Smart Grid Test Facility	Boston University

TI university program

TI Innovation Challenge 2015 Project Report

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Video:	https://www.youtube.com/watch?v=rrS2u2TGiJs
Date:	May 23, 2015

Qty.	TI Components	Explain where it was used in the project? What specific features or performance made this component well-suited to the design?
2	MSP-EXP430G2	The MSP430s are used in the feedback control loop. Our grid includes three independent generators, two of which are built mechanically. The output of these generators must be made stable with a frequency stability system, implemented via a feedback control loop. This loop employs a rotary encoder that provides frequency information to the MSP430s, which determines how far from the ideal 60Hz the alternator is; based on that information, the MSP430 modulates its output signal, which ultimately impacts the frequency of the alternator. This loop occurs continuously and maintains stable frequency on each generator.
6	LM2937ESX-5.0	The LM2937 acts as a 5V supply for an Allegro ACS712 current sensor on our sensor PCB. When prototyping the circuitry, there was need for a way of supplying 5V with moderate current to the ACS712 without utilizing a separate power supply. Since the op-amps in our circuitry already utilized a 15V/-15V AC-DC convertor as a power supply, we utilized the 15V pin in conjunction with a LM2937 to synthesize a cheap, highly reliable 5V supply source without the ripple or notorious noise associated with buck convertors.
6	TL082IDR	The TL082 dual op amps act as voltage buffers in the voltage/current interface circuitry used to collect data. One of the key engineering tasks to utilize our data acquisition unit was the analog based manipulation of the current/voltage signals. Since our implementation of the signal manipulation is through inverting summer amplifiers, we needed voltage buffers in order to not draw power away from our surrogate grid. For the same reasoning, the buffers needed very low input bias currents and a large common mode input range, which the TL082 provides.
6	TL084IDR	The TL084 quad op amps perform the analog signal manipulation in the voltage/current interface circuitry. Based on the sinusoidal behavior of AC, the voltage and current signals needed manipulation in order to fit in the 0 V – 2.4 V window that our data acquisition unit is capable of measuring. Additionally, our analog signal manipulation method is inverting summer amplifiers. Thus in order to achieve the highest degree of summing accuracy, we needed the low input bias currents the TL084 provides.

Project Abstract: The Smart Grid Test Facility is an educational tool for engineering students, facilitating in-class experiments, demonstrations, and active learning. Students in power and electric energy courses can study grid elements using this test bench, which includes a collection of fixed generators, variable loads, a transmission line network, and sensors feeding into a visual display. The overall technical approach involves breaking down the small-scale grid into its main components: generation, transmission, loads, and metrics. These facets are integrated to create a classroom-friendly power grid, made mobile by being affixed to a cart. Further, this project provides the infrastructure for future integration of Smart Grid components, devices used to improve grid efficiency through communication networks. Ultimately, this project will help engineering students learn about the power grid and how it reacts to various arrangements of generators, loads, and wiring networks. Teaching students about the grid encourages pursuit of new challenges associated with the aging grid infrastructure; the more that engineers focus on updating the electrical grid, the more improvements in Smart Grid technology and clean energy generation that will arise. This Smart Grid Test Facility aims to provide a fun and modular testing environment for students studying the power grid.

BUEngineering College of Engineering BOSTON UNIVERSITY

POWER POOCHES

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1.0 <u>Project Description</u>

The Smart Grid Test Facility is designed to introduce engineering students to how a power grid works. The motivations behind this type of project are the current global challenges associated with fossil-based power generation. In order to adapt to renewable energy technologies, engineers must be familiar with the functionality of the power grid and the role of clean energy systems. Professor Horenstein, who instructs the university's Power Electronics course along with other power and energy-related courses, requested this project for classroom experiences. This test facility is situated on a cart for mobility and will be used for experiments and demonstrations primarily in courses at the university, such as Power Electronics and Electric Energy Systems.

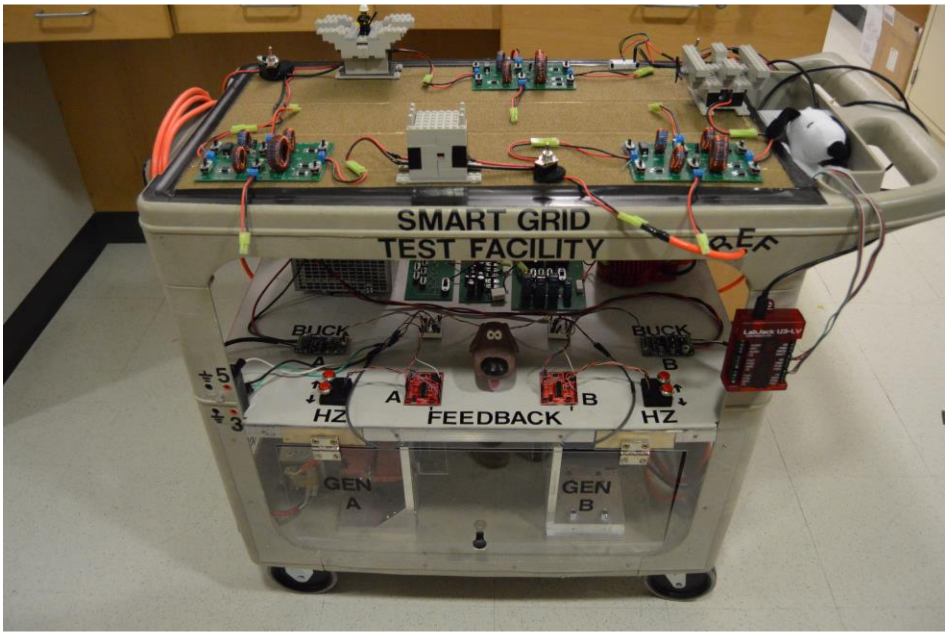


Image 1: Smart Grid Test Facility Front View

2.0 <u>Hardware Design</u>

2.1 Generation

2.1.1 Three Generators

This test facility includes three generators, which together feed into the grid simultaneously. These generators each create $12V_{PP}$-AC power at approximately 60Hz, which serves as the nominal system voltage and frequency throughout the grid. These generators are intended to be both visual and safely enclosed for student use in a classroom.

Two of the three generators are mechanical generators: a 24V-DC power supply feeds a DC-DC buck converter (whose use is described in the frequency stability section), which drives a DC motor, which drives a wind turbine alternator via a belt and pulleys on each machine's shaft. Both mechanical generators use this motor-alternator setup to produce 60Hz power. The output voltage of these alternators is separately stepped down to $12V_{PP}$

from about 17V_{RMS} using a transformer. The mechanical generators are mounted on aluminium brackets on the lowest shelf of the cart and housed in transparent safety enclosures with air ventilation and access doors on both sides of the cart.

The third generator is a variable step-down transformer that is connected to a wall outlet. It is set to produce 12V_{PP} at 60Hz, which serves as a reference generator. As described in the section regarding synchronization, the reference generator can be used as an ideal signal to which the mechanical generators synchronize.

2.1.2 Frequency Stability: Feedback Control

Frequency stability is vital to the functionality of the entire grid network. Without feedback, the output frequency of the alternators would change as loads, transmission line lengths, and other system properties change. This is because when the motor has a fixed DC voltage input, the alternator is limited, and when it is required to power a larger load, its frequency reduces in order to increase torque and power the load. Thus, without feedback, the grid is inherently unstable from a frequency perspective. With three generators synchronized, it is vital that the alternators individually remain at a nearly constant 60Hz.

This is accomplished via a feedback control loop that is attached to both mechanical generators, as shown in Figure 1. A rotary encoder is attached to the shaft of each alternator. The encoder reads the frequency of the alternator and outputs a PWM signal with a frequency proportional to the frequency of the alternator's power. The MSP430 takes this information and determines how close or far from 60Hz (the desired frequency) the alternator's power is. Based on this information, the MSP modulates its output duty cycle. For example, if the frequency of the alternator drops to 55Hz, the encoder's PWM signal will have a frequency corresponding to 55Hz, which the MSP recognizes. In response, the MSP will increase the duty cycle of its output PWM so that the buck converter (or motor driver) increases its output voltage and thus pushes the alternator's frequency back up to 60Hz. The degree of modulation depends on how close or far from 60Hz the alternator is at each sample. The MSP is continuously sampling the data from the rotary encoder, thus making it a continuous feedback loop. Ultimately, this system ensures frequency of the alternators will be 60Hz +/- 5% on each mechanical generator, independent of other actions along the grid.

2.1.3 Synchronization of Generators

In general, a power grid has an existing signal propagating along the transmission lines, and when new generators are to be connected to the grid, they must be synchronized to the existing grid at their point of connection. Thus, it is vital in our system to demonstrate the process of synchronization and provide an interactive mechanism for combining generators. The objective of synchronization is to make two 60Hz sine waves that are out of phase made in phase. We accomplished this by designing synchronization circuits: an LED is placed between the existing grid signal and the signal we wish to synchronize to the grid, as shown in Figure 2. The LED experiences the combination of the waveforms: when the line-to-line voltage is zero, the generators are in phase, and the LED is dim;

when the line-to-line voltage is large, the generators are out of phase, and the LED is bright. Thus, when a student sees that the LED is dimmest, he or she closes a main toggle switch to attach the generator onto the existing grid safely and effectively. As visible on the oscilloscopes used during the video demonstration, the waveforms synchronize when this method is used.

To operate the grid, students turn on one generator to begin, which feeds the entire grid network. Next, the student can add generators onto the grid using these synchronization circuits to create a total of three generators feeding the grid simultaneously.

2.2 Transmission Lines

Transmission lines are the mediums that propagate power throughout a grid network. Thus, we wished to represent transmission lines in our grid by their resistive, inductive, and capacitive characteristics. We researched transmission lines and calculated typical per-unit length characteristics for typical 115kV aluminium transmission lines (750 MCM). After consulting a colleague at a local utility for confirmation of our calculations, we designed transmission line PCBs that include lumped-element RLC components to model real transmission lines. As visible in Figure 3, these PCBs have a matrix configuration that allows students to change transmission line lengths before or during operation of the grid. Loads are connected to ground via the two load points available on each transmission line PCBs.

Ultimately, the RLC characteristics of real transmission lines impact the behavior of a power grid, and in order to demonstrate these impacts to students, we modelled real-grid, interactive, and changeable lines. With three transmission line PCBs, one at each branch, we have created a triangular layout with generators at each point and transmission lines along the legs—this creates the grid layout.

2.3 Loads

The purpose of a power grid is to provide power to loads—whether it be a washing machine, a computer charger, a heart monitor, or a motor, the grid supplies power to different types of loads with different demands. Thus, we aimed to provide various types of loads to students for testing and learning purposes. This includes resistive, inductive, and capacitive loads, which are all variable and provided on load PCBs. Further, we have included a luminous load.

The RLC binary loads have been designed to be multi-modal and function as up to 255 different loads at the flick of a switch. This configuration has been achieved by assigning a bit number to each of the 8 control switches found on each of the boards. Each switch functions by shorting the component(s) that it is mapped to on the board. These values ascend in order from a base value, 1kΩ for example, by orders of 2, where the [8th bit] = 27 * [base value]. Mapping the values in this way permits the user to arrange switches in any binary combination up to 8 bits to make a unique load (e.g. 111kΩ = b0110 1111, 12kΩ = b0000 0110 etc.). These RLC load boxes create changes visible on the data acquisition system. Meanwhile, the LED load is particularly useful for observing power flow and the consequences of outages.

2.4 Data Acquisition System

The data acquisition system is available so that students can monitor the electrical signals at various points along the grid. In particular, students observe voltage and current waveforms in addition to power factor and phase angle. Students choose which points along the grid they wish to monitor via the collection of sensor board PCBs that are provided with the project. Each PCB is designed to connect in series in order to collect information about that node on the grid. The data acquisition system centers around a MATLAB script activated via the command window. To collect data, one simply needs to attach a sensor board at the prescribed point. Then, the user must attach the power supply wiring and signal wiring, run the script, and answer the prompts in the command window. Once completed, MATLAB will display waveforms in figures and provide important information via the command window. These PCBs employ several TI components, including op-amps and voltage regulators.

3.0 Software Design

3.1 Frequency Stability: Feedback Control

The purpose of frequency stability is to maintain approximately 60Hz on each of the alternators of the mechanical generators. Each feedback loop is centered around an MSP430 on a LaunchPad. As visible in Figure 4, the flow of information as coded into the MSP430s revolves around the alternator’s frequency. Based on the frequency relative to the desired frequency, the MSP430 alters its signal into the buck converter. This buck converter feeds the DC motor, which spins the alternator, and so ultimately the output frequency of the alternator is changed by the MSP430. The code is made available to students so that any desired changes in the functionality of the feedback loop can be made. Further, BU engineering students learn about the LaunchPad in the introduction to circuit theory course, and thus we expect that students will be familiar with the microcontroller environment and will be comfortable using the MSP430s.

3.2 Data Acquisition System

The data acquisition system collects instantaneous voltage and current data from discrete nodes in our system. From these data points, students can calculate various parameters including RMS values, power factors, and phase angles between waveforms and power flow through global scale processing (i.e. analyzing the data from multiple sensor boards).

For our language of choice, we decided to use MATLAB. Not only is it highly used in industry, but also all Boston University engineering students have extensive experience with it through required coursework. This means potential users are not limited to the code we provide. Instead, they can modify or create new code to suit their preferences or needs, which provides a highly flexible source of potential innovations. For this reason, our code is meant to provide an introduction to the activation and utilization of the data acquisition system for educational or experimental purposes. Essentially, it provides example code on how to configure the data acquisition unit, acquire data, put the data in a usable form, and analyze the data to collect important data points.

4.0 Testing & Conclusions

4.1 This section provides an overview of the testing done in order to confirm the success of our various systems within the project. Further data and analyses are available in both the Functional Test Report and the User's Manual.

4.2 Generation Testing

The objective of our generators is to produce 60Hz power at $12V_{PP}$ at three separate generation points. Thus, the primary metrics for testing were frequency and voltage. However, during each test, we checked current values as well for safety purposes. Testing the mechanical generators included testing the components individually, then testing components together until all parts were included. Testing began with the DC motors, which were tested at various input voltage levels to determine output RPM. The alternators were tested at various input RPM values to determine the output frequency and voltage, from which we could calculate the pulley ratio between the shafts of the motor and the alternator.

4.3 Transmission Lines Testing

Transmission lines were modeled after real-grid lines; thus, our primary metrics for testing were the resistive, inductive, and capacitive characteristics of the transmission lines on each PCB. Since the inductors were hand-wound, each inductor was measured using an L-meter to confirm inductance within +/-5% of the desired values. Once the components were soldered onto the PCBs, we checked for conductivity along all possible line configurations on each PCB to ensure proper connections. Transmission lines were then tested under currents (~1.5A) above normal operation currents (~0.5A) to ensure safe conditions even in fault situations.

4.4 Loads Testing

Loads were tested by changing the switches on the PCBs and ensuring that resistance, inductance, and capacitance, changed accordingly. We created a programmed spreadsheet that allowed us to quickly calculate impedance values (along with the real and reactive components) for various combinations of loads and transmission lines. This helped us efficiently measure and confirm via calculations the functionality of the load boxes.

The luminous load is an array of LEDs inside a 3D-printed housing. The grid's AC signal is rectified to DC before being provided to the LED load. Because this load is available to users as a means of observing the impacts of changes to a grid (outages, imbalances, etc.), this load simply needed to illuminate and be visible for users. Like our other loads, the LED load connects directly onto a transmission line to ground.

4.5 Data Acquisition Testing

The sensor network measures voltage and current and calculates several other metrics based on that information. To confirm the voltage waveforms, we used an oscilloscope at the same location and compared results. To measure current, we used an ammeter and also used basic calculations to check the expected current waveforms with the waveforms shown on the computer from the data acquisition boards.

4.6 Integration Testing

For each major system within the project, we outlined specific criteria for success to determine whether the system worked. After performing these tests on the components in isolation, a significant portion of testing was done interfacing the components. To test synchronization, we used our synchronization circuits and connected a mechanical generator to a wall outlet to confirm successful synchronization. We tested each generator separately in synchronization with the wall, or infinite bus, before synchronizing all three generators to each other. Similarly, feedback control was tested using a simulated generator before applying it to an actual mechanical generator; first, the code was tested to ensure proper output PWM signal modulation, then MSP430 was connected to a buck converter (which itself had many stages of testing to confirm functionality and safety under high currents) to check for proper DC voltage changes. Once the feedback loop proved functional in isolation, it was applied to one mechanical generator, which was tested for frequency stability under various conditions. Once the two mechanical generators were equipped with feedback loops for stability, the generators could be synchronized and other elements could be changed along the grid safely. We also included up and down buttons for frequency, as described in the video; these were tested by measuring the alternator's frequency and ensuring that it increased or decreased accordingly. Testing the system altogether involved synchronizing all three generators, changing transmission lines, changing loads, moving and using sensor boards, causing outages, checking the integrity of our safety housings, confirming system mobility, and more. Overall, integration required extensive testing to ensure that our system is user-friendly, safe, and in accordance with our original requirements and goals.

4.7 Results

The final specification sheet for this system is as shown in Figure 5. As aforementioned, data and analyses are available in both the Functional Test Report and the User's Manual. The goal of our many testing procedures was to confirm that we were meeting our goals of building a fun, user-friendly, safe system that allows students to learn about the power grid.

5.0 Future Work & Recommendations

5.1 Smart Grid Components

As our project title suggests, we would like to incorporate Smart Grid technologies into our system. In particular, we would like students to be able to explore Smart Grid devices such as communication systems and measurement systems. Specifically, this would likely include components from Saturn South, a manufacturer that we had been in touch with frequently in the earlier stages of this project regarding Smart Grid. Their mini Smart Grid devices, such as the mini Smart Meter and CT Meter, would be ideal for our project. We would use a central communication hub that would collect data from the various meters along the grid, and that hub would provide information to a local computer or network. This could introduce students to Smart Grid devices and also provide a forum for basic experiments and demonstrations.

5.2 Project Interface & Protection

Due to budgetary limitations, we were restricted in the amount and types of generators built in our system. However, in the future, with more financial flexibility, we would like to incorporate more generators and make them easily interchangeable. For example, in BU's Power Electronics course, students build a solar cell inverter via an H-Bridge, which converts the DC output of a solar cell into the AC signal of a typical wall outlet. We would like students to be able to synchronize this generator to the grid in order to include a green energy source on the power grid. As built, this project does allow for this function, but it may be challenging by the nature of the connectors we used between components. With more universal connectors, especially to the synchronization circuits, this may be more easily accomplished.

Further, we would like to incorporate more fault protection equipment along the grid. Although our system rarely requires such protection, we would like to introduce students to protection engineering of power systems, including relays and breaker systems.

5.3 Data Acquisition System

In hindsight, there are quite a few opportunities to improve on the physical circuitry of the data acquisition system. As it stands, the current sensing is only useful for currents in the range of 20 mA to 2 A before the signal either exceeds the desired 0 V to 2.4 V input range of our data acquisition unit or becomes exceedingly noisy. One possible way to fix includes additional circuitry purpose built to measure below 20 mA and above 2 A and providing a physical switch on the PCB, similar to options on a handheld multi-meter. Then we would simply modify the MATLAB code for the new options. Another possible way is to look into additional filtering options for the ACS712. Another potential improvement is better connectors for the PCB supply. One of the current worries of the system is students could potentially plug in the power supply backwards and fry the op-amps. Polarized connectors such as molex will alleviate this concern.

6.0 <u>Acknowledgements</u>

The Smart Grid Test Facility Team is incredibly thankful to our many supporters for their guidance and help along the way. We'd like to thank Professor Pisano, Professor AlShaykh, and Professor Kia for their continuous stream of positive feedback and encouragement. We'd also like to thank Professor Horenstein, who conceived this project and who will use our system in his classes in the future. In addition, we're grateful for the support of the Senior Design Teaching Assistants and the ECE Department. We'd also like to thank the Kilachand Honors College at BU for making so much of this project possible through supplemental funds. As part of the Senior Design experience, our project required specific budgetary and scheduling guidelines. Our budget was limited to $1,000; however, due to the multifaceted nature of our project, our team needed further funding to complete the project as requested. We were very grateful to receive additional funding from both the ECE department and the Kilachand Honors College at BU, bringing our total budget just below $2,000, as shown in our cost breakdown on page 27 of the

User's Manual. We also appreciate the guidance of the staff at the manufacturing center at BU, EPIC, who helped us with much of the machining processes throughout this project.

We'd also like to note our appreciation for the kindness, responsiveness, and support of many teams in the industry, such as TI, Grainger, McMaster Carr, Advanced Circuits, and more. We learned so much from this project and we're grateful for the encouragement and support we gained along the way. We are happy to have contributed to the learning and growing community of engineers, and we're excited to do more in the future!

7.0 <u>Appendix</u>

7.1 Figures & Images

7.2 Hardware Documentation

7.2.1 Hardware ReadMe

7.3 Software Documentation

7.3.1 Software ReadMe

7.4 Functional Test Report

7.5 Resources

Appendix 1: Figures & Images

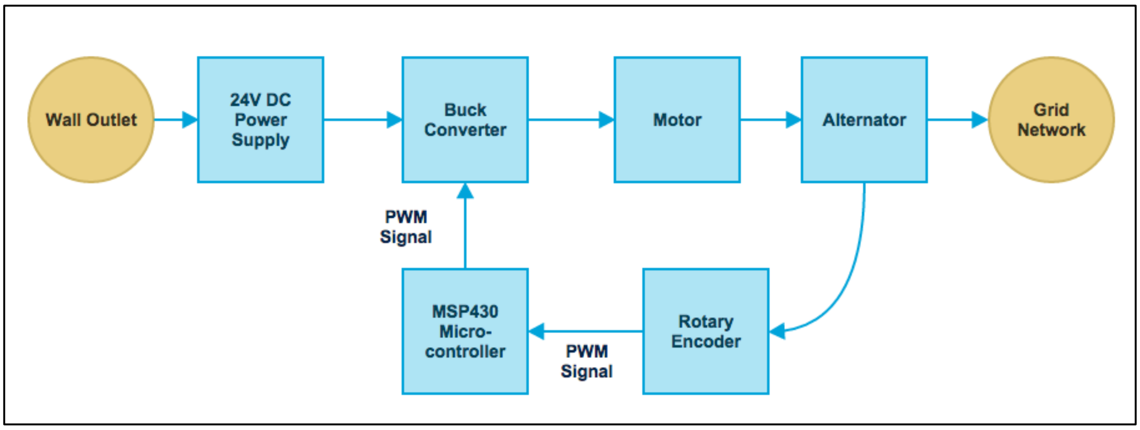


Figure 1: Feedback Control Loop Circuit

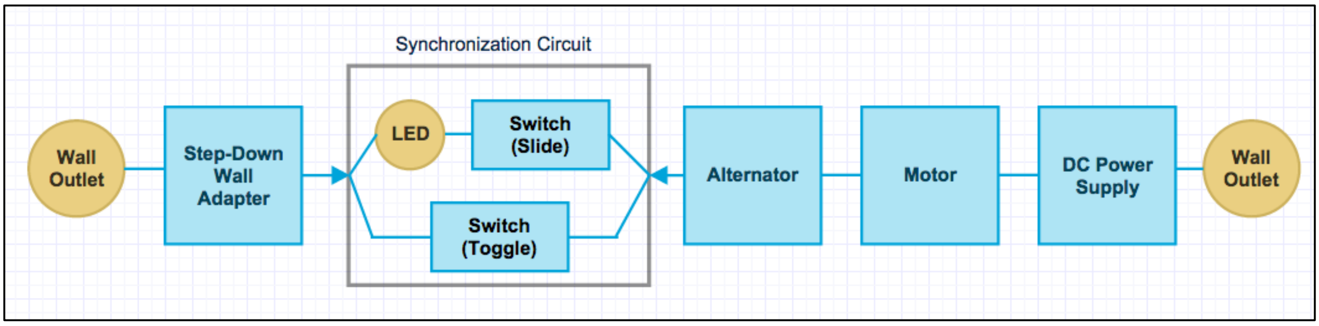
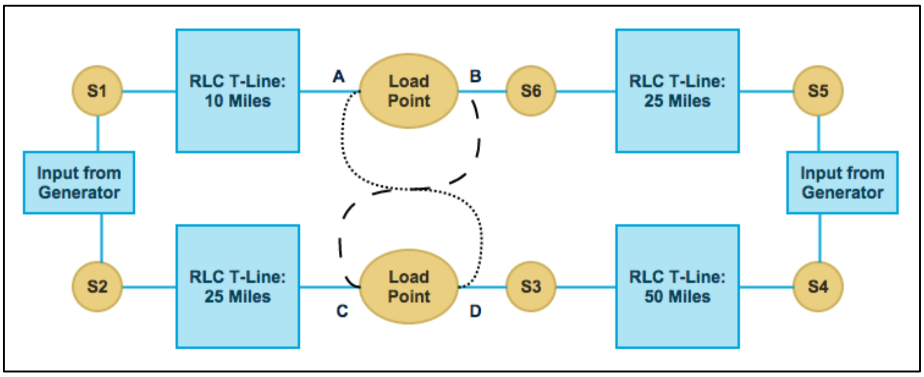


Figure 2: Synchronization Circuit Layout



Transmission Line Configurations			
Load Point 1	Load Point 2	Switches ON	Miles Simulated
A	B	1, 6, 5	35
C	D	2, 3, 4	75
A	D	1, 3, 4	60
C	B	2, 6, 5	50

Figure 3: Transmission Line PCB Matrix Design & Switching Configurations

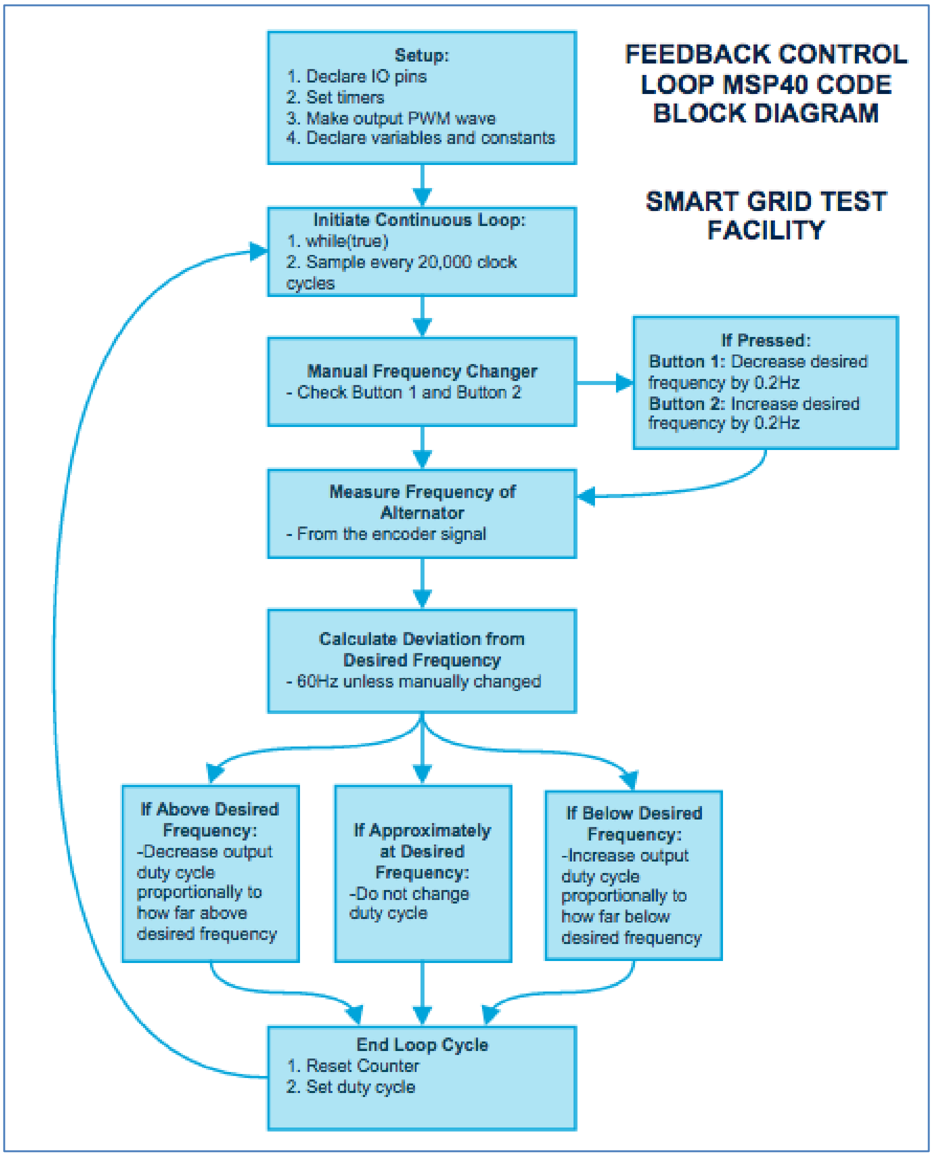


Figure 4: Feedback Control Loop MSP Data Flow

SYSTEM SPECIFICATIONS				
GENERATION				
Component	**Rating**	**Min**	**Max**	**Typ**
Motor	Input Voltage (V)	0	24	17
Motor	Input Current (A)	0	9	5.5
Alternator	Output Voltage (V)	0	120	17.2
Alternator	Output Current (A)	0	100	0.06
Motor Driver	Output Current (A)	0	13	5.5
Motor Driver	Input Voltage (V)	5	25	24.11
Motor Driver	Output Voltage (V)	0	25	17
Variable XFMR	Output Voltage (V)	0	130	8
Transformer	Input Voltage (V)	0	230	17.2
Transformer	Output Voltage (V)	0	56	8
Transformer	Output Current (A)	0	1.8	0.12
SYNCHRONIZATION & FEEDBACK				
Component	**Rating**	**Min**	**Max**	
Switches	Current (A)	0	3	
LEDs	Voltage (V)	1.8	2.1	
Resistors	Power (W)	0	0.25	
TRANSMISSION				
Component	**Rating**	**Min**	**Max**	**Typ**
Resistors	Power (W)	0	4	0.05
Inductors	Current (A)	0	7	0.1
Capacitors	Voltage (V)	0	16	8
Terminal Blocks	Current (A)	0	2	0.1
Switches	Current (A)	0	2	0.1
Wires	Current (A)	0	16	0.1
SENSING				
Measurement	**Value**			
|Vmax| (V)	12			
|Imax| (A)	2.1			
Vrms Precision	2%			
Irms Precision	2%			
LOADS				
Component	**Rating**	**Min**	**Max**	
Resistor Box	Power (W)	0	0.5	
Resistor Box	Resistance (kΩ)	1	255	
Inductor Box	Current (A)	0	9	
Inductor Box	Inductance (mH)	1.5	384	
Capacitor Box	Voltage (V)	4.1	5	
Capacitor Box	Current (mA)	0	20	

Figure 5: Smart Grid Test Facility System Specifications

Appendix 2: Hardware Documentation

This ReadMe file is provided to users or a future project team as a description of hardware in different detail from what is provided in the User's Manual. Users look to this document before diving into our Altium PCB files or before performing any revisions or additions to the project regarding hardware. Users should always refer to the User's Manual for basic start-up and operation information.

To: Future Senior Design Team, Users

From: Power Pooches

Date: 5/3/2015

Subject: Hardware ReadMe

1.0 POWER-UP SEQUENCE

1.1 A detailed description of power-up is available in the User's Manual. Also, additional photos are available in the User's Manual and also in the "Pictures" folder of this USB drive.

1.2 Power-up sequence:

1.2.1 Plug LabJack USB drive into computer to be used for data measurement on MATLAB.

1.2.2 Plug orange power strip cord into nearby wall outlet.

1.2.3 Provide 5V and 3V (DC) to the cart's side outlets, as labeled. A typical 1A source is sufficient.

1.2.4 Make sure all loads are disconnected from the transmission lines.

1.2.5 Ensure that each transmission line has at least one path for flow (i.e., all top switches on or all bottom switches on, where the on-state is indicated by the green tab).

1.2.6 Turn on V_{REF} by flipping the switch on its top (middle shelf, red device labeled GEN REF).

1.2.7 Flip the main power switch on the top of the cart (24V)**.**

1.2.8 Energize one of the generators (A or B) by pressing the MSP430's RESET button.

1.2.9 Synchronize that generator to the rest of the grid.

1.2.10 Energize the other generator by pressing its button and synchronize it as well.

1.2.11 Now, the system is running with three generators synchronized and simultaneously feeding the power grid. Plug and play by changing loads and transmission line lengths, and observe those changes on the MATLAB interface. A user can also model an outage by disconnecting a generator during operation.

2.0 GENERATION SYSTEM

2.1 The generation system gets its input from the 120V, 60Hz power supplied by an ordinary wall socket. All supply and source plugs are gathered on the 9ft (heavy-duty orange) extension cord creating a single-outlet solution for the power supplied to the grid. There are two cutoff switches to the generation points, one is a built-in switch on the third (reference) power source and the other is the single pole ON/OFF switch on top of the cart that controls the power to the DC power supply.

2.2 The DC power supply (Siemens SITOP 6EP1336-3BA00) has two-output ports and is rated at 24V (24.4-28V capacity). The current provided by this source (rated at 20A max) is split between its outputs and is enough to drive our motors at any loading. The 24V, 2.6A, 1/18HP permanent magnet DC motors (Bodine 24A4BEPM) drive the 12V, 7 dipole wind turbine alternators (Hurricane Windpower Cat 4 Mark I Neo Core Platinum) through a belt-driven configuration that makes use of cast iron pulleys and a 4L V-belt. The pulleys create a 2:3 ratio between the motor and alternator (established through testing). This ratio requires the motor to be supplied with roughly 17.5V in order establish 60Hz at no loading, allowing enough room for the power supply to provide more voltage accordingly. The output voltages of the alternators are then stepped-down using 100.8VA/56V, 1.8A transformers (Hammond 186F56) to the desired 12Vpp, roughly 8Vrms.

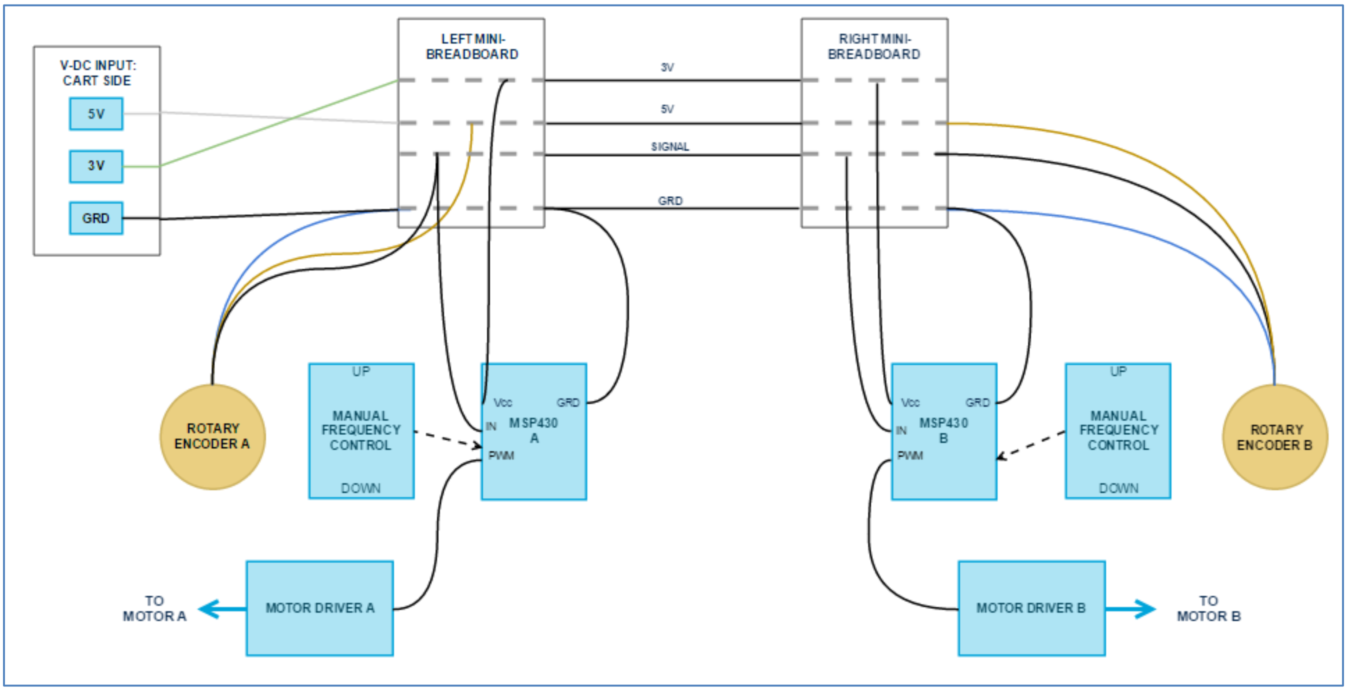
2.3 The third (reference) generation point is established using a variable voltage regulator (PHC Enterprise, Model: SC-3M) rated at 0-130VAC, 3A. This source, like the DC power supply, is powered by the wall connection (INPUT: ~117V at 60Hz) and for use in this project set to roughly 8V in order to provide the grid with 12Vpp.

3.0 FEEDBACK

3.1 The feedback loop will operate without any required action taken by the user. Refer to the User's Manual for details on the layout of the feedback loop.

3.2 You can manually change the alternator's frequency by pressing the up and down buttons on the sides of the MSP430s. If you want the alternator frequency to be slightly higher or lower, press the buttons accordingly. To reset the frequency to 60Hz, simply press the MSP430's RESET button. However, do not do this while the generators are synchronized. These buttons are intended to slightly change frequency so that synchronization is easier (it can make the LED dim and brighten slower).

3.3 Each feedback system is composed of an MSP430, a Cytron 13A, 5-25V Single DC Motor Driver, and a Yumo 200P/R rotary encoder. The rotary encoder provides a pulse signal to the MSP430, which outputs a PWM signal to the motor driver, which provides DC voltage to the motor. There are many wires that connect these parts together; the following wiring layout is implemented and should be used:



This diagram shows the proper wiring of the DC voltage input, the rotary encoders (based on wire color), and shows some information about the layout of the breadboards. This diagram is not intended to show the complete MSP430 wiring, motor driver wiring, or manual frequency control wiring. One important distinction is that the PWM signal from the MSP430 to the motor driver occurs via the breadboard.

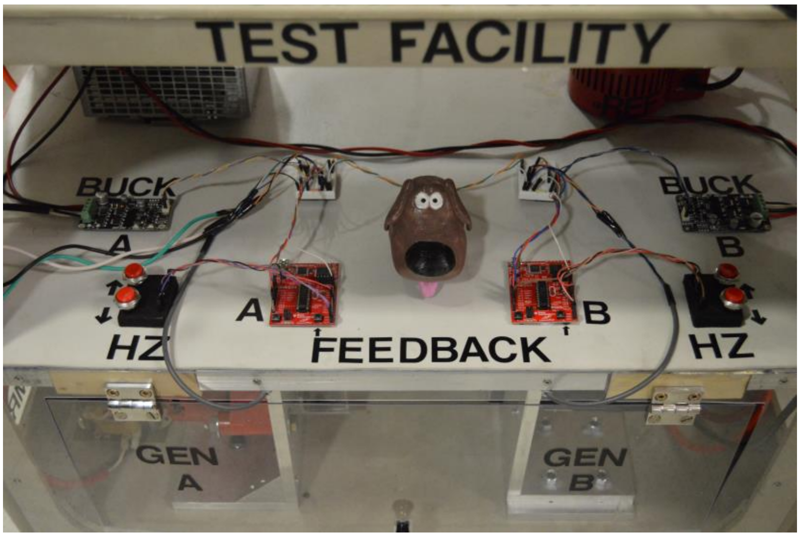


FIGURE 3.3.1 – Feedback Control Loops

The image above shows the application of the system, where the encoders are on the lower shelf, while the MSPs, motor drivers (or buck converters), breadboards, and manual frequency control are on the middle shelf.

4.0 TRANSMISSION LINES

4.1 Development Tool Information

4.1.1 Altium Designer is required to run the transmission line files including the schematic document and the PCB file. The preferred version of the software is Altium Designer Summer 09. Directly contact the BU IT Help Department to provide an updated license on Altium if the software does not allow you to proceed.

4.2 Vendor Information/Significant Datasheets

4.2.1 See excel spreadsheet attached, It documents vendors and contains links for transmission component datasheets.

4.3 Power Requirements

4.3.1 Just like loads, the transmission line PCBs are powered by the three generators that are provided in the project. Since a motor-alternator feeds a synchronization circuit, the transmission line immediately becomes energized when the female connector leaving a sync circuit is attached to a male header from the PCB's IN terminal. The optimal voltage for the transmission lines is $12V_{peak}$, which is also the rated system voltage. At that designated voltage, there is already a current-limiting design for the input line feeding the transmission lines, regardless of loading. In an overcurrent scenario, the user needs to ensure that I_{max} does not exceed 2A.

4.4 Power Up Sequence

4.4.1 The three transmission boards begin connected in a loop. For example, if the reference generator is turned on as the first energized source, it will power the entire delta network provided that its respective load switch is closed. Depending on the combination of six disconnect switches; the board will be powered along different RLC path lengths. If the all the switches are off, the transmission line will not conduct. In all other scenarios, see the User's Manual to determine which switch configurations will deliver power to the load.

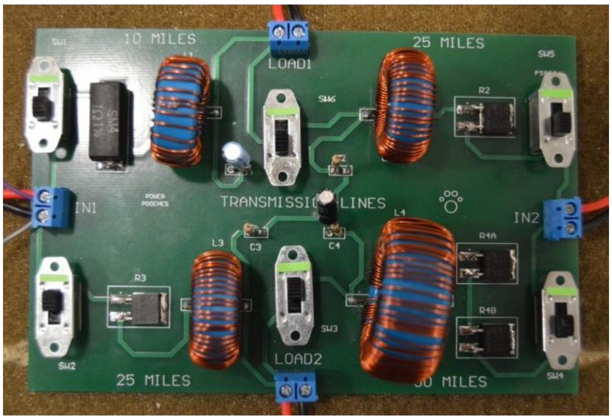


FIGURE 4.4.1 – Transmission Line PCB

5.0 LOADS

5.1 Binary Coded Load Boxes:

5.1.1 Using Altium Designer use the included PCB files to produce Gerber files to reproduce the provided circuit boards. The bill of materials for these boards includes the following.

Component	Description	Quantity
T38 Ferrite Core	36x23X15 Radial Ferrite Core	8
Assorted Resistors	Values Ranging from 1k-128kΩ	8*
Assorted Capacitors	Values Ranging from 12-1440uF	8*
SPST	Single Pole Single Throw	24
SPDT	Single Pole Double Throw	6
Magnetic Insulated Wire	#18-#22 Gauge Wire **	1 Spool

*Actual quantities dependent on part availability.

**Gauge selected at discretion of user, for design purposes.

The included excel spreadsheet aids the user in selecting parts for the intended application.

All resistive components should have a minimum power specification of 10A and capacitive components must be specified at no lower than 35V-rms.

This board does not have a power up sequence. It simply must be connected to the transmission network using the matching connectors that are soldered onto the board. *(Connectors appear in general BOM).*

Below can be found the URL linking to the Ferrite Core manufacturer for this application:

http://en.tdk.eu/inf/80/db/fer_13/R3600x2300x1500.pdf

6.0 DATA ACQUISITION

6.1 Setup:

6.1.1 To setup the sensor PCB, start by attaching the 15V/-15V power supply using the provided 3 conductor wiring and the header to the left of the pcb, and match the values printed on the PCB to the supply voltages. However you orient the wiring is personal preference, however recommended convention is 15 volts/ **15V** (red wire), -15 volts/**-15V** (black wire), and ground/**GND** (green wire). For the supplied power supply 15 volts is **V1**, -15 volts is **V2**, and ground is one of the **COM** pins.

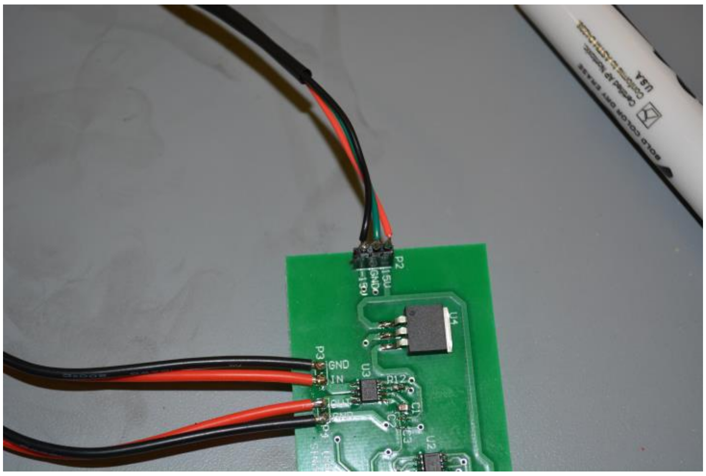


FIGURE 6.1.1 – Correct Attachment of Power Supply Wiring to PCB

6.1.2 Next, connect the PCB to the grid using the Tamiya connectors located on the bottom of the board. The **IN** reference should be attached closest to the source and **OUT** reference closest to the load. If incorrectly attached, readings will be altered due to the reference direction of power flow from source to load. (if reversed, negative power factors will be a main symptom in the output.)

6.1.3 Lastly, attach the PCB to the LABJACK utilizing the header to the right of the board, the provided 4 conductor wiring, and the screw terminals on the LABJACK. In order for the code to provide correct readings, **V_SIG** must be attached to even numbered inputs and **I_SIG** attached to odd numbered outputs. (i.e. V_SIG attached to FIO0,FIO2,…. ; I_SIG FIO1, FIO3,FIO5,…..). Take care to ensure both signal wires use the same terminal block on the LABJACK as they come from the same sensor. Recommended wiring convention is green for **GND,** red for **V_SIG**, and black for **I_SIG**. This leaves the white as an extra **GND** reference.

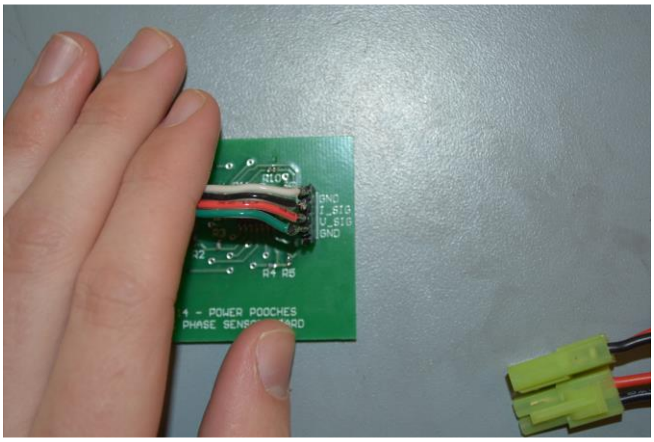


FIGURE 6.1.2 – Correct Attachment of Signal Wires to PCB

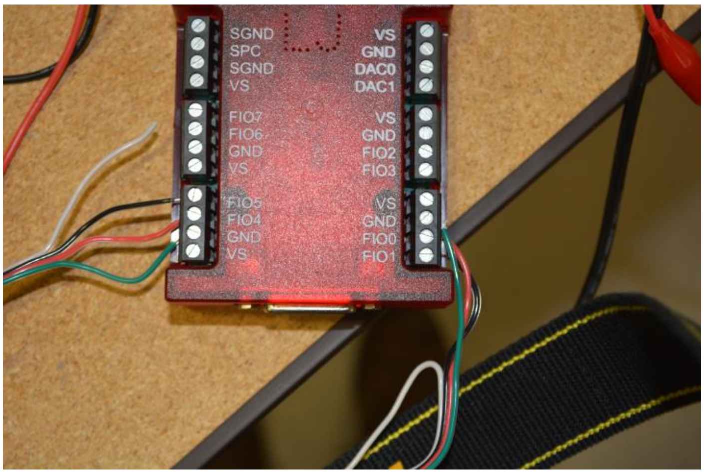


FIGURE 6.1.3 – Correct Attachment of Signal Wires to LABJACK – note that each group of wires utilizes the same terminal block.

6.2 THE PCB: The sensor board is composed of two separate parts, a voltage interface and a current interface.

6.3 Voltage Interface: The voltage module performs analog manipulation of the voltage reference to fit it in the 0V to 2.4V input range of the LABJACK U3-LV. Thus, -12V corresponds to 0V and 12V corresponds to 2.4V. Ideally, this would mean the transfer function of the circuit is Vout = Vin/10 + 1.2. However, 12.5 KΩ SMD resistors are expensive so a 12.4 KΩ resistor was used instead. From left to right on the schematic: U2A is a simple buffer, U1C performs the analog operation, and U1D is an inverting amplifier to achieve the correct sign.

6.4 Current Interface: The current interface performs analog manipulation of the ACS712 output to fit the LABJACK input parameters as well. For our project, we found 2 amps would be the maximum current flow and thus the circuit is designed around that parameter. However unlike the voltage interface, there is an additional low-pass filter and a 5V reference/source provided by a Texas Instruments LM2937-5.0. From left to right on the schematic: U2B is a low pass buffer, then U1A and U1B perform the analog operation.

6.5 Board Construction: The PCB is composed of primarily SMD components and utilizes the footprints provided in the Sensor PCB folder of the resource USB. Refer to the Altium files if you wish for a more detailed look into how the board is constructed. The PCB was manufactured by 4PCB.com for the $33 student rate. All components were bought on Digikey.com.

7.0 SELECTED DATA SHEETS

Part Number Dual Primary 115/230VAC	Fig.	Secondary (RMS) VAC	Secondary (RMS) Current (Amps)	VA Rating
NOT AVAILABLE	-	56V C.T.	0.04	2.5
186B56	6B	56V C.T.	0.11	6.16
186C56	6B	56V C.T.	0.21	12.3
186D56	6D	56V C.T.	0.53	30.0
186E56	6D	56V C.T.	1.00	56.0
186F56	6D	56V C.T.	1.80	100.8

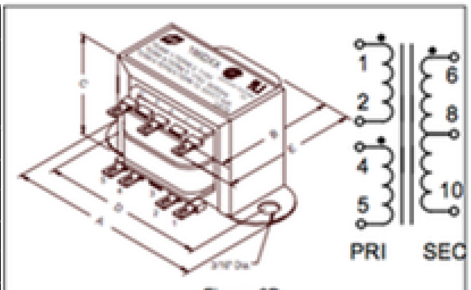


Figure 6D

Permanent Magnet DC Motors

1/50 - 1/7 HP

Standard Features

- Totally Enclosed, Non-Ventilated (IP-40)
- Class "F" insulation, Class "B" rating
- External brush access for easy inspection and replacement
- Oversized brushes for long life
- Skewed armature for smooth low speed operation
- Oversized magnets resist demagnetization, stabilized to common strength for consistent performance
- High starting torque and self-braking
- Noise-tested ball bearings permanently lubricated
- Locked bearing minimizes endplay

Application Information

- For connection diagram 074 10101 see page 66
- Performance ratings of 130 V models based on use with filtered controls
- Flange mount or base mount

Optional Accessories

- Encoder model 0940, see page 101
- "L" bracket mount kit model 0990 available, see page 100

Matching Controls

- Bodine stocks a full line of speed controls for Bodine PMDC motors. See pages 86-99

90 COMPATIBLE WITH 90 V CONTROLS

SEE PAGES 98 & 99

													Model Number[1]				
													24 V. Winding		130 V. Winding Base	130 V. Winding Flange	
Speed (rpm)	Rated Torque (oz-in.)	Rated Amp	HP	K_T (oz-in/A)	K_E (V/krpm)	Winding Resistance (ohms)	Winding Inductance (mH)	Rotor Inertia (oz-in-sec.^{2})	Radial Load (lbs.)	Length XH (inch)	Wt. (lbs.) Shaft	Product Type Shaft	Acc'y. Shaft	No Acc'y. Shaft	No Acc'y. Shaft	Acc'y.	No Acc'y.
2500	8	1.2	1/50	8.3	6.1	5.7	6.7	.003	25	3.31	2.0	24A0BEPM	N4440	N0040	–	–	–
2500	8	.22	1/50	42	31	176	220	.003	25	3.31	2.0	24A0BEPM	–	–	–	N4439	N0039
2500	16	1.8	1/29	10	7.5	2.5	3.6	.005	25	3.93	2.5	24A2BEPM	N4445	**0045**	–	–	–
2500	14	.30	1/29	55	41	84	133	.005	25	3.93	2.5	24A2BEPM	–	–	**0042**	N4441	**0041**
2500	22	2.6	1/18	9.2	6.8	2	6.7	.007	25	4.68	3.0	24A4BEPM	N4444	**0044**	–	–	–
2500	24	.45	1/17	55	40	5	184	.007	25	4.68	3.0	24A4BEPM	–	–	–	**0047**	**0043**
11,500	12	1.1	1/7	14	10	3.15	4.5	.007	25	4.68	3.0	24A4BEPM	–	–	**0049**[2]	–	–

[1] **NOTE: Model numbers shown in bold type are in stock. "N" model numbers require lead time and minimum quantities.**

[2] **NOTE: Ratings for model 0049 are based on 115 V, not 130 V.**

Overview

SITOP modular

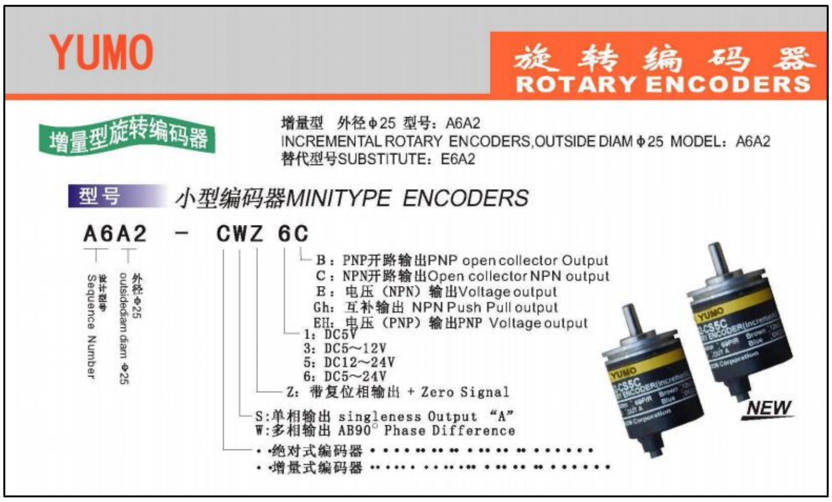
SITOP modular

Application

The modular power supply units with single-phase and two-phase inputs for global use in many different fields of application; expansion of functions possible using add-on modules.

Technical specifications

Power supply, type	**20 A**	**40 A**
Order No.	**6EP1 336-3BA00**	**6EP1 337-3BA00**
Input	Single/two-phase AC	Single/two-phase AC
Rated voltage $V_{in\ rated}$	**120/230 V AC** Settable using wire jumper on device	**120/230 V AC** Settable using wire jumper on device
Voltage range	85 to 132/176 to 264 V	85 to 132/176 to 264 V
Overvoltage strength	2.3 x $V_{in\ rated}$, 1.3 ms	2.3 x $V_{in\ rated}$, 1.3 ms
Mains buffering at $I_{out\ rated}$	> 20 ms at V_{in} = 230 V	> 20 ms at V_{in} = 230 V
Rated line frequency; range	50/60 Hz; 47 to 63 Hz	50/60 Hz; 47 to 63 Hz
Rated current $I_{in\ rated}$	7.7/3.5 A	15/8 A
Inrush current limitation (+25 °C)	< 60 A	< 125 A
I^2t	< 9.9 A^2s	< 26 A^2s
Integrated line-side fuse	Yes	Yes
Recommended circuit-breaker (IEC 898) in mains supply line	10 A Char. C (2-pole coupled with 2-phase operation) or motor circuit-breaker 3RV1421-...	20 A Char. C (2-pole coupled with 2-phase operation) or motor circuit-breaker 3RV1421-...
Output	Stabilized, floating direct voltage	Stabilized, floating direct voltage
Rated voltage $V_{out\ rated}$	**24 V DC**	**24 V DC**
Total tolerance	± 3 %	± 3 %
• Stat. mains compensation	Approx. 0.1 %	Approx. 0.1 %
• Stat. load compensation	Approx. 0.1 %	Approx. 0.1 %
Residual ripple (clock frequency: approx. 50 kHz)	< 100 mV_{pp} (typ. 30 mV_{pp})	< 100 mV_{pp} (typ. 60 mV_{pp})
Spikes (bandwidth: 20 MHz)	< 200 mV_{pp} (typ. 60 mV_{pp})	< 200 mV_{pp} (typ. 120 mV_{pp})
Setting range	24 to 28.8 V (max. 480 W)	24 to 28.8 V (max. 960 W)
Status display	Green LED for 24 V O.K.	Green LED for 24 V O.K.
Power ON/OFF behavior	Overshoot of V_{out} approx. 3 %	Overshoot of V_{out} approx. 3 %
Starting delay/voltage rise	< 0.1 s/< 50 ms	< 0.1 s/< 50 ms
Rated current $I_{out\ rated}$	**20 A**	**40 A**
Current range		
• Up to +45 °C	0 to 20 A	0 to 40 A [1]
• Up to +60 °C	0 to 20 A	0 to 40 A [1]
Dyn. V/I with		
• Starting on short circuit	Approx. 23 A constant current	Approx. 46 A constant current
• Short-circuit in operation	typ. 60 A for 25 ms	typ. 120 A for 25 ms
Parallel connection for increased output	Yes, 2 (selectable current characteristic)	Yes, 2 (selectable current characteristic)



Cytron Technologies

ROBOT . HEAD to TOE
Product User's Manual – MD10C

3. PRODUCT SPECIFICATION AND LIMITATIONS

Absolute Maximum Rating

No	Parameters	Min	Typical	Max	Unit
1	Power Input Voltage	5	-	25	V
2	I_{MAX} (Maximum Continuous Motor Current)	-	-	13	A
3	I_{PEAK} – (Peak Motor Current) *	-	-	30	A
4	V_{IOH} (Logic Input – High Level)	3	-	5.5	V
5	V_{IOL} (Logic Input – Low Level)	0	0	0.5	V
6	Maximum PWM Frequency	-	-	20	KHz

*** Must not exceed 10 seconds.***

Appendix 3: Software Documentation

This ReadMe file is provided to users or a future project team as a description of software in different detail from what is provided in the User's Manual. Users refer to this document for information about the setup and back-end of our software on both the sensor boards and the MSP430s on the feedback control loop. The system comes with all necessary code with detailed comments so that students can revise the code as they would like. Users should always refer to the User's Manual for basic start-up and operation information.

To: Future Senior Design Team, Users

From: Power Pooches

Date: 5/3/2015

Subject: Software ReadMe

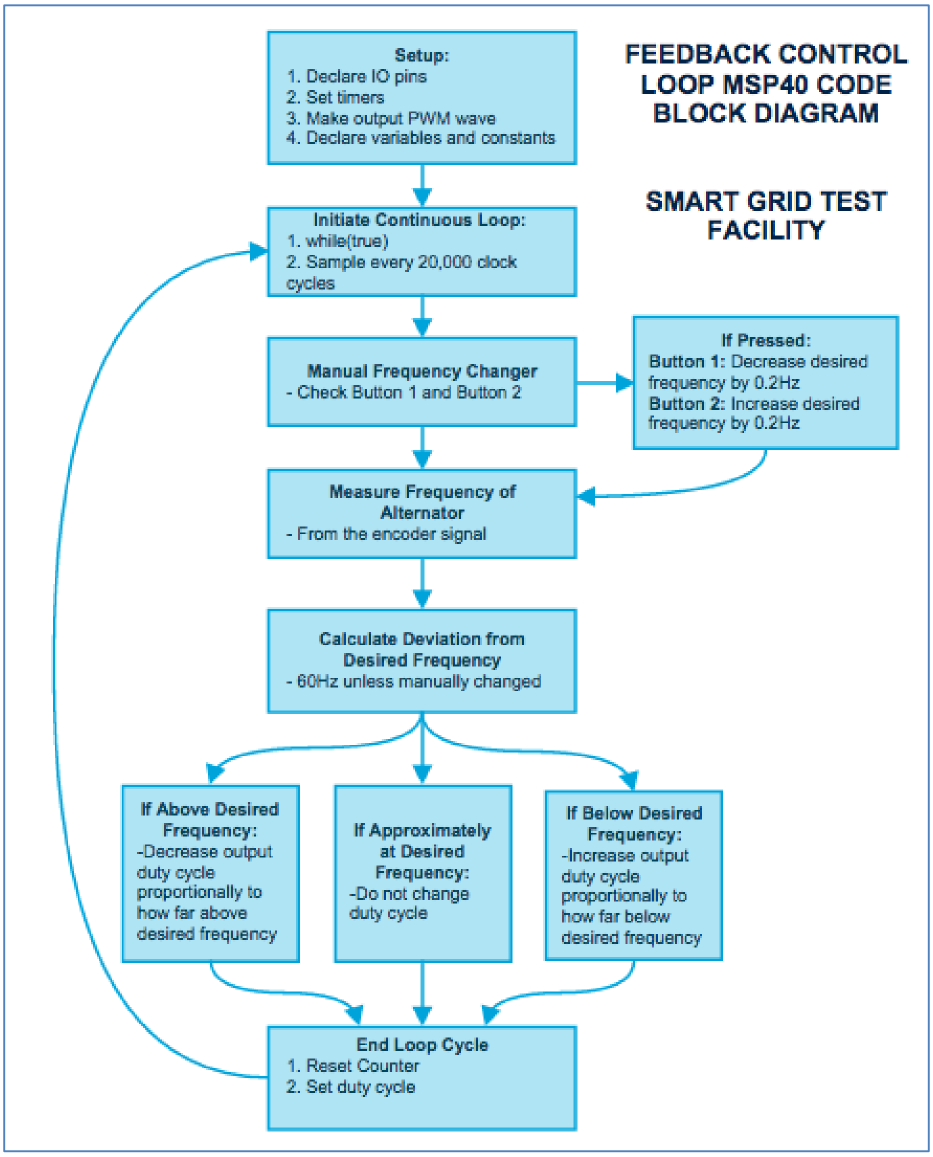
8.0 FEEDBACK CONTROL LOOP: MSP430

8.1 The code for both generators is in this USB drive. The code is well commented and is written in C and also some Arduino code, which is similar to C/C++. Because the microcontrollers were programmed on an Apple computer, Code Composer was not used. Instead, Energia was used, which can be downloaded simply from the Internet (available for Mac, Windows, Linux at http://energia.nu/download/). The environment looks very similar to the Arduino coding environment. The version used during the creation of this project was V.0101E0014.

8.2 The generators have their own (A and B) code, and the programs are not identical. The code takes into account experimental factors that depend on the specific motor and alternator, as noted in the programs.

8.3 To edit the code, save a copy of the original code and make a duplicate for edits. Compile the code using the check button at the top ("verify"). Resolve any errors and upload to the MSP430 using the "upload button," shaped like a rightward arrow.

8.4 Make sure to select the exact board under Tools >> Board (the design team used an MSP430 G2553).



The diagram above shows the flow of information occurring in the MSP430 code. This applies to the MSP430 used on both feedback control loops.

9.0 DATA ACQUSITION

9.1 Setup: Setup of the data acquisition system is comprised of three parts: installation of support software, installation of MATLAB programming, and hardware setup.

9.1.1 To get started, log onto a windows computer with .NET framework installed and install the Labjack driver available at **labjack.com/support/u3** . **(specific information regarding driver installation)**

9.1.2 Connect the USB cable, and windows should prompt with "Found New Hardware" and the Found New Hardware Wizard will open. Here you have the option of which items you specifically wish to install, however it is recommended to accept all defaults. At a minimum install LJControlPanel.

9.1.3 Next, check to make sure the support software is installed by clicking on the Windows Start menu, going to the LabJack group, and running LJControlPanel.

Once the program launches, click the **Find Devices** button, and if the software is installed correctly, and entry should appear under U3 as **USB-1**.

9.1.4 Once the LABJACK driver and software is installed, unzip the 'runlabjack.zip' file in a directory of choice. If you prefer it could be in the default directory Documents/MATLAB, however a new directory is recommended. Once the unzipped folder titled 'runlabjack' is in the directory, set the path to the folder and its contents. To set the path right click on the 'runlabjack' folder in the MATLAB file navigator and select 'add to path' then 'selected folders and subfolders'.

9.2 The Code: The main reason for utilizing MATLAB is engineering students at Boston University have extensive experience with it. This means future BU students/project groups can incorporate their own MATLAB based control systems into the system and utilize the LABJACK wherever necessary. With our project we've included basic example code that calculates data points and plots V-I waveforms. This is what the 'runlabjack' folder contains.

9.2.1 There are three functions within the folder: configurelabjack.m, GetData.m, and AnalyzeData.m. In addition, basic configuration is done via the main script runlabjack.m.

configurelabjack.m: takes the configuration decimal (refer to users manual for more info) and the timing parameter and configures the device using LABJACK corporation provided functions.

GetData.m: has DAQ unit collect analog data points from the sensor board and stores it in a .NET-based array.

AnalyzeData.m: converts the analog values collected by the LABJACK back to their actual values via mathematical operations and plots the waveforms. Then calculates VRMS, IRMS, V-I phase, and power factor. In addition, there is the option of FFT filtering if desired.

9.3 Abnormal Operation/Things for consideration: It should be noted the current sensor (ACS712) will have a noise of about +/- 4 milliAmps. If you run the software and the output plot for current seems very noisy, look at the axis for values. If the axis is in the range of +/- 20 milliAmps or so (.02 Amps), what is plotted is the extensive noise the ACS712 puts out.

9.3.1 In addition, the LABJACK does not like configuration decimals that do not include the first two pins FIO0 and FIO1. If you come across an error regarding line 12 in GetData.m, it is usually because FIO0 and FIO1 are not included.

9.3.2 Lastly, if you see saturated waveforms in the plots but the maximum voltage values are not around +/- 12 volts, check the ground connections of the hardware. Most likely, one or more are loose/not connected.

9.4 Future Capabilities: It should be noted that because we've provided a MATLAB code does not mean you have to use either the code or MATLAB with the system. Should you wish, LABJACK provides support for other languages including C++, Labview, and Python. This makes it very flexible for future projects. If you wish to program in any of the languages including MATLAB, LABJACK offers great support on their website in addition to coding examples. Have fun!

Appendix 4: Functional Test Report

This test report was submitted about a month before the final demonstration of the project. It includes several vital tests and also describes some work that remained after this test was performed. Please refer to the User's Manual for final, as-built components.

To:	Professor Pisano, ECE Senior Design Faculty
From:	Smart Grid ECE Senior Design Team, Power Pooches
Date:	4/3/2015
Subject:	Functional Test Report

1.0 INTRODUCTION

1.1 The Smart Grid Test Facility is an educational tool for engineering students, facilitating in-class experiments, demonstrations, and active learning. Students in power and electric energy courses can study grid elements using this test bench, which includes a collection of fixed generators, variable loads, a transmission line network, and sensors feeding into a visual display. The overall technical approach involves breaking down the small-scale grid into its main components: generation, transmission, loads, and metrics. This Smart Grid Test Facility aims to provide a fun and modular testing environment for students studying the power grid.

1.2 This test report describes the functional testing performed on April 2. During this procedure, our team demonstrated the various functional requirements set forth by our customer. This report explains both the experiments conducted and the conclusions made based on those experiments. Finally, this report explains the remaining work required to complete the project based on the results of functional testing

1.3 Customer Requirements

1.3.1 Generation:
- 12V-AC (+/- 5%) at 60Hz (+/- 5%)
- Three generators: minimum of two motor-alternator sets

1.3.2 Transmission:
- Real-world, lumped-element (per unit length) parameters
- 3+ total transmission lines

1.3.3 Loads:
- RLC Binary Boxes (1 each)

1.3.4 Safety:
- Motors/alternators inside a safety enclosure
- No exposed high voltage (12V) for classroom setting

1.3.5 Data Acquisition:
- Measure voltage and current of waveforms
- Measure power factor and phase angle (+/- 5%)

2.0 GENERATION SYSTEM

2.1 MOTORS & ALTERNATORS

2.1.1 Equipment and Setup

The generation scheme was demonstrated during functional testing. The motors and alternators in the design first and foremost fulfill our customer's academic needs. The motors that were used in this setup are 24V, 2.6A DC motors, rated at 1/18HP at approximately 2500 RPM. On the other hand, we used 7 dipole (14 pole) wind turbine alternators, which we purchased from a US based manufacturer. The motors and alternators are mounted onto a bracket that was designed and manufactured in house at the EPIC laboratory/shop. The power transfer is established through a belt-driven design, which makes use of a 4L V-belt and cast-iron V-belt pulleys. This generation scheme was demonstrated through the synchronization circuit testing and the feedback testing.

2.1.2 Measurements Taken

Although we did not display this particular data during functional testing, we were able to conduct our testing on a finished bracket giving us precise and repeatable data. While the DC motors were exactly the same, we wanted to observe the alternator outputs. The following data was obtained:

	Input (DC)	Output (AC)	Frequency
Alternator 1	15 V	14.2 V	53 Hz
	24 V	33.4 V	124 Hz
Alternator 2	15 V	15.8 V	53 Hz
	24 V	34.8 V	121 Hz

The data obtained shows a slight difference between the two alternators, which we will account for in purchasing transformers to step down the output voltage. The transformers will need to step down the alternator output voltage down to our nominal system voltage of $12V_{pp}$. Our third generator is a wall adapter that serves as a reference supply for phase and frequency.

2.1.3 Data Assessment

Based on the data shown in the previous table, by obtaining two data points of the alternator outputs, we are able to roughly estimate and test the input voltage that the DC supply needs to be stepped down to. We estimated that we needed to supply the DC motors with approximately 17.5 V DC. Given that this voltage is within the limits of our supply we can conclude that we have made the correct decision with our gear ratio. Also we are able to provide an extra 10V if need be (due to loading). Our power supply is a 24V, 20A supply that will provide sufficient power for both motor/alternator sets.

2.1.4 Conclusions & Remaining Work

Through the results obtained from the testing we can conclude that the components purchased and the brackets manufactured function properly. The cart, including the safety enclosure and bracket attachment, is also complete and fully functional. There is no remaining work for the motor/alternator portion of the project. The only remaining work regarding overall generation is purchasing transformers and affixing them to the cart in a safe and user-friendly way.

2.2 SYNCHRONIZATION

2.2.1 Equipment and Setup

The objective of the synchronization circuit testing was to demonstrate the phasing process of two out-of-phase waveforms. This process involved using the setup shown in the diagram below. The only unexpected challenge that we faced involved the batteries, which are used to step up the DC voltage of the 15V DC power supply. We replaced the batteries during testing and the circuit worked as planned.

As described on the test report, the following steps were taken in order to demonstrate the synchronization circuit in operation.

1. On the synchronization circuit, turn the slide switch on (conducting) and the toggle switch off (non-conducting).
2. Turn on both AC signals and ensure that both are at approximately 60Hz and 17.5V (+/- 5%).
3. Observe the LED's illumination as it brightens and fades; the LED experiences the combination of the two waveforms. When the LED becomes its dimmest, the waves are in phase; close the toggle switch to short the circuit together.
4. Via an oscilloscope or frequency meter, confirm that the final waveform is 60Hz at 17.5V (+/- 5%).

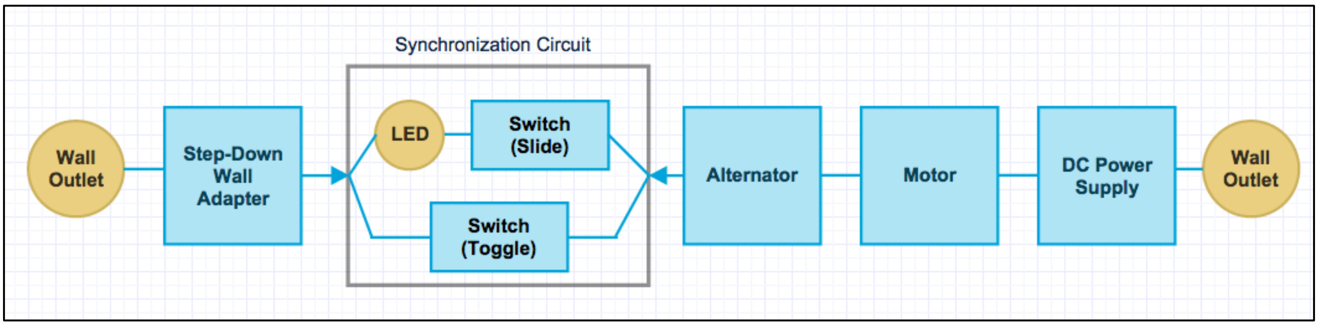


Figure 1: Synchronization Circuit Setup

2.2.2 Measurements Taken

While constructing and testing this circuit, the most important metrics to measure and compare are load values, frequency of both generators, and alternator current. For safety purposes, the output current of the generator is extremely important. Not only do we want to keep our components safe, but we also do not want to subject users to unexpectedly high currents. These values are also vital because they demonstrate the waveform that we expect to exist along our grid network immediately after synchronizing the waveforms.

The following data was collected while testing the synchronization scheme. It shows the motor/alternator trying to power various loads; as current demand increases, and the alternator must provide that increased power, the frequency of the alternator drops. This is because the motor is driven by a fixed 15V DC power supply, and the motor drives the alternator; thus, when the alternator needs to output more power due to a different load, its frequency drops in order to create more torque and power the load. This is resolved via feedback, which detects low or high frequencies (relative to the desired 60Hz) and alters the frequency accordingly.

Generator Alone		
Load (Ω)	Alternator Output Current (mA)	Outcome
10,000	1	~60Hz signal
1000	10	~60Hz signal
100	70	Frequency drops by ~5%
51	100	Frequency drops by ~10%
21	700	Resistor melts
10	900	Frequency drops by ~20%

Generator + Wall Adapter		
Load (Ω)	Generator Output Current (A)	Wall Adapter Output Current (A)
1000	1	1.2
560	1.4	1.8
330	1.4	1.8
270	1.6	1.85
150	1.3	1.5
100	1.4	1.6

2.2.3 Data Assessment

This data helped us better understand the mechanics of the motor and alternator and the overall power flow of the system. The criteria for success of the synchronization system was that the final waveform was a 60Hz, 17.5V, stable sine wave (+/-5%). This was achieved during testing and proved the functionality of the synchronization circuit.

The data in the tables above show, as mentioned, that feedback is required in order to stabilize the frequency of the alternator. This is vital because once synchronized, students should be able to change loads or transmission line lengths while the generators are running. In order to maintain synchronization and a 60Hz signal, feedback must be implemented in combination with synchronization. Further, we collected data when we included an RLC transmission line in series with the synchronization circuit, and the output waveform dropped to 50Hz. Similar to the changing loads, the transmission lines introduce reactive elements that can alter the voltage and current waveforms, and thus feedback is needed to create stability among generators.

2.2.4 Conclusions & Remaining Work

The remaining work on synchronization involves connecting it to the feedback loop in order to ensure stability once the generators are synchronized. Then, we will incorporate a transmission between the generator and the synchronization circuit. As before, the frequency should drop to about 50Hz, but the feedback loop will raise the frequency back to 60Hz via the buck converter and rotary encoder, as described in the next section. Once this is implemented, the circuits must be affixed to the cart and well labeled so that students using this system understand what each component is and how it operates.

2.3 FREQUENCY STABILITY: FEEDBACK

2.3.1 Equipment and Setup

The feedback loop was also demonstrated during functional testing. Frequency stability is a vital component of a power grid, and our frequency controller feedback loop layout is shown in the diagram below.

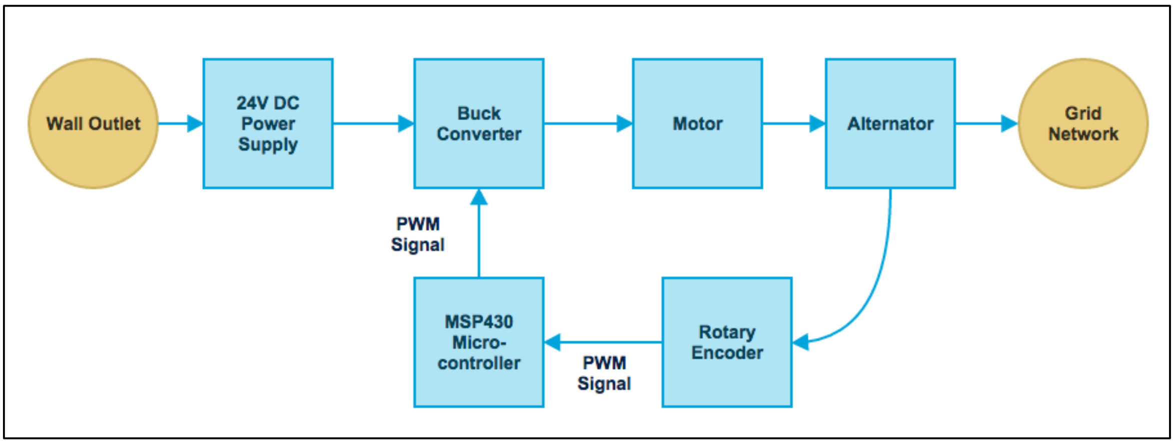


Figure 2: Feedback Controller Circuit

As described in the test plan, this system is used to keep the generators at a desired frequency (60 Hz). For this test, we operated the system at approximately 41Hz due the limited power ratings of our MOSFETs. Per the diagram above, the rotary encoder measures the RPM output of the alternator. The rotary encoder then outputs a PWM signal to the MSP430, which reads in the frequency of the signal. Based on the frequency, the MSP modulates the duty cycle of its PWM output signal. This signal is given as input to a gate driver, which then drives the buck converter output voltage up or down. The MSP430 code is complete and functional, while the buck converter is operating but still in breadboard stages.

One of the key challenges associated with the feedback loop has been the gate driver chip needed for the buck converter. Although our typically used S2004 gate driver chip operates for low-power applications, this chip did not suffice for higher power flow. For this testing procedure we instead used an IRS2153 gate driver, which is similar to the S2004, but was better suited for our needs. The following circuit diagram* shows this driver chip and its topology with the buck converter.

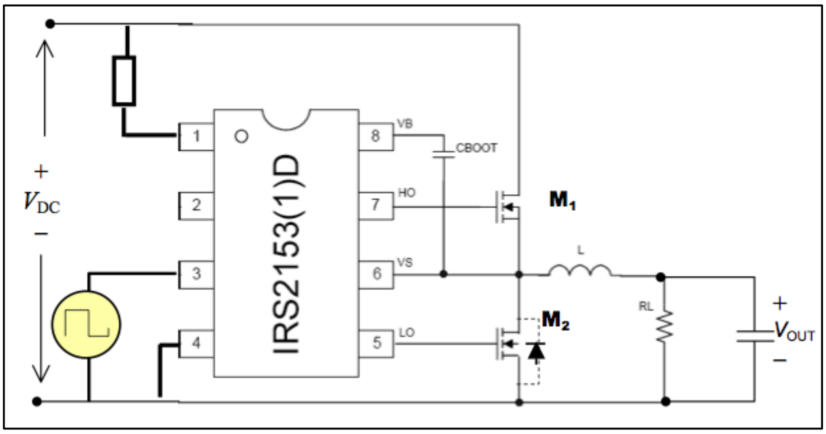


Diagram from EC583 – Power Electronics for Energy Systems DC-AC Converter: PWM Control Signal by Mark Horenstein.

2.3.2 Measurements Taken

Although not demonstrated during functional testing, the MSP430 code was initially tested using an imitation input signal instead of the rotary encoder. In that setup, a function generator provided a square wave at 60Hz and $2V_{pp}$ to the MSP430, which then outputted a square wave with a frequency of 50kHz (chosen based on the switching frequency of the MOSFET to maintain continuous conduction through the inductor). The duty cycle of that output signal started at 50% and changed based on the input frequency's deviation from 60Hz, the desired frequency. These deviations from 60Hz are expected to occur when loads or transmission lines are changed, and thus the feedback controller loops repeatedly, keeping the frequency steady.

The MSP and encoder were tested in a complete feedback loop during functional testing and proved successful in stabilizing the frequency of the alternator. Due to the limited availability of power MOSFETs, we spun the alternator at about 41Hz, the natural output frequency from the 15V DC input bucked to about 8V. We then connected the feedback loop and observed on the oscilloscope the frequency of the alternator. With the motor integrated into the feedback loop, a nominal frequency of 41.5Hz was achieved with a roughly 10.9V, 4.1A input current and this was programmed into the MSP430 as a temporarily desired frequency. This allowed us to observe a variance in duty cycle of approximately ±5%. When frequency began to decline (perhaps a result of the resistors heating and becoming more resistive), the duty cycle of the MSP430 increased until the output frequency returned to approximately 41Hz. Thus, this test was successful in demonstrating the functionality of the feedback loop.

During functional testing, the success of feedback was shown by observing the waveform on the oscilloscope. However, prior to functional testing, we collected data on the feedback loop in order to confirm its functionality. The data below was collected by testing the MSP430 with a function generator and oscilloscope as described above. The program was considered successful if it properly responded to changes in input frequency (duty cycle should change by a percent proportional to how far from 60Hz the input signal is).

MSP430 Testing Data			
Input Signal (from Encoder)		Output Signal (by MSP430)	
Frequency (kHz)	Alternator Frequency	Frequency (kHz)	Duty Cycle (%) (Instantaneous)
1.7	60	49.88	49.9
1.72	59.7	49.75	51
1.72	60.1	49.75	50
1.8	61.25	50	50
1.83	65.2	49.75	49.8
1.9	66.9	49.75	48.5
1.92	66.8	49.8	48
2	72	49.8	42
2.03	70.7	49.8	45

2.3.3 Data Assessment

Based on the desired functionality of the feedback loop, we considered the MSP430 code, the buck converter, and the rotary encoder all successful. Based on the data, when the alternator's frequency fell below 60Hz, the duty cycle increased to compensate. Similarly, when the frequency grew above 60Hz, the duty cycle decreased to compensate. These duty cycle values were collected immediately after initializing the test (duty cycle eventually saturated to 0% or 100%, because this test did not include feedback to the motor).

In terms of testing the buck converter, we did so in isolation from the rest of the feedback loop, and ensured that the output voltage was a bucked version of the input voltage. This output voltage needed to correspond to the duty cycle of the input signal to the gate driver chip. The buck converter was functioning as planned, and was also functional (providing the correct output voltage based on input duty cycle) when connected into the feedback loop.

2.3.4 Conclusions & Remaining Work

Overall, we were pleased with the outcome of the feedback loop, as we faced many challenges with the buck converter and the MSP430 code while designing, constructing, and testing this system. The next step in feedback is to increase the power across the system, which requires using our newly acquired 30A MOSFETs and possibly other components with higher power ratings than the ones in our current buck converter. As this point, we are constructing an improved buck converter, which employs higher rated components, but also a new interface component. After discussing with the electronics lab advisor, we realized that the gate driver chip can output current only on the order of mA. However, our system requires a much more powerful signal. Thus, we will be using a BJT to interface between the gates of MOSFETs and the output pins of the gate driver chip. This way, the electrical signal will still propagate from the chip to the MOSFETs, but it will have a higher current due to the BJT interface. We will test this circuit in the coming days in order to attempt feedback at 60Hz instead of 41Hz. Once this design is finalized, we will either create PCBs for the buck converters (depending on time remaining) or we will solder them to boards. We have also considered purchasing a buck converter chip, per the suggestion of our customer, and will continue researching for a chip that may be fit for these purposes.

3.0 TRANSMISSION LINES

3.1.1 Equipment and Setup

During functional testing, we showed the three transmission line PCBs and described their operation. The transmission lines use a matrix design that allows students to change transmission line lengths via a collection of switches. The system diagram is shown below, along with the corresponding switching arrangements needed to simulate different transmission line lengths.

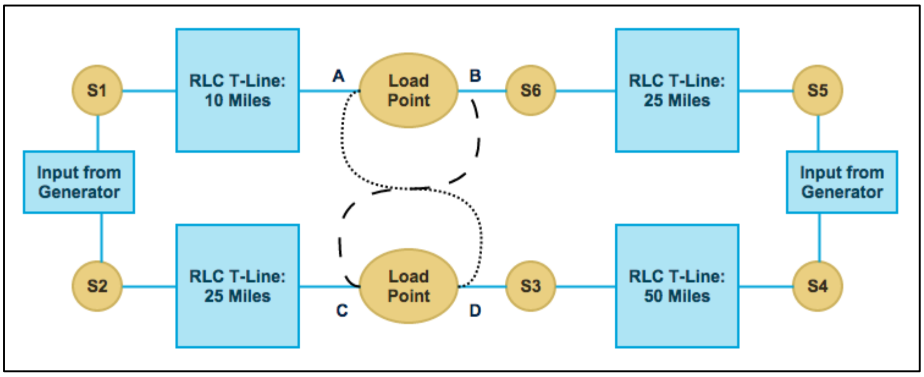


Figure 3: Transmission Line PCB Matrix Design

Transmission Line Configurations			
Load Point 1	Load Point 2	Switches ON	Miles Simulated
A	B	1, 6, 5	35
C	D	2, 3, 4	75
A	D	1, 3, 4	60
C	B	2, 6, 5	50

As shown during functional testing, the transmission lines are soldered onto PCBs. In order to test these, we measured the RLC characteristics and confirmed that they aligned with our intended design. Because the sensor part of the project was not tested at the time of functional testing (as described in the final section), these PCBs were not electrically tested during the demonstration, but rather discussed. However, prior to functional testing, we completed our own data-driven tests, as described in the next section.

3.1.2 Measurements Taken

The most important measurements for transmission are the RLC characteristics. As described on our test plan, the resistors and capacitors were purchased at low tolerances, approximately 5%. The inductors were self-wound, and their values were individually measured to ensure that each was below a 10% margin of the actual value; the reason for the high tolerance is the nature of the windings, as they are discrete and each winding contributes a certain fixed amount of inductance.

TRANSMISSION LINE CHARACTERISTICS		
R (Ω/mi)	L (mH/mi)	C (nF/mi)
0.1128	1.329	22

FINAL TRANSMISSION LINE SPECS				
TL No.	Length (mi)	R (Ω)	L (mH)	C (nF)
1	10	1.1	13.3	220
2	25	2.8	33.2	550
3	25	2.8	33.2	550
4	50	5.6	66.5	1100

The other essential test for transmission lines is confirming that they conduct in all possible configurations and checking that the impedance levels correspond to the desired levels from our original design.

3.1.3 Data Assessment

Although this was not demonstrated during functional testing, we have conducted these tests and we have observed that the PCBs function in all possible configurations. We have tested each path for current flow and have confirmed that the switch-based system does indeed function; it allows a user to actively change the simulated transmission line length by reconfiguring the switches on the board. Further, the values of the components were confirmed by measurement and have proven to be within tolerance of our desired values.

3.1.4 Conclusions & Remaining Work

The remaining work regarding transmission lines simply involves affixing them to the cart and screwing the connecting wires into the terminal blocks. As mentioned regarding synchronization, the transmission lines must be tested within a synchronization circuit in combination with the feedback loop.

4.0 LOADS

4.1.1 Equipment and Setup

By the time of functional testing, the binary load PCBs had just arrived and were not yet soldered. However, breadboard versions of all three loads were created and shown at functional testing. They include a resistive, inductive, and capacitive load bank capable of being used within the system as a grid in order to simulate various types of grid consumers as well as altering power flow in desirable ways, as required by our customer. As described within our test plan, the test for these deliverables is simple, however the loads are essential to the testing of the DAQ unit and therefore must be measured consistently. The binary load boxes each come with 8 “bits” (L and C have an applied scale factor to permit common components) and these values must be within a 5% tolerance of desired values that have been calculated for the purposes of maintaining a range power flow characteristics when connected with a 25-25 (mi-mi) transmission branch. These flow calculations have prioritized a wide range of possible phase shifts when connecting the loads at designated points along the transmission network. Listed in the table below are the included bit values (in base units):

L	C	R
1.500E-03	1.125E-05	1.000E+03
3.300E-03	2.250E-05	2.000E+03
6.800E-03	4.500E-05	4.000E+03
1.200E-02	9.000E-05	8.000E+03
2.400E-02	1.800E-04	1.600E+04
4.800E-02	3.600E-04	3.200E+04
9.600E-02	7.200E-04	6.400E+04
1.920E-01	1.440E-03	1.280E+05

4.1.2 Measurements Taken

Fully testing these loads requires testing them with the transmission lines and the DAQ and comparing the results with the calculated values in the phase chart below.

25-25 Impedance		
Z1	Z2	Z3
2.8+1.992i	2.8+1.992i	15151.5151515152i
Parellel Comp (Z3 || Load Box)		
(C LOAD)	Z_Tot	Ø ANGLE
-1642.03612479474i	5.6-1638.05212479474i	89.804
-778.816199376943i	5.6-774.832199376943i	89.586
-379.650721336371i	5.6-375.666721336371i	89.146
-187.476565429321i	5.6-183.492565429321i	88.252
-93.1619154089808i	5.6-89.1779154089808i	86.407
-46.4381907680877i	5.6-42.4541907680877i	82.486
-23.1835674873648i	5.6-19.1995674873648i	73.739
-11.5829221395974i	5.6-7.5989221395974i	53.612
(L LOAD)		
0.0899994654031756i	5.6+4.07399946540318i	36.036
0.197997412569813i	5.6+4.18199741256981i	36.752
0.407989013671841	5.6+4.39198901367184i	38.107
0.719965787225788i	5.6+4.70396578722579i	40.030
1.43986315540571i	5.6+5.42386315540571i	44.085
2.8794526736358i	5.6+6.8634526736358i	50.788
5.75781111052822i	5.6+9.74181111052822i	60.108
11.511247768097i	5.6+15.495247768097i	70.130
(R LOAD)		
995.662892440529+65.7137509010747i	1001.26289244053+69.6977509010747i	3.982
1965.74879303024+259.478840679991i	1971.34879303024+263.462840679991i	7.612
3739.38016034462+987.196362330977i	3744.98016034462+991.180362330977i	14.825
6255.94314598872+3303.13798108203i	6261.54314598872+3307.12198108203i	27.841
7564.52540167632+7988.13882417017i	7570.12540167632+7992.12282417017i	46.553
5860.22198520883+12376.788832761i	5865.82198520883+12380.772832761i	64.649
3396.6352930787+14347.3874779644i	3402.2352930787+14351.3714779644i	76.663
1768.72035735228+14942.149578912i	1774.32035735228+14946.133578912i	83.230

4.1.3 Data Assessment

The load boxes were considered successful if they were compliant with the +/-5% tolerance set forth by our customer and provided the desired impedance when connected along the transmission lines. These values are tabulated extensively in a spreadsheet that will be provided to the customer so that applying the loads as variable impedances will be very straightforward for the customer. For reference, the above table shows the impedances of each bit of each load just as they would be connected with a 25-25 mi transmission line. This table is programmed to perform detailed calculations about power flow based on arrangements of loads.

4.1.4 Conclusions & Remaining Work

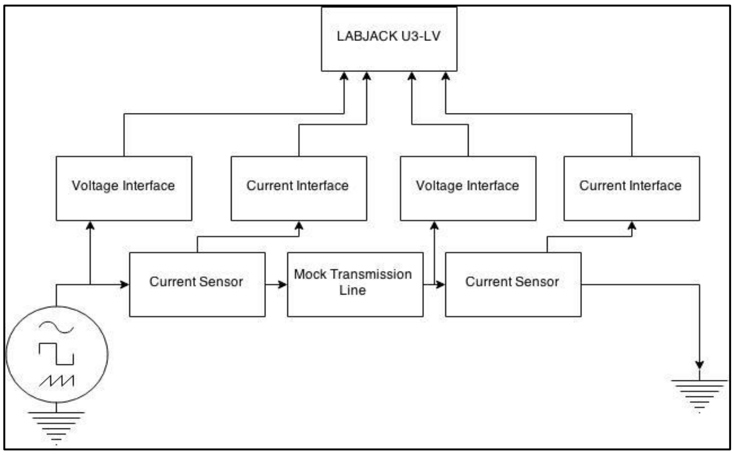
Remaining work includes the assembly of load box PCBs and the manufacturing of a luminous load. After these loads are assembled, they must be affixed to the cart in user-friendly ways. The load boxes will need to be connected to the male/female headers used by the transmission lines.

5.0 DATA ACQUISITION

5.1.1 Equipment and Setup

As discussed at functional testing as well as previous deliverable testing demonstrations, the sensor suite is a system that enables a user to measure current and voltage at various points along the grid and thereby calculate phase and power flow characteristics of the grid. The suite interfaces with MATLAB, so users can work on their available lab monitors to observe changes in the power flow within the grid when they are in a lab setting and the customer will be able to easily modify the sensing network in the future. This is also important because engineering students at Boston University are all introduced to MATLAB and could theoretically modify the code themselves.

The setup of the sensor suite test bench is similar to that of the first deliverable test. In this functional test, the LabJack DAQ was planned to be used in conjunction with two current sensing circuits to measure a test signal from an AC power supply as it passed through a load. The overall system layout of the data acquisition system is shown in the diagram below.

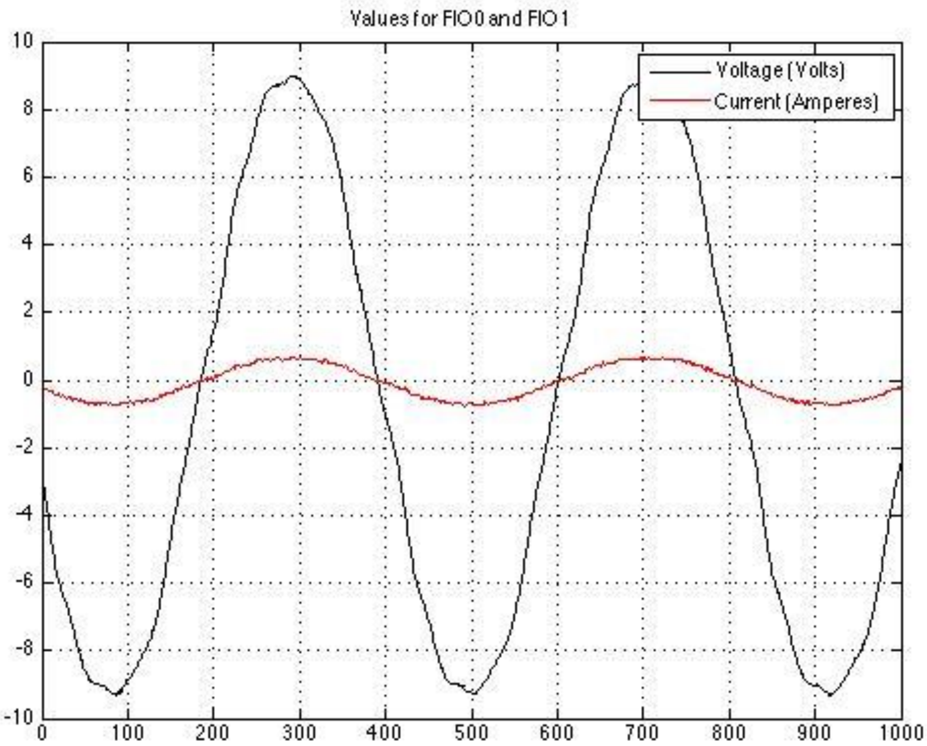


5.1.2 Measurements Taken

In an effort to reduce the amount of noise and parasitic effects the LABJACK sees from the current sensor and breadboard, soldered prototypes of the interface circuitry were created with the same general component specifications as previously tested in our earlier deliverables tests. However, due to circumstances regarding either the construction/fabrication of the physical prototype board or perhaps bad integrated circuits, measurements could not be made during functional testing, as the zero current points (1.2V) for the current sensors were not as anticipated/designed during testing. However, through ORCAD simulation and previous deliverables tests with breadboard versions of the interface circuitry before and after the functional testing period, the circuit design is proven and capable of its design as shown below.

Below are measurements taken by the LABJACK through a breadboard version of the exact same interface circuitry attempted during functional testing. For these measurements, an AC power source operating around 6.6 V_{RMS} was passed through only a power resistor, which in turn should mean a power factor of 1 and calculated RMS values correlating to that input.

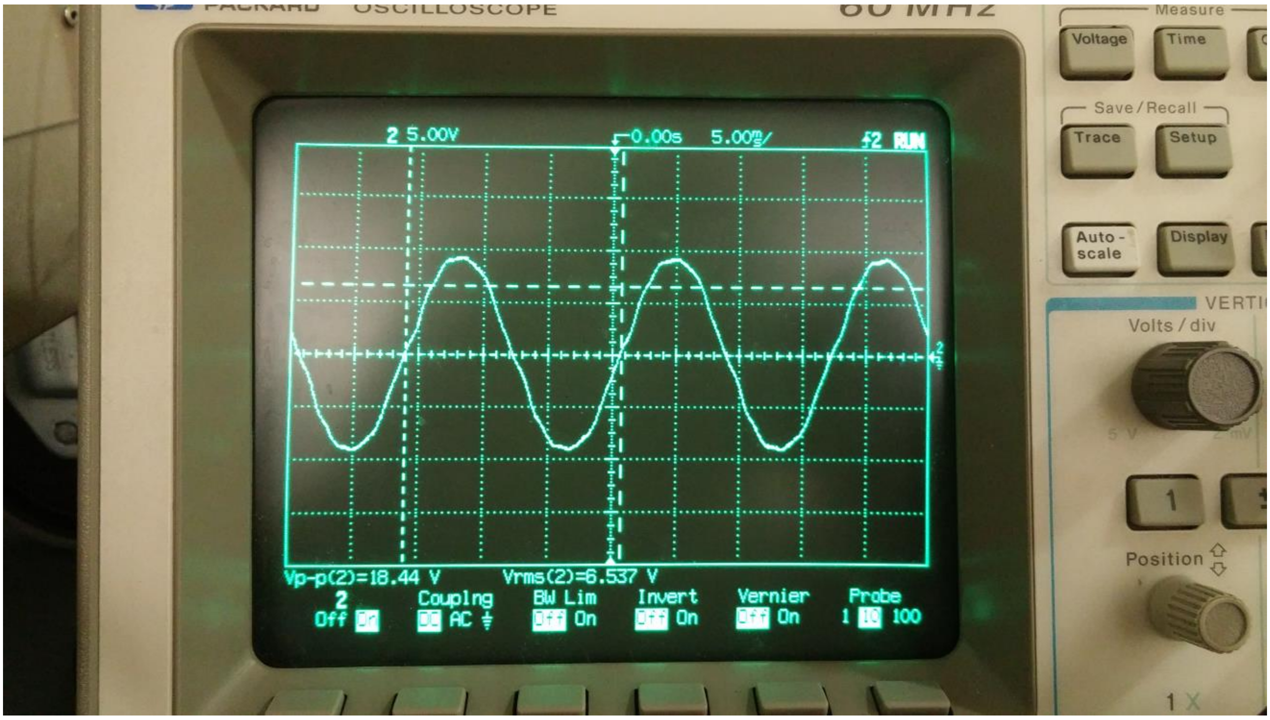
<u>Sample MATLAB Output From Previous Deliverables</u>
Output waveforms of current and voltage interfaces into the DAQ.



MATLAB Prompt/Results

Please input LABJACK pin configuration decimal value: 3
How many periods should we analyze? : 2
Initiating LABJACK Configuration
UD Driver Version = 3.45
U3 Hardware Version = 1.3
U3 Firmware Version = 1.46
User Defined Scan Rate = 25000
Actual Scan Rate = 25000
Actual Sample Rate = 50000
Number Of Data Points Read = 2000
Done Logging Data Points
VI lagtime in seconds=0
Calculated VI-Phase via correlation = 0 radians
Calculated Power Factor = 1
Vrms = 6.6748
Irms = 0.49997

Power Supply Output



5.1.3 Data Assessment

The criteria for success with the data acquisition system are as follows: By Design, there must be a wave form read by the current interface circuits that is centered around 1.2V +/- .05 V due to part precision. This is median voltage that will give the best resolution for the DAQ. The phase between current and voltage is being read from the interface circuits. This can be used to calculate power factor for power flow in the system. The input and output power factor will be calculated so that the power flow of the system can be characterized through the system. This is necessary for the ultimate functioning of the DAQ within the final system.

Through mathematics done within the code, if the interface circuitry was not correct, the output waveforms would not be centered around 0 and would have an offset of some marginal value. RMS values are correct as well, as the V_{RMS} is correctly calculated to around 6.7V_{RMS} (i.e. almost the same reading a secondary oscilloscope provided during measurement periods). In addition, the power factor was correctly calculated to be 1 (i.e. only real impedance) through use of MATLAB's x-correlation function.

Any differences between the oscilloscope and LABJACK calculations can be attributed to using 5% precision through-hole components and a breadboard instead of the very precise SMD components that will populate the PCBs. But even then, the calculated and actual values are well within tolerances.

5.1.4 Conclusions & Remaining Work

Given the data collected, DAQ is ready for the next step of populating PCBs, from 4PCB, with SMD components and running more thorough tests. The PCBs will provide for less noise from outside sources and more stable current readings, in addition to allowing for multiple test points to be established. The final remaining work after this has been completed will be wiring the necessary components together within and around the cart.

Appendix 5: Resources

Thank you for looking through our description of the Smart Grid Test Facility! Please refer to the User's Manual for the final, as-built information about our project. The attachments on this submission include the PCB files, the manual, software code, and additional project photos.

POWER POOCHES