Boston University
Electrical & Computer Engineering
EC464 Capstone Senior Design Project

User's Manual

Smart Grid Test Facility

Submitted to:

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Smart Grid Test Facility

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Executive Summary

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 and the integration of clean energy systems. This Smart Grid Test Facility aims to provide a fun and modular testing environment for students studying the power grid.

1 Introduction

Project Purpose

The Smart Grid Test Facility is designed to introduce engineering students to how a power grid works. The motivation behind this type of project is 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, formed this project. This test facility is expected to be used for experiments and demonstrations primarily in Power Electronics and Electric Energy Systems.

Generation System

Per our customer requirements, it was crucial for the generation design to portray the mechanisms of power generation. In approaching this problem, we turned to a less efficient yet a more representative way of generating power for our grid. A single main generation point consists of a DC motor driving an alternator as well as a transformer used to step-down the output voltage. Due to various limitations, only two main generation points are made use of in the design. The third generation point is established through an AC/AC power supply, a simple yet useful addition to the grid generation, which also serves as the reference generator. In totality, the grid is supplied with power from three independent sources that are synchronized in phase and frequency.

In any power system, as loads and generators change, power flow of the system changes. Therefore, our test facility is equipped with a frequency feedback system that stabilizes the three generators at 60Hz at $12V_{pp}$. Students can change the simulated length of transmission line lengths in addition to load values and the system voltage and frequency will return to nominal values naturally. In order to ensure that the generators are synchronized upon startup, our test bench includes synchronization circuits that take two out-of-phase 60Hz sine waves and synchronizes them into one 60Hz, $12V_{pp}$ wave.

Transmission Lines

The transmission network is the backbone of the grid. It provides the electrical connections between generators and load points. On the power grid, transmission lines exhibit a characteristic impedance. The project's transmission circuit boards model real-world line resistance, inductance, and capacitance over various distances. The purpose is to demonstrate the actual line losses associated with a three-generator transmission scheme as the mode of power transport.

Load Network

The modern electrical grid can readily be reduced into a system of sources, transmission lines, and loads. For every sized grid network the connection points for loads are found at the junctions between transmission lines, as such the loads provided with the test facility are designed bearing this connection configuration in mind. More so, these loads that have been provided with the system are modeled at high values (three orders of magnitude above the transmission lines) to simulate the relative power loss as power flows from generator to ground through a loaded network. Three basic loads are included with the test facility (resistive, inductive, and capacitive), each with an 8-bit binary setting allowing for each load to take 255 different values. In addition to these consumers, a model CITGO sign has been included that is backlit with LEDs as a representation of a luminous power consumer on the grid.

Data Acquisition System

In order to provide for experimentation and testing, this test facility includes a data acquisition system involving a LABJACK U3-LV and MATLAB that collects data from arbitrary points in the grid and provides key data points such as RMS voltage, RMS current, phase between the voltage and current waveforms, and power factor. In addition, it also plots the waveforms flowing through the point, which can be inspected for distortions or abnormalities.

The LABJACK U3-LV is a lower-cost USB data acquisition device available for around $110. With 16 possible analog inputs available to collect data from (with a minimum sampling rate of 3.125 kHz), it is ideal for collecting experimental data from many different points at once. In addition, LABJACK provides free example code and support for many different languages on multiple operating systems including: python, C/C++, MATLAB, and LabView. This means a student and/or professor is not limited to the code we provide for experimentation. If they choose, they may write additional or perhaps another entirely unique program to suit their personal needs while working with the project. However, for our project we used MATLAB and Windows to provide maximum flexibility and minimum hassle for prospective users.

Document Objective

The remainder of this document details the functional, technical, and systematic elements of this test bench. This document should be used to understand the layout and usage of the Smart Grid Test Facility. Finally, this document aims to provide engineering frameworks for the development and construction of this project.

2 System Overview and Installation

2.1 *Overview Block Diagram*

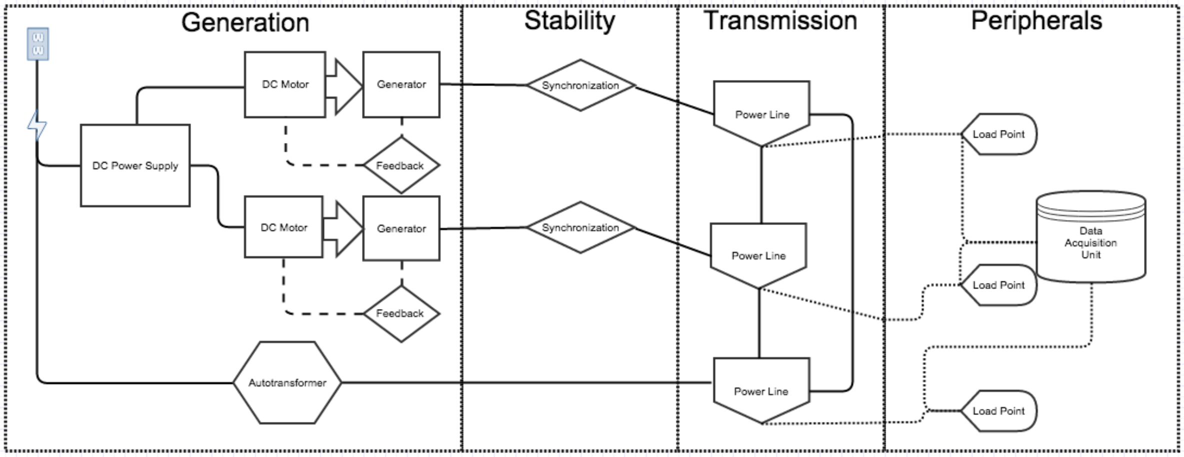


Figure 2.1.1 – Overview Block Diagram

The generation portion of the grid consists of three alternating-current generators. They are representative of the gas and steam turbines that generate electricity for our transmission and distribution networks. The two generators at the bottom of the cart convert mechanical energy to electrical energy. Each is driven by a DC motor acting as a "prime-mover". Those two DC motors are powered by a 24V DC power supply that is plugged into a wall outlet. In the overall system block diagram, there is a feedback loop drawn for the two motor-alternators. The feedback block consists of an encoder, an MSP430 controller, and a buck converter. The two alternator-generators spin with an encoder attached to their shafts. The encoder outputs a packet of pulses to represent one revolution seen by the MSP430. By integrating the number of poles with the actual revolutions per minute into the calculation, the MSP430 compares the frequency that it sees with a reference of 60 Hz. If the frequency read in is above the desired frequency, the chip will output a duty cycle that is below the normal operation duty cycle. The buck converter receives the PWM signal and proceeds to decrease the input voltage going to the DC motor for frequency stability. The third generator is a variable transformer used as an AC power supply. Since the other two generators have their output voltages stepped down by transformers, the autotransformer ties into the system voltage of $8V_{RMS}$, 60 Hz with ease.

The stability section denotes the points of connection from generator to transmission line. The autotransformer will typically be the first source powering the transmission network. It will not require a sync circuit, as it may be closed in by a simple load switch. The synchronization blocks symbolize sync LEDs and switches that help synchronize Generator A and Generator B with the grid's reference voltage. When the LEDs become dark, the disconnect switches can be closed. This is because the line-to-line voltage seen by the sync bulb is near zero. The generators are in phase.

Transmission will be set up so that it resembles are triangular "delta" configuration. This is congruent to most three-bus power systems. Each power line block designates a transmission line printed circuit board. The boards simulate line losses and RLC characteristics for any combination of four different line distances. Power resistors, toroidal inductors, and ceramic capacitors compose the 10 mile, 25 mile, and 50 mile lumped-element lines. Due to their arrangement, all three transmission modules will be powered immediately (if one conducting path exists) when the reference generator is closed in. The RLC components can handle up to 2A. Six switches are present on each transmission PCB. They allow for current from generation to flow through several different paths before reaching the load. The switches can operated safely even when the transmission lines are energized on both input terminals.

The load points of the transmission lines allow for the connection of resistive, inductive, and capacitive loads. When these loads are connected with the headers provided, they become in parallel with the generators. Bigger resistive loads will experience a voltage closer to the grid voltage of 8V. Transmission line losses often appear negligible. To add a minimum of three loads onto the network, three load PCBs are available (resistor box, inductor box, capacitor box). Each box has a column of switches to increase and decrease the magnitude of impedance. As a peripheral aspect of the project, a data-acquisition unit is provided as a deliverable. With a computer running MATLAB software, the user can load on a script via USB. The code allows for the measurement of voltage, current, phase difference, power factor, and power flow. This data can be read in from up to six different voltage/current sensor PCBs. All sensors join as inputs through the USB LabJack device. The sensor boards include input and output headers. For example, data can be acquired when a sensor board is placed in series between transmission load point and load.

2.2 *User Interface*

Generation System

Power generation requires minimal user interaction during operation. The design consists of an ON/OFF switch located on top of the cart for the DC power supply and aside from initial setup of generation sources, the design does not require any attentiveness. However, given the mechanical nature of the two main generation points, the users should be responsive to any unlikely faults. For that reason, the safety enclosure has been constructed out of transparent material. The user also does not need to tend greatly to the feedback control loops, which keep the generator frequencies at approximately 60Hz. However, the user must work with the synchronization circuits, which are simple. Detailed explanation of their use is provided in later sections; ultimately, the user must simply change the state of the switches on the synchronization circuits.

Transmission Lines

Transmission lines are modeled in this system as printed circuit boards. The user interface is comprised of the set of switches on each board. These switches are described in detail in following sections based on their orientations. The user must simply select a transmission line length to simulate by configuring the switches appropriately. The user may also connect loads using the plug in connectors on the PCBs or by using the terminal blocks.

Load Network

The loads included with the grid test facility have been designed using wire color-coding standards for both hot and neutral wires, so that the polarity of loads is obvious to the user (Black = Hot, Green = Neutral).

