# Boston University
# Electrical & Computer Engineering
**EC463 Senior Design Project**

First Semester Report

# Smart Grid Test Facility

Submitted to


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# Executive Summary

Smart Grid Test Facility
Team 14 – Power Pooches

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 their designed grid elements using this test bench. Teaching students about the electrical grid will encourage pursuit of new challenges associated with the aging grid infrastructure. This test bench 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 the classroom-friendly power grid. The final product will be a system embedded on a mobile classroom cart. Ultimately, this project will help students learn about the power grid and how it reacts to various arrangements of generators, loads, wiring networks, and sensors.

## 1.0 Introduction

As a professor at the university, the customer has requested an educational tool for undergraduate and graduate engineering students in classroom settings such as Power Electronics (EC583) or Electric Energy Systems (EC417). The desired product is a test bench with which students can observe how their own designed circuitry (in the form of loads and green energy sources) interacts with an active power grid. In order to mimic the behavior of the utility-scale power grid, this test bench must have the core grid elements: generators, transmission lines, loads, and real-time data acquisition. Students in a class, research project, or simply out of interest may create, for example, an LED display that they wish to incorporate into a power grid to see how the grid responds. Through load ports on the test bench, the student will be able to connect his load circuit, turn on the machines, and via a local monitor, observe how power flow changes as a result of his circuit. This student may then replace the LED array with an incandescent bulb and compare grid response results. These types of experiments are vital because they directly show students the impacts of energy usage and how an overall greener power infrastructure can lead to major improvements in terms of power flow and harmful emissions.

This product is a key device for engineering students because the power and energy sector currently faces some of the world's greatest challenges. The more prepared that students are to contribute to these fields, the better armed the engineering community is to tackle anthropogenic climate change and adapt the power grid toward renewable sources. Traditional energy sources, such as coal, present environmental and non-sustainable threats worldwide. In response, the power grid industry has begun turning to clean energy sources and Smart Grid technologies in order to improve efficiency, reliability, and cleanness of our electricity. This product will be a major advancement for our learning environment by allowing students to study a power grid in a hands-on, active way. A future project team will likely continue to enhance this project by incorporating Smart Grid technologies, which use communication systems to improve overall grid behavior. This project will provide the necessary infrastructure for this type of component integration, which will support this project as an even better educational tool.

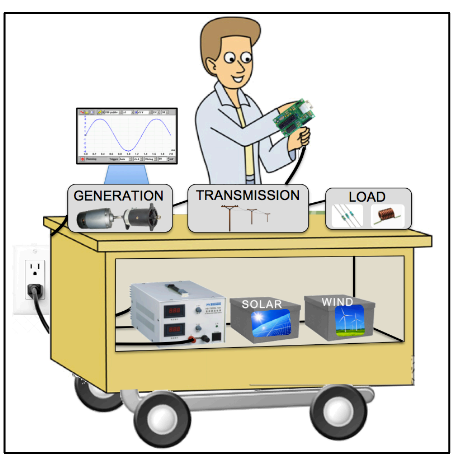


**Figure 1: Product Visualization**

Ultimately, the customer would like a mobile test bench that shows students how a grid behaves and allows for interactivity in a safe, constructive way. The visual in Figure 1 represents a simple image of what this process will be. A student has in hand his own designed load, which he can attach to a transmission line. On the monitor, he can observe electrical behavior of the grid through metrics such as the current and voltage sinusoidal characteristics, power factor, and overall system flow. It is important to note that as an educational tool, the test bench must incorporate safety measures across all aspects of the product. The customer has guaranteed that the student or instructor using the device will be trained in using the system. Thus, our team plans to create clear and complete documentation of proper product usage, in addition to integrated safety measures.

The overall approach toward designing and implementing this system involves breaking down the grid into its key divisions: generation, transmission, loads, and data acquisition. Generators provide power to the network, which is propagated along the transmission lines, and finally delivered to the loads. The data acquisition system collects information about various locations along the grid network and displays it on a nearby monitor. These grid components are designed in parallel and tested both in isolation and in integration. This method ensures that the system is modular (i.e., a future team or student group may revise the setup by removing or adding more elements) and can function as a whole.

## 2.0 Concept Development

The conceptual development of this project has occurred in steps throughout team meetings, brainstorming sessions, customer meetings, and independent work. On a basic level, although we operate as a team, we have designated leadership roles for the various elements within the project. These key areas are: alternator/motor generation, clean energy generation, transmission, loads, and data acquisition. With a team-determined baseline power flow (nominal system voltage, etc.), we design outward in order to ensure that part integration can occur as smoothly as possible. The conceptual details of these core areas are described below.

For the generation aspect of the test bed, our customer put forth several specifications he would like see in the final product. With the recent updates to the requirements, the generation system must consist of multiple generation sources that output single-phase, 60Hz AC into the test grid. Additionally, our customer put emphasis on several design aspects such mechanical to electrical power conversion and synchronization of generators in order to obtain a product that represents power generation in the real grid.

With the given needs of our customer, the team put together certain specifications for our generation scheme. First of all, the frequency of the AC input to the grid was determined to be 60Hz with a 5% tolerance (a range of 57Hz-63Hz) but we plan to design a system with a tighter tolerance range. Secondly, due to the main use of the product defined by our customer, we determined that it would be safer to provide the test bed with a low voltage magnitude of 12V with a 5% tolerance (a range of 11.4V-12.6V). While the power generation could be done in ways that will require a less complex system with fewer components, the system developed makes sure that the design in visually and mechanically fulfill our customer's needs.

In addition to the three prime generators, the customer also requested that the grid include connection points where green forms of energy can be attached. The customer has also pointed out that simulating green energy sources is optional for this project. As team, we see the major educational value in incorporating green energy into this grid infrastructure. Therefore, we will include a fourth generator, which will be driven by either a solar array (outputting DC) or a DC supply directly. Students can replace the provided solar panel with a DC supply, a solar array of their own, or any other DC-generating source. This fulfills the requirement of making a clean energy connection port while also providing a sample source for students to use with the port.

In order to meet our customer's design requirements for lumped-element transmission lines, we knew that there would be two major transmission theory questions in need of answers before going on to energize components in the lab. What type transmission line conductors would we be simulating? After choosing what type of cable to model, how can we obtain the specific RLC values per unit length of a transmission line? In settling the above questions, a few high-level problems arose. For example, when we decided to go with aluminum conductor modeling, we needed to address wire sizing since it is dependent on the transmission voltage that we want to scale our grid from. We also drew RLC characteristics from a three-phase bundled conductor design that many transmission towers exhibit. This led to into us researching geometric mean distances (GMD) and geometric mean radii (GMR) for transmission structures in the New England region.

Following tedious calculations to determine the series resistance, series inductance, and parallel capacitance of our transmission line, we had to implement real-value circuit designs in lab. For a 30-mile and a 100-mile transmission line, it is critical for all breadboard recreations to be accurate line representations. Inductors provided in our lab kits are commonly rated at 33mH. We made an effort to ensure +/-5% error in many aspects of our project and total combined transmission line inductance is one of them. During team testing periods, we found out what gain to expect traveling across the transmission line in both loaded and unloaded scenarios. This involved a litany of equations to solve for a complex (real and imaginary) transfer function from which losses and phase change can be derived. We ended up recording greater losses across the transmission lines that expected. It took much troubleshooting to confidently attribute lower load voltage outputs to circuit board resistance and a high internal waveform generator resistance when acting as a series voltage divider on our grid. Data acquisition values on our LabJack USB unit were compared with oscilloscope and multi-meter readings to make sure there were no voltage magnitude or phase angle measurement discrepancies.

The customer has requested that a variety of loads be provided along with the grid so that students may easily simulate the energy consumers found on the grid. The customer specifically requested a binary load design, which would provide the highest number of possible load combinations for students to examine. The project is also going to include a variety of visually and manually engaging loads that reflect common elements connected to the grid. The grid will include a speaker, a hobby fan, LED light displays, and incandescent lights as well as energy storage elements. These elements will fulfill the requirements of providing a grid test facility that is valuable as both a presentation tool and an experimentation environment.

Lastly, the customer requested real time data acquisition from various points along the grid. The implementation of the data acquisition should be able to find both voltage and current values at any given time, in addition to calculating power factor and power flow to and from each load and generator. Data collection will be through a data acquisition unit, or DAQ, and the devices analog inputs. In addition, the device will be MATLAB compatible. This not only allows for real time data to be displayed on any compatible computer with MATLAB, but also allows future teams to easily access the data and modify code to suit their own needs. After considering the requirements, MATLAB compatibility, and cost, it was decided the project would use the Labjack U3-LV Data Acquisition unit as the DAQ.

# 3.0 System Description

**Overall System Structure**

The Smart Grid Test Facility is going to be constructed out of several different subsystems, broken into four major sections: power generation and clean energy generation, data acquisition, transmission structure and distribution, and energy consumers (loading). The overall connections between these parts of the project are indicated in Figure 2. Please see Attachment 2 for images of the mockup. The mockup serves a model for the overall structure of the final product.

