Senior Design
ENG EC 464

To: Professor Pisano, ECE Senior Design Faculty
From: Smart Grid ECE Senior Design Team
Team: Power Pooches: Team 14
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%).

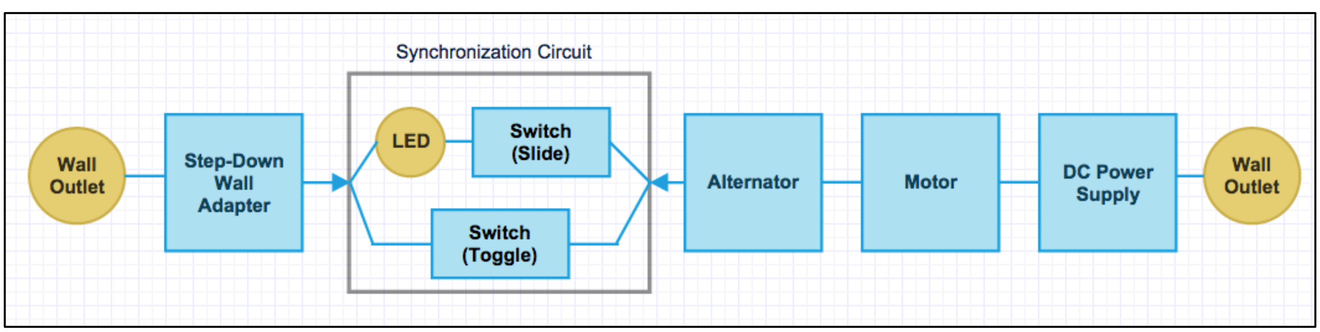


Figure 1: Synchronization Circuit Setup

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 <u>FREQUENCY STABILITY: FEEDBACK</u>

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.

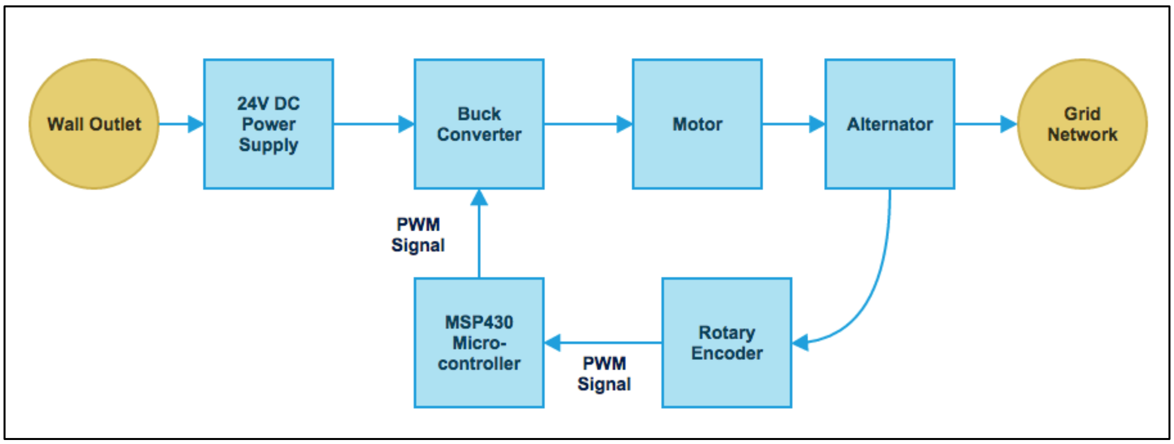


Figure 2: Feedback Controller Circuit

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.

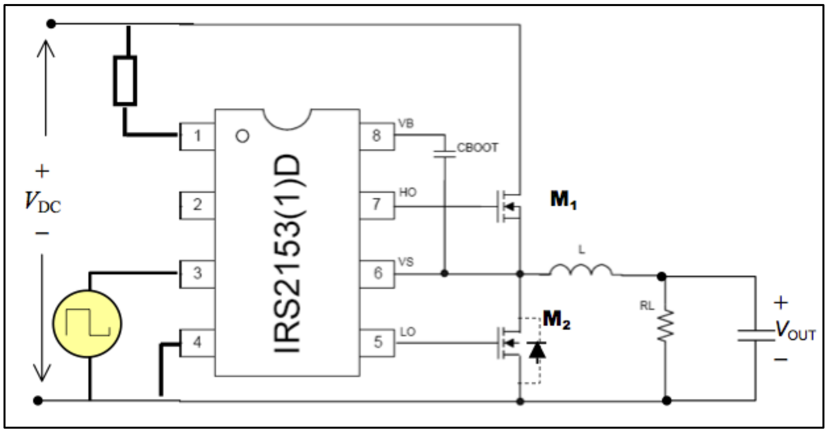


Diagram from EC583 – Power Electronics for Energy Systems DC-AC Converter: PWM Control Signal by Mark Horenstein.

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.

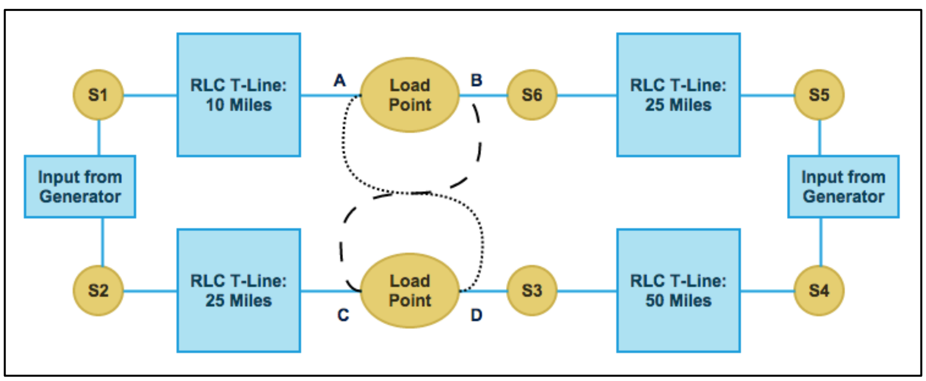


Figure 3: Transmission Line PCB Matrix Design

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
0.40798901367184i	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

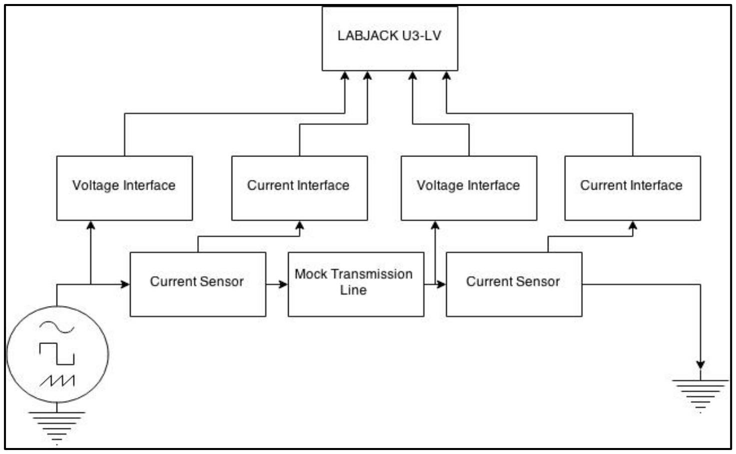
Remaining work includes the assembly of load box PCBs and the manufacturing of a luminous load. After these loads are assembled, they must be affixed to the cart in user-friendly ways. The load boxes will need to be connected to the male/female headers used by the transmission lines.

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.



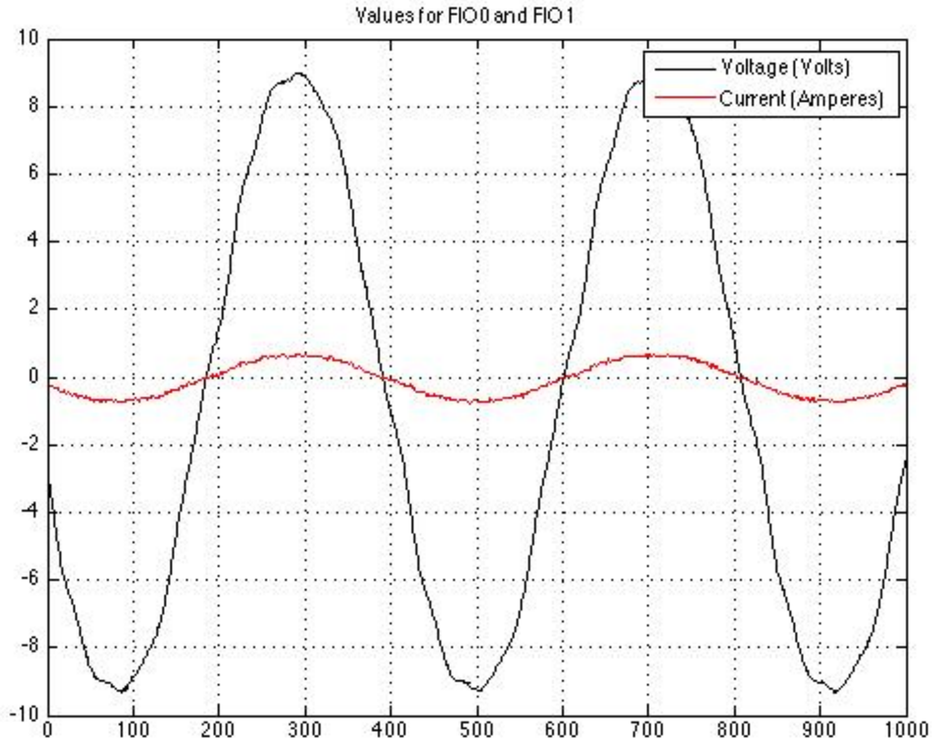
5.1.2 Measurements Taken

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>

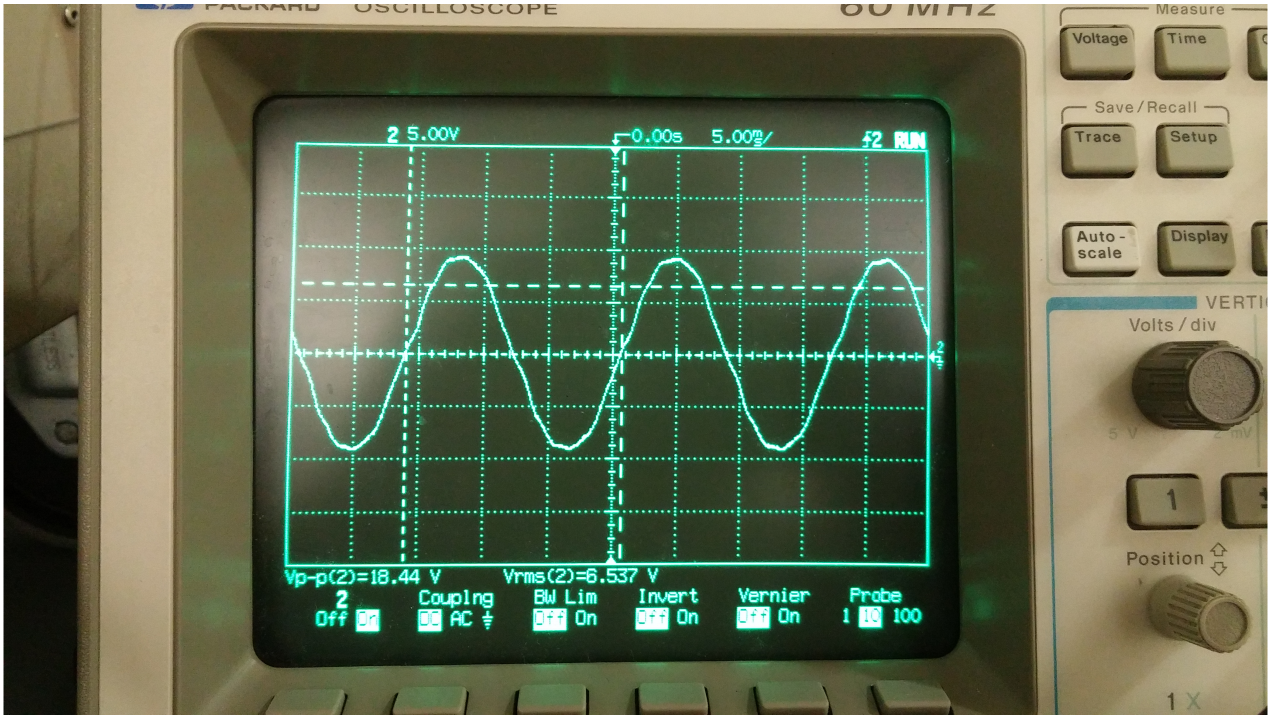
Output waveforms of current and voltage interfaces into the DAQ.



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.