The binary loads have been designed to be multi-modal and function as up to 255 different loads (per) 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.). An LED light sign will be included as a decorative load and it is necessary for the user to provide signal rectification from the grid to the LEDs for consistent illumination.

Data Acquisition System

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. Images and details of this process are provided in the following sections.

2.3 *Physical Description*

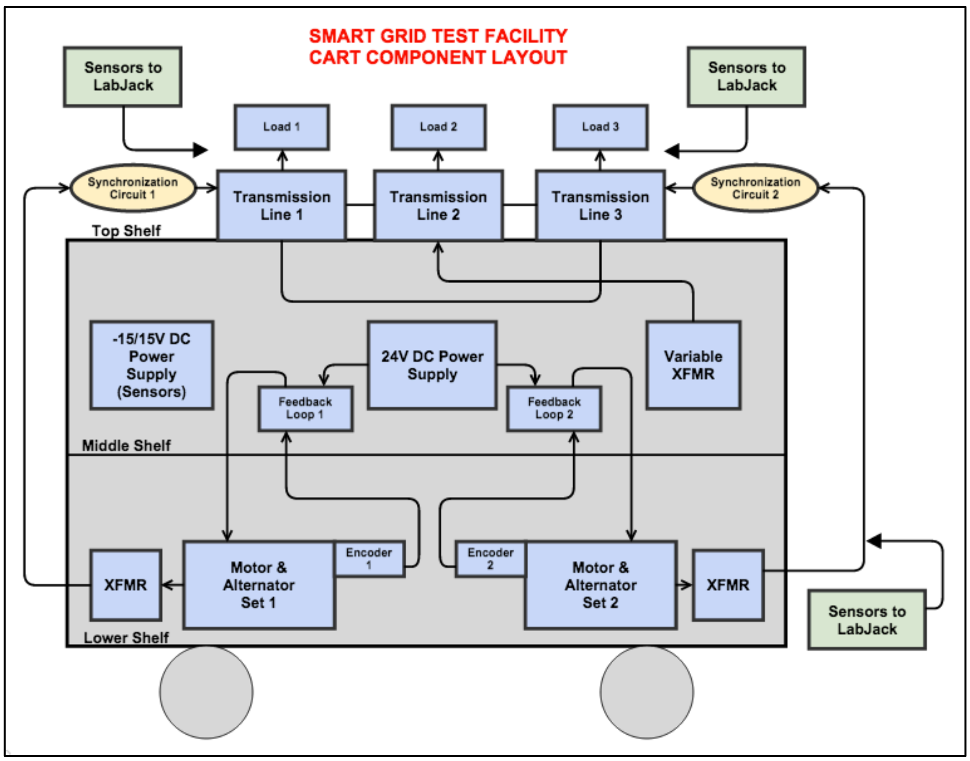


Figure 2.3.1 – Project Hardware Layout Diagram

Figure 2.3.1 illustrates the overall layout of the test facility. The lower shelf includes all high-power components such as the motors, alternators, and transformers, protected with a safety enclosure. The middle shelf includes power supplies and the feedback loops for frequency stability. The top shelf includes the interactive components such as transmission lines and loads where users can alter the grid while power is flowing. The sensors to the LabJack may be placed at various points along the grid to probe voltage and current waveforms at those points.

Photographs of selected individual components are provided below.

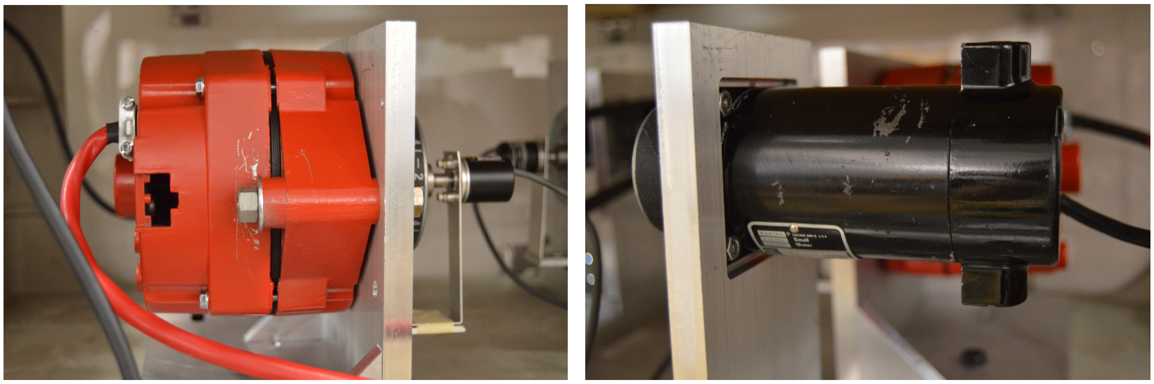


Figure 2.3.2 – Alternator and Encoder (Left), Motor (Right)

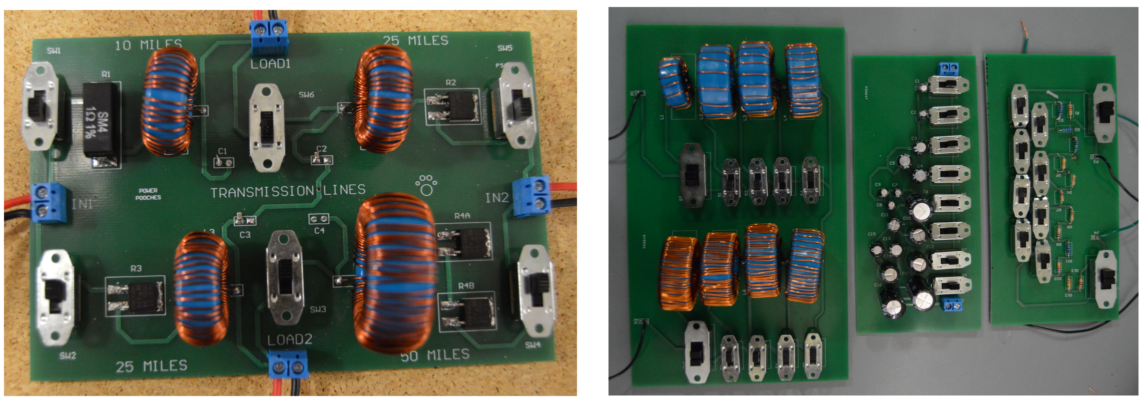


Figure 2.3.3 – Transmission Line PCB (Left), Load PCBs (Right)

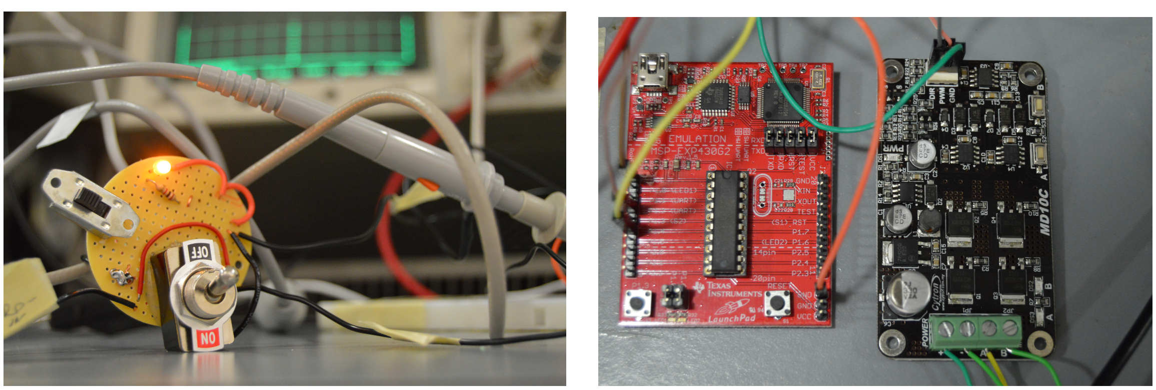


Figure 2.3.4 – Synchronization Circuit (Left), Feedback Components (Right)