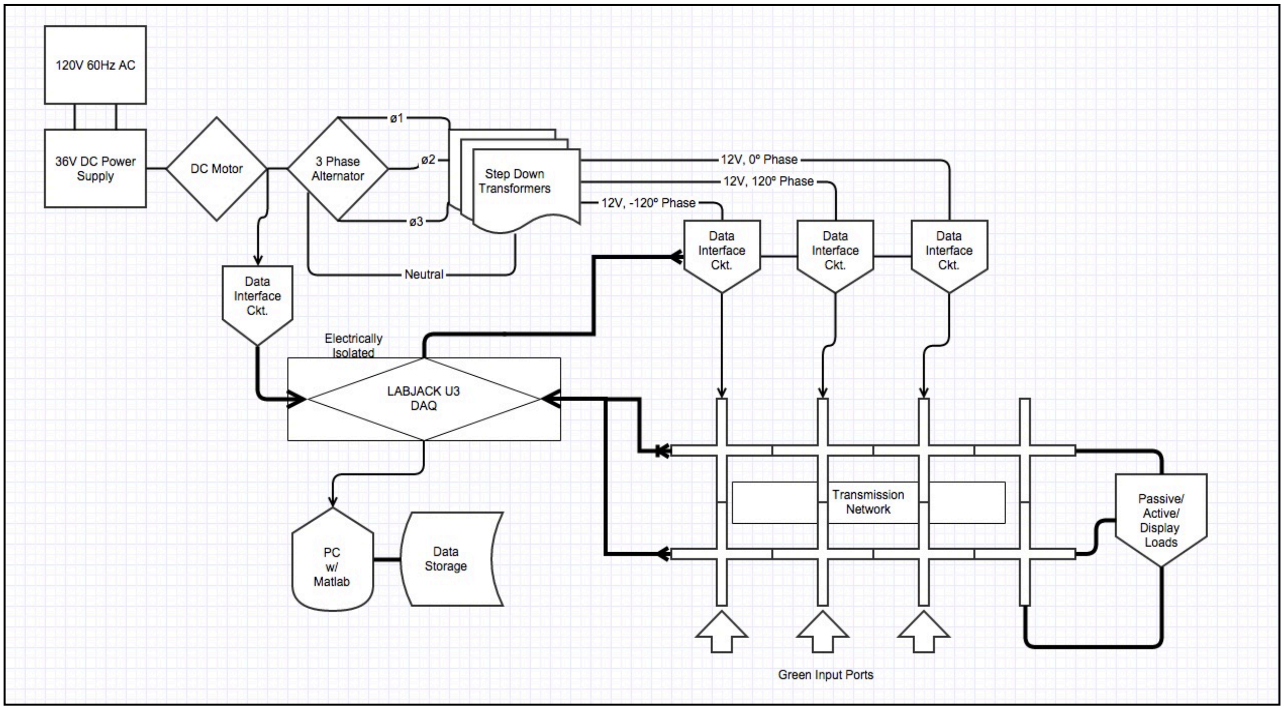



**Figure 2: Overall System Block Diagram**

**Motor/Alternator Generation**

The designed generation system consists of various mechanical and electronic components working in synchronization to provide the test grid with the desired power. Figure 3 is a wire diagram representing a very basic infrastructure to be built for the new system (not limited to the components shown in the figure).

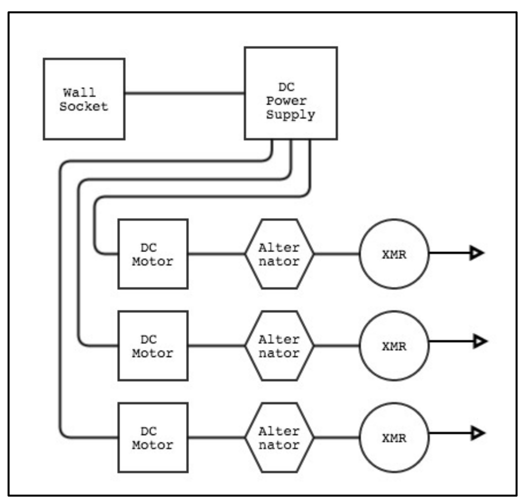



**Figure 3: Generator Scheme**

As seen in Figure 3, the DC Power Supply will be powered by 120V, 60Hz AC provided by an ordinary classroom wall socket. The DC motors of the each generation source will be connected in parallel to the single output of the power supply. Using a belt-driven configuration with custom gears, we will spin the alternators that will generate AC. The high-voltage output of the alternators will be stepped-down using transformers, that will be used in combination with each other and have custom windings to achieve right ratio, to a safe magnitude of 12V.

There might be several anticipated alterations to the current design after component selection. For example, if the alternators purchased provide a DC output we would need to integrate inverters prior to voltage transformation to create AC. Also given that the alternators used have three-wire, three-phase outputs we will simply use and load one of the wires of the alternator and leave the others unused. The wire diagram at this level also does not include the integrated feedback system and synchronization components.

**Clean Energy Generation**

The solar/DC based generator serves as the fourth generator for this learning tool. It must integrate smoothly, both mechanically and electrically, into the grid. Because two project members are taking Power Electronics, EC583, next semester, the team will have a good understanding of how students will use this device. The final course project is this clean energy system, and thus the customer has proposed that the final project be adapted to fit the test bench. The two team members will follow through with this component of the project in order to integrate clean energy. Figure 4 shows a basic diagram as to how this process can occur. Since the overall structure may change depending on in-class learning in EC583, these diagrams are preliminary and are subject to development in class.

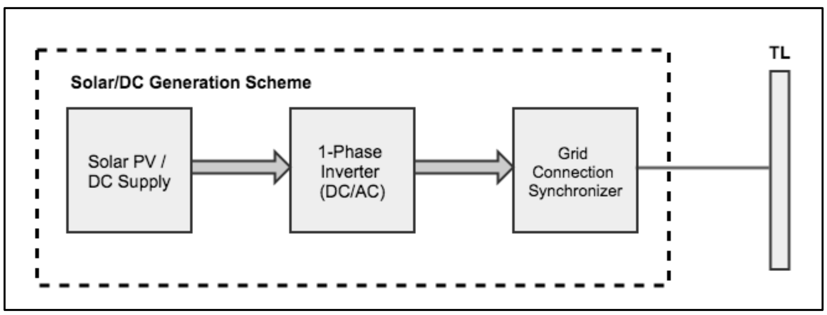



**Figure 4: Level 1 Diagram Solar Energy Generation**

A solar panel or DC supply outputs direct current into a single phase inverter, which converts DC to AC at approximately 60Hz in order to align with the remainder of the grid. The nominal voltage of the system is 12V, and thus the output of the inverter must be at 12V (or if not, altered via a transformer). The grid connection synchronizer interfaces the AC output and the transmission line that is already powered by a different, nearby generator. Since the AC output must be in phase with the waveform propagating along the transmission line, feedback into the grid synchronizer is required. Figure 5 indicates the details of how this feedback might operate.

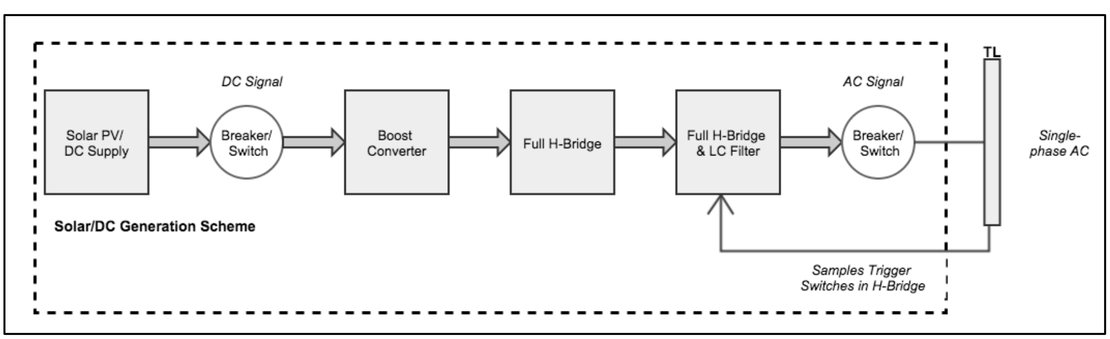



**Figure 5: Level 2 Diagram Solar Energy Generation**

Each of the elements within these block diagrams will be provided as the technical solution to the solar energy generation. The DC input will be boosted, inverted, and safely synchronized with the other generators. The scheme will be isolatable by breakers for safety purposes.

**Transmission Network**

The real-value transmission lines in the project make the grid very realistic for learning power systems theory. Users can get a feel for line losses in power distribution. As a part of the overall teaching tool, it allows the user to gauge the role that line distance plays in determining the net power factor and voltage drop. Figure 6 illustrates a transmission line junction that connects source to load.

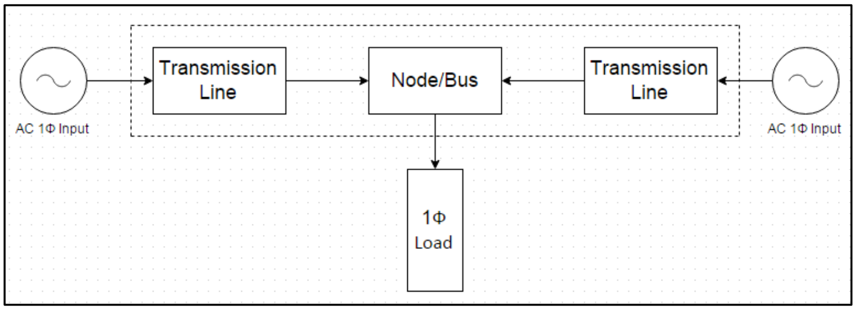



**Figure 6: Transmission Line Junction**

A single-phase line-to-neutral voltage of 12V is tapped off of each three-phase generator. The AC inputs are then directly attached to transmission lines of varying distances before the power flow is met at a simple bus bar. Although the bus does not carry the switching capabilities of a substation, it represents a critical node at which the two alternating waveforms above meet. We go in depth regarding sync-checking the phase difference between the sinusoids in the section detailing generation synchronization. Multiple single-phase loads will be inserted at the node, which has many connection points. Transmission lines complete the circuit as they tie together AC generation and the loads.

**Loads**

Each of the loads provided with this learning tool serves as the representations of homes, businesses, energy consumers, and all of the appliances on the power grid. They are being designed such that they are qualitatively proportional to the aforementioned elements. More so, they are being designed so that a small set of loads can be used to simulate a variety of different real-world appliances/consumers based on parameterization (setting R, L, and C). This modularity will improve the easy usability of this device in a classroom environment where there may be untrained users or if the user is presenting to a group (short set up time). A binary load is illustrated in Figure 7.

