Boston University
Electrical & Computer Engineering
EC464 Capstone Senior Design Project

User's Manual

Smart Grid

Submitted to:

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by

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Smart Grid

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Smart Grid

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Executive Summary

Initially built by a previous senior design team, The Smart Grid test facility is an educational tool for engineering professors to facilitate in-class demonstrations. After several years, we are restoring the test facility in order to make it functional for a professor to easily set-up and use in class through a user interface and testing procedures that we design. The user interface will collect and analyze recorded data, which students can observe and understand through the lens of what they have already learned. 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.

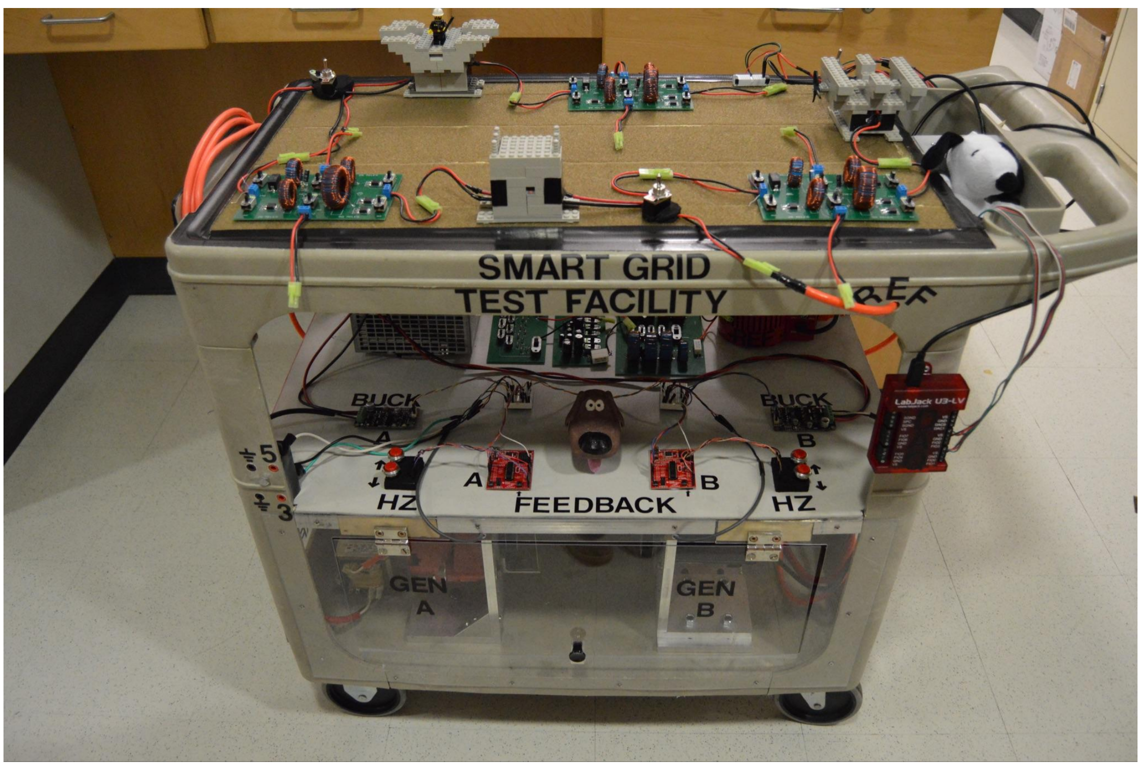

Figure A - The Smart Grid Test Facility

1 Introduction

Project Purpose

The Smart Grid test facility is designed to introduce engineering students to how a power grid's generators, transmission lines, and loads work together to provide electricity. In order to adapt and work in energy technologies, engineers must be familiar with the functionality of the power grid and how different components work together. Professor Pisano, who instructs the university's Electric Energy Systems 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 Electric Energy Systems.

Generation

A majority of the electric grid model was completed by a previous team, who ensured that the design incorporated the basic aspects of power generation. 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. 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. Overall, the three sources generate 8.48 Vrms (12 Vmax) at 60 Hz. The grid maintains these values through changes in load and transmission line lengths.