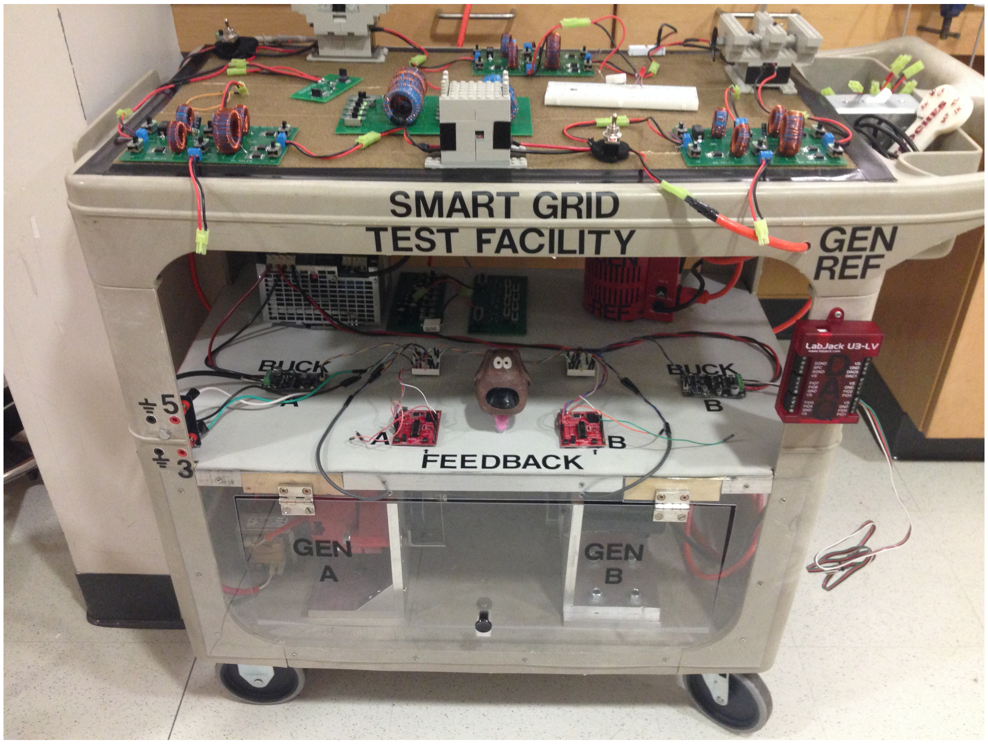


Figure 2.3.5 – Final Product Side View

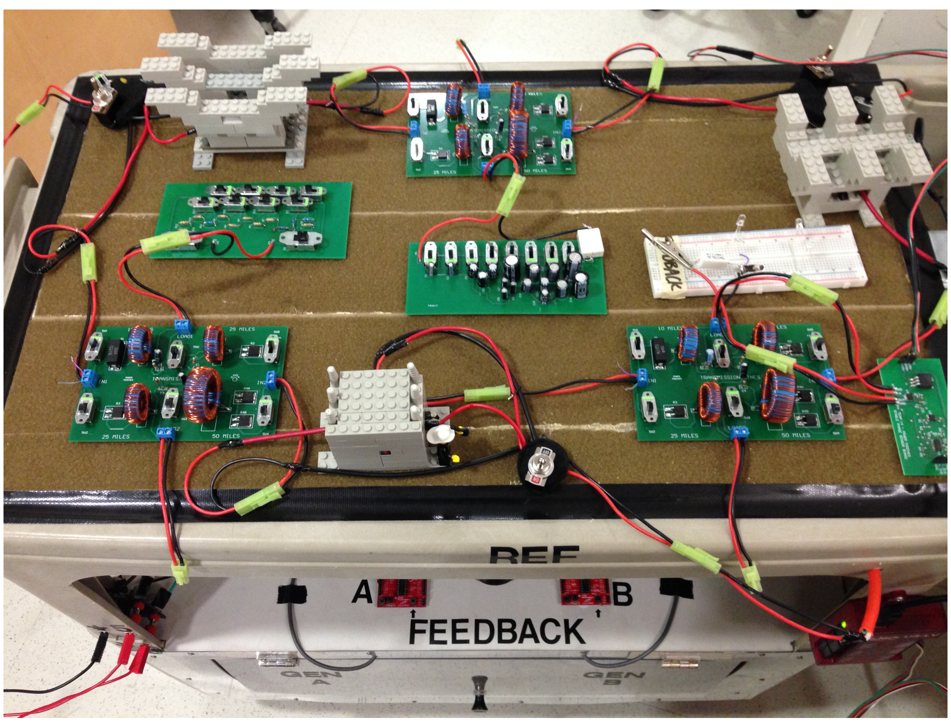


Figure 2.3.6 – Final Product Top View

2.4 *Installation, Setup, & Support*

Sensor Board Setup

To begin, the users must set up the sensor network configuration on the computer they intend to use during testing. The sensor suite is used to monitor voltage and current at various points along the power grid. Setup of the data acquisition system is comprised of three parts: installation of support software, installation of MATLAB programming, and hardware setup.

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

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.

<u>MATLAB:</u>
In order to use MATLAB, first install Microsoft's .NET framework on the computer if not already installed. Next, unzip the runlabjack.zip file, simply move the runlabjack folder to a directory of choice, and set the path to the folder. The folder contains all necessary items for the script's execution. In order to set the path, simply right click on the folder and select 'Add to Path' then 'Selected Folders and Subfolders'.

<u>Hardware:</u>
To set up 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.

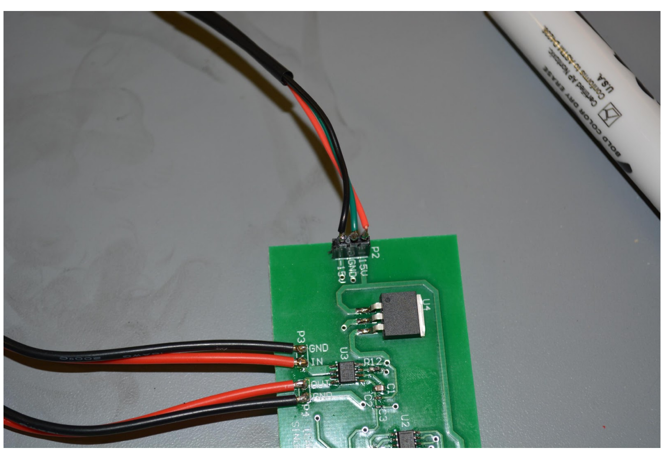


Figure 2.4.1 – Correct Attachment of Power Supply Wiring to PCB

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).

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.

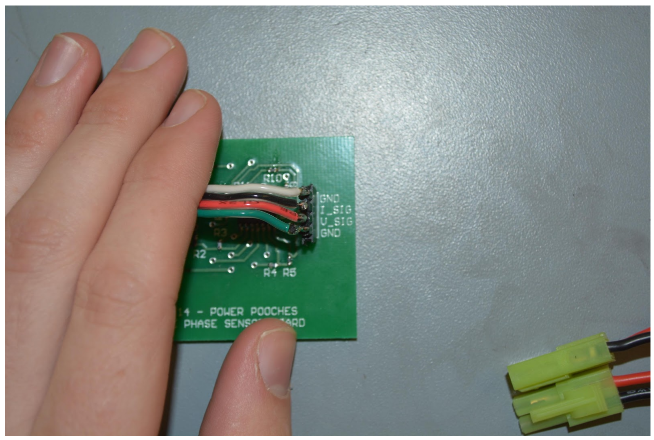


Figure 2.4.2 – Correct Attachment of Signal Wires to PCB

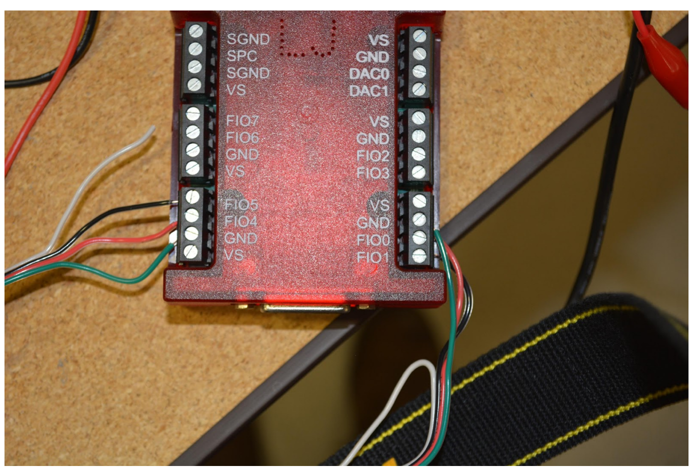


Figure 2.4.3 – Correct Attachment of Signal Wires to LABJACK
Note: Each group of wires utilizes the same terminal block

With those steps, data acquisition is setup. All that is left is to run the MATLAB script.

Safety Measures

This power grid is just that—powerful. Thus, important safety measures must be taken in order to operate this system properly and safely. Several during-operation safety procedures will be described in a later section, but during setup there are a collection of essential tasks that all users must follow.

First, the users must find a suitable environment for this test system: an even-ground surface, a well-ventilated area, and sufficient space for users to move about the cart. Before operating the system, all loose wires, components, or materials must be removed from the cart surfaces. The lowest level of the cart must be closed via the Velcro closures. Users should also follow typical electronics lab safety measures such as avoiding loose sleeves or dangling jewelry. Users should have sufficient space to walk around the entirety of the cart and should have easy access to the various power switches on the cart.

Pre-Operation Checks & Defaults

Certain points within this system should be looked over by the users before operation. Prior to operation, the user must establish sufficient tension on the V-belts in order to prevent slip by sliding the motor brackets down the railings and tightening the bolts/nuts. If for any reason the safety enclosure must be accessed, the main switch must be switched OFF. On the synchronization circuits, all switches should be in the OFF position. The isolated toggle switch connected to the output of the red variable transformer should be in the ON position.

The transmission lines require some basic set up before the power grid can begin full operation. There will be three identical transmission line PCBs in a delta network for the project. Each board has two input headers to connect generators and two output headers to connect loads in parallel with those generators. The user can operate a combination of the six disconnect switches to allow power to flow down a particular path. Since there are four transmission lines on a single board, the user will refer to the line distance labels (in miles) to simulate a certain length of transmission generator-to-generator. The block diagram of these transmission lines is show in the diagram below. The user must select a particular transmission line length for each of the three lines and set the switches accordingly.

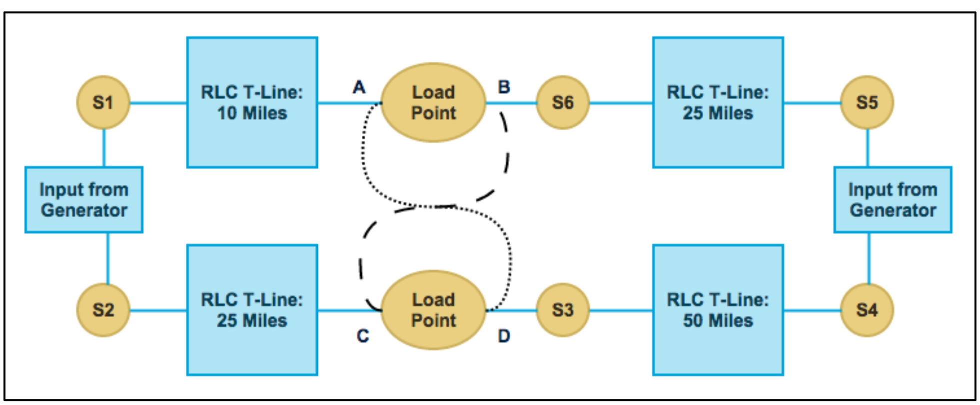


Figure 2.4.4 – Transmission Line PCB Block Diagram

To install all three transmission PCBs on the system, the user should ensure that the power outputs of two different generators are attached to the input terminals on the left and right side of the board. The three transmission boards should be attached to the top of the cart in a triangular configuration. At a minimum, either the top three switches or the bottom three switches should be closed to prepare for the line to be energized. Once the PCB is conducting, additional generators may be phased into the line. A load or voltage/current sensor can be snapped into the top or bottom load points as soon as there is power flow.