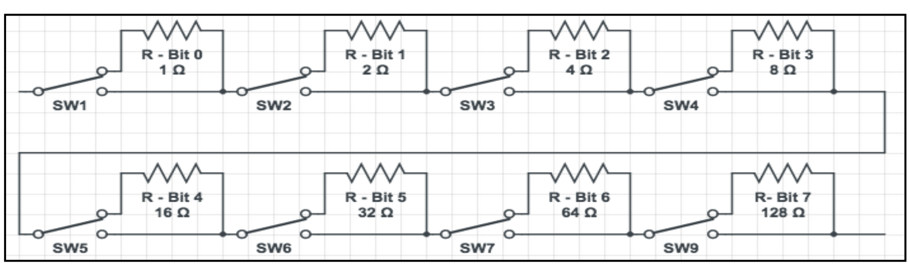



**Figure 7: Binary Resistive Load Circuit**

The secondary use case of these loads will be to forward learning goals that are already common to power electronics and also energy technology courses. A prime use case is the study of different lighting type technologies and their power needs. For this purpose, various luminous loads will be included with the end product, including an LED display and an incandescent light. As these elements are discrete in and of themselves, there is no reasonable way to scale their behavior as will be done with the binary loads and therefore operating specifications will be provided with these loads for studying power flow.

**Data Acquisition**

Data acquisition is separated into two distinct modules: hardware and software. The hardware module (Figure 8) acts as the sensors for the data acquisition, and will convert the voltage and currents located throughout our grid into usable analog signals for the DAQ. The hardware module consists of four separate parts: current sensor, current interface, voltage interface, and the DAQ. The current sensor outputs an analog signal ($V_I$) based on the current flow at the various load and source points in the grid. The analog signal then goes through a current interface circuit constructed of operational amplifiers, which amplifies and DC shifts the signal to match the analog input specifications of the DAQ or 0 V to 2.4 V. Similarly, the voltage interface also amplifies and DC shifts the voltage at points ($V_s$) along the grid to within the DAQ specifications. These two newly formed signals ($V_s$' and $V_I$') are then fed into analog input pins on the Labjack DAQ, where the software takes over.

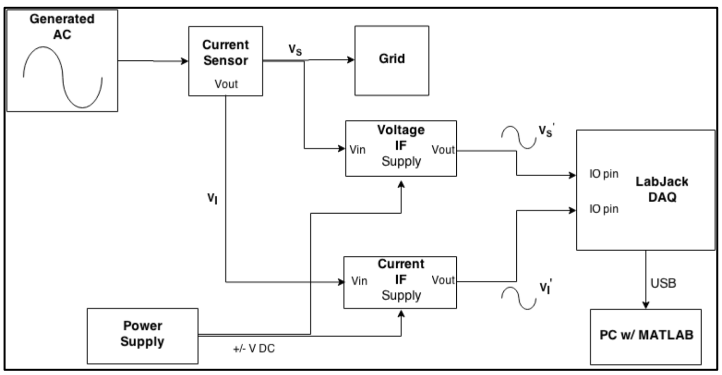



**Figure 8: DAQ Hardware**

The software module (Figure 9) collects, processes, and displays the collected data to the user. Data collection mostly utilizes high-level functions provided by Labjack through their Labjack UD driver, which fosters communication between MATLAB and the DAQ through Microsoft's .NET framework. Data processing and display is strictly MATLAB based, and processes the data, then displays waveforms and key information derived from the data including voltage, current, phase, power factor, and power flow.

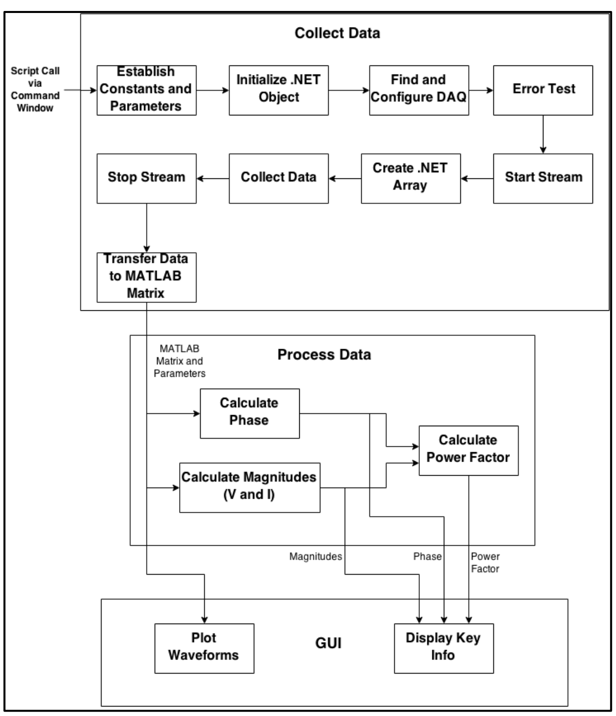



**Figure 9: DAQ Software**

## 4.0 First Semester Progress

**Motor/Alternator Generation**

Due to the recent updates to the requirements brought forth by our customer, the generation design process was pushed back along will the progress that has been made with the previous design. With the addition of a new requirement stating the necessity of multiple generation sources, a new generation design has been created with three separate generation blocks, as shown in Figure 3.

Currently we are in the research and design process of the feedback system that will regulate the frequency within the tolerance limits as well as the components that will be used to keep the single-phase output of the alternators in sync with each other. As per the feedback system, we are currently working on a design that will create a feedback loop (possibly through PWM) to the voltage regulator of the DC motor that varies the voltage, hence the RPM, depending on the grid loading. When it comes to synchronizing the generators, the team as a whole is putting an effort into researching and designing a way to accomplish what seems to be the most difficult task in generation. By establishing a reference 60Hz source (like the wall socket), we will be able to create a system that will keep the generators outputs in synchronization with each other.

In terms of purchasing components, the team is close to purchasing a new DC power supply as well as the DC motors that are be suitable for the design above. We plan to purchase a lab grade, single-output 0-30V, 0-10A DC power supply that will power three 24V, 2.2A DC motors (proposed by our customer) connected in parallel to its output.

**Clean Energy Generation**

The progress regarding clean energy integration was minimal within the first semester for several reasons. Firstly, a large portion of the team's efforts regarded the motor-alternator generation scheme throughout the first semester. Additionally, while although it was known throughout the semester that clean energy integration was a requirement, it was considered a second semester task because it depends on many other areas of the project. However, toward the end of the first semester, it was recognized that clean energy connection (particularly, solar or DC input) is a complex task and should be assigned to a team member as their leadership position. Once this reorganization was complete, efforts began toward developing designs for integrating a fourth generator: solar energy.

At this point, we have determined several core characteristics of the clean energy integration. These decisions have been based upon research, preliminary design, and previous experience in classes and internships. First, the green source will be a photovoltaic (PV) panel, which can be interchanged with a DC source. The PV cells will most likely be crystalline modules because they are most common in residential applications, which we aim to model. Since the output current of each cell depends on the intensity of the incident light, a lamp will need to be affixed to the cart so that students can properly generate power from the solar array. The greatest challenge associated with this task is synchronizing the inverted output with the rest of the generators. The circuit schematic shown in Attachment 4 is our baseline circuit at this point; the DC input is boosted, then inverted, and then triggered by sampling the signal you wish to match. As described in the System Description, this component will be developed in EC583, a course taught by the customer. Throughout the spring semester the team will learn how to construct this clean energy generator as part of EC583. This will serve as a sample system for future Power Electronics students. As described, because this component of the project had a delayed start, progress within the first semester was minimal, but will continue throughout the second semester, as detailed in section 5.0.

**Transmission Network**

We built two transmission lines for lab testing. One simulation was a 30-mile line and the other was a 100-mile line. The breadboard test circuits are made of series power resistors, multiple 33mH inductors in series, and capacitors in parallel. These models were carefully constructed to follow RLC values of a real-value high-voltage transmission line made of 115kV 750MCM aluminum. Such a cable has a cross sectional radius of approximately 0.433 inches. For our project, the generator voltage is stepped down significantly, but these lumped-element RLC transmission values are not scaled down at all. One of our logbook entries is dedicated to explaining why it is cheaper to install aluminum versus copper. Additionally, each phase that we model has values derived from a typical 3-phase bundled conductor system. On transmission towers, overhead lines are typically placed in bundles of three conductors (all of the same phase) because the method reduces the corona effect and mutual inductance between wires. To be precise, we spoke to local utility professionals to learn about phase-to-phase measurements. We found out that the average spacing between the centers of adjacent bundles is 15 feet. In line with that, the universal distancing between phases in the same bundle is 1 foot spacing. Using the aforementioned GMD and GMR, we could solve for inductive and capacitive reactance via a sum of natural logs. We know the resistance/mile, inductance/mile, and capacitance/mile of each chunk of our transmission line. As the line distance increases, the RLC characteristic values go up proportionally. The transmission lines yielded low losses across them (as expected) when connected to a large load. Also, we plotted a slight phase shift since the line is a bit more inductive than capacitive. Below are the exact values of the test circuits.

R = 0.1128 Ω/mi

L = 1.329 mH/mi

C = 22.11 nF/mi

| Distance | R | L | C |
|---|---|---|---|
| 30 mi | 3.38Ω | 39.87mH | 663.3nF |
| 100 mi | 11.282Ω | 132.9mH | 2,211nF |

First off, we had to determine that our R, L, and C values per mile were realistic. Verification involved comparison with power systems texts and aluminum conductor steel reinforced (ACSR) spec tables. In general, most entries for similar aluminum cable types showed 60Hz AC resistances around 0.15 Ω/mile at ambient temperature. This is only slightly higher than the 0.1128 Ω/mile measurement for our conductor. A 30 mile line, for example, should only have a couple ohms of resistance in general. We made comparisons similar in nature for L and C per unit length. For one mile of transmission line, inductance should be substantially greater than capacitance. According to L = 1.329 mH/mi and C=22.11 nF/mi listed later in this report, our values follow that assumption. In theory, capacitance is actually negligible for transmission lines below 50 miles.

