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: 4/2/2015

Subject: Functional Test Plan

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 **Customer Requirements:**

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

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

1.2.3 Loads:
- RLC Binary Boxes (1 each)

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

1.2.5 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 Significance of Deliverable

The motors and alternators in the generation first and foremost fulfill our customer's academic needs. While we could have supplied the simulation grid in a more efficient manner, this setup is able to relay the mechanics of power generation to the user in a basic and easy to understand form.

2.1.2 Equipment and Setup

The motors that are used in this setup are 24V, 2.6A DC motors manufactured by the Bodine Electric Company. They are 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 design allows for tension on belt through a shifting base for the motor. The power transfer is established through a belt-driven design, which makes use of a 4L V-belt and cast-iron V-belt pulleys.

2.1.3 Measurement Plan and Data Collection

We were able to conduct our final testing on a finished bracket giving us precise and repeatable data. While the DC motors were exactly the same, we wanted to make sure how different the alternator outputs would be. 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.

2.1.4 Data Assessment and Criteria for Success

By obtaining two data points of the alternator outputs we can estimate and test the input voltage that the nominal voltage needs to be stepped down to. The main criterion for success is to achieve a frequency and output voltage within the set tolerance. It is also crucial that the components and the cart design are secure/safe for classroom use.

2.2 SYNCHRONIZATION

2.2.1 Significance of Deliverable

Per the requirements of our customer, we must have a 60Hz signal propagating through our grid network. Thus, in order to ensure the generators are synchronized and feeding the transmission lines and loads, we created a synchronization circuit. This circuit is used to synchronize the motor/alternator generators to the wall adapter supply so that all three generators are synchronized.

2.2.2 Equipment and Setup

The arrangement of this synchronization circuit is shown in the diagram below. The objective is to make two 60Hz out-of-phase sine waves in phase. This arrangement is often called the “Synch Bulb” method. In the grey box is the synchronization circuit itself, which includes and LED, a sliding switch, and a large toggle switch. To set up, two out-of-phase 60Hz waves are generated. One of these waves derives from a wall outlet to a wall adapter, which outputs 60Hz at variable voltage. The other source is the motor/alternator generator, which creates 60Hz at about 17.5V_{rms}. The first generator is set to 17.5V in order to ensure the waves have the same frequency and voltage within approximately 5%.

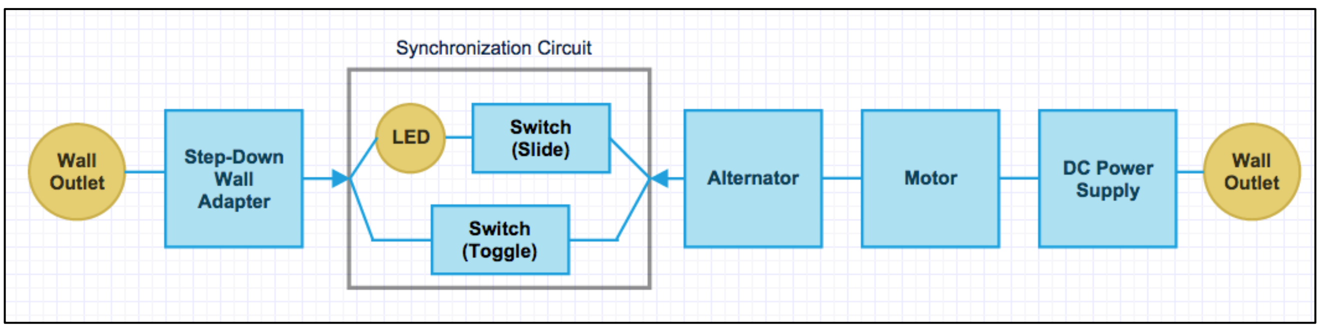


Figure 1: Synchronization Circuit Setup

2.2.3 Measurement Plan and Data Collection

In order to successfully operate the synchronization circuit, the following steps are taken:

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%).

This experiment has been conducted numerous times and its success confirmed. It is important to note that there is also a resistor in series with the synchronization LED in order to limit the voltage experienced by the LED. Our testing procedures for this setup involve measuring voltage, current, and frequency. In particular, we observe the voltage and frequency of the final waveform and the current across a load resistor and diode that we typically apply from the output of the synchronization circuit to ground. These values are vital because they demonstrate the waveform that we expect to exist along our grid network immediately after synchronizing the waveforms.

2.2.4 Data Assessment and Criteria for Success

The criteria for success of the synchronization system are that the final waveform is in a 60Hz, 17.5V, stable sine wave (+/-5%). If this is achieved, which we have completed, then the synchronization circuit is considered successful.

In terms of data assessment, through testing we have identified many challenges associated with the generator and transmission system. When we include an RLC transmission line in series with the synchronization circuit, the output waveform drops to 50Hz. However, since this testing setup does not include feedback, it is planned that feedback will detect this deviation from 60Hz and increase the duty cycle so that the buck increases its output voltage, thus turning the motor faster and increasing output frequency. Without feedback, the alternator has a fixed input power and cannot change its output current that the load demands. Thus, it drops its speed in order to increase torque and supply the load properly. With the addition of feedback, the alternator will only drop frequency temporarily and by a marginal value because the input power will increase or decrease as necessary to keep frequency constant. The data table below 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.

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

In order to overcome this problem, the feedback circuit must be implemented together with the synchronization circuit. The frequency stability circuit is currently functional but due to delays in receiving high-power MOSFETs for the buck converter, this setup has not yet been implemented.

2.3 FREQUENCY STABILITY: FEEDBACK

2.3.1 Significance of Deliverable

Frequency stability is a vital component of a power grid. The customer required that we provide 60Hz within a defined tolerance, and we have achieved this component of the project through a feedback controller. A rotary encoder measures the alternator's output frequency and provides this information to an MSP430, which in turn creates a PWM signal for a buck converter with a duty cycle dependent on how close or far the alternator is from 60Hz.

2.3.2 Equipment and Setup

The frequency controller feedback loop layout is shown in the diagram below.

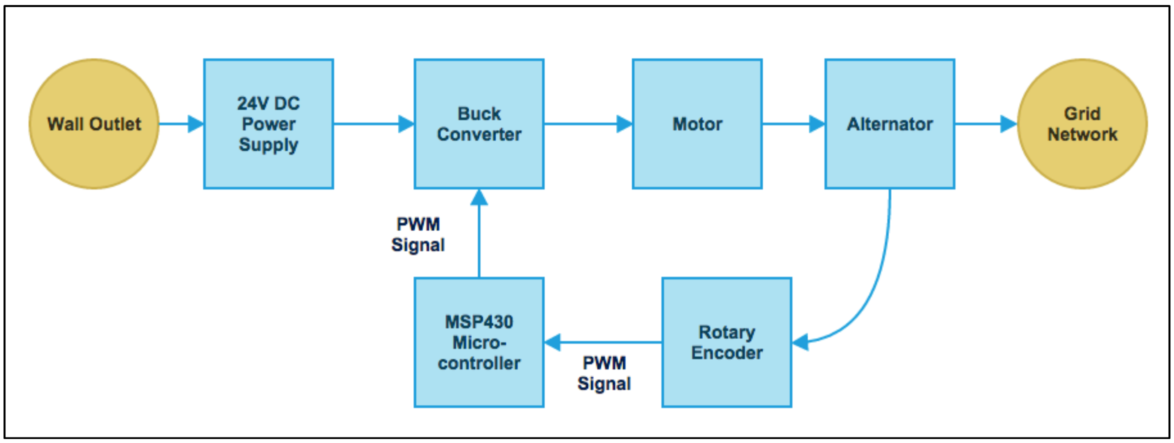


Figure 2: Feedback Controller Circuit

In this setup, the rotary encoder measures the RPM output of the alternator. The rotary encoder 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 an IRS2530D gate driver, which then drives the buck converter up or down based on the information transmitted in the feedback loop. This functionality is essential in this application because it introduces digitally controlled feedback and only requires user action at start up time. This varying voltage powers the motor, directly influencing the torque on the motor. Our design assumes that the generator will regularly operate under a time invariant load, so by changing torque without changing the load we can control the output frequency of the alternator using this feedback system. The MSP430 code is complete and functional. It accepts a PWM signal and outputs another PWM signal based on the input frequency's deviation from 60Hz.

The following circuit diagram* represents the buck converter topology and ICs that are used to control the frequency output of the motor-generator unit. This system has been designed to operate under higher current and voltage conditions than what will be tested during the functional test. Ultimately, unregulated current supplied by the Siemens SITOP power supply will be at 24V in the range of 0-10A. To accommodate for this potential maximum current ripple high power inductive and capacitive components will be used in the final design.

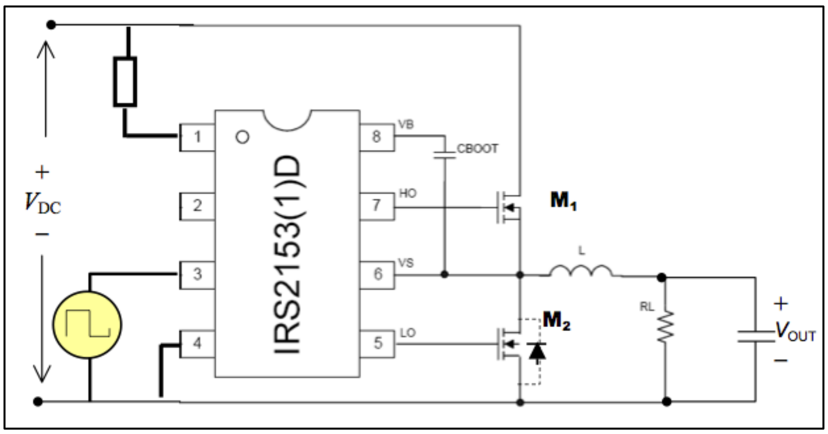


Diagram from EC583 – Power Electronics for Energy Systems DC-AC Converter: PWM Control Signal by Mark Horenstein.

2.3.3 Measurement Plan and Data Collection

The MSP430 code was initially tested using a dummy input signal instead of the rotary encoder. In that setup, a function generator provides a square wave at 60Hz and $2V_{pp}$ to the MSP430, which then outputs a square wave with a frequency of 50kHz (chosen based on the switching frequency of the MOSFET to maintain continuous conduction through the load inductor). The duty cycle of that output signal starts at 50%. If we decrease the output frequency of the function generator (mimicking the alternator's frequency dropping below 60Hz), the output duty cycle increases so that the buck converter outputs a higher voltage to the motor, which spins the alternator faster and increases its output frequency. The reverse phenomenon occurs when the alternator is spinning too quickly and the frequency goes above 60Hz. 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 have also been tested in a complete feedback loop and proved successful in stabilizing the frequency of the alternator. Due to the limited availability of power MOSFETs, we spun the motor and alternator at a lower frequency (via a lower voltage). 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 duty cycle output of the MSP430 and the frequency of the alternator. 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.

2.3.4 Data Assessment and Criteria for Success

The data below was collected by testing the MSP430 with a function generator and oscilloscope as described above. The program is considered successful if it properly responds to changes in input frequency. The degree to which it responds (how quickly it responds, and how much it changes duty cycle) may be altered in the future depending on the behavior of the buck converter with the IRF510 high-power MOSFETs. However, at the moment, it has been estimated that the duty cycle should change by a percent proportional to how far from 60Hz the input signal is. These proportions have been programmed into the microcontroller effectively, as demonstrated by the data below.

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

As visible, when the alternator's frequency falls below 60Hz, the duty cycle increases to compensate. Similarly, when the frequency grows above 60Hz, the duty cycle decreases to compensate. These duty cycle values are the data collected immediately after initializing the test. This is because the duty cycle eventually will saturate to 0% or 100%, because this test did not include feedback to the motor.

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 temporary "target" frequency. This allowed us to observe a variance in duty cycle of approximately ±5%. These values are somewhat of a compromise compared with the ultimate goal of 12V, 60Hz electricity but they are the best condition available with the 15V power supply that we are using for this functional test. In order to reach the aforementioned goal, the SITOP power supply must be integrated into the system, which requires more robust redesign of the buck regulator (specifically, higher power MOSFETs). As such, these test values will be accepted under the premise that they are a proof of concept that we can iterate upon as we finalize the project.

3.0 TRANSMISSION LINES

3.1.1 Significance of Deliverable

Transmission lines are a direct requirement set forth by our customer. The transmission lines must model real-grid lines by their resistive, inductive, and capacitive characteristics. These values were previously calculated for various transmission line lengths, and then capacitors and resistors were purchased accordingly. The inductors were self-wound and measured. In this way, we have completed the design, construction, and testing of the transmission lines that were required by our customer.

3.1.2 Equipment and Setup

The transmission line PCBs use a matrix design that allow 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.

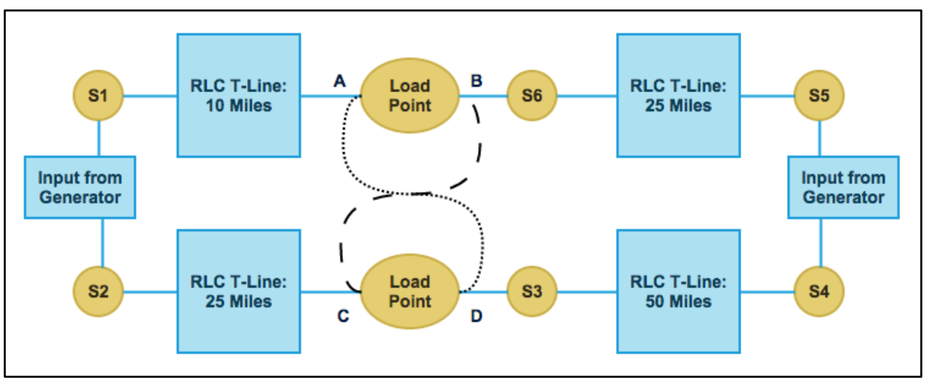


Figure 3: Transmission Line PCB Matrix Design

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

The transmission lines are soldered onto a PCB. In order to test these, we measure the RLC characteristics and confirm that they align with our design. We also incorporate this PCB into the synchronization circuits in order to observe how synchronization will occur with transmission lines, as it will be done in our final product when users wish to synchronize the generators.

3.1.3 Measurement Plan and Data Collection

The table below provides the values for the transmission line characteristics. The resistors and capacitors were purchased at low tolerances, approximately 5%. However, 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

3.1.4 Data Assessment and Criteria for Success

The transmission lines are considered successful if they conduct in all possible configurations and if the impedance levels correspond to the desired levels from our original design. 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.

4.0 LOADS

4.1.1 Significance of Deliverable

Binary loads are a base requirement set forth by the customer. They are to 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.

4.1.2 Equipment and Setup

The test for these deliverables is simple, however they 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

4.1.3 Measurement Plan and Data Collection

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
0.407989013671840i	5.6+4.39198901367184i	38.107
0.719965787225788i	5.6+4.70396578722579i	40.030
1.43986315540571i	5.6+5.42386315540571i	44.085
2.87945267363580i	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

4.1.4 Data Assessment and Criteria for Success

These loads will be considered successful if they are capable of accurately offering 255 modes and show the correct phase shift when connected from a transmission line to ground. These phase angles represent the line-to-line phase shift induced by tapping the load between the transmission line and the local ground.

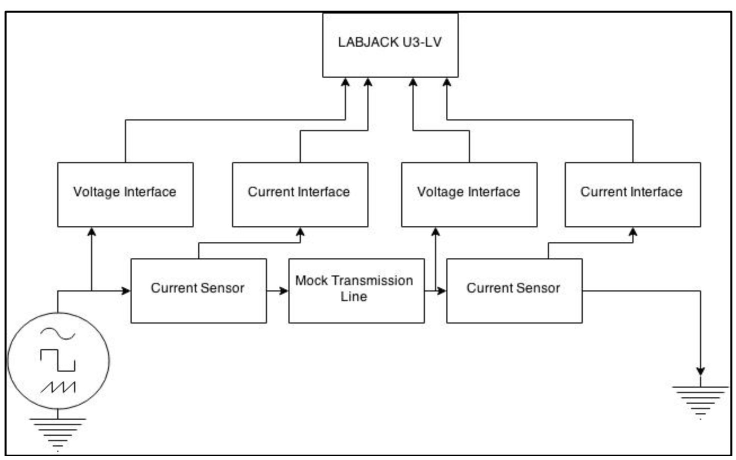
5.0 DATA ACQUISITION

5.1.1 Significance of Deliverable

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.

5.1.2 Equipment and Setup

The setup of the sensor suite test bench will be similar to that of the first deliverable test. In this functional test the LabJack DAQ will be used in conjunction with two current sensing circuits to measure a test signal from an AC power supply as it is provided to a transmission line connected to a binary load. The current sensing capabilities of our data acquisition unit were not available during the previous deliverables test, because we had not devised a way to correctly measure the signal without altering its characteristics too much. We will now be using an RLC circuit (Transmission Line + Load Box) to interface to the LabJack.

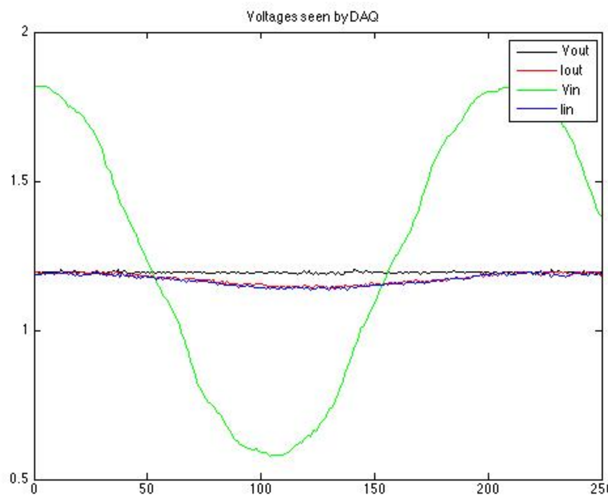


5.1.3 Measurement Plan and Data Collection

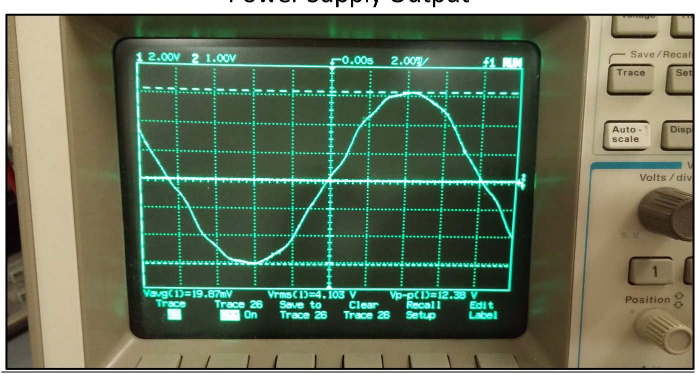
For testing the DAQ, the ground of the DAQ should be connected to the ground of the circuit. Then, the other DAQ ports should probe various points throughout the grid network. This can be done by simply connecting a lead from a flexible input output port (FIO) to a part of the circuit and observing the output on a computer via our MATLAB program. For testing purposes, we have attached leads to the outputs of two voltage interface and two current interface circuits attached to our circuit. It should be noted, what might seem like major irregularities in the Vin sine wave is not due to interface design. Instead, it was due to irregularities of the power supply output.

Sample MATLAB Output

Output waveforms of current and voltage interfaces into the DAQ.



Power Supply Output



5.1.4 Data Assessment and Criteria for Success

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 read 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. Current sensors show a value within 5% of one another (on the same line).