Loads do not require any particular amount of setup, but the user must understand their overall functionality. Once the system is in operation, the loads can be used to show how different loads impact power flow in a system. Each of the loads are assembled on printed circuit boards manufactured by Advanced Circuits. The passive components used for the resistive and capacitive boards were taken from stock components. For the inductors, the board components were all hand-wound in order to produce the appropriate values of inductance. The switches for these boards were all purchased can be cheaply replaced from digikey.com or a local electronics store. The part numbers for all components ordered offline can be found in Appendix A. Each of these boards requires no initial maintenance by the user, however the parts are all hand soldered and can be modified at the user's discretion. Each board can be isolated from the rest of the circuit by opening the single-pole double-throw switches located at the terminals of the boards. The luminous loads were not designed to be altered. They are comprised of white LEDs isolated from one another and connected in series on proto-board. This allows the user to light the board with a low voltage (~4.1V) without consuming very much power (I_{LOAD} ~ 40mA), but offers no avenue for repair in the event that the LEDs are burnt out during use.

Power Setup

There are several places along this system that require power supply setup. First, the user should have a DC power supply available; it is recommended to use the typical electronics lab 1A DC power supply for this purpose. As visible by the labels (to be added) on the middle shelf of the cart, 5V, 3.3V, and ground must be supplied into these ports. Next, the on-board power supplies must be powered. There are three cords total that must be plugged into a 120V 60Hz wall socket: two DC power supply cords and a variable transformer cord. These cords are all connected to an orange power strip, so simply plug in the one orange cord into a power outlet.

To begin powering the system, the main switch on the top of the cart must be turned on. This powers the 24V DC power supply, which ultimately powers the motors. Next, the switch corresponding to the sensor suite supply must be turned on. Next, the 3.3V and 5V as provided by the users must be turned on. Finally, the variable transformer switch (which is on its chassis) must be turned on. At this point, the user is ready to begin operation!

3 Operation of the Project

3.1 *Operating Mode 1: Normal Operation*

As described previously, there are a series of steps required to set up the system into normal operation. Before beginning these procedures, the user must follow the steps provided in Section 2.4 regarding software setup, safety procedures, and power setup.

It is important to note that this system will be equipped with a USB drive which includes various useful documents. It is planned that this drive will include a video of the Power Pooches setting up and operating the system—we recommend that users refer to that video while using this test facility—just follow along!

Generation System

After plugging in the main power cord, the switch must be in the ON position for the DC power supply to be operational. When the motors and alternators are operating, the brackets should not show signs of instability. However, the encoder bracket might be a bit loose given its design and that should not be a sign of abnormal operation (it will still restrict the slip of the encoder). When the main switch is powered OFF, the power supply will gradually decrease its output voltage and the components will slowly reach a full de-energization. A diagram of the overall generation layout is shown in the image below.

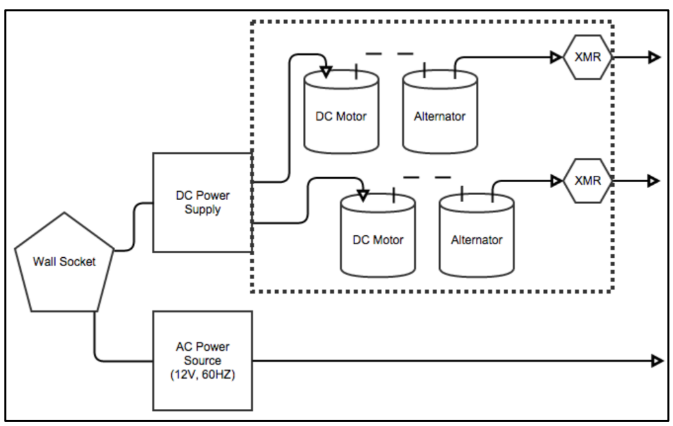


Figure 3.1.1 – Generation System Diagram

Synchronization & Feedback

The first step in operation of this test facility is the synchronization of the three generators. Once this process is complete, the three generators will be in-phase at approximately 60Hz and users can change loads, transmission line lengths, simulate power outages, and more. The following steps provide the exact way in which users should synchronize generators. It is recommended that users practice the art of synchronization on only two of the generators several times to become comfortable with the process before synchronizing all three generators. These steps assume that the setup steps provided in Section 2.4 have all been completed.

1. Synchronize the reference generator (the red variable transformer) to one of the motor/alternator generators:

    a. Turn on the reference generator by flipping its on-chassis switch to ON (if not completed already per Section 2.4)
    b. Choose either Generator A or B to synchronize first; for the sake of these instructions, we will choose Generator A
    c. Power Generator A by pressing its corresponding MSP430 RESET button (as labeled) on the middle shelf of the cart
        i. Generator A will begin generating power
    d. Locate Generator A's synchronization circuit via the labels, and turn the sliding switch (NOT the larger toggle switch) to the ON position
        i. The LED on the synchronization circuit will illuminate
    e. When the LED is completely off (or dimmest), close the toggle switch
        i. Note: This is made even easier with an oscilloscope with two probes—connect a probe to both inputs to the synchronization circuit and look at the waveforms to help synchronize. Users will need to close the switch when the waveforms align. This method also is more visually demonstrative of the synchronization process.
        ii. This synchronizes Generator A to the reference generator
2. Synchronize Generator B to the reference generator:
    a. Follow steps 1.a through 1.e to synchronize the second generator exactly as the first one had been done
3. It is recommended to confirm that the waveforms are synchronized at 60 Hz via an oscilloscope or frequency sensor

Once these steps are complete, all three generators are synchronized, and the grid (the transmission lines and any added loads) are being powered by all three generators simultaneously. These steps must be followed exactly as described every time the user wishes to start up this system!

The frequency feedback system is inherent to this project and does not require the user to perform any additional setup or work in order to make it functional. Refer to Section 4 for detailed information on the functionality of the feedback control loop that is implemented on both motor/alternator generators.

Please note that the black boxes with two buttons on each side of the feedback loops are used to manually change the frequency of the corresponding alternator. 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).

At this point, the power grid is up and running. Users can change loads, transmission line lengths, simulate generator or line outages, and monitor power flow all while this is up and running. These changeable elements are described below.

Transmission Lines

1) Prepare for Switching
Under normal operation, the three transmission line PCBs should begin already set up in the aforementioned delta configuration. They will essentially be joined in a triangular loop before any generator in the grid is up and running. This configuration allows power to flow to all three PCBs immediately when the first generator is closed in. This strategy for synchronization is implemented in electric utility networks. This way, if a generator is taken off of the grid (a potential outage), the remaining generators will output higher current to compensate for the loss in power input. Loads at any transmission line load point will continue to be energized. In such a scenario, there will be no circumstance where there is a "blackout".

2) Designate Path of Power Flow
The six switches on each transmission line determine where electricity will flow. If all switches are open, the transmission lines will see no current. They will act as an open circuit. As a consequence, no load that is expected to operate should be connected onto an un-energized transmission line.
Switch Position Indicator:
-When the switch is flipped into the upward position, the switch is closed.
-When the switch is flipped into the downward position, the switch is open.

Before the network is powered, please follow one of the steps below to power all transmission channels on the power grid. For each PCB, set up one of the following switch configurations.
1) Close only the 3 switches on the top row (S1, S6, S5 closed)
2) Close only the 3 switches on the bottom row (S2, S3, S4 closed)
3) Close all 6 switches on the board (current split at input junction)

After the network is powered by at least one generator, switches can be safely operated in all possible combinations. Here are potential factors to consider when switching under load:

A) If S1 and S2 are open, there will **NOT** be bidirectional power flow to load
B) If S4 and S5 are open, there will **NOT** be bidirectional power flow to load
C) If S3 and S6 are open, there will **NOT** be bidirectional power flow to load
D) If S1 and S2 are closed, LOAD1 and LOAD2 will be powered by generator input IN1
E) If S3, S4, S5, and S6 are closed, LOAD1 and LOAD2 will be powered by generator input IN2.

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 3.1.2 –Transmission Line Switch Configurations

3) Diagonal Path of Power Flow
-A load connected diagonally from Load Point **A** to Load Point **D** will be energized if **S1** is closed
-A load connected diagonally from Load Point **C** to Load Point **B** will be energized if **S2** is closed
-The S1, S3, S4 path will be powered if a **jumper** wire is placed from Load Point **A** to Load Point **C**
-The S2, S6, S5 path will be powered if a **jumper** wire is placed from Load Point **A** to Load Point **C**

Load Network

Under normal operation, the loads will consume power from the grid and draw/supply real and reactive power from the grid following Ohm's Law. The values for the components were calculated recognizing that the impedance that results from connecting them into the grid will affect a phase shift of the current running through them. They were selected from a range of values that could ultimately be used to balance the power flow through the grid by connecting them in various configurations. Under normal operating conditions, these power values should match the phase shifts predicted in a Microsoft Excel calculator that is included with this project.

Data Acquisition System

Once the necessary installation steps are completed for data acquisition, normal operation consists of typing in the command 'runlabjack' into MATLAB. This command will initiate the script, and will return a prompt for a 'configuration decimal' number.

The configuration decimal is simply the sum of the analog inputs used if we were to assign powers of two to them (i.e. if FIO0 and FIO1, FIO4 and FIO5 are used for a total of two sensors, the configuration decimal will be 1 + 2 +16 + 32 = 51). To continue operation, simply type in this decimal number. However, make sure you are typing in the correct value for your configuration, as an incorrect value will cause abnormal results in the waveform figures and faulty data.