When loads are placed on the output side of my transmission line, do we read minimal losses? Minimal losses in national utility grids are close to 3-5%. Using our 30-mile transmission line loaded with a 100Ω resistor, we calculated a gain of 0.946 at a phase angle of 6.61°. That translates to about 5% in power losses over transmission. To be sure, we plugged the input and output voltage into our USB DAQ system and extracted plots closer to 3% losses when replacing the 100Ω with a bigger 10kΩ load. Our data got significantly better because the AC power supply on our lab bench has a documented internal resistance of 50Ω. Since we ended up making the resistive load far larger than this internal resistance, we essentially eliminated its undesired impact on the electrical grid.

What should the change in phase angle of the voltage plots be on the load side? In the last paragraph, our transfer function solution for the gain also produced a phase difference between input and output of 6.61°. We look forward to performing good engineering practice by redoing our phasor calculations a second time to double-check. However, with help from our MATLAB algorithm, we compiled our code to run for 50 trials and pulled an average of the change in phase. This was done to compensate for a lower sampling rate. Nevertheless, our team found a 6° average phase difference on MATLAB to back up our concepts. We plan on ordering predesigned PCBs with more than one layer (ground grid necessary) for "snap-in" integration as the next step on the transmission line process.

**Loads**

All three of the required passive loads been designed for this project and the resistive load has been prototyped. Since the inductive and capacitive iterations require a special part order they will be completed in the third week of January 2015.

Given that building passive loads is not very time intensive the team has elected to broaden the scope of load implementations on the grid thereby adding avenues of interactivity to our test facility. This has guided the focus of the load design process to providing an engaging learning tool. Moreover, it should be relatable to a range of power electronics and electric energy systems topics for the sake of class discussion. To this end LED and Incandescent light sources, inductive loads, and also storage devices have been selected off to include with the test facility in order to forward the study of common energy consumers on the real grid.

The philosophy of our load design shifted toward presentability and scalability after the first deliverable test (described later in this section). The load portrayed in Figure 7 was not exact enough and the scale of resistance was too close to the impedance of our test lines, which resulted in errant results. Ideally the transmission lines are low resistance with respect to the rest of the system loads but this was not the case when we tested the maximum binary load (255Ω). The quick fix to this problem is that we will include high impedance loads to resolve scaling issues. As covered already, presentability will be addressed by including lights and more interactive loads in the future.

**Data Acquisition**

There has been much progress for the data acquisition aspect of our project. So far, after careful consideration of factors including cost, compatibility, specifications, and ease of use, it has been decided to use the Labjack U3-LV Data Acquisition device for data collection purposes. Though it does have a lower clock rate than many DAQ, it provides significant data acquisition capabilities through its 16 available analog input ports, and it's easy to use high-level functions associated with the Labjack UD driver. All while costing only $120 which allows for more funds to be directed towards the generation, transmission, and load aspects of the project. In addition, various voltage interface circuits have been tested and a final one (Figure 10) consisting of a buffer for minimal current draw, followed by a summer for DC offset and an inverting amplifier. Lastly, a preliminary MATLAB code has been written that allows for display of waveforms, as well as providing finite measurements including phase difference between two waveforms and voltage. This is a big step; since it is the technical gateway for finding current values, power factor, and eventually power flow throughout the grid. The separate parts were then integrated together and tested for our first deliverables testing.

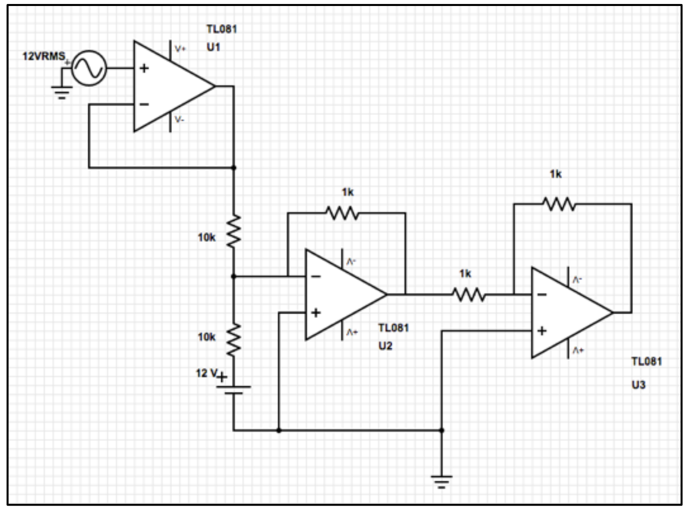



**Figure 10: Interface Circuit**

## Smart Grid Integration

Originally, the team planned to integrate Smart Grid components, which was an optional element of the project, per the customer. Due to some customer feedback, it was decided toward the end of the first semester to replace the Smart Grid integration with clean energy integration. However, progress regarding Smart Grid occurred throughout the semester. A scheme was devised that would allow for interconnection of Smart Grid components which require a lower voltage than the nominal voltage of the system. A substation-type architecture would involve a transformer, breakers, and voltage regulation, which would step down the nominal voltage to 5V, which was needed for the Smart Grid components. Additionally, miniature Smart Grid off-the-shelf components were selected to suit our system, which involved contact with the manufacturer, review of specification sheets, and part selection. Once this was completed, basic plans for testing the equipment ensued; the measurements collected by the smart components would be compared to those of the DAQ in order to confirm success. The Smart Grid components would serve to show students what Smart Grid components are, how they work, and why they are vital to the future of the power grid. Ultimately, customer feedback led the team to decide to leave Smart Grid integration for a future endeavor due to many complexities and need for support elsewhere within the project. The efforts put toward this facet of the project were adapted to clean energy integration, which is considered far more vital to the project.

## First Deliverable Testing Results

A preliminary test was conducted in November in order to verify the success of initial designs. The test setup is presented in Figure 11. The test procedure focused on the data acquisition, transmission lines, and variable load circuit. A signal generator supplied power to a transmission line, which passed the power onto the resistive load. Meanwhile, the DAQ measured the AC wave across the load. Although this setup implemented was in a simple form, this test confirmed that our basic arrangement was successful and proved the concepts that will be employed in the final design. Images from this testing are available in Attachment 3.

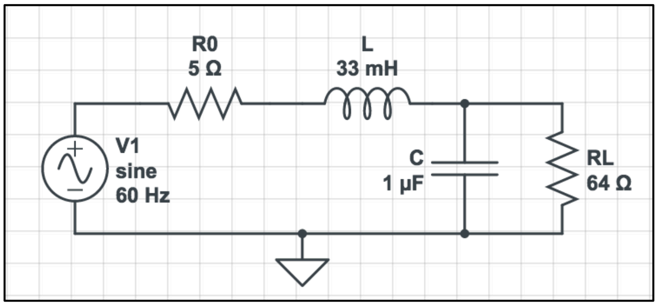



**Figure 11: First Deliverable Test Circuit**

Key results from this testing procedure involve the DAQ, the transmission lines, and the resistive variable load. The transmission design was tested by comparing expected output voltage (across the load) to the measured output voltage by an oscilloscope. At small load values (64Ω), the error was large, at about 50%. Upon investigation it was determined that the load was comparable to the waveform generator's internal resistance of 50Ω, and likely causing issues. To test this, the load was increased gradually, and it was observed that the percent error reduced. At about 10kΩ of load, the error had reduced to 0.3%. Although we will not use this waveform generator in the final product, this was an important and unexpected phenomenon that we have kept in mind while designing and moving forward. The resistive load behaved as planned; the key takeaway was to demonstrate how we will need resistors with smaller tolerances in order to have more accurate measurements. The DAQ was deemed successful based on its display of data as compared to the oscilloscope and hand-performed calculations. The DAQ performed successfully; for example, using the data it was found that the waveform frequency was 59.81Hz, which is nearly exact compared to the expected 60Hz. Ultimately, this testing validated our core circuit arrangement, provided some keen insight to unexpected problems, and demonstrated the success of the DAQ system.

## 5.0 Technical Plan

**<u>Motor/Alternator Generation</u>** (Lead: Suleyman, Assist: Chris, Tim)
*Task 1: Generation Design*
Design process that will be focused solely on generating AC power through our generation system. Emphasis will be put on integration of motors, alternators and transformers to provide grid with a 12V output.

*Task 2: Selection of Generation Components*
Selection and purchasing of components defined by the design created in previous task. Includes DC power supply, three DC motors, three alternators, and multiple transformers.

*Task 3: Testing of Generation Components*
Testing of components purchased in previous task.

*Task 4: Feedback and Synchronization Design*
Design process dedicated to the creation of the feedback and synchronization systems. A crucial task in keeping the generation frequency of 60Hz within the designated tolerance and keeping the phase of the separate generators in sync with each other.

*Task 5: Selection of F/S Components*
Selection and purchasing of components defined by the design created in previous task. Includes feedback system and synchronization parts.

*Task 6: Testing of F/S Components*
Testing of components purchased in previous task.

*Task 7: Construction/Integration of Generation System*
Final step in creation of the generation system as a whole. Following the testing of power generation and F/S systems, the team will integrate the components to function properly with each other before finalizing product completion.

**<u>Clean Energy Generation</u>** (Lead: Marissa, Assist: Tim)
*Task 1: Solar Generation Overall Specs*
The voltage and current values must be decided for all interface points within the generation scheme. This will be determined by working backwards from the transmission line nominal voltages as produced by the motor/alternator generators.

*Task 2: Inverter Research & Grid Tie Research*
Based on the values determined in Task 1, inverter designs and ICs must be researched in order to determine a best fit for this purpose. This will involve online research, circuit design and simulation, and looking for market availability. This will also derive from class-based learning in EC583 (as will the entire development process).

Grid tie connector designs and ICs must be researched in parallel with inverter research. If it is decided to purchase a circuit to perform this task, it must be able to interface with the surrounding components; otherwise, designs must be simulated and tested.

*Task 3: Solar Array Design*
Based on the outcome of the inverter and grid tie designs, a crystalline PV solar array will be designed to satisfy the voltage and current needs of the inverter. A lamp will also be selected based on illumination, which accounts for the output current of the PV cells. Also, purchase PV cells upon finalizing design.