The Grid: Transmission and Loads

The transmission network that comprises the "grid" of the model 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 a mode of power transport. Just as a house or commercial building's energy draw affects aspects of real grid transmission, various loads can be added to the system to simulate real-world scenarios. 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. Two 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 modular loads, 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

In order to provide experimentation and testing, this test facility includes a PicoScope and DAQ unit integrated with MATLAB App Designer. The PicoScope allows the user to measure live oscilloscope data in order to synchronize the generators and ensure the grid is working properly. The model's original design did not include oscilloscope capabilities, so the ability to view the voltage signals directly in the grid was a critical improvement. Additionally, a new measurement system was designed, utilizing a more robust data acquisition board (National Instruments myDAQ), which allows the user to measure and save voltage and current data, calculate phase difference, power factor, and visualize all of the inner workings of the grid.

Document Objective

The remainder of this document details the test facility's functional, technical, and systematic elements. 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 this project's development and construction.

2 System Overview and Installation

2.1 Overview block diagram

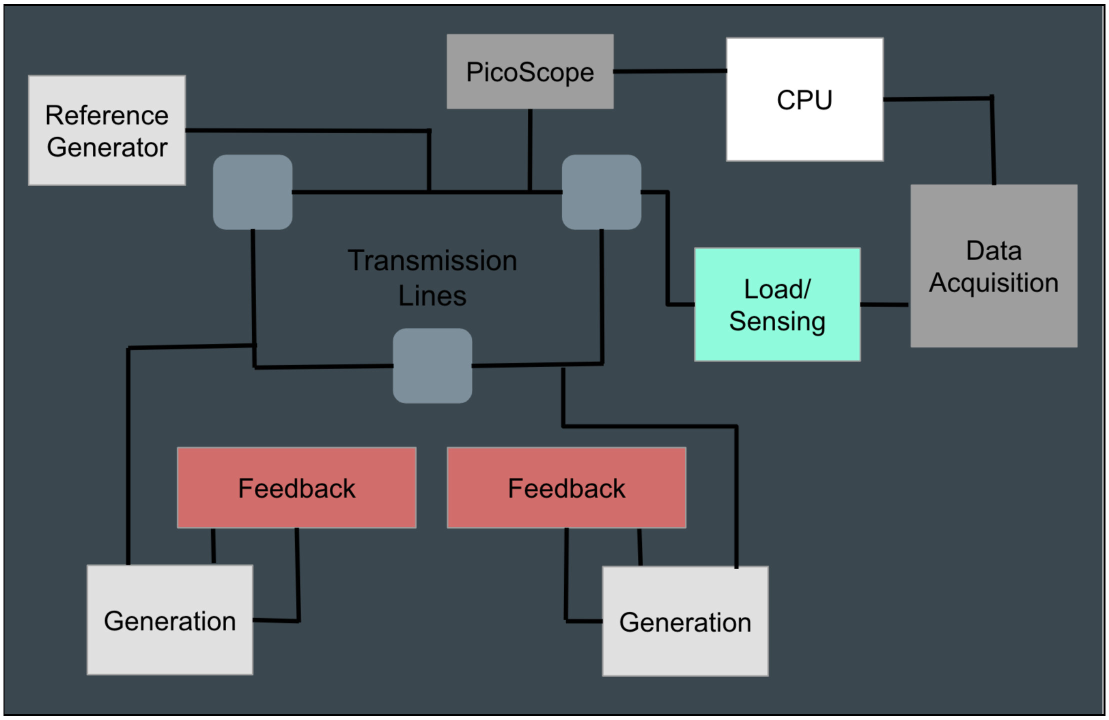

Figure 2.1.1 - High level schematic of the main components of the model.