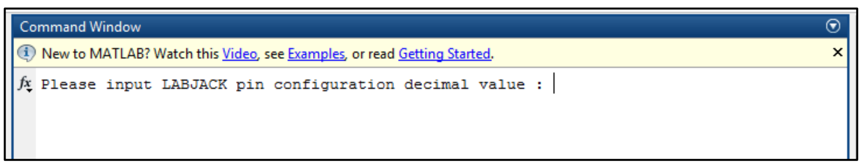


Figure 3.1.3 – Configuration Prompt

Lastly, you will be prompted for how many periods the LABJACK should analyze. This is simply a means to determine how much or little data a user wants, and will optimally be used to look for oscillatory abnormalities amongst other things. Thus, if you want to see two periods of the waveforms, simply type in the number 2. It is recommended to use 5 or 6.

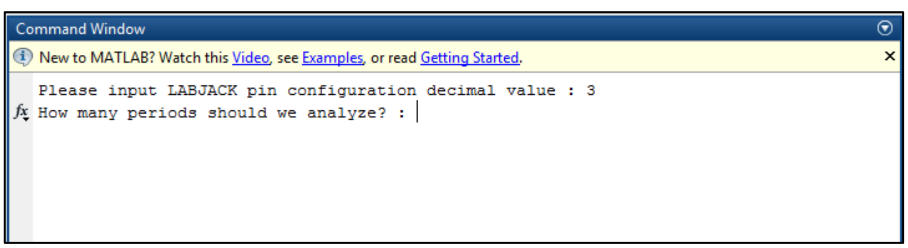


Figure 3.1.4 – Period Number Prompt

Once this is done, for a single sensor you will get the following output in the command window, as well as a similar waveform plot. For this example, we are only using one sensor (FIO0 and FIO1) and wish to analyze 4 waveforms. Therefore the inputs are 3 and 4 respectively.

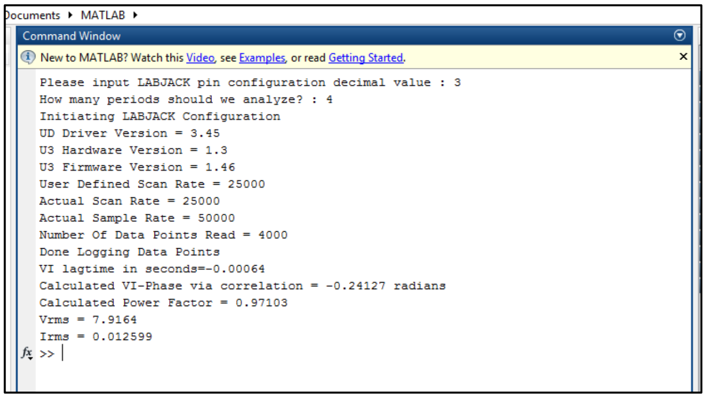


Figure 3.1.5 – MATLAB Command Window Output

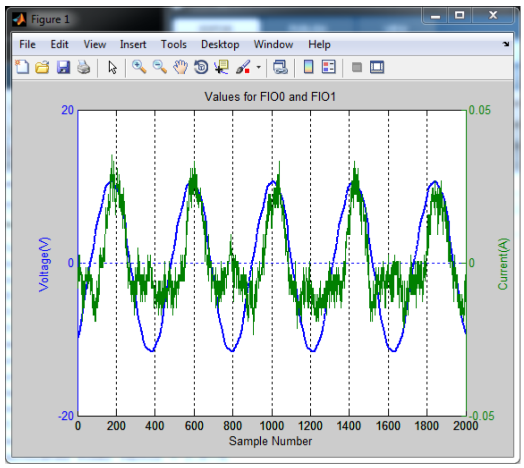


Figure 3.1.6 – MATLAB Figure Containing V-I Waveforms of an LED-Based Circuit

Note: The current waveform will always contain noise when analyzing on the order of tens of milliAmperes

As with all MATLAB programs, if the program takes a long time to complete or appears stuck, simply use ctrl-c to end the program and start again. Future features of the data acquisition aspect will include a calibration system for the PCB boards, since there is still variations between the optimal zero point and actual zero point of the boards.

De-Energizing Process

The ideal way to turn off this entire system is to close the large switch on the top of the cart (corresponding to the 24V DC power supply), which will turn off both motor/ alternator generators. Next, turn off the third supply, the red variable transformer. This will de-energize the power lines and loads completely.

3.2 *Operating Mode 2: Abnormal Operations*

Abnormal operations of this project may occur for a variety of reasons: accidental short circuits, poor connections, failure to follow setup instructions, and more. However, the creators of this system have included mechanisms to maximize robustness in hopes of avoiding most abnormal operation situations. By sub-system, abnormal operation is described in the following sections.

Generation System

The motor/ alternator generators may behave in unexpected manners if the exact synchronization instructions are not followed. However, such unexpected or abnormal behaviors have been tested repeatedly and prove not to cause irreversible damage to the system. For example, if the generators are turned on (by pressing the RESET button on the MSP430), and the corresponding synchronization circuit's toggle switch is ON, then the user has accidentally shorted two out-of phase generators. This may cause backfeeding into one of the two generators or unexpectedly high currents (typically under 2A). In this situation, users should simply turn off the large switch on the top of the cart to de-energize the motor, then immediately turn off the variable transformer. There are many situations like this in which synchronization may fail if generators are not synchronized properly. In the process of constructing this project, the creators have done this many times—simply turn off the power and all will be recovered. The components in this system are rated at or over 2A, so while although some components may heat up, they will be in safe conditions even if synchronization fails. It is much easier to see this failure with an oscilloscope, and so it is recommended that users synchronize with an oscilloscope while first learning to synchronize.

Transmission Lines

Under abnormal operations, the three transmission lines are designed to be safe and easy to switch. Consider the scenario when three generators are up and running. The user can simulate a generator outage by removing one generator from the grid. Generators are typically cut off the actual grid when there is either a planned or unplanned outage. A planned outage is often performed when there is scheduled maintenance. Generator checks and work on high-voltage lines are common practice. In the case of an unscheduled outage, storm conditions or overvoltage/overcurrent faults may trip and lockout (isolate) a generator. This is to protect the expensive equipment when there is a permanent fault.

As described previously, the delta transmission line network is well-protected. A switch that is accidentally turned on will just provide a new path for current to flow. Along those lines, a switch that is accidentally turned off can only cause an open circuit. Loads that are terminated at LOAD1 or LOAD2 are designed to resist damaging current levels. The user's manual details the proper precautions to take while synchronizing generators. Thus, if the system voltage is momentarily doubled, the current will not burn out any resistors, inductors, or capacitors on the PCB. The boards are designed to handle a maximum continuous current of 2A.

Load Network

Under abnormal operation, these resistive and inductive loads should act as open circuits and the capacitive load should act as a short circuit. These conditions assume that a component on one of the boards gets burnt out. If this is the case, then the associated parts should be replaced.

Data Acquisition System

There are three anticipated forms of abnormalities for operation of the data acquisition system: data saturation, hardware, and general errors.

First, if the characteristics of the point tested exceeds either the magnitudes of 12 volts or 2.1 amps, the system will behave abnormally. The output figure from MATLAB will indicate this by showing saturation and 'chopping off' the peaks of the waveforms. Since the other data calculations are also the result of saturation, they will also be incorrect. It is not anticipated that these points should be reached, however, given our design of the provided power sources, loads, and transmission lines.

The second form of abnormalities stems from incorrect setup of the hardware connections, and will result in either unusual numbers such as the negative power factor discussed earlier and/or unusually large or small waveforms, and can simply be fixed by following the recommended conventions seen in the setup section.

Lastly, if there are any other abnormalities associated with running the code, MATLAB should throw a general error your way to indicate what the abnormality is. For example, running the code without the LABJACK plugged in results in an error message saying there is no LABJACK detected.

3.3 *Safety Issues*

During operation, there are a collection of safety-related mechanisms that should be understood by the user. As described previously, the generators may push out unexpectedly high currents if the synchronization process is not followed correctly, or if accidental short circuits occur. All power flow wires in this grid are insulated to protect the user, but components may become hot and user should not touch them if it is expected that the parts have heated.

The generation design has several features that specifically address the safety concerns of the team and faculty. Any issues that might arise from the RPM of our belt-driven design have been isolated within the safety enclosure. Also, any exposure to high voltage (120V) has been isolated within the safety enclosure as well. All power cables used are insulated and the housing for the switch has been grounded for additional protection. However, users should be alert at all times. The enclosure should be entered only when the main switch is OFF and the components have halted operation. As with all other electrical setups, liquids are not permitted around or near the cart.

The primary safety concern for the transmission lines is overcurrent. Each RLC element has specifications to withstand a rated current of 2A. The project has a number of components that have this 2A specification. Since, the transmission lines will either be unloaded or lightly loaded (large parallel resistances), the expected ceiling for current is closer to 1A. This high-wattage safety precaution is designed to protect against I^2R, which is main equation used to calculate power dissipation. Power is dissipated as heat. When resistors overheat, they will burn through and create a permanent open circuit that will impede the flow of current. In an emergency overcurrent situation, it is optimal to block current flow across the transmission lines in a timely manner. The six switches on the transmission line board are not designed to be load disconnect switches. However, if the board is hot and the current sensor measures an input/load current greater than 2A, opening four switches can immediately guarantee fault isolation. Assuming switches S1 and S2 are open, open either S3 & S6 or S4 & S5. This action will preserve the transmission line and loads downstream of it.

Concerning loads, it is recommended that the isolation switches be held open while the generators for the grid are in start-up. If the loads are connected fully while this is happening they can be damaged by over-current conditions presented by the generation system being out of phase between generators. Additionally, this is important because the loads offer a path to ground. This additional current path will interfere with the synchronization process used between the generators.

Regarding data acquisition, due to the nature of the board, it is recommended users make sure that the power supply connections are correct before applying a power source. If the polarities are incorrect, users will end up destroying the op-amps on the board and ruining it.