*Task 4: Array and Inverter Setup & Testing*
Test the solar array with the inverter by comparing the DC output of the solar panel to the AC output of the inverter. Ensure that 60Hz, 12V AC is created within minimal tolerance. Ensure a safe current is produced for input to grid tie.

*Task 5: Grid Tie Setup & Testing*
Test the grid tie circuit by connecting the solar array and inverter to the grid tie and measuring the output. For feedback, trigger with signal generated by waveform generator and confirm that output is in phase with generator signal.

*Task 6: Grid Network Interface Testing; Labels, Housing, Documentation*
Repeat task 6 but replace the waveform generator with the output of the motor/alternator generators. Finalize integration of solar input by providing labels and housing as needed for students. Also provide documentation on safety measures and system components. Note: this task will occur *after* April 1. Since this will be developed within EC583, the final course project will not be completed before April 1. The customer has approved of this timeline: the connection ports will be available by April 1, but the sample generator (final project of EC583) will be available before the end of the semester.

**Transmission Network** (Lead: Tim, Assist: Marissa)
*Task 1: Transmission Line Component Verification*
The resistors, inductors, and capacitors used on the transmission breadboard circuits will be individually measured. Their respective values must meet their nameplate specifications. Components with excessive overheating or inaccurate labels will be disregarded in future designs. This approach finds the most effective way to reproduce transmission lines at desired lumped-element RLC values.

*Task 2: Transmission Line PCB Design*
Based on the RLC values carefully devised in Task 1, a printed circuit board template for transmission lines will be devised. From the basic transmission PCB design, power resistors, capacitors, and inductors will be placed on the boards so as to achieve bidirectionality (independence from voltage source direction). RLC values will be selected to satisfy line distance requirements. The conclusion of this task will be the purchase of several, multi-layered (one for grounding of the neutral) PCB designs that will be in the final deliverable design.

*Task 3: Transmission Line Setup and Testing*
Test the transmission line for full conductivity throughout. Ensure that the RLC values ordered on the board meet our design expectations by utilizing the data-acquisition unit. Perform an overall performance test using the input and output ports while confirming the functionality of the ground grid.

*Task 4: Transmission Line "Snap-in" Interfacing*
Provide foundational support for all transmission lines so that the user can physically snap in any version of transmission line and limit a line's freedom of movement. This will organize and structure the grid's layout for the optimal connection of leads. Transmission lines may be custom-covered enabling comfort when swapping lines in and out of the grid.

*Task 5: Transmission Line Labeling and Documentation*
Label each transmission line circuit accordingly with its numerical RLC characteristics, wire size/type (aluminum), and length for user reference.

**Loads and Safety** (Lead: Jeremy, Assist: Suleyman, Marissa)
*Task 1: Safety System Design*
The safety system of the test grid will consist of clear acrylic housings for the various subsystems as well as circuit breakers at vital connection points in the test bed (generation, DAQ, loads).

*Task 2: Safety System Fabrication and Assembly*
The safety system will require machining and assembly at the Boston University EPIC.

*Task 3: Load PCB Design and Selection*
The PCB design and selection will get lumped into the group PCB design, since it is a project requirement for all circuits to be affixed to PCB.

*Task 4: PCB / Display Load Testing*
Once the PCB's and display loads are completed we will move on to testing them. The tests will require that power is delivered properly to each circuit and that they can be mounted and operate properly. If any requirement is not met, repeat task 3.

*Task 5: Full Load Assembly*
Once all components are tested and working together, they will be assembled in their housing so that they can be interchanged and incorporated with the rest of the project as described in the system description.

*Task 6: Transmission / Subsystems Modularity Check*
An extension of Task 5. Incorporation with the rest of the project is completed so that safety systems and loads are working exactly as expected under 'teaching' conditions.

**<u>Data Acquisition</u>** (Lead: Chris, Assist: Jeremy)
*Task 1: Current Sensor and Current Interface*
Pick an optimal current sensor based on the maximum operating specifications of the grid (i.e. max current possible), then design a current interface circuit that amplifies and dc shift the current sensor output with operational amplifiers. The output of the current interface should be between 0 V and 2.4 V inclusive to maximize the precision of the Labjack U3-LV.

*Task 2: Test Current Data Acquisition*
Using the current sensor and current interface combined, run various known amounts of current through a circuit and compare the output of the interface with the actual current values.

*Task 3: Test Combined Current and Voltage Sensing/Program Power Factor*
Build a preliminary data interface module that finds the current and voltage of a specific point in a circuit. Then using the preliminary MATLAB script written for the first deliverables test and a similar procedure, find the phase between current and voltage and calculate power factor using the cosine of the phase. Ideally, test along with generation module.

*Task 4: Program Power Flow*
Create a function in MATLAB that uses user derived parameters and data acquired from the circuit to calculate power flow at sources and loads.

*Task 5: Program GUI*
Program GUI that will visually display waveforms and important data to user of the system.

*Task 6: Fabricate Data Acquisition PCB*
Order precision parts for data interfacing PCB, layout PCB, and have PCB fabricated. Solder parts onto PCB board and test.

*Task 7: Integration and Documentation*
Integrate data acquisition module with the rest of the project, and start work on documentation that explains how the MATLAB program works, and how the data acquisition circuitry should be connected.

**<u>Misc: Team Tasks</u>**
*Task 1: Safety and Training Documentation*
Provide all necessary documentation needed for a student or instructor to safely use this test bench. Should provide important component specifications and data needed in the case of part replacement or malfunction.

*Task 2: Functional Integration and Testing*
Integrate all components of the project within the mobile cart and test for all functionality.

## 6.0 Budget Estimate

| Componential Description | | Est. Price | Totals |
|---|---|---|---|
| Generation | Motor | $75 | |
| | Alternator | $450 | |
| | Transformers | $200 | |
| | Feedback System | $75 | |
| | Synchronization | $100 | |
| | Enclosure | $75 | |
| | | Total: | $975 |
| Transmission Lines | PCB | $50 | |
| | Passive RLC | $25 | |
| | | Total: | $75 |
| Generic Loads | Passive Loads | $175 | |
| | Display Loads | $50 | |
| | PCB | $50 | |
| | | Total: | $275 |
| Data Acquisition | DAQ | $120 | |
| | Sensor Boards | $40 | |
| | | Total: | $160 |
| Renewable Energy Generation (KHC) | Solar Array | $75 | |
| | Inverter | $50 | |
| | Grid Tie Circuit | $50 | |
| | | Total: | $175 |
| | | Net Total: | $1,660 |
| | | Budgetary Total: | $1,485 |

A large portion of the project's budget will be dedicated to power generation and this will cause the project to be over budget by ~50%. Due to the multiple generation points in our system design, the team will need to purchase multiple motors, alternators, transformers, etc. adding to the cost of generation. This budgetary concern has been noted to our customer and will be discussed in the near future. The team plans to obtain external funds for the renewable energy generation components from Kilachand Honors College and for this reason the cost was deducted from the net total. Furthermore, the cart that will carry the test bed components will be provided by our customer and was not included into the budget summary.

# 7.0 Attachments

## 7.1 Appendix 1 – Engineering Requirements

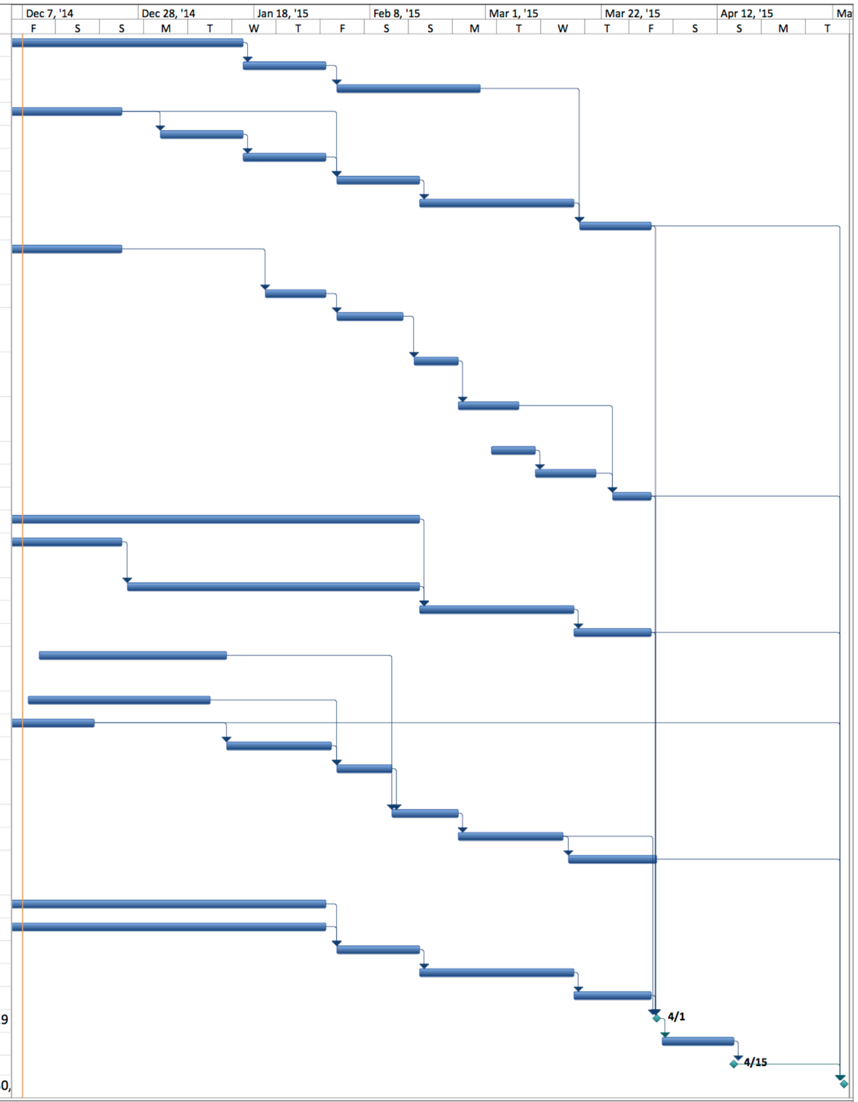
Team # 14 Team Name: Power Pooches

Project Name: Smart Grid Test Facility

| Requirement | Value, Range, Tolerance, Units |
|---|---|
| Line Voltage | 6-12V AC (+/-5%), 60Hz (+/-5%) |
| Simulated Transmission Lines (per-unit length parameters) | Bundled Al, R = 0.1128 Ω/mi, L = 1.329 mH/mi<br>C = 22.11 nF/mi |
| Generation | 3 DC Motors to 3 Alternators, 1 Phase connected, 2 Phases OC |
| Green Generation Technology | 1 Simulated Solar Cell with Inverter |
| Loading | 3 Binary Load Modules (R/L/C)<br>>4 Display Loads, 2 Luminous, 2 Magnetic |
| Data Acquisition | Measures V-I, Power Factor, Phase (+/-5%); Power flow tracking |
| Safety | Generator inside isolate enclosure, network loads and branches attached with circuit breakers |

