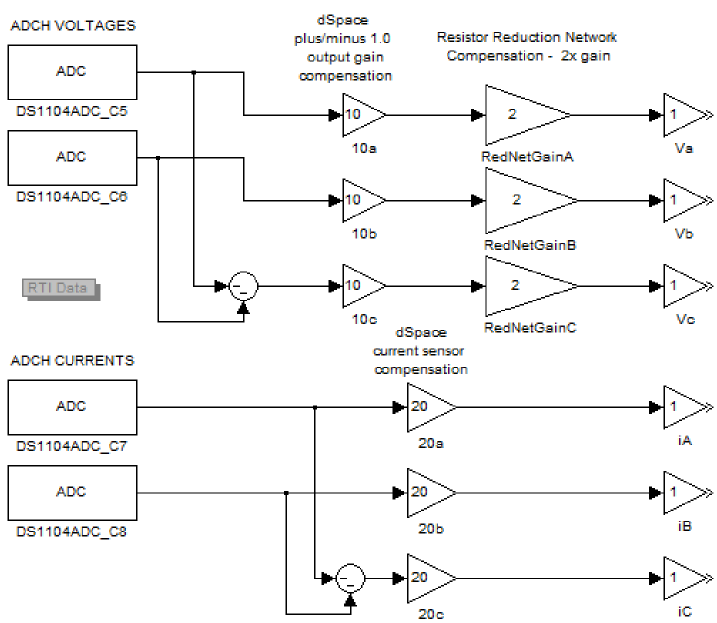

Figure 3: ADCH data capture blocks

As a result of using only two channels to capture phase voltages and two channels for phase currents, the third phases of each will be constructed computationally. Use of separate summation blocks creates the third phase assuming a balanced system. Once all three phases are established, the lines connect to their respective gain blocks. Remember that the **10x** and **20x** gains compensate for dSPACE's data capture gains, the **RedNetGainx** gains compensate for the voltage divider network in place to limit the voltages to 10V. The **Vx** and **iX** gain blocks are simply in place for signal identification in dSPACE.

<u>>>Matlab</u>

The model should reside in the current directory. This model will correctly build if the value for **Ts** is properly defined. Set **Ts** to 0.0001 by entering Ts = 1e-4.

<u>>>Simulink</u>

Now, ensure that the model configuration parameters are set as given in the checklist on the lab website (this was also provided to you in the previous lab, as well as the tutorial file). Then the model can be built. Press Ctrl+B, the Matlab command window may display warnings about ports not being connected, which can be disregarded. They will be taken care of as connections and progress are made throughout the lab.

2. Preliminary Testing

<u>>>Hardware Setup</u>

Follow the steps outlined in the introductory tutorial of Lab 1 to correctly assemble and test the equipment.

- SET THE POWER SUPPLY TO 42 VOLTS BEFORE CONNECTING ANY WIRES.
- TURN OFF THE SUPPLY, THEN CONNECT TO THE INVERTER BOARD
- TURN THE BOARD ON AND DOUBLE CHECK THAT 42 VOLTS IS APPLIED

Set up the DC motor to conduct tests. Connect leads from Phase A1 and Phase B1 on the PEDB to the positive and negative terminals of the DC motor, respectively. Couple the DC motor to the PMSG generator. Hook the encoder cable from the I/O board to the DC motor.

<u>>>dSPACE</u>

Once the Simulink build process has finished in Matlab, use the dSPACE ControlDesk program to run the actual experiment. With dSPACE, create a new *Project + Experiment* structure, as described in the tutorial, in the appropriate folder, choosing the right **.sdf** file for variable description. Close the blank layout presented and import the layout downloaded from the lab webpage (lab_4.lax) by clicking on the **Layouting** tab > **Import Layout.**

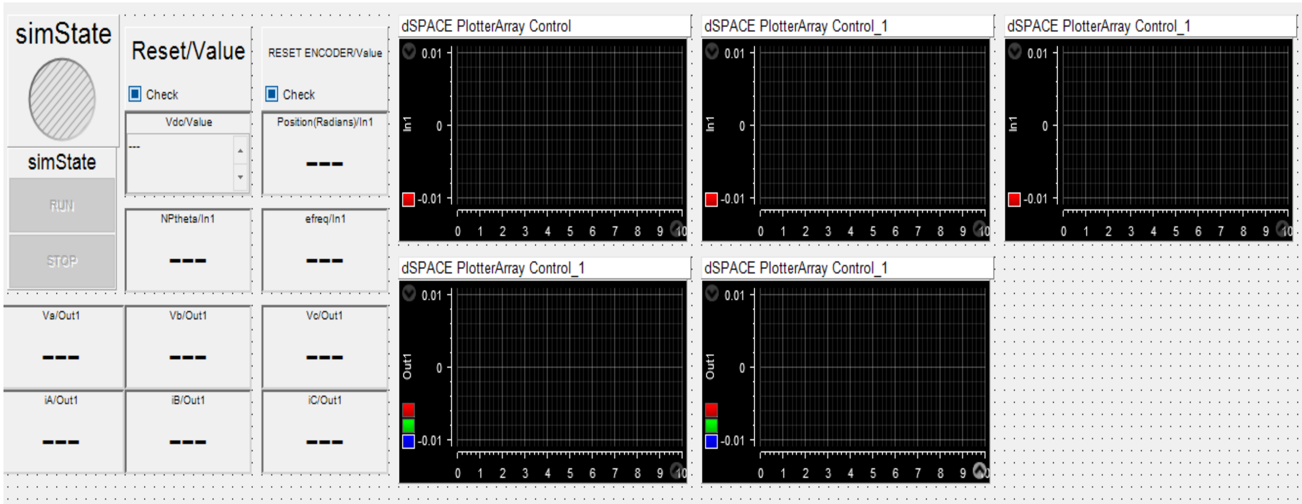

Figure 4: Provided dSPACE layout for experiment

Activate the experiment and verify that a positive voltage applied to the DC motor results in a positive position reported by the encoder. Confirm that speed, position, and frequency are correctly displayed. If this is not the case, request assistance from the TA.

3. PMSG Back-EMF Measurements

Carefully read the instructions below to assemble your equipment. A layout of the final system may be viewed in Appendix I. DO NOT go straight to this figure and setup your experiment; make sure you thoroughly follow the instructions before assembling because equipment is slowly added into the experiment as progress is made. Also, explanations of the grid connection box and current sensor board are provided in Appendix II.

3.1 Back-EMF voltages

>>Hardware Setup

In order to capture back-emf voltage outputs from the generator, connect the generator side phases A and B of the grid connection box terminals to the proper ports on the I/O board using two BNC cables. Verify that the ADCH channel you connect matches that of your Simulink model and the phase you wish to capture data from. Connect phases A, B, and C of the PMSG to the respective terminals on the generator side of the grid connection box. Noise in this system will distort captured data. To reduce system disturbances, connect an alligator cable from the frame of the generator to the neutral on the grid connection box.

>>dSPACE

With everything connected, put the experiment online and increase the voltage applied to the DC motor until an output electrical frequency of 120 Hz is obtained. Once the generator is in steady state, capture 1 second of data. To do this, set up the Automatic export, export file destination, type and name along with a stop condition of type *Time limit*, of 1s in the *Recorder* properties. Note that you will now need to use the *Start Triggered Recording* since the stop condition is implemented. Save the data set to be unpacked in Matlab using Mat_Unpack. Provide a plot of the phase voltages over 25ms. Comment on what is observed, including the peak magnitude of the captured line-to-neutral voltages.

Data post-processing considerations:

When post-processing captured steady-state data, all of the outputs as well as the real and reactive power should be averaged or filtered. The code below is provided to filter the noise. The majority of noise will be a ripple at 120 Hz. Use the code for post-processing your captured data.

```
[b,a]=butter(3,0.1);
variable_filtered=filtfilt(b,a,variabletobefiltered);
```

Note that more additions will be made to this layout further on in the lab. At this point, it would be good to have the TA look over your Simulink model, dSPACE layout, and equipment setup.

4. PMSG Characteristics Under Load

The behavior of the generator under various load conditions will be examined in the following section. Again, refer to Appendix I to view the system setup. First, we must modify our Simulink model and update dSPACE.

>>Simulink

The three-phase computation block that outputs real and reactive powers (PQVC) should be added to the Simulink model. You can find this block in the simulink model (generator_blocks.mdl) that can be downloaded from the lab webpage. Employ two *Mux* blocks with three input ports each, one for the phase voltages and one for the phase currents. Feed the outputs from these *Mux* blocks to the PQVC block. Create *Outport* blocks for the outputs of the PQVC block and connect them.

Upon addition of the new blocks build the model again by clicking the icon for 'incremental build' or the keys CTRL+B.

>>dSPACE

Add plotter arrays for the new power outputs. It is advised to place the real and reactive power outputs on separate plots. Also, the dSPACE layout can now be altered to feature plotter arrays of the phase currents produced from the PMSG.

>>Hardware Setup

The addition of more sensing equipment and a resistive load are required for this section. It is advised to disconnect whatever system is presently setup and start fresh for the new wiring connections.

In order to capture current outputs from the generator, use the current sensor board and the three-phase resistor box. Connect outputs from two phases (A and B) of the 3 phase resistor box into separate output terminals on the current sensor box. Note that current is positive flowing into the generator; therefore, the black terminal of the current sensor board should be connected to the generator. So, make sure to connect the leads from the red terminals on the current sensor board to the three-phase resistor box. The third phase (C) can be directly connected from the generator to the three-phase resistor box.

Connect two BNC cables from the signal ports on the current sensor board to their respective ADCH channels on the I/O board. Verify that your Simulink model ADCH blocks match the phases you have selected to capture in the physical experiment. This setup will enable current measurements. In order to gather data with the current sensor board, it needs to be powered with the provided power supply. The power supply to the current sensor board will be provided through a 24V adaptor found in the blue cable bin handed to you.

Voltage must also be measured; in order to capture the phase voltages from the PMSG, connect three additional leads from the terminals on the three-phase resistor box to the generator side terminals on the grid connection box. As before, two BNC cables will be used to connect the appropriate ADCH ports on the dSPACE I/O box to two phases (A and B), on the generator side of the grid connection box. Verify that the ADCH channels you connect match those of your Simulink model and the phase you wish to capture data from.

Noise in this system will distort captured data. To reduce system disturbances, connect a wire from the frame of the generator to the neutral on the three-phase resistor box and the neutral on the voltage reduction box (grid connection box). This system can be compared with the setup shown in Appendix I.

The system is now ready for experiments with the system under load. Have the TA look over your setup, Simulink model, and dSPACE layout.

Once the setup and layout are ready for the real-time experiments, perform the tasks on the numbered list below.

4.1 Generator experiments with resistive load

In this section, both the frequency and voltage output will be observed for an incrementally increasing resistive load.

Calculate the following:

i. Calculate the expected output phase currents (rms and peak) and real power for line to neutral load size 5Ω. Assume the generator outputs 10 Volts (peak) at 120Hz. Write down the values in the table below to compare to observed values resulting from the experiment. ***Note that the line to neutral load value used for calculation is equal to half of the line to line load (~10) that is listed on the three-phase resistor box***.

Perform the following:

ii. Set the three-phase resistor box to 10Ω. Engage the experiment online and increase the DC motor voltage until 120 Hz output frequency is obtained. Once the generator has reached steady-state, capture 1 second of data. Save the data set so that it may be unpacked and the variables plotted. Measure the peak voltage, peak current, and output power to compare with the calculated values.

	$I_{(peak)}$	$I_{(RMS)}$	$V_{(peak)}$	Real Power
Calculated				

Experimental				

Answer the Following:

How do the calculated values for power and current compare with the captured data?

iii. Set the resistive load box to the 40Ω (line-to-line). Run the experiment and increase the voltage until 120 Hz output frequency is obtained. Once this steady-state is achieved, capture and save data over 10 seconds during which the resistive load is changed gradually from 40Ω down to 10Ω. Save the data set and analyze using Matlab. In the table provided, write down the steady state speeds, peak phase output voltage, and output frequency. This information will be used later to produce plots comparing the droop curves of load vs. frequency and load vs. voltage. Filtering of data is advised.

Load	Velocity (RPM)	V_{peak}	Frequency
40			
30			
20			
10			

4.2 Generator experiments with a resistive & capacitive load

>>Hardware Setup

Use the three phase capacitor box to add a capacitive load in parallel with your resistive load (do not connect the neutral). This is a set of 100-μF (wye-connected) capacitors.

Calculate the following:

i. Calculate and report the impedance (both the real and imaginary parts in polar form) associated with the combined resistive and capacitive load assuming a resistive load of 5Ω (line-to-neutral) and a frequency of 120 Hz.

ii. Given a wye-connected resistive load with a line-to-neutral phase resistance of 5Ω and a parallel wye-connected 100-μF capacitive load, calculate the single-phase output current (rms and peak) and power (apparent, real, and reactive) from the generator when the generator outputs 10 Volts (peak) at 120 Hz. Write the values in the table provided to compare to observed values resulting from the experiment.

Perform the following:

iii. Set the resistive load box to 10Ω (line-to-line). Run the experiment and increase the DC voltage until 120 Hz output frequency is obtained. Once this steady state is achieved, capture and save data over 1 second. Make comments and tabulate the single-phase values of peak voltage, current (rms and peak), real power, and reactive power for both experiments. Use P and Q to calculate apparent power. Filtering is advised.

	$I_{(peak)}$	$I_{(RMS)}$	$V_{(peak)}$	Real	Reactive	Apparent
Calculated						

Experiment						

Answer the Following:

How do the calculated values for power and current compare with the captured data?

iv. Set the three-phase resistor box to 40Ω. Run the experiment and increase the DC voltage until 120 Hz output frequency is obtained. Once this steady state is achieved, capture and save data over 10 seconds in which the resistive load is changed gradually from 40Ω down to 10Ω. Save the data set and analyze using Matlab. In the table provided, write down the steady state speeds, peak phase output voltage, and output frequency. Filtering of data is advised.

Load	Velocity (RPM)	V_{peak}	Frequency
40			
30			
20			
10			

Using the tabulated data from the resistive experiment and the resistive/capacitive experiment, provide droop plots of load vs. frequency and load vs. voltage comparing the two experiments.

4.3 Discussion

Provide a conclusion summarizing the concepts and procedures covered in this lab. Discuss the impact the capacitive load had on the generator outputs with reference to power factor and reactive power.

Report Requirements: Consider this requirement list a guide to what would be viewed as a minimum to submit for your lab report. Always include discussion and comments on procedures, observations, and findings.

- Introduction with objectives.
- Include the equipment number of all of the major components used
- Section 3.1

    - Plot of back-emf voltages from PMSG. Report peak values and make comments.
    - With the two-phase voltages calculated, plot V_A plot -10*sin(NP*θ) on the same figure. Deduce the encoder offset by measuring the phase difference between these two signals.
- Section 4.1
    - Calculations: (i) Show derivations and expected values of power and current.
    - Experiments: (i) Compare measured peak current, voltage, and real power to the calculated values. (ii) Tabulated velocity, power, voltage, current, and frequency outputs.
    - Answers: provide a short answer for each question.
- Section 4.2
    - Calculations: (i) Show derivations and expected values. (ii) Include values for S, P, Q, and I.
    - Experiments: (i) values for P, Q, V, and I at 10Ω. (ii) Tabulated velocity, power, voltage, current, and frequency outputs. Make comparisons to Section 4.1. Include plots of the droop curves of both load vs. voltage and load vs. frequency. Make comparisons between the two experiments.
    - Answers: provide a short answer for each question
- Section 5.3- Discussion (Also, describe what worked well and did not work well in this lab, and make suggestions for possible improvements.)

Appendix I: System Layout

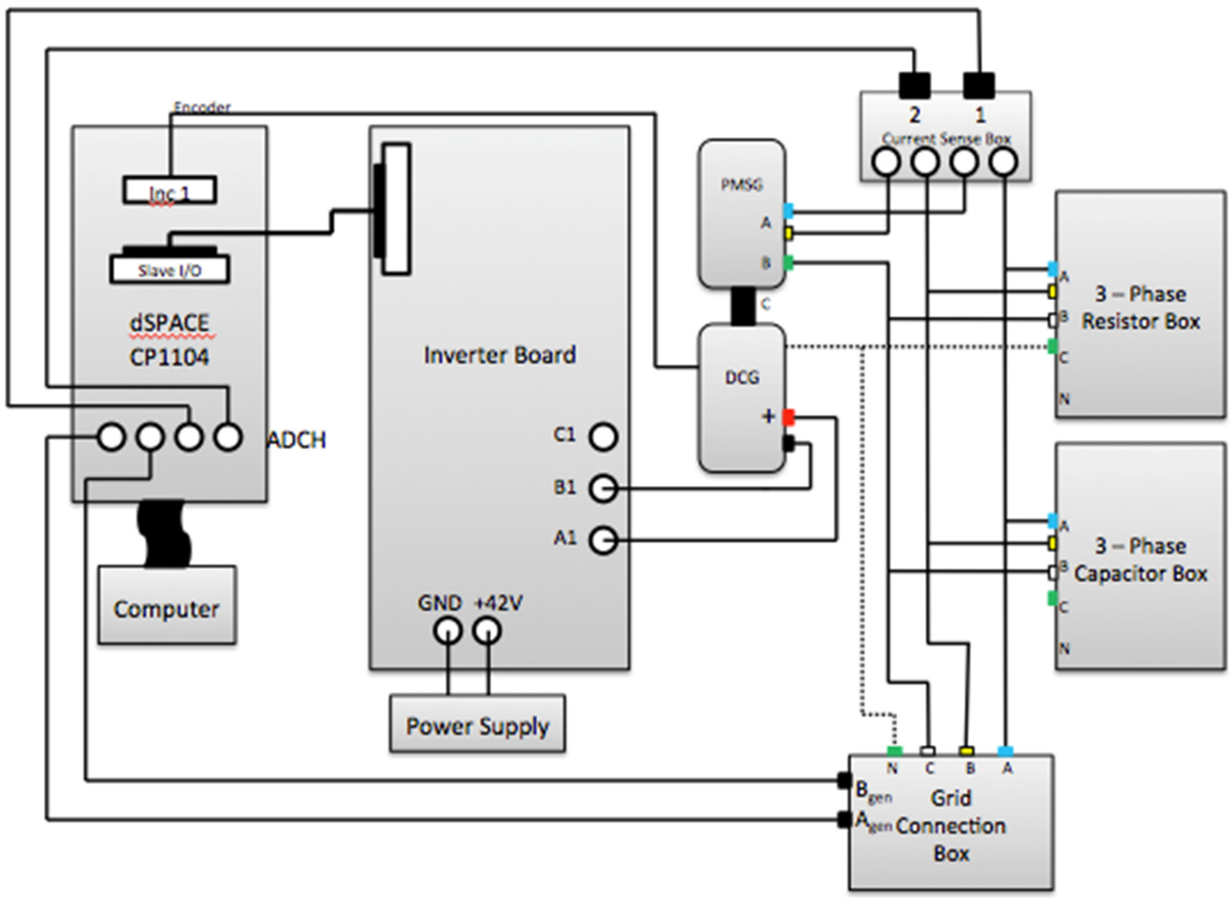

Figure 5: System Layout

Appendix II: Grid Connection and Current Sensor Explanation

Grid Connection Box: the grid connection box will be used to connect the generated windings to the three phase grid in later labs. For this lab the low side terminals are used in order to more easily capture the generated voltages.

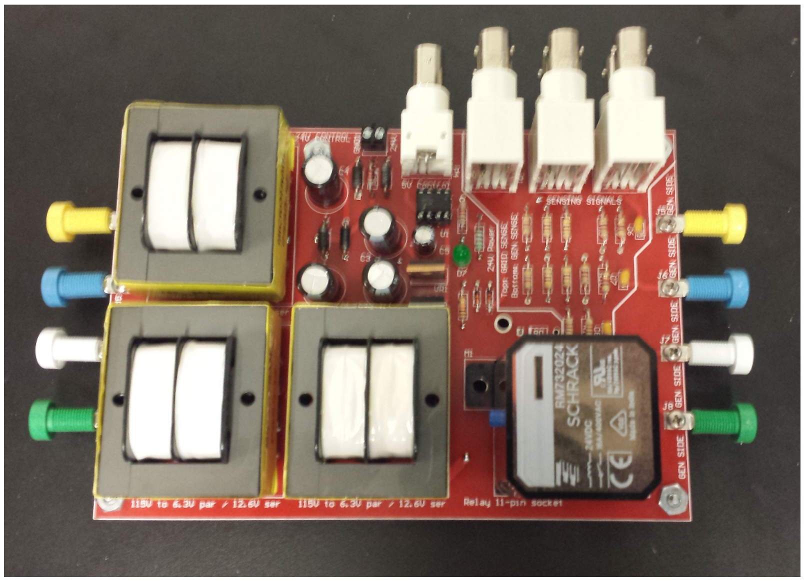

Figure 6: Grid connection board

The left side terminals in figure 6 are used to connect the board to the three phase grid. The right side terminals are used to connect to the generator windings. The BNC connections are shown from the front view in figure 7.

Figure 7: Grid connection board BNC terminals

The three BNC terminals on the top correspond the grid side phases A, B, and C. The bottom three BNC terminals correspond to the generator side phases A, B, and C. The single BNC terminal on the right is supplied a 5V dc signal to active the relay.

Current Sensor Board: The current sensor measures the current flowing into the generator and supplies a signal via BNC that corresponds to the current. Figure 8 shows the current sensor board. Current is measured as positive if flowing from the red terminal to the black terminal.

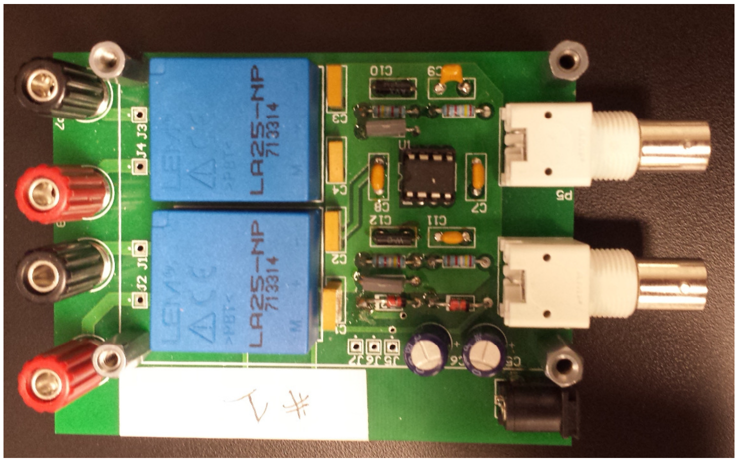

Figure 8: Current sensor board

For this lab, the current is considered positive flowing into the generator. When wiring the current sensor board, make sure the generator terminals are connected to the black terminals of the current sensor board.