4 Technical Background

Generation System

The generation design makes use of several components working in harmony with each other. The 24V, 2.6A, 1/18HP permanent magnet DC motors (Bodine 24A4BEPM) are powered by a two-output DC power supply (Siemens SITOP 6EP1336-3BA00). The power supply provides the motors with a max nominal voltage of 24VDC at a max 20A, and is powered by the 120V, 60Hz output of an ordinary wall outlet. The DC motors are then able to 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 12V peak-to-peak, roughly $8V_{RMS}$.

Synchronization

The method used to synchronize generators is often called the "synch bulb" method. Although the method has been adapted for the specific needs of this system, the overall concept is similar. The objective of synchronization is to make two 60Hz sine waves that are out of phase made in phase. By design, the reference generator (the red variable transformer) has a voltage magnitude nearly equivalent to the voltage magnitude output of the alternators (after the step-down transformers). Thus, the waveforms have nearly equivalent magnitude and frequency, but are out of phase. To synchronize them, this system uses the layout shown in the simplified diagram below.

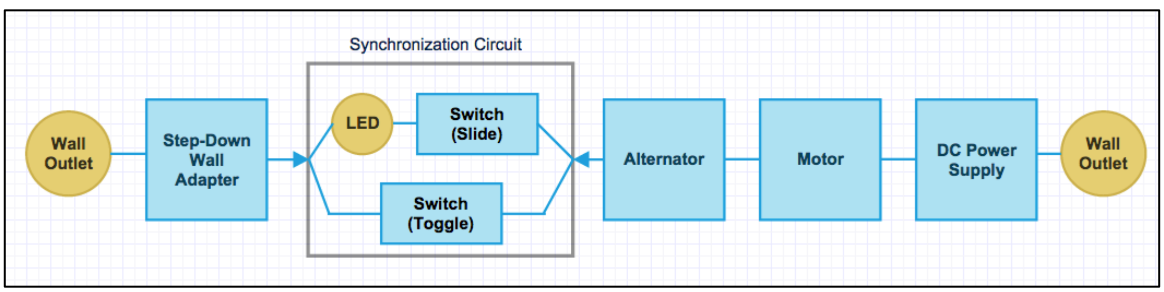


Figure 4.1 – Synchronization Circuit Layout

The system begins by turning on the reference generator, which is the step-down wall adapter (variable transformer). When this is done, both the sliding switch and the toggle switch are in the OFF position. Next, the motor/ alternator generator is energized. Now, we have two generators that are open-circuited. Next, the sliding switch is closed. The LED experiences the combination of the out-of-phase waveforms from the wall adapter and the alternator. It illuminates accordingly; at its brightest, it is most powered, and the generators are completely out of phase. At its dimmest, the generators are in phase. When this occurs, the toggle switch is closed, shorting the generators together exactly as they are in phase. This results in one final 60Hz waveform across the circuit. Although this diagram is a simplified version of the implemented synchronization setup, it accurately demonstrates the physical events that occur in order to make the generators synchronize.

Feedback Control

Feedback is a vital element of this entire project. 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 motor/ alternator setups. The diagram below shows the basic layout of the system.

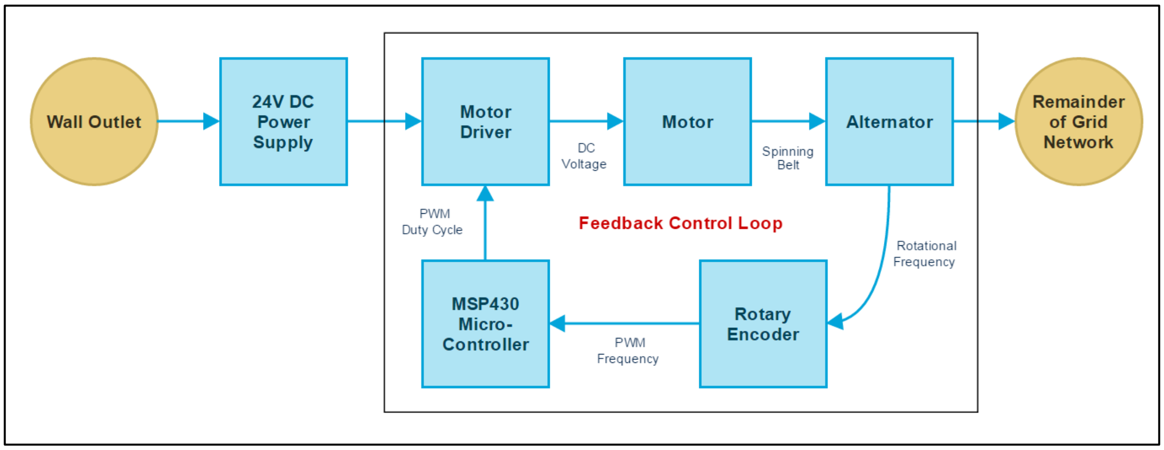


Figure 4.2 – Feedback Control Loop Layout

The motor driver board has two inputs: a PWM signal and a DC voltage. The DC voltage is supplied by the 24V DC power supply. The PWM signal is generated by the MSP430. Depending on the duty cycle of the PWM signal, the motor driver board outputs a higher or lower DC voltage relative to the DC input voltage. For example, as duty cycle of the PWM decreases, the output voltage of the motor driver decreases.

The voltage supplied to the motor determines its speed, which then determines the output frequency of the alternator. The output frequency of the alternator is exactly what we aim to keep constant at 60Hz. Thus, the motor driver must provide a variable input voltage to the motor based on the alternator's frequency.

To accomplish this, 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 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 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. The code for the MSP is well-commented and will be made available on the USB drive provided with this system.

Transmission Lines

The PCBs were designed on Altium Designer and ordered online from Advanced Circuits. The circuit board allows for ease-of-soldering and has silkscreen labels for its components. Each board has four snap-in input/output male headers. Header terminations link transmission to generation, sensors, and loads with one click. The power resistors on the lines have heat sinks to maximize performance under heavy load conditions. The inductors on the circuit were hand-wound on toroidal cores to obtain a precise amount of inductance for 10, 25, and 50 mile lines. The transmission module meets the customer’s requirements to model an unscaled, proportional version of lumped-element HV transmission cables. The 10/25/25/50 mile setup on each board allows the user to simulate four different line distances (35/50/60/75 miles). All data can be backed up by real and reactive power calculations. The project models a typical 115kV aluminum cable type with a diameter of 750 MCM. The line resistance is a function of the resistivity of aluminum, the line length, and the cross-sectional area of the conductor. Similarly, the inductive and capacitive reactance includes the analysis of mutual inductance and transmission tower structure. The final RLC values were determined per unit length. See the table below for the standard impedances per mile.

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

Figure 4.3 –Transmission Line Characteristics per Unit Length

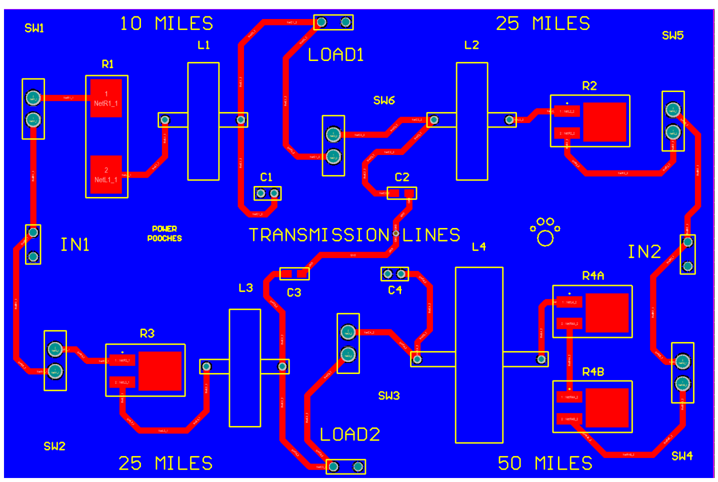


Figure 4.4 –Altium Transmission Line PCB Layout

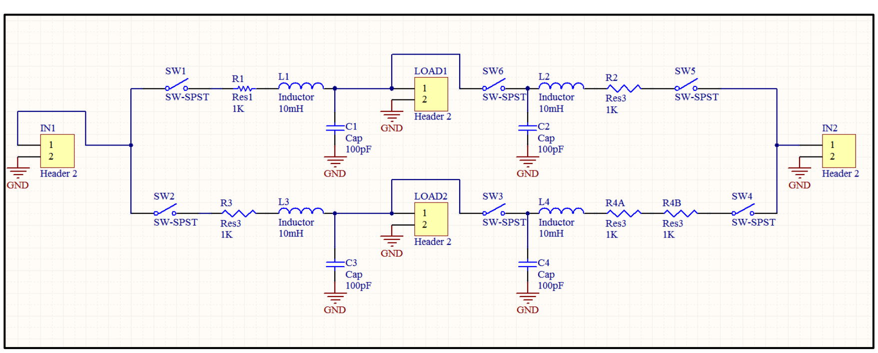


Figure 4.5 – Altium Transmission Line PCB Schematic

Load Network

Load Power Dissipation

The loads included with the power grid test facility were developed with the expectation that they would be operating as complex impedances under alternating current conditions. This representation is motivated by the configuration of the grid system as shown in the following circuit diagram.

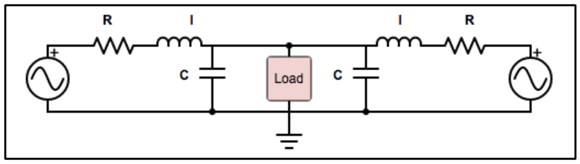


Figure 4.6 –In this figure the load is connected at a point between the two generation points and transmission lines as it would be on a real power grid. This configuration causes the load to be seen as a parallel path to ground.

The load in the above diagram is seen as a parallel path to ground so, in order to analyze the power that is consumes from the two generators, one must make the following two assumptions: both Generators are effectively acting as parallel current sources at the same potential, and the capacitive element of each transmission line is in parallel with the load. Following from this assumption, then we can transform the circuit in Figure 4.6 to the circuit in Figure 4.7.