# 7.2 Appendix 2 – Gantt Chart

| ID | Task Mode | Task Name | Duration | Start | Finish | Predecessors |
|---|---|---|---|---|---|---|
| 1 | | (DAQ) Program Data Processing | 34 days | Mon 12/1/14 | Thu 1/15/15 | |
| 2 | | (DAQ) Test Data Processing | 11 days | Fri 1/16/15 | Fri 1/30/15 | 1 |
| 3 | | (DAQ) Program and Test GUI | 20 days | Mon 2/2/15 | Fri 2/27/15 | 2 |
| 4 | | (DAQ) Pick Components | 17 days | Tue 12/2/14 | Wed 12/24/14 | |
| 5 | | (DAQ) Design Interface Circuits | 11 days | Thu 1/1/15 | Thu 1/15/15 | 4 |
| 6 | | (DAQ) Test Interface Circuits | 11 days | Fri 1/16/15 | Fri 1/30/15 | 5 |
| 7 | | (DAQ) PCB Layout | 11 days | Mon 2/2/15 | Mon 2/16/15 | 4,6 |
| 8 | | (DAQ) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 | 7 |
| 9 | | (DAQ) Project Integration | 9 days | Wed 3/18/15 | Mon 3/30/15 | 8,3 |
| 10 | | (Generation) Select Components | 18 days | Mon 12/1/14 | Wed 12/24/14 | |
| 11 | | (Generation) Test Components | 9 days | Tue 1/20/15 | Fri 1/30/15 | 10 |
| 12 | | (Generation) Design Feedback and Synchronization System | 10 days | Mon 2/2/15 | Fri 2/13/15 | 11 |
| 13 | | (Generation) Pick Feedback and Synchronization Components | 6 days | Mon 2/16/15 | Mon 2/23/15 | 12 |
| 14 | | (Generation) Feedback and Synchronization Testing | 9 days | Tue 2/24/15 | Fri 3/6/15 | 13 |
| 15 | | (Generation) Design Enclosure | 6 days | Mon 3/2/15 | Mon 3/9/15 | |
| 16 | | (Generation) Construct Enclosure | 9 days | Tue 3/10/15 | Fri 3/20/15 | 15 |
| 17 | | (Generation) Project Integration | 5 days | Tue 3/24/15 | Mon 3/30/15 | 16,14 |
| 18 | | (Transmission) Integration Design | 56 days | Mon 12/1/14 | Mon 2/16/15 | |
| 19 | | (Transmission) Select RLC Components | 18 days | Mon 12/1/14 | Wed 12/24/14 | |
| 20 | | (Transmission) PCB Layout | 37 days | Fri 12/26/14 | Mon 2/16/15 | 19 |
| 21 | | (Transmission) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 | 20,18 |
| 22 | | (Transmission) Project Integration | 10 days | Tue 3/17/15 | Mon 3/30/15 | 21 |
| 23 | | (Solar) Grid Tie Research | 24 days | Wed 12/10/14 | Mon 1/12/15 | |
| 24 | | (Solar) Inverter Research | 25 days | Mon 12/8/14 | Fri 1/9/15 | |
| 25 | | (Solar) Solar Generation Overall Specs | 15 days | Mon 12/1/14 | Fri 12/19/14 | |
| 26 | | (Solar) Solar Array Design | 14 days | Tue 1/13/15 | Sat 1/31/15 | 25 |
| 27 | | (Solar) Array and Inverter Setup and Testing | 8 days | Mon 2/2/15 | Wed 2/11/15 | 26,24 |
| 28 | | (Solar) Grid Tie Setup and Testing | 8 days | Thu 2/12/15 | Mon 2/23/15 | 23,27 |
| 29 | | (Solar) Grid Network Interface Housing | 14 days | Tue 2/24/15 | Sat 3/14/15 | 28 |
| 30 | | (Solar) Labels, Housing, and Documentation | 12 days | Mon 3/16/15 | Tue 3/31/15 | 29 |
| 31 | | (Load) Safety Design and Part Selection | 45 days | Mon 12/1/14 | Fri 1/30/15 | |
| 32 | | (Load) Load Selection and Testing | 45 days | Mon 12/1/14 | Fri 1/30/15 | |
| 33 | | (Load) PCB Design | 11 days | Mon 2/2/15 | Mon 2/16/15 | 31,32 |
| 34 | | (Load) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 | 33 |
| 35 | | (Load) Project Integration | 10 days | Tue 3/17/15 | Mon 3/30/15 | 34 |
| 36 | | Project Functional Testing | 0 days | Wed 4/1/15 | Wed 4/1/15 | 35,29,22,17,9 |
| 37 | | Final Preparation/Details | 9 days? | Thu 4/2/15 | Tue 4/14/15 | 36 |
| 38 | | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 | 37 |
| 39 | | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 | 25,22,17,9,30, |



## 7.3 Appendix 3 – Other Appendices

### 7.3.1: Team Member Biographies

### 7.3.2: Mockup Images

### 7.3.3: First Deliverable Testing Images

### 7.3.4: Grid Tie Inverter (Sample)

### 7.3.5: Gantt Charts – Individuals

## Attachment 1: Team Member Biographies

**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.

**Jeremy Kramer**
*jlkramer@bu.edu*

I am an electrical engineer from Santa Monica, California and my interest's 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.

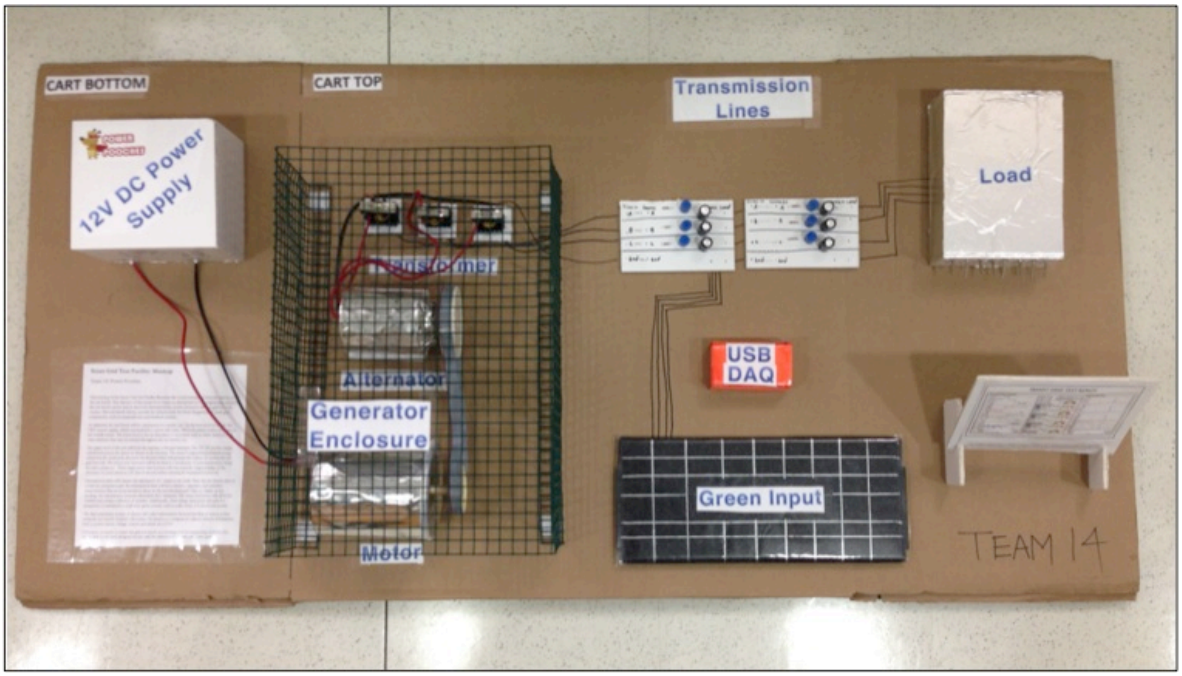
**Marissa Petersile**
*misspete@bu.edu*

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. Looking forward, I'm aspiring toward a career in clean energy as a method of decelerating climate change.

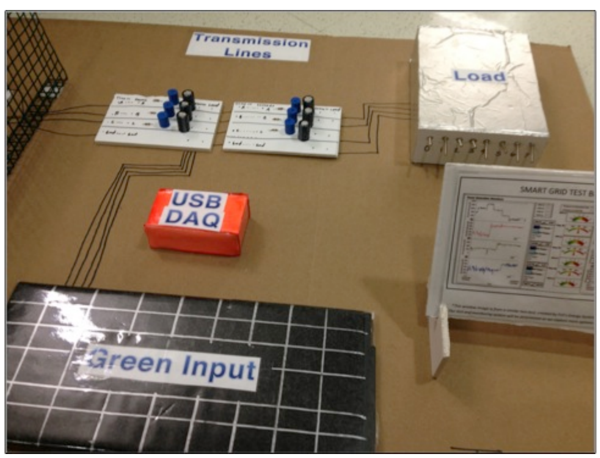
**Christopher Powers**
*chrisp@bu.edu*

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 robust electrical infrastructure for renewable energy systems.