The Smart Grid model is housed on a cart with 3 levels. The bottom shelf hosts the wind turbine generators with their motor driver systems. The feedback MSP430's on the middle shelf constantly measure and update the generators to ensure proper frequency and voltage. This middle level also holds the variac/reference generator being sent directly to the grid. There is some storage and power supply on this shelf, but the rest of the transmission, loading, sensing, and data acquisition stages are found on the top of the model. An extended power strip provides power to the reference generator, a 24V DC power supply, and a 15V power supply. The 24V powers the motor drivers that turn the turbine generators, while the 15V is separated down to 3.3V for the MSP430 and 5V for the encoder measuring frequency for the MSP430.

2.2 User interface

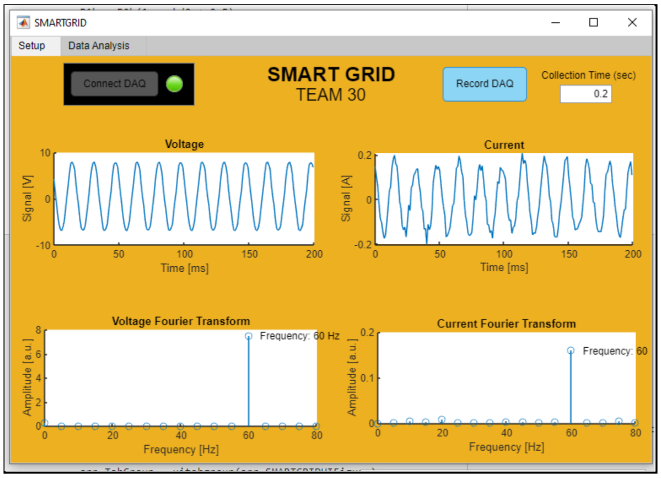

Figure 2.2.1 - Setup tab of the GUI. Includes Voltage and Current waveforms with frequency analysis.

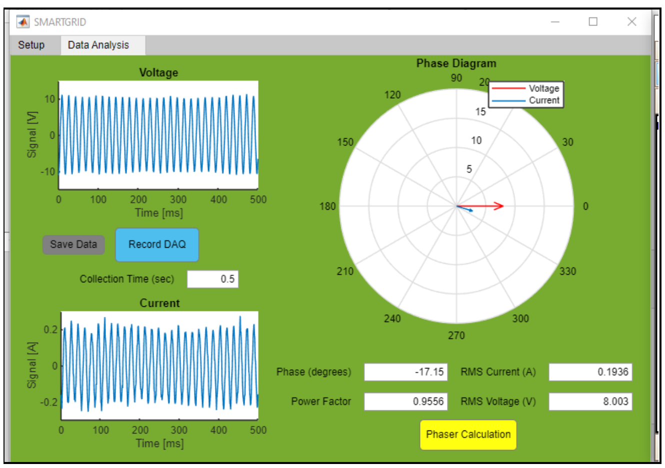

Figure 2.2.2 - Data Analysis tab of the GUI.

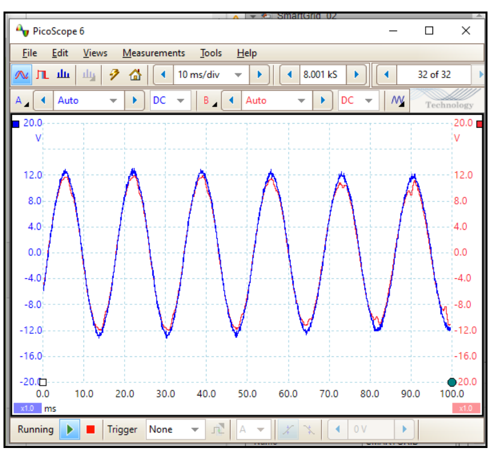

Figure 2.2.3 - PicoScope User Interface

2.3 Physical description

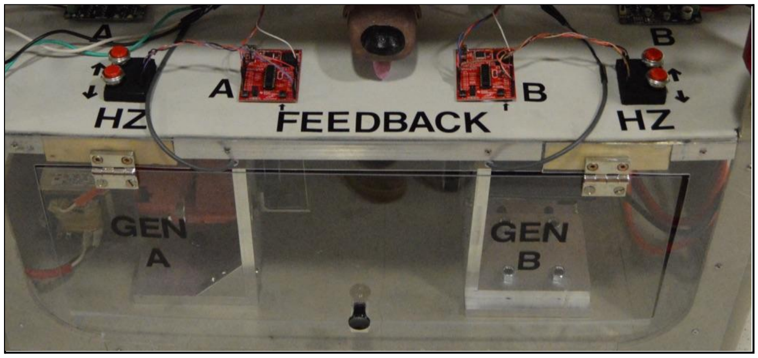

Figure 2.3.1 - Location of MSP430 controllers referenced in section 2.4.