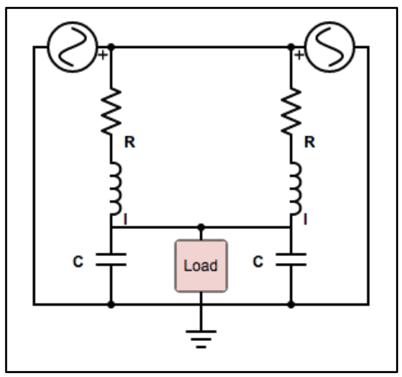


Figure 4.7 –This configuration assumes phase locked generators supplying equal power through a series of different loads to ground.

By using this approach, the user can study the phase plot of the current passing through the load to determine the power flow characteristics of any load inserted into the grid. Some general information as well as a calculator have been included in the form of an Excel spreadsheet that can be used to perform the phase calculations to determine the expected phase angle of the current passed by any given load that is inserted into the transmission network. By virtue of knowing this information, it is possible to use complex algebra to determine the power dissipated by given load.

Inductor Winding

The process of winding inductors for use as loads is significantly more accurate than using off-the-shelf parts and it provides the user better control over which inductor values they choose to include as loads. In this product the transmission network and one of the binary loads each include wound inductors.

The process for manufacturing these inductors involved three major steps that will be outline in the following example calculation:

Step 1: Parameter Selection

To design an inductor one must be mindful of the two factors affecting its operation: $I_{LOAD, MAX}$ and L_{MAX}. In this product the values for the parameters were driven both by the short circuit expected on the grid and the desired phase behavior as described in the previous section.

For this example let, $I_{LOAD, MAX} = 2A$ and $L_{MAX} = 192mH$.

Step 2: Wire Selection

American Wire Gauge (AWG) standards tables include the allowable current that can be passed through a wire of a given gauge. Since wires gauge is a measure of diameter, wire gauge is the primary limiting factor in core selection. Thus, it is important to select a wire gauge that is correct for the application.

The following table from Powerstream.com shows the values for commonly used wire gauges.

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring
OOOO	0.46	11.684	0.049	0.16072	380
OOO	0.4096	10.40384	0.0618	0.202704	328
OO	0.3648	9.26592	0.0779	0.255512	283
0	0.3249	8.25246	0.0983	0.322424	245
1	0.2893	7.34822	0.1239	0.406392	211
2	0.2576	6.54304	0.1563	0.512664	181
3	0.2294	5.82676	0.197	0.64616	158
4	0.2043	5.18922	0.2485	0.81508	135
5	0.1819	4.62026	0.3133	1.027624	118
6	0.162	4.1148	0.3951	1.295928	101
7	0.1443	3.66522	0.4982	1.634096	89
8	0.1285	3.2639	0.6282	2.060496	73
9	0.1144	2.90576	0.7921	2.598088	64
10	0.1019	2.58826	0.9989	3.276392	55
11	0.0907	2.30378	1.26	4.1328	47
12	0.0808	2.05232	1.588	5.20864	41
13	0.072	1.8288	2.003	6.56984	35
14	0.0641	1.62814	2.525	8.282	32
15	0.0571	1.45034	3.184	10.44352	28
16	0.0508	1.29032	4.016	13.17248	22
17	0.0453	1.15062	5.064	16.60992	19
18	0.0403	1.02362	6.385	20.9428	16
19	0.0359	0.91186	8.051	26.40728	14
20	0.032	0.8128	10.15	33.292	11
21	0.0285	0.7239	12.8	41.984	9
22	0.0254	0.64516	16.14	52.9392	7

Figure 4.8 –AWG standard parameters for gauges OOOO-22

For the purposes of the power grid test facility the #18 gauge wire provides a significant safety factor with a $I_{MAX, CHASSIS} = 16A$ so we will select that value. Note the conductor diameter: D18 = 1.024mm. (This wire must be insulated.)

Step 3: Choosing a core of the appropriate size and permeability

Once the maximal operation conditions are identified, it is necessary to select a core with adequate permeability and internal diameter to support to enable the user to wind an inductor with the maximal inductance. The following equations are principal in making this decision.

(1) $$N_{max} = C_{Inner}/D_{wire}$$

(2) $$N_{req} = \sqrt{(2\pi L_{max} R_i)/(A\mu_I \mu_o)}$$

Setting equation equations (1) and (2) equal to one another, we develop the following decision rule for selecting appropriate cores.

(3) $$N_{max} > N_{req}$$

Performing iterative calculations with the available core material parameters and geometries we found that a [36x23x15] T38 type core would be adequate for this application. Selecting this core value guarantees that the highest inductance value can be wound, so it was advantageous to approach the problem from this direction because this core will suffice for any smaller inductance.

Step 4: Winding the Inductor

Winding an inductor simply involves making the necessary number of loops around the toroid core and winding them as tightly as possible to the core to ensure accurate values. Once all windings are complete, the endpoints of the winding wire must be exposed to provide leads for the device.

Data Acquisition System

For development, data acquisition was essentially separated into distinct hardware and software components:

HARDWARE

For the hardware component, all that is essentially done is the voltage reference of the point being tested and the output of the current sensor are mathematically manipulated, using summing and inverting op-amp circuits, to the form of V_{OUT} = A * Vin + B, where A and B are values that maximize resolution within the 0V to 2.4V range of the LABJACK. In effect, that means for a 12V magnitude sine wave A = 1/10 and B = 1.2V.

Why 12V magnitude? As it turns out, the TL08x series op-amp circuits chosen to minimize parasitic effects on the grid has an effective common mode input range of -12V to 15V with good linearity. Thus, in order to provide for the maximum amount of available power without possibly jeopardizing the components or relative accuracy of the sensor board, 12V maximum voltage reference magnitude is the design constraint used.

In addition to the voltage reference, a mathematical operation also needed to be performed on the output of the current sensor to shift the zero current output of 2.5V down to 1.2V or the point of maximum resolution for the DAQ. After much discussion, it was also determined 2A should be the theoretical maximum current going through the grid. However, in order to make creating the hardware easier a maximum value of around 2.1A was assumed. This made the output range of the ACS712 sensor to be 2.1V to 2.9V, which corresponds to -2.1A to 2.1A respectfully. However, current sensors are notoriously noisy at low currents due to environmental conditions such as external magnetic fields among other things. Therefore, to improve the signal to noise ratio considerably, a 0.33uF capacitor was attached to the filter pin and a passive low pass filter followed by a buffer was also utilized as the first stage for further filtering.

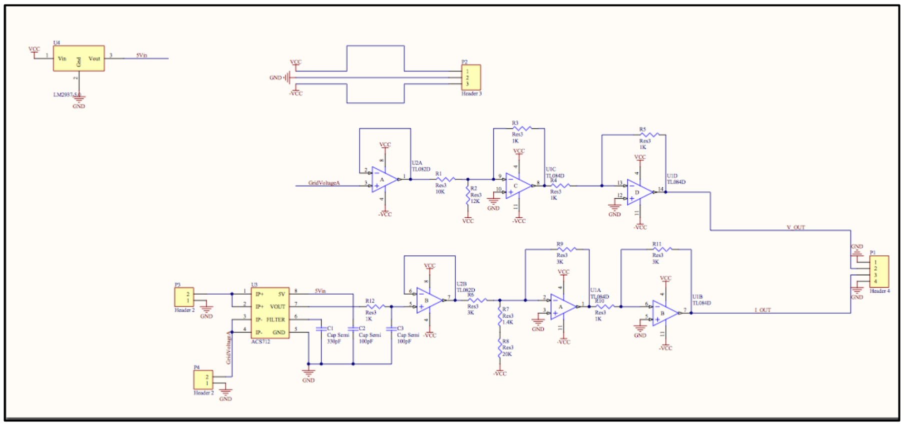


Figure 4.9 – Schematic Representation of Sensor PCB

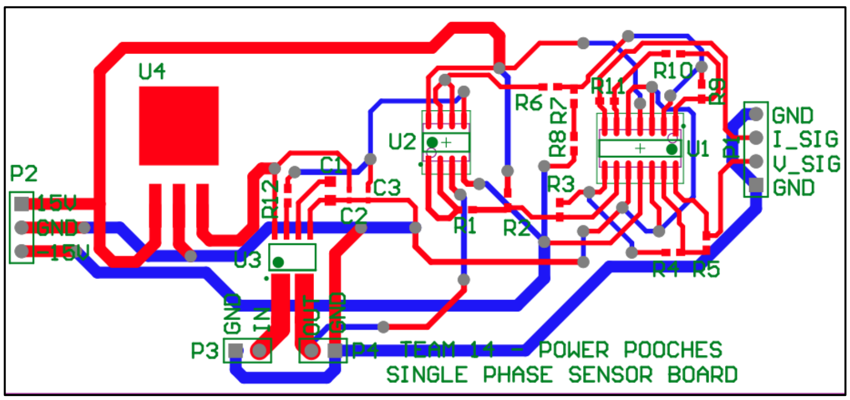


Figure 4.10 – Layout of Sensor PCB

MATLAB

Simply put, MATLAB was chosen as the environment of choice since it is an industry standard in engineering and commonly known amongst students. As stated before, this in turn means users can modify our code or create unique code to suit their own goals and tastes. For the purposes of our project, this was measuring characteristics from the grid and plotting waveforms. However, other possibilities include implementation of additional devices that can be controlled via MATLAB including controllers and relay boards amongst other active devices. Therefore, students may also use the system to develop Smart Grid techniques and/or smaller scale alternative energy sources.

SCRIPT / runlabjack.m

The main MATLAB script runlabjack.m is composed of three key functions: configurelabjack.m , GetData.m , and AnalyzeData.m. As the function names would suggest, they configure the LABJACK, collects the data, and processes the data respectively in addition to displaying the RMS values, phase between voltage and current, and power factor.