## Attachment 2: Mockup Images

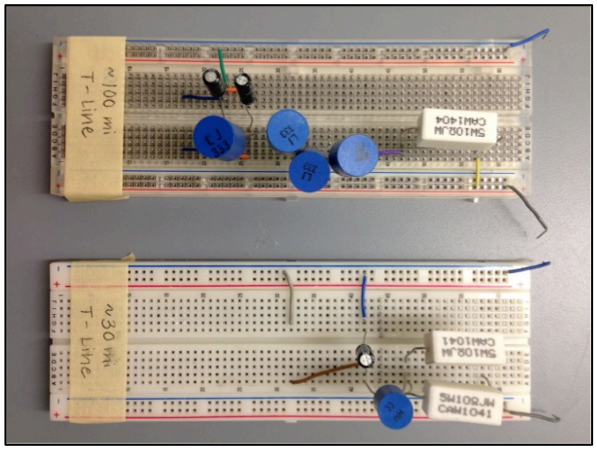



*Mockup: Overall Product Structure*

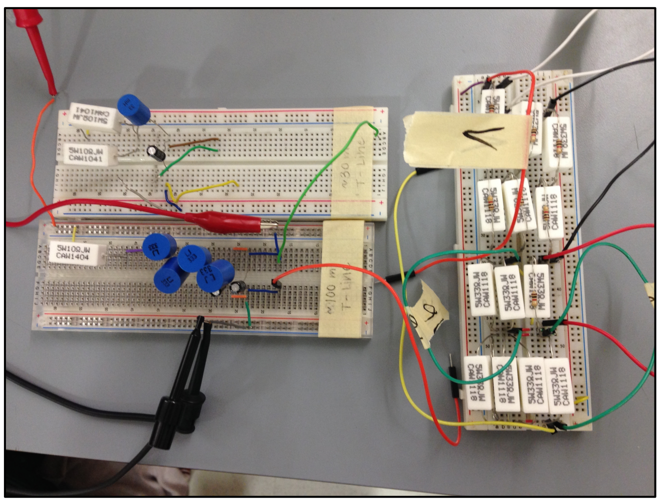



*Mockup: Close-Up*

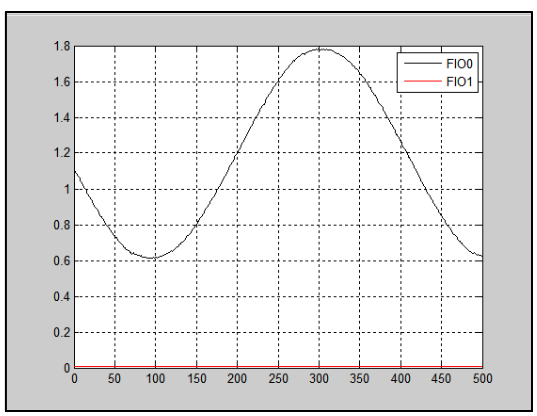
## Attachment 3: First Deliverable Testing Images




*Testing: Transmission Lines*



*Testing: Transmission Lines and Resistive Load*




*Testing: DAQ Output via MATLAB*

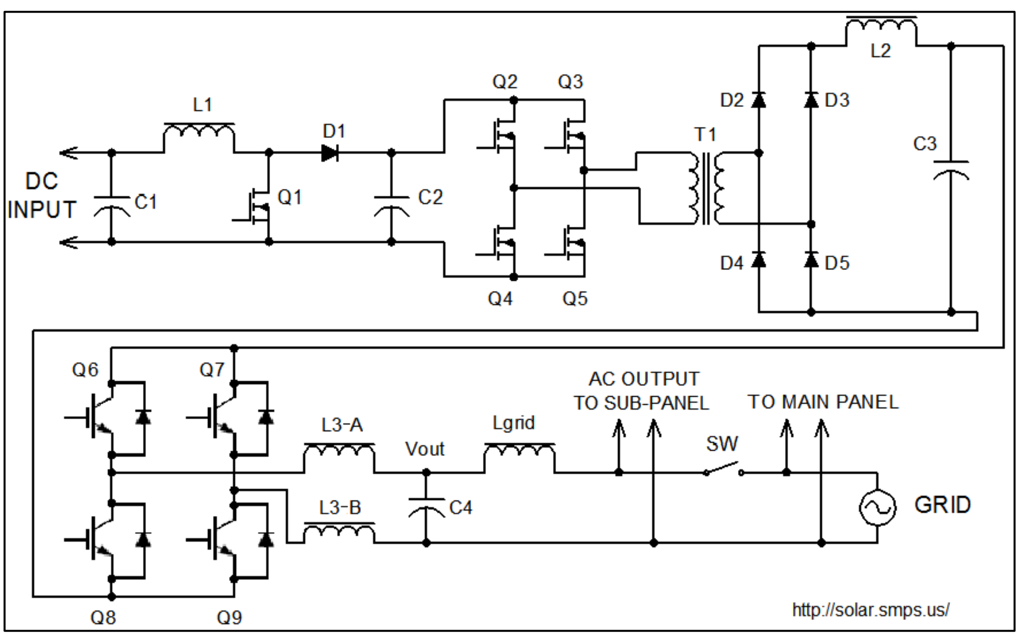
## Attachment 4: Grid Tie Inverter (Sample)



# A GRID TIE INVERTER FOR SOLAR SYSTEMS

Operating a renewable energy system in parallel with an electric grid requires special grid-interactive or **grid tie inverters** (GTI). The power processing circuits of a GTI are similar to that of a conventional portable **DC-AC converter** that operates as a stand-alone device. The main differences are in their control algorithm and safety features. A GTI basically takes a variable voltage from a DC source, such as solar panels array or a wind system, and inverts it to AC synchronized with the mains. It can provide power to your loads and feed an excess of the electricity into the grid. Depending on power and voltage levels, GTIs circuits normally have from one to three stages. A conceptual power train schematic diagram below illustrates the principles of operation of a three-stage grid tie inverter. Such a topology can be useful for low-voltage inputs (such as 12V) in grounded systems. The control circuits and miscellaneous details are not shown here. As I mentioned above, there are also two-stage and single-stage configurations (see examples of **sinewave topologies**).

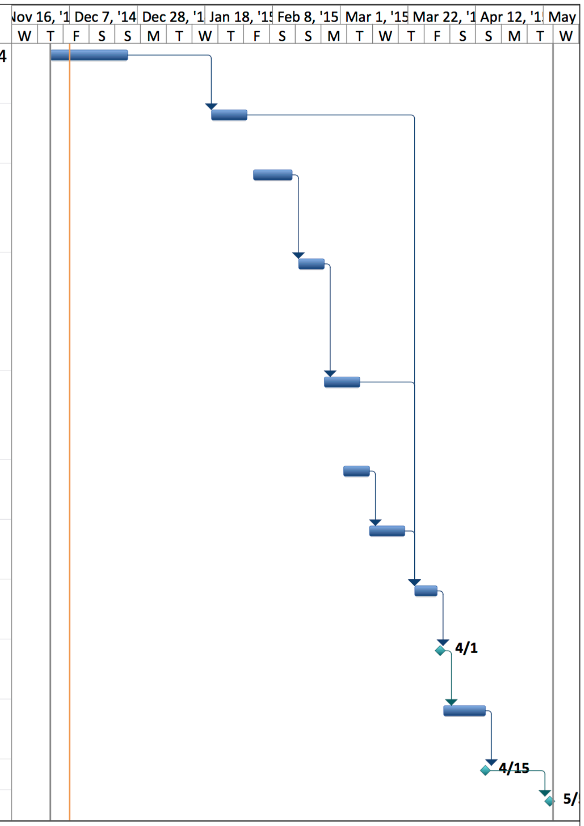
- Home
- Solar energy
- Solar homes
- Inverter
- PV systems
- Off grid
- Grid tied
- Grid tie backup
- PV panels
- PV cells
- Cost
- Pros and Cons
- Efficiency
- Lighting



## Attachment 5: Gantt Charts – Individuals

### *Generation*

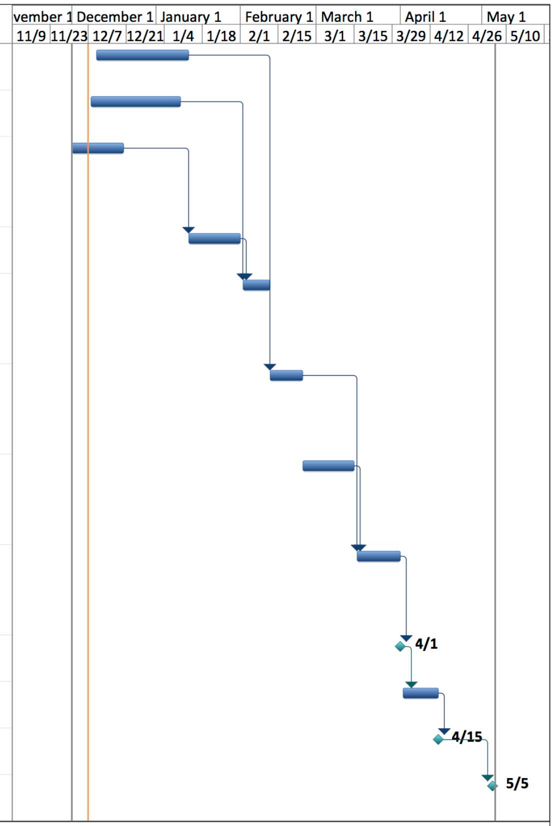
| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | (Generation) Select Components | 18 days | Mon 12/1/14 | Wed 12/24/14 |
| 2 | (Generation) Test Components | 9 days | Tue 1/20/15 | Fri 1/30/15 |
| 3 | (Generation) Design Feedback and Synchronization System | 10 days | Mon 2/2/15 | Fri 2/13/15 |
| 4 | (Generation) Pick Feedback and Synchronization Components | 6 days | Mon 2/16/15 | Mon 2/23/15 |
| 5 | (Generation) Feedback and Synchronization Testing | 9 days | Tue 2/24/15 | Fri 3/6/15 |
| 6 | (Generation) Design Enclosure | 6 days | Mon 3/2/15 | Mon 3/9/15 |
| 7 | (Generation) Construct Enclosure | 9 days | Tue 3/10/15 | Fri 3/20/15 |
| 8 | (Generation) Project Integration | 5 days | Tue 3/24/15 | Mon 3/30/15 |
| 9 | Project Functional Testing | 0 days | Wed 4/1/15 | Wed 4/1/15 |
| 10 | Final Preparation/Details | 9 days | Thu 4/2/15 | Tue 4/14/15 |
| 11 | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 |
| 12 | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 |




Page 1

## *Clean Energy*

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | (Solar) Grid Tie Research | 24 days | Wed 12/10/14 | Mon 1/12/15 |
| 2 | (Solar) Inverter Research | 25 days | Mon 12/8/14 | Fri 1/9/15 |
| 3 | (Solar) Solar Generation Overall Specs | 15 days | Mon 12/1/14 | Fri 12/19/14 |
| 4 | (Solar) Solar Array Design | 14 days | Tue 1/13/15 | Sat 1/31/15 |
| 5 | (Solar) Array and Inverter Setup and Testing | 8 days | Mon 2/2/15 | Wed 2/11/15 |
| 6 | (Solar) Grid Tie Setup and Testing | 8 days | Thu 2/12/15 | Mon 2/23/15 |
| 7 | (Solar) Grid Network Interface Housing | 14 days | Tue 2/24/15 | Sat 3/14/15 |
| 8 | (Solar) Labels, Housing, and Documentation | 12 days | Mon 3/16/15 | Tue 3/31/15 |
| 9 | Project Functional Testing | 0 days | Wed 4/1/15 | Wed 4/1/15 |
| 10 | Final Preparation/Details | 9 days | Thu 4/2/15 | Tue 4/14/15 |
| 11 | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 |
| 12 | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 |

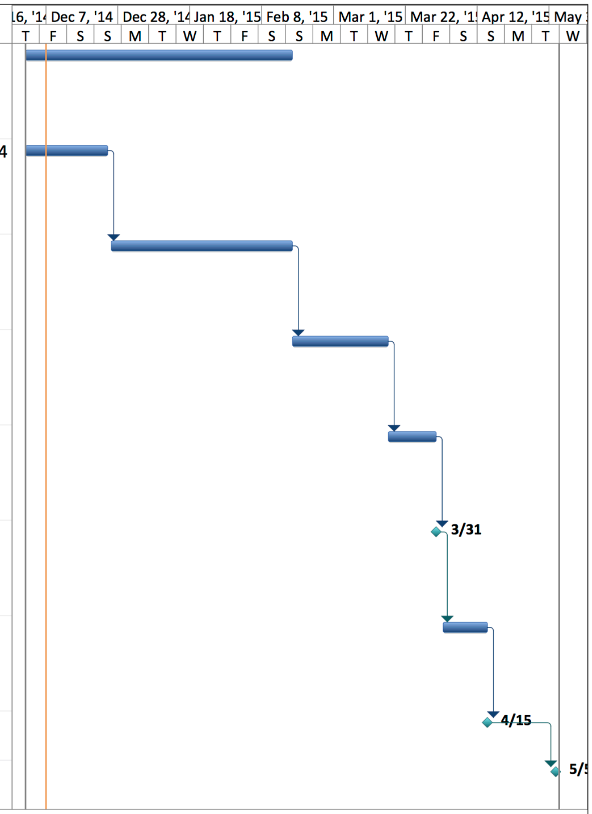



Page 1

*Note: To be updated to align with EC583 class schedule once provided curriculum.*

## *Transmission*

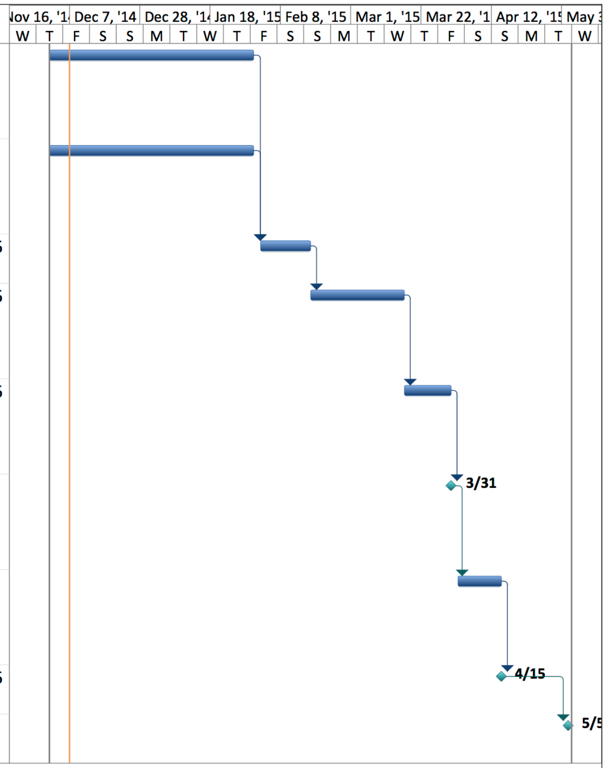
| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | (Transmission) Integration Design | 56 days | Mon 12/1/14 | Mon 2/16/15 |
| 2 | (Transmission) Select RLC Components | 18 days | Mon 12/1/14 | Wed 12/24/14 |
| 3 | (Transmission) PCB Layout | 37 days | Fri 12/26/14 | Mon 2/16/15 |
| 4 | (Transmission) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 |
| 5 | (Transmission) Project Integration | 10 days | Tue 3/17/15 | Mon 3/30/15 |
| 6 | Project Functional Testing | 0 days | Tue 3/31/15 | Tue 3/31/15 |
| 7 | Final Preparation/Details | 9 days | Thu 4/2/15 | Tue 4/14/15 |
| 8 | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 |
| 9 | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 |




Page 1

## *Loads*

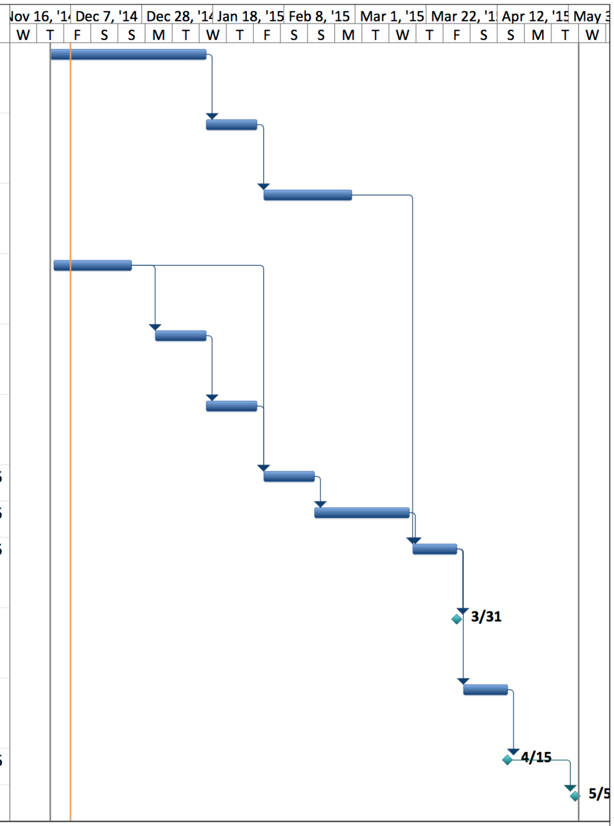
| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | (Load) Safety Design and Part Selection | 45 days | Mon 12/1/14 | Fri 1/30/15 |
| 2 | (Load) Load Selection and Testing | 45 days | Mon 12/1/14 | Fri 1/30/15 |
| 3 | (Load) PCB Design | 11 days | Mon 2/2/15 | Mon 2/16/15 |
| 4 | (Load) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 |
| 5 | (Load) Project Integration | 10 days | Tue 3/17/15 | Mon 3/30/15 |
| 6 | Project Functional Testing | 0 days | Tue 3/31/15 | Tue 3/31/15 |
| 7 | Final Preparation/Details | 9 days | Thu 4/2/15 | Tue 4/14/15 |
| 8 | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 |
| 9 | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 |




Page 1

## *Data Acquisition*

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | (DAQ) Program Data Processing | 34 days | Mon 12/1/14 | Thu 1/15/15 |
| 2 | (DAQ) Test Data Processing | 11 days | Fri 1/16/15 | Fri 1/30/15 |
| 3 | (DAQ) Program and Test GUI | 20 days | Mon 2/2/15 | Fri 2/27/15 |
| 4 | (DAQ) Pick Components | 17 days | Tue 12/2/14 | Wed 12/24/14 |
| 5 | (DAQ) Design Interface Circuits | 11 days | Thu 1/1/15 | Thu 1/15/15 |
| 6 | (DAQ) Test Interface Circuits | 11 days | Fri 1/16/15 | Fri 1/30/15 |
| 7 | (DAQ) PCB Layout | 11 days | Mon 2/2/15 | Mon 2/16/15 |
| 8 | (DAQ) PCB Fabrication | 20 days | Tue 2/17/15 | Mon 3/16/15 |
| 9 | (DAQ) Project Integration | 9 days | Wed 3/18/15 | Mon 3/30/15 |
| 10 | Project Functional Testing | 0 days | Tue 3/31/15 | Tue 3/31/15 |
| 11 | Final Preparation/Details | 9 days | Thu 4/2/15 | Tue 4/14/15 |
| 12 | Delivery Day | 0 days | Wed 4/15/15 | Wed 4/15/15 |
| 13 | ECE Day | 0 days | Tue 5/5/15 | Tue 5/5/15 |

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