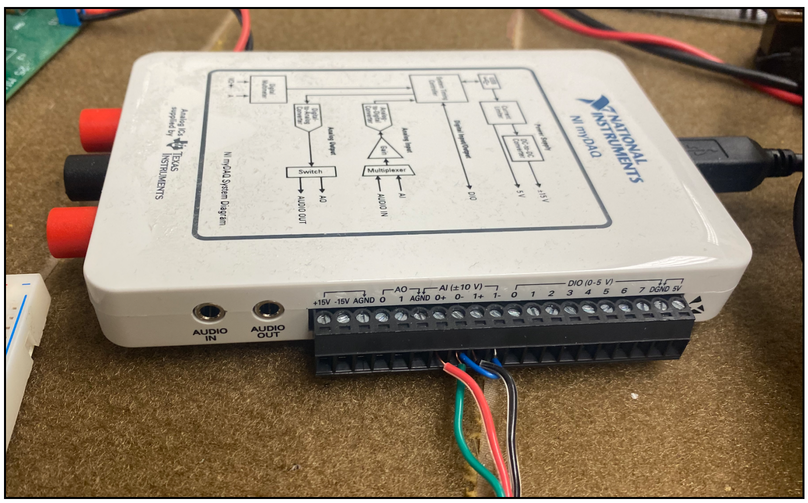

Figure 2.3.2 - NI myDAQ. 4 wires carry the signal data and ground from the sensor board for measurement of voltage and current signals. The ground ports are connected, so only 3 wires enter the DAQ.

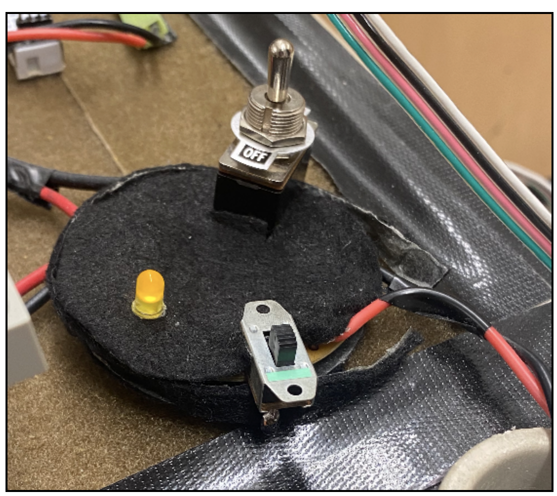

Figure 2.3.3 - One of the synchronization circuits. The on position of the bottom black switch is marked with green tape. The top "on/off" switch adds the generator to the grid.

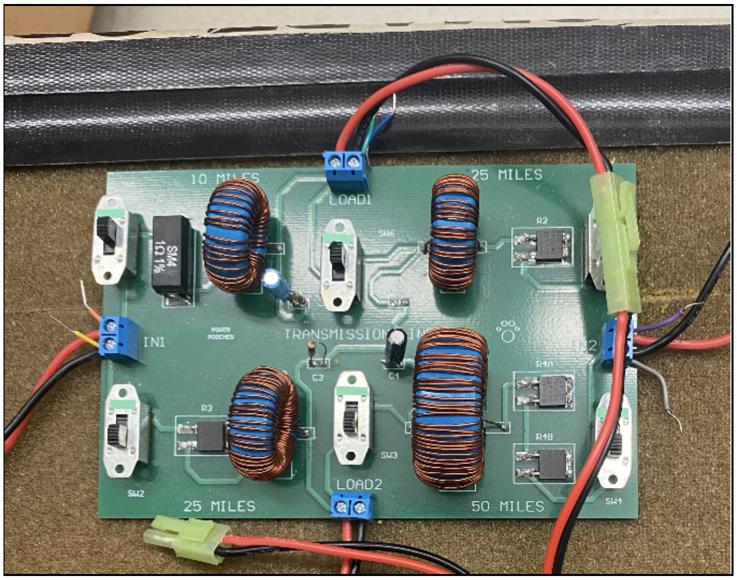

Figure 2.3.4 - Transmission line board. There are three of these delta-connected on the cart. The user can adjust the transmission length by flipping the switches.

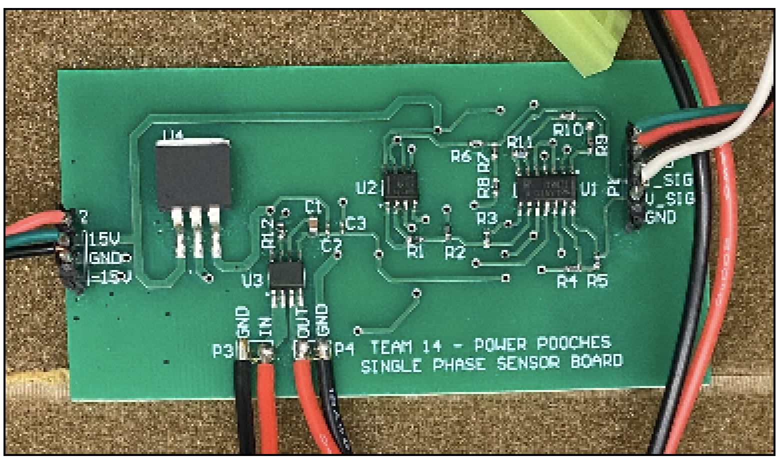

Figure 2.3.5 - Sensing board. This board turns the current signal into a voltage signal and scales the voltage signal down in order to save input into the myDAQ. The GUI then scales up appropriately to get the proper waveforms.

2.4 Installation, setup, and support

Since we are building the software directly on the client’s computer, all necessary drivers and packages should already be installed. If the user needs to use a different computer with the model, the following list of software components should be installed:

- MATLAB
- MATLAB Add-Ons:
  - MATLAB Signal Processing Toolbox
  - MATLAB Data Acquisition Toolbox

- MATLAB Data Acquisition Toolbox Support Package for NI-DAQmx Devices
- Phase Difference Measurement function

➢ DAQ driver software: NI DAQmx Elvis
➢ Final MATLAB GUI
➢ PicoScope 6 App

Before starting up the grid, the user should be able to collect data from the DAQ and PicoScope in order to make the setup process more efficient. To connect to the DAQ, the user presses "Connect DAQ" in the GUI as shown in Figure 2.2.1. After the connection is successfully completed, the lamp to the right of the button will turn from gray to green. If there is a problem with the connection, this lamp would turn red, and the user should restart the application after unplugging and replugging the connection cable. Running the PicoScope 6 App while the PicoScope is plugged in should automatically connect, and the user should select "Auto" for both channels, and the "Run" button will begin data streaming. Figure 2.2.3 shows PicoScope 6 with both channels running.

To bring power to the model, plug the orange extension cord/power strip into any wall outlet. This should automatically power up the MSP430 boards, and then the variac should be switched on to send the reference 60 Hz to the grid. Next, the user can start either generator A or B by pressing the reset button on the corresponding MSP430. The reset button is indicated by a taped arrow next to the board. Once the button is pressed, the generator should turn on and is now ready to be added to the grid.

The designed synchronization circuit can be activated by sliding the black switch to its on position (green), and the user should see the synchronization-indicating LED begin to flash. This LED can be used as a visual cue for a proper time to add the generator to the grid. When the LED is off, the generator waveform is perfectly in phase with the reference generator's waveform. It's important that it's only added to the grid when these phases are matched and the LED is off. Otherwise, current could backfeed into the turbine generator and cause damage to it. Once the "on/off" switch is turned on, the PicoScope helps determine if synchronization is successful. Before closing this "on/off" switch, the user should connect the PicoScope probes to either side of the synchronization circuit to view the desired generator compared to the signal in the grid. Closing the "on/off" switch will add this generator to the grid, and then the user can view the PicoScope data to ensure that the voltages are remaining stable.

This synchronization process will be repeated for the other generator after activating it from the MSP430.

3 Operation of the Project

3.1 Operating Mode 1: Normal Operation

Before the test facility and the myDAQ can operate properly, it is critical to perform the steps described in Section 2.4. These steps ensure the grid is working properly and safely before continuing on.

Note that because a previous team worked on this project, there is a large amount of additional information and resources that will be compiled onto a USB drive and provided to the client.

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 at least one generator begins powering the network, 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 3.1.1 – 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*.

Phasors

The most important aspect of the myDAQ is its ability to calculate the phasors associated with current and voltage. Here, students can learn and understand how different load and transmission line configurations impact the VI characteristics.

In order to visualize the phasors, the user first needs to press the "Test DAQ" button in the Setup tab of the GUI. This allows the DAQ to collect and save the data in MATLAB, which then performs the analysis. Then, on the Data Analysis tab, there is a "Phasor Calculation" button to press. In the corresponding boxes, the phase and power factor will appear and the current and voltage phasors will appear on the graph. For more information on how the phasors should appear, see Section 4.

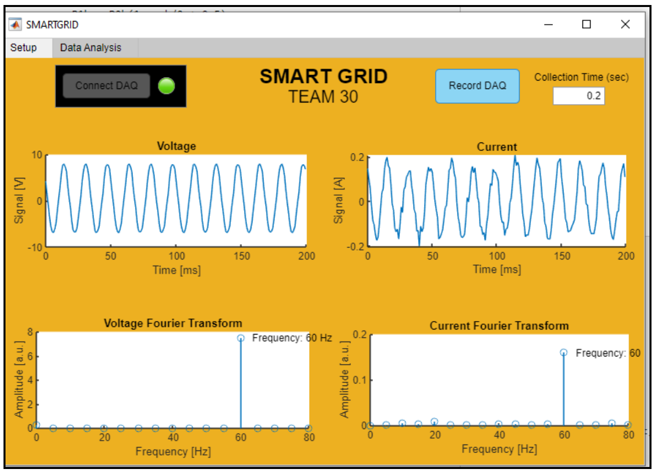

Figure 3.1.2 - The GUI after pressing "Record DAQ" on the Setup tab. The plotted data should look reasonably sinusoidal, with roughly 60 Hz frequency.

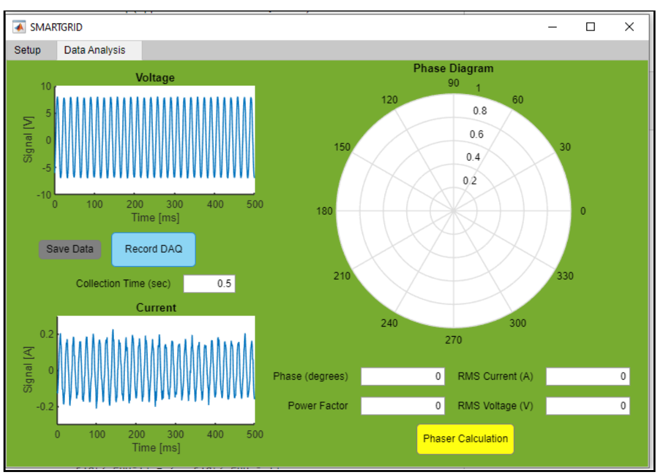

Figure 3.1.3 - The GUI after pressing "Record DAQ" on the Data Analysis tab. The voltage and current waveforms show up and should be sinusoidal with potentially some noise.

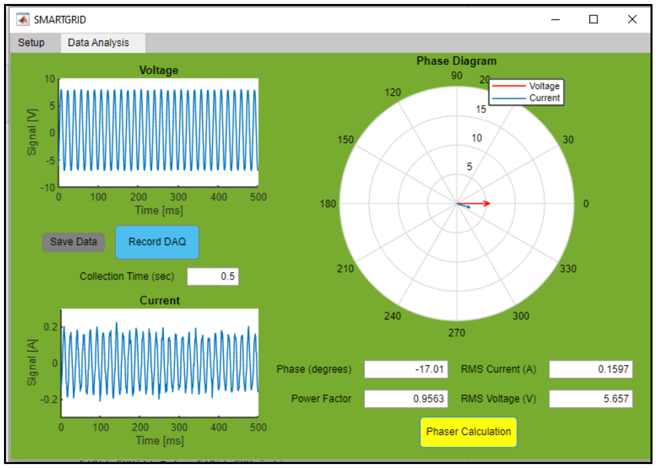

Figure 3.1.4 - The GUI after pressing "Phasor Calculation." This example had a small inductive load, which is why the phase is negative.

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.

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, which 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, and 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 failed to synchronize many times—simply turn off the power, and there will be no further issues. The components in this system are rated at or over 2A, so 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, so the creators recommend that users synchronize with the PicoScope to help visualize the process.

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 to protect the expensive equipment.

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 components break, then the associated parts should be replaced.

Synchronization

Occasionally, synchronization can cause some issues if done improperly. If a generator is switched into the grid when unsynchronized, it can cause backfeeding into the generators due to the potential voltage difference. It's critical that the user looks at the PicoScope live data to ensure that the grid maintains a roughly 60 Hz, 8.48 Vrms (12 Vmax) waveform. Once synchronization is completed correctly, there should be no issues with generation.

Data Acquisition System

When connecting the myDAQ to MATLAB, some issues can arise if the processes are not performed correctly. The user may get errors such as "no DAQ found" or "DAQ is being used by other processes." Errors can occur if the DAQ was accessed outside of the GUI or if connections are loose. The user can simply turn the electrical grid off, replug connections, and start the process over again, resolving any issues.

After the myDAQ is connected, there can sometimes be an error of connections where an influx of current rushes into the DAQ. This error can occur if the myDAQ connects to the load before connecting to MATLAB, prompting the DAQ to stop collecting data and give an error message that says that the power input was too high. The user should disconnect the load from the transmission lines, restart the GUI, and then try again after letting the system rest for a minute.

If either of these errors persist, the user should unplug the myDAQ from the computer and restart MATLAB before attempting the connection again.

3.3 Safety Issues

During operation, the user should understand all safety-related mechanisms. 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 to touch.

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 the 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 and S6 or S4 and S5. This action will preserve the transmission line and downstream loads.

Concerning loads, the creators recommend the isolation switches be held open while the generators for the grid are in start-up. While the generator starts up, overcurrent conditions can damage the loads if they are fully connected. This additional current path will interfere with the synchronization process used between the generators.

Regarding data acquisition, due to the nature of the board, users should make sure that the power supply connections are correct before applying a power source to the sensor PCBs. 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, powered by an ordinary wall outlet, provides the motors with a max nominal voltage of 24VDC at a max 20A. 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. This ratio requires the motor to be supplied with roughly 17.5V in order to establish 60 Hz at no loading, which allows 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 12 Vmax, roughly 8 V_{RMS}.

Synchronization

The synchronization method modifies the "synch bulb" method that is commonly used in real-world applications. The objective of synchronization is to make two 60 Hz sine waves that are out of phase, in phase. By design, the reference generator (the red variable transformer) has a voltage magnitude nearly equivalent to the alternators' output voltage (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.

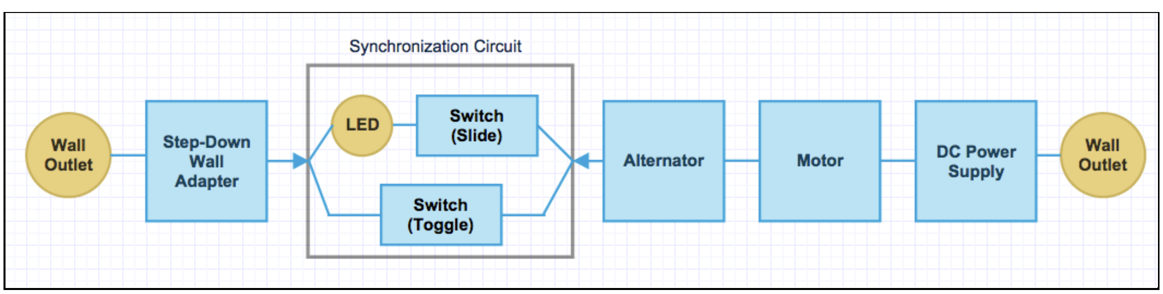

Figure 4.1 – Synchronization Circuit Layout. The area inside the gray box is shown in Figure 2.3.3.

The system begins by turning on the reference generator, which is the step-down wall adapter (variable transformer). Next, both the generator's sliding switch and toggle switch are in the off position. Next, the motor/alternator generator is energized. 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 according to their phase: when they are in phase, the LED dims, and when they are out of phase, the LED is bright. When the LED dims, the user should close the toggle switch, which connects the in-phase generators together. After, there should be one final 60 Hz 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 alternator's output frequency would change as loads, transmission line lengths, and other system properties change. The variation in frequency occurs 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's frequency is unstable.

Stability is achieved via a feedback control loop that is attached to both motor/ alternator setups. The diagram below shows the basic layout of the system.

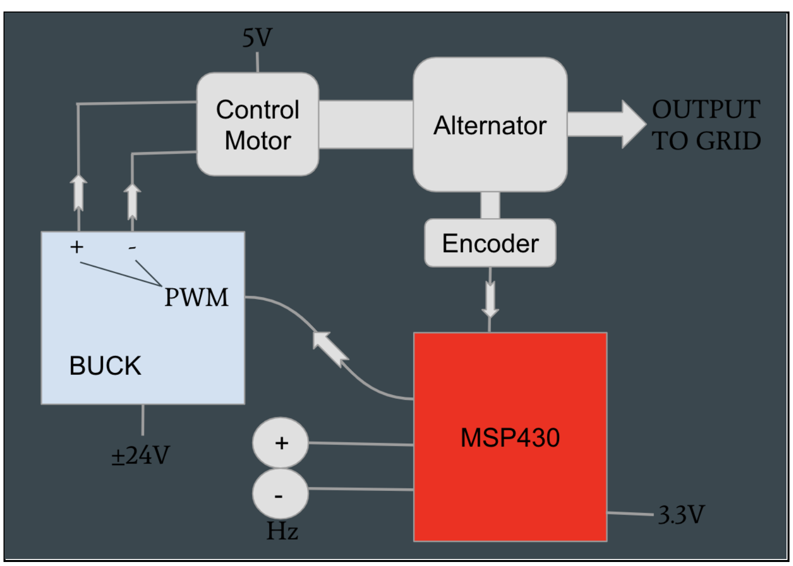

Figure 4.2 – Feedback Control Loop Layout

The motor driver board (buck converter) has two inputs: a pulse-width modulated (PWM) signal and a DC input voltage. The input voltage comes from the 24V DC power supply plugged into the power strip. The MSP430 generates a square wave PWM signal. This signal is a square wave, and the modulation affects the duty cycle of the wave. When the buck converter receives a longer duty cycle, it outputs a higher voltage to drive the motor. A shorter duty cycle supplies less voltage to the motor.

The amplitude of the voltage supplied to the motor determines its rotation speed, which dictates the alternator's output frequency. This frequency is exactly what we aim to keep constant at 60 Hz. To achieve 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 to the MSP430 with a duty cycle proportional to the frequency of the alternator's output. The MSP takes this information and determines how close or far from 60 Hz the alternator's power is. Based on this calculation, the MSP adjusts the duty cