ECE 5671/6671 – Lab 7

Doubly-Fed Induction Generator (DFIG)

1 Lab Experiment

1.1 Introduction

The objective of this lab is to demonstrate the generation of power on the grid at variable speed using a DFIG. Data captured from the machine will be analyzed. 3-2 phase transformations and DQ transformations will be implemented in the experiment. The first part of the lab will demonstrate the manual synchronization of the DFIG to the grid. The second part will connect the generator to the grid and check the effect of the DQ rotor voltages on the real and reactive power. Lastly, a real (P) and reactive (Q) power controller will be implemented so that the generator will produce the desired power levels when commanded.

The DFIG is a unique generator in that the user of the machine has access to the stator and rotor windings. This type of generator is often used in wind power generation, due to its ability to generate power with a direct grid connection and at variable speeds.

--NOTE-- for grid synchronization, the voltages of the DFIG's stator need to match those of the grid in: **phase sequence (ABC), frequency, phase angle, and voltage magnitude**.

A notification will be given distinguishing whether a procedure is to be completed on the computer (Matlab, Simulink, or dSPACE) or on the actual equipment.

Equipment needed:

- DFIG generator
- DC generator, frame mounted, with coupler
- dSPACE I/O box
- PEDB with ribbon cable and +12V supply
- Grid Connection Box
- Current Sensor Board
- Box of Cables

1.2 Manual Control: Simulink model

<u>>>Simulink</u>

Download, open, and examine the provided preliminary model (lab_7.mdl) to gain a sense of how this system will work. The prime mover (DC motor) will be set at a constant voltage to simulate a constant wind speed.

Locate the boxes labeled **Nominal Field** and (Angle) **Offset** in the Simulink model. These values will be varied in dSPACE until the DFIG's stator voltages match those of the grid. Once you have a sense of how this Simulink model functions, proceed.

1.3 PART 1: Open-loop control of DQ rotor voltages.

For the experiment, build the Simulink model studied in 1.2 in order to compile a c-file that creates an **.sdf file** for dSPACE to load. Note that two ADCH channels (5-6) will be used for measuring the grid voltages, V_{Ga} and V_{Gb}.

>>Matlab

The model should reside in the current directory. This model will correctly build if the value for **Ts** is properly defined. Set **Ts** to 0.0002 by entering Ts = 2e-4 (sampling frequency = 5kHz).

>>Simulink

The Simulink code provides control of the rotor voltages in a DQ reference frame such that the D axis is aligned with the grid voltages. This is achieved by first applying a 3-2 transformation to the grid voltages. Then, the angle Θ_F defining the D axis is computed from the 2-phase voltages using:

$$\cos(\theta_F) = \frac{V_{GA}}{V_{pk}}, \sin(\theta_F) = \frac{V_{GB}}{V_{pk}}, V_{pk} = \sqrt{V_{Ga}^2 + V_{Gb}^2} \quad (1)$$

The equation also gives the peak magnitude of the two-phase equivalent voltages. Then, rotor voltages can be commanded using equation 2, where V_{RX} and V_{RY} are the physical voltages on the rotor:

$$\begin{bmatrix} v_{RX} \\ v_{RY} \end{bmatrix} = R(-\theta_F)R(n_p\theta_R)\begin{bmatrix} v_{Rd} \\ v_{Rq} \end{bmatrix} \quad (2)$$

and R(Θ) is a rotation of angle Θ. Because the direction given by the encoder measurement may not be aligned with the x-axis, due to its incremental nature, the code gives the ability to add an offset to the encoder measurement. Alignment is correct if, at 1800 RPM, the stator voltages are in phase with the grid voltages for a negative V_{RQ} and $V_{RD} = 0$.

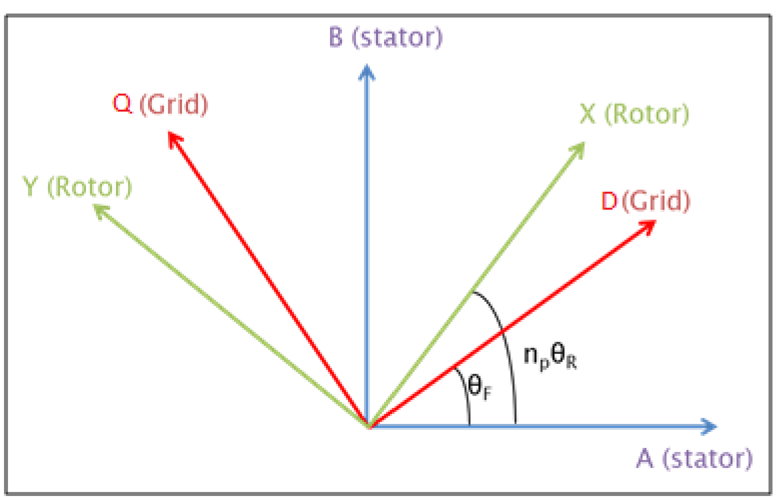


Fig. 1 Vector diagram showing transformations

>>Experiment Equipment

Follow similar steps outlined in the introductory tutorial to correctly assemble and test the equipment.

- SET THE POWER SUPPLY FOR 42 VOLTS BEFORE CONNECTING ANY WIRES.
- TURN OFF THE SUPPLY, THEN CONNECT TO THE HI-REL BOARD
- TURN THE BOARD ON AND DOUBLE CHECK TO VERIFY 42 VOLTS
- REFER TO THE TABLE OF CABLES IN APPENDIX I
- Remember to reference Appendix III of lab #5 when placing components on the desktop

Set-up the DFIG & DC motor to conduct tests. Connect the encoder cable from the INC1 encoder port to the encoder port of the DC motor. Connect the three grid phases from the three-phase supply to the grid connection box. Then, connect phases A and B from the grid and generator side BNC terminals of the grid connection box to the correct ADCH channels on the dSPACE I/O box. Connect leads from Phase A1, Phase B1, and Phase C1 on the Hi-Rel board to the X, Y, and Z terminals of the DFIG's rotor. Also, connect the A2 and B2 phases on the Hi-Rel board to positive and negative leads of the DC motor. Hook-up phases A & B of the grid and the DFIG's stator (from the Grid Connection Box) to the oscilloscope. Connect the DFIG stator terminals to the grid connection box on the generator side, using banana cables. Phases A and B should be connected through the current sensor board. Connect DACH1 to the relay control BNC terminal.

--A complete layout of this system can be viewed in Appendix II--

>>dSPACE

Once the Simulink build process from **1.3** has finished in Matlab, use the dSPACE ControlDesk program to run the actual experiment. With dSPACE open, create a new Project + Experiment framework, selecting the correct **.sdf** file (this should be the same folder as your current Matlab directory).

A dSPACE layout is provided for data observation and capture on the lab webpage. Download this layout into the folder that was selected for the creation of your ControlDesk project. You will see that the variables may have already been mapped to the appropriate instruments.

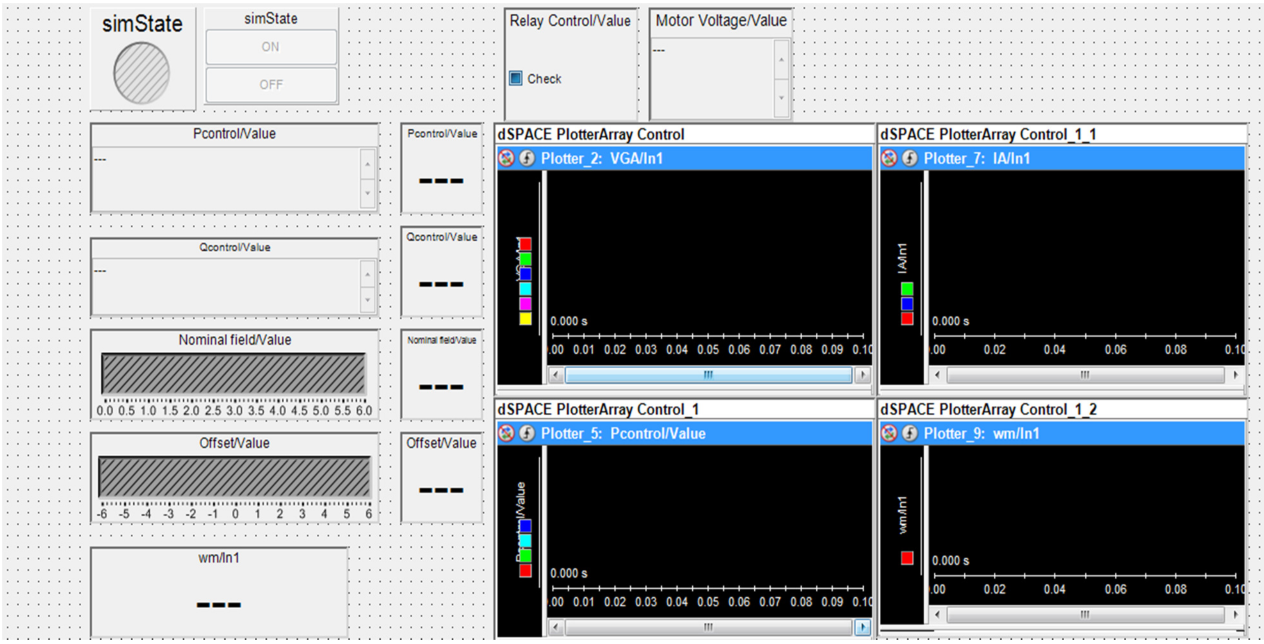


Fig. 2 Lab7 layout

Right-click and select properties on the sliders to adjust the limits to the following (if it isn't already done): Nominal field (0 to 6) and Offset (-6 to 6); also, right click the *numericinput* input boxes for Pcontrol and Qcontrol and change the increment to 0.5 by enabling custom increments as explained in one of your previous labs. The plotter windows should already be filled in with the speed (wm), voltage (VGA, VGB, VGC, VSA, VSB, VSC), current (IA, IB, IC), and power (Pcontrol, Qcontrol, pgen, qgen) plots required. As soon as Pcontrol and Qcontrol are mapped to the appropriate plotter, click on the recorder and change the recording mode for these variables from OnChange to HostService as shown in Fig. 3. This will allow for continuous capturing of these variables. (If the layout does not allow you to make this change, save your experiment, close and reopen it. This should solve the problem.) Using dSPACE, apply a voltage to the DC motor (Motor Voltage Numeric Input) until the system is spinning at the synchronous speed of 1,800 RPM. Verify that the system is rotating in a counterclockwise direction when looking from the DFIG back towards the prime mover. While the DC motor is running at 1,800 RPM, change the rotor values attached to the sliders, ***Nominal Field & OFFSET***, to change the magnitude and phase angle of the stator voltages. Observe the waveforms on the oscilloscope, and adjust the variables until the generator voltages match the grid voltages. Capture these waveforms from the oscilloscope for your report. Vary the speed between 1,650 RPM and 2,000 RPM using the DC motor voltage. Capture a plot of the waveforms during sub-synchronous operation and super-synchronous operation. Observe that the generator frequency remains the same as the grid; however, small magnitude and phase errors develop. Explain why this occurs.

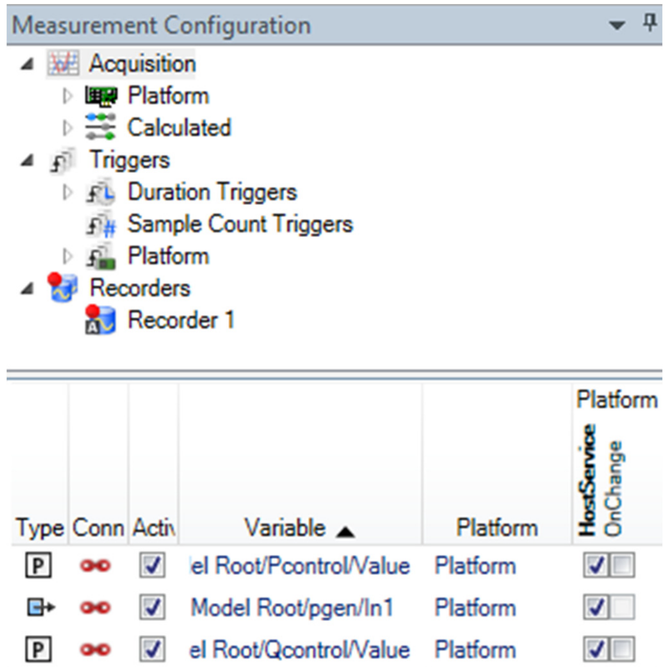


Fig. 3 Changing recording mode for OnChange variables

Show the TA that this is functioning properly. Next, the generator will be connected with the grid.

1.4 PART 2: Connecting to the grid

>>Simulink

The same Simulink model is used for syncing to the grid.

>>Experiment Equipment

The same setup is used as before.

>>dSPACE

Once the generator and the grid have matching waveforms while operating at synchronous speed (1,800 RPM), trigger the relay using the Relay Control checkbox; this will connect the generator to the grid.

Show the TA that you were able to connect the generator to the grid properly

Check the effect of **Pcontrol** and **Qcontrol** on the real and reactive power (P, Q) separately, by varying the *numericinput* values from 0 to 0.5 to -0.5 and back to 0 over 5 seconds and report your results. Utilize Matlab to provide a plot showing the synchronized generator and grid voltages *vs.* time over at least one period. Also, provide 2 plots of the real and reactive power response to steps of Pcontrol and Qcontrol values over 5 seconds at synchronous speed showing that they are decoupled (at least approximately).

1.5 PART 3: Integral controller for active and reactive powers

In this section, the generator's output will be examined from the perspective of the direct and quadrature coordinate system. Assuming that the DFIG is in steady-state and running at or near the synchronous speed so that the slip is close to zero; the following equations describe approximately the generator in the dq reference frame.

$$
\begin{aligned}
v_{sd} &= V_o, v_{sq} = 0 \\
V_o &= -\omega_e L_s i_{sq} - \omega_e M i_{rq} \\
0 &= \omega_e L_s i_{sd} + \omega_e M i_{rd} \\
i_{Rd} &= \frac{V_{Rd}}{R_R},\ i_{Rq} = \frac{V_{Rq}}{R_R}
\end{aligned}
\tag{3}
$$

After connecting the DFIG to the grid, control of the active and reactive powers generated is accomplished by changing the dq rotor voltages based on the steady-state relationships:

$$
\begin{aligned}
P_{GEN} &= -Vo\, i_{sd} = \frac{MV_o}{L_S R_R} V_{Rd} \\
Q_{GEN} &= Vo\, i_{sq} = -\frac{V_o^2}{L_S \omega_e} - \frac{MV_o}{L_S R_R} V_{Rq}
\end{aligned}
\tag{4}
$$

Note that the bias term **Nominal Field** applied to V_{RQ} in the connection step cancels the term $\frac{-V_o^2}{L_S\omega_e}$.

<u>>>Simulink</u>

With the information provided above and your knowledge of Simulink, implement an integral controller for the active and reactive power (refer to the figures in appendix III). Also, implement a switch to engage the controller after the connection of the DFIG to the grid. Adjust the integrators so that the integrator memory is cleared once the controller is disengaged. This is to prevent unknown voltages from being applied to the rotor once the controller is turned off.

The basic idea is that the user will apply steps of Pref and Qref (positive or negative) and the system should be able to control the powers to reach these reference inputs. Once you have created the Simulink model, build (CTRL+B) your model in order to obtain the **.sdf** file.

<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 0.0002 by entering Ts = 2e-4.

<u>>>Experiment Equipment</u>

The setup remains the same for this portion of the experiment.

<u>>>dSPACE</u>

For the dSPACE model, use the previous layout and modify it to add the extra features. There should be two additional sliders for the P and Q integral gains (Ki_P and Ki_Q), input boxes for the P and Q reference values, and a check box to activate the power controller. *Note: start the integral gain value at some value > 0 so that there are no integration issues.* Update the power plotter by removing *Pcontrol* and *Qcontrol* and mapping *Pref* and *Qref* instead. Change the custom increments on *Pref* and *Qref* to 5.

Here is an image of the layout after the required changes are made:

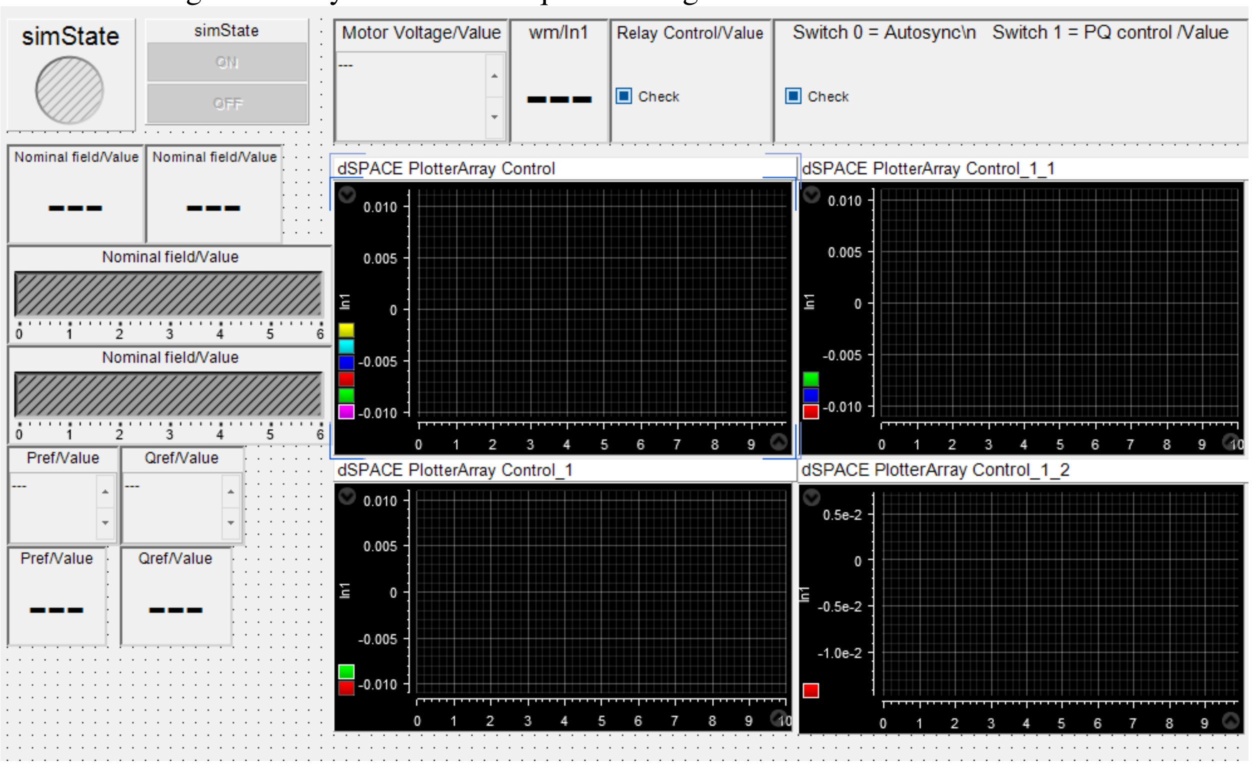


Fig. 4 layout after necessary changes

Once the layout is finished, connect the generator to the grid at synchronous speed and then engage the integral controller by checking the appropriate check box (named "Switch" in Fig. 4) <u>Remember to change the Pref and Qref recording modes from Onchange to HostService</u>. Obtain data over a period of 10 seconds each, for a single step response by changing the real power reference from 0 to + 5 to 0 to -5 and back to 0; then, a single step response for reactive power by changing the reactive power reference from 0 to + 5 to 0 to -5 and back to 0. Adjust the Ki gains in order to achieve the best response. Next, set reference values for P and Q to +5 and vary the prime mover speed between 1,700-1,900 RPM. Use Matlab to plot the speed, reference and generated real power, and reference and generated reactive power versus time using 3 subplots.

The power data obtained should be filtered by a second order Butterworth filter with a cutoff frequency of 50 Hz:

```
[b,a] = butter(2,0.01);
Variable_filtered = filtfilt(b,a,Variable_to_be_filtered);
```

1.6 Discussion

Provide a conclusion summarizing the concepts and procedures covered in this lab.

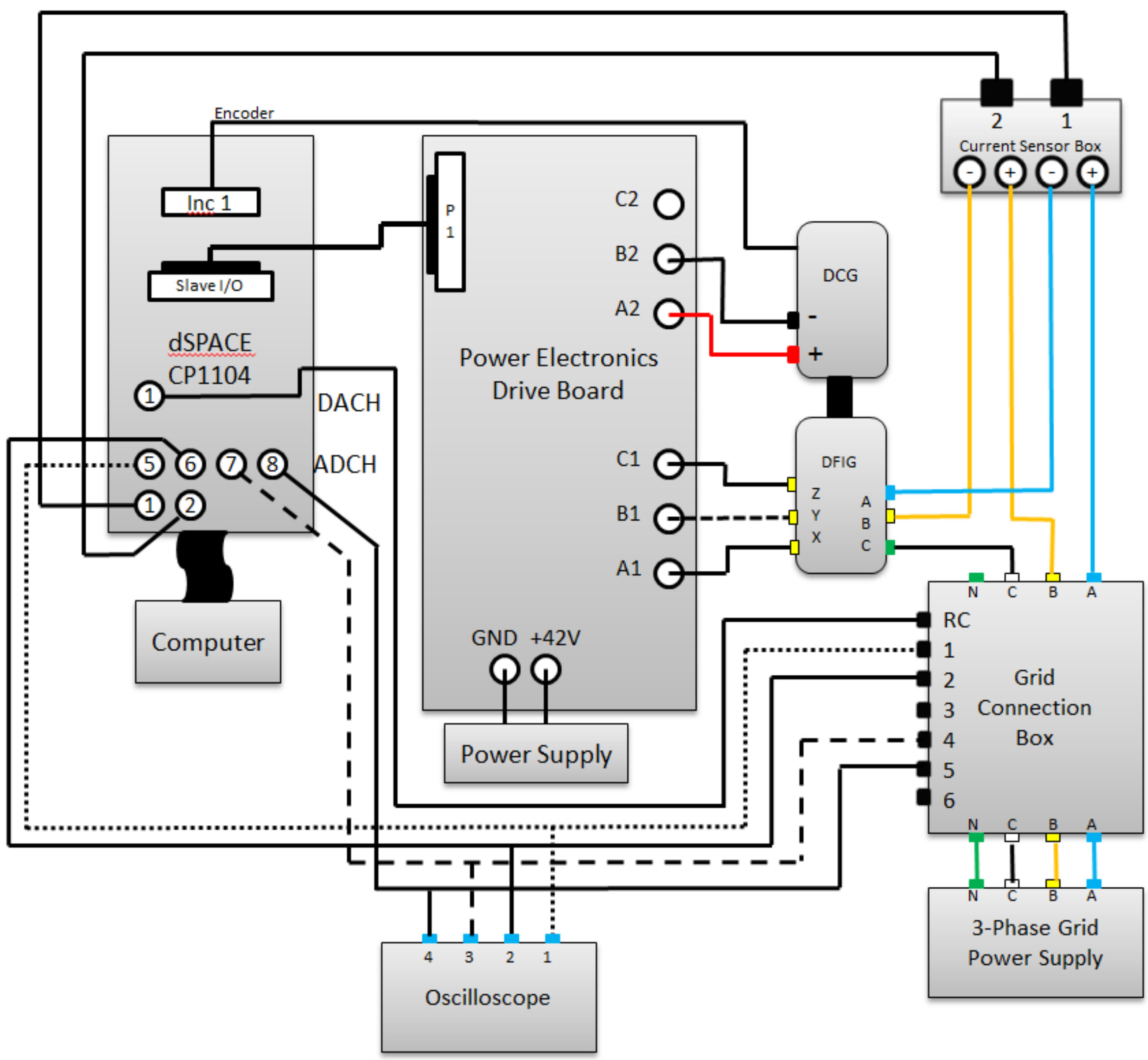
Report Requirements: Consider this requirement list a guide to what would be viewed as a minimum to submit for your lab report. Always include discussion and comments on procedures, observations, and findings.

- Describe the objectives of this lab in your own words.
- Include the equipment number of all major components used
- Section 1.3
  - Brief description of manual rotor voltage control
  - Values of Nominal Field and OFFSET to match grid and stator voltages
  - Screen capture of matching grid & stator voltages from oscilloscope during sub-synchronous, synchronous, and super-synchronous speeds
  - Explain why the small magnitude and phase errors occurred when the speed was changed from the synchronous speed.
- Section 1.4
  - Matlab plot of synchronized grid & generator voltages vs. time
  - Plots of the active and reactive powers, explain the effect of $P_{control}$ and $Q_{control}$.
- Section 1.5
  - Screenshot of Simulink layout of completed power controller
  - Explanation of Simulink model
  - Integral gain values for the real and reactive power controllers
  - Matlab plot with real and reactive power step response
  - Matlab plot with speed, real, and reactive power vs. time for varying prime mover speed.
- Section 1.7 - Discussion

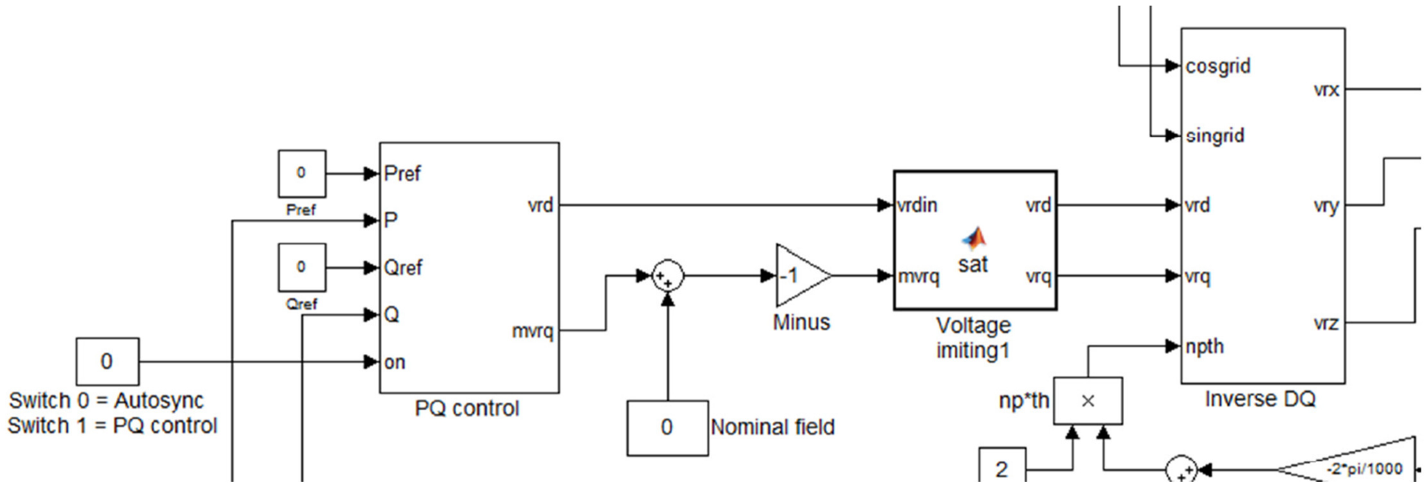
Appendix I. Cable List

Cable No.	# Cables/Bundle	Colors	Length	From	To
#2	4 - banana	Y/B/W/G	12”	Grid (A/B/C/N)	Grid Connect Box (A/B/C/N)
#3	2 - banana	W/B	12”	Grid Connect Box $(A/B)_{gen}$	Current Sensor
#4	2 - banana	W/B	12”	Current Sensor	Generator Stator (A/B)
#5	1 - banana	Y	24”	Grid Box (C)	Generator Stator (C)
#6	3 - banana	Y/B/W	24”	Hirel Board (A1/B1/C1)	Rotor (X/Y/Z)
#7	2 - banana	R/Blk	24”	Hirel Board (A2 & B2)	DC Motor Terminals(+/-)
#8	2 - banana	R/Blk	32”	Power Supply(+/-)	Hirel Board (+/-)
#9	3 - BNC	W/B/Y	24”	Grid Connect Box $(A/B)_{gen}$	dSPACE (ADCH 7 & 8) w/ T
#12	2 - BNC	W/B	32”	dSPACE (ADCH 7 & 8) w/ T	Oscilloscope
#15	2 - BNC	W/B	24”	Grid Connect Box $(A/B)_{grid}$	dSPACE (ADCH 5 & 6) w/ T
#11	2 - BNC	W/B	32”	dSPACE (ADCH 5 & 6) w/ T	Oscilloscope
#10	1 - BNC	Blk	24”	dSPACE (DACH 1)	Grid Connect Box Relay
#13	1 - BNC	B	32”	Current Sensor Board (A)	dSPACE (ADCH 1)
#14	1 - BNC	R	32"	Current Sensor Board (B)	dSPACE (ADCH 2)

Appendix II. System Layout



Appendix III. Feedback Controller



The below block diagram needs to be places in the PQ control block above.