5 Cost Breakdown

Componential pricing was pulled from our vendors' sites on April 12th, 2015 and is subject to change. In various cases auction-based sites were used due to budgetary limitations. However, similar components can be found at similar pricing to be made use of. The "additional materials" for generation cost includes costs for wiring, power cables/switch, shaft sleeve stock material, plywood shelving, hinges/knobs, nuts/bolts/rivets, etc. that contributed to the generation system costs. The table below demonstrates the cost of reconstructing this test facility, assuming similarly priced components are located.

It is important to note that in the making of this first version of the product, our funding sources derived from ECE, the Kilachand Honors College, and the creators of the project. Several essential parts, such as the cart itself, were provided to the team and did not need to be purchased in order to create the product.

PROJECT COST BREAKDOWN				
GENERATION				
Item	QTY.	Description	Unit Price	Item Price
1	2	DC Motor	$79.96	$159.92
2	2	Wind Turbine Alternator	$134.99	$269.98
3	2	Encoder	$29.95	$59.90
4	1	AC/AC Power Adapter	$64.99	$64.99
5	2	Transformers	$23.01	$46.02
6	1	Aluminum	$137.76	$137.76
7	2	Belt and Pulleys Set	$33.95	$67.90
8	1	24V DC Power Supply	$75.00	$75.00
9	1	Polycarbonate	$40.64	$40.64
10	1	Additional Materials	$120.00	$120.00
			Total Price:	$1,042.11
SYNCHRONIZATION & FEEDBACK				
Item	QTY.	Description	Unit Price	Item Price
1	3	Switch & Circuit Board	$10.25	$30.75
2	2	Motor Driver Board	$24.65	$49.30
3	1	Connectors & Wire (Project-Wide)	$67.04	$67.04
			Total Price: $	$147.09
TRANSMISSION				
Item	QTY.	Description	Unit Price	Item Price
1	1	Resistors & Capacitors	$86.59	$86.59
2	1	Inductor Cores	$49.09	$49.09
3	3	Printed Circuit Board	$33.00	$99.00
			Total Price:	$234.68
SENSING				
Item	QTY.	Description	Unit Price	Item Price
1	1	LABJACK U3-LV DAQ	$108.00	$108.00
2	1	15V/-15V AC-DC convertor	$66.67	$66.67
3	8	Sensor Board PCBs	$4.13	$33.00
4	8	Components for Sensor PCBs	$8.00	$64.00
			Total Price:	$271.67
LOADS				
Item	QTY.	Description	Unit Price	Item Price
1	8	Ferrite Core (T38)	$1.53	$12.24
2	26	Single Pole Single Throw Switch	$0.83	$21.58
3	6	Single Pole Double Throw Switch	$1.05	$6.30
4	40	White LED	$0.30	$12.00
5	2	Printed Circuit Board	$33.00	$66.00
			Total Price:	$118.12
OTHER				
Item	QTY.	Description	Unit Price	Item Price
1	1	Cart	$219.99	$219.99
2	1	Velcro Tape	$20.00	$20.00
			Total Price: $	$239.99
			TOTAL COST: $	$1,906.57

6 Appendices

6.1 *Appendix A - Specifications*

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	

Note: Many of these "Typ" or typical values depend directly on the user's selected orientation of the transmission lines, loads, and generators and may change throughout operation. Refer to Appendix C for further specifications of important components.

6.2 *Appendix B – Team Information*

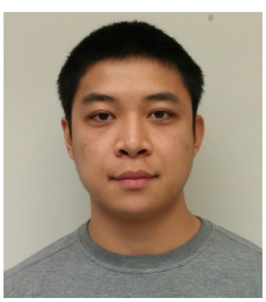
Suleyman Kahyaoglu
kahyaogs@bu.edu

I am a senior in Electrical Engineering pursuing a concentration in Technology Innovation. Given my interest in a career in the construction sector, I am very excited to contribute to this project and learn more about the power generation/distribution in an electrical grid. I will be attending Columbia University for a MSRED in the Graduate School of Architecture, Planning and Preservation. I hope to establish a career in Real Estate Developer.

Jeremy Kramer
jlkramer@bu.edu

I am an electrical engineer from Santa Monica, California and my interests lie in green technology and energy technology. I am excited to be working on this project because it is providing me with valuable experience in the design process of a complicated electrical system with multiple interdependent parts.

Tim (Edward) Leung
etl@bu.edu



I am a senior Electrical Engineering major with a concentration in Energy Technologies. With my background in the power industry, I am enamored by the opportunity to engineer a testable model of the electrical grid. Upon graduation I'll be working at Braintree Electric Light Department in the electrical engineering department.

Marissa Petersile
misspete@bu.edu

I am a senior studying Electrical Engineering with a concentration in Energy Technologies. I'm excited about this project because I'm passionate about clean energy systems and I think this educational tool can be a great way for students to learn about how clean energy integrates into the power grid. After graduation I'll be working at National Grid in the Transmission Planning department.

Christopher Powers
chrisp@bu.edu

I am a senior studying Electrical Engineering with an emphasis on Microelectronic and Photonic devices. I'm thrilled to be a member of the team, since I understand the need to build and optimize a secure, robust electrical infrastructure for renewable energy systems. After graduation, I am reporting to Keesler AFB, Mississippi to begin training as a Cyberspace Operations Officer (17D) in the United States Air Force.

6.3 *Appendix C – Specification Sheets & Component Information*

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

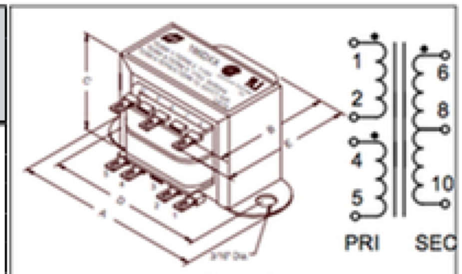


Figure 6D

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

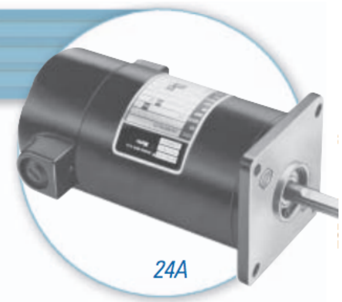
- For connection diagram 074 10101 see page 66
- Performance ratings of 130 V models based on use with filtered controls
- Flange mount or base mount

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

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	Model Number[1] 24 V. Winding Acc'y. Shaft	Model Number[1] 24 V. Winding No Acc'y. Shaft	Model Number[1] 130 V. Winding Base No Acc'y. Shaft	Model Number[1] 130 V. Winding Flange Acc'y.	Model Number[1] 130 V. Winding Flange No Acc'y.
2500	8	1.2	1/50	8.3	6.1	5.7	6.7	.003	25	3.31	2.0	24AOBEPM	N4440	N0040	–	–	–
2500	8	.22	1/50	42	31	176	220	.003	25	3.31	2.0	24AOBEPM	–	–	–	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)

E6A2 — omron — E6A2

Specifications

Part number		E6A2-CS3E	E6A2-CW3E	E6A2-CWZ3E	E6A2-CS3C	E6A2-CW3C	E6A2-CWZ3C	E6A2-CS5C	E6A2-CW5C
Supply voltage		5 VDC -5% to 12 VDC +10%; max. 5% ripple peak-to-peak						12 VDC -10% to 24 VDC +15%; max. 5% ripple	
Current consumption		30 mA max.		50 mA max.	20 mA max.		30 mA max.	20 mA max.	
Resolution (pulses per revolution)		10, 60, 100, 200, 300, 360	100, 200	100, 200	10, 60, 100, 200, 300, 360	100, 200	100, 200	10, 60, 100, 200, 300, 360	100, 200
Output phases		A	A, B	A, B, Z	A	A, B	A, B, Z	A	A, B
Output form		Voltage output			Open collector output			Open collector output	
Output capacity		Output resistance: 2 kΩ Residual voltage: 0.4 V max. Sink current: 20 mA max.			Applied voltage: 30 VDC max. Residual voltage: 0.4 V max. Sink current: 30 mA max.			Applied voltage: 30 VDC Residual voltage: 0.4 V Sink current: 30 mA max.	
Maximum response frequency		30 kHz	20 kHz	20 kHz	30 kHz	20 kHz	20 kHz	30 kHz	20 kHz
Rotation direction		Reversible, CW + CCW			Reversible, CW + CCW			Reversible, CW + CCW	
Phase difference of output		—	90° ±45°	90° ±45°	—	90° ±45°	90° ±45°	—	90° ±45°
Output rise and fall times		1.0 µs max. (at sink current of 10 mA with 2 m cable)			1.0 µs max. (at control output voltage of 5 V and load resistance of 1 kΩ with 2 m cable)				
Starting torque		10 g-cm (0.14 oz.-inch) max.							
Shaft loading	Radial	1 kgf (7.2 ft.-lbs.)							
	Axial	0.5 kgf (3.6 ft.-lbs.)							
Moment of inertia		1 g-cm^2 (0.0055 oz.-inch^2)							
Maximum rpm		5,000 rpm							
Electrical connection		Prewired with 0.5 m (1.64 ft.) length cable							
Weight		Approx. 35 g (1.2 oz.)							
Enclosure rating		IEC: IP50							
Ambient temperature	Operating	-10° to 55°C (14° to 131°F)							
	Storage	-25° to 80°C (-13° to 176°F)							
Ambient humidity		35 to 85% RH							
Vibration resistance		Mechanical durability: 10 to 55 Hz, 1.5 mm double amplitude, in X, Y, and Z directions for 2 hours each							
Shock resistance		Mechanical durability: 500 m/s^2 (approx. 50 G) in X, Y, and Z directions, 3 times each							
Insulation resistance		10 MΩ minimum at 500 VDC between current-carrying part and housing							
Dielectric strength		500 VAC, 50/60 Hz for 1 minute between current-carrying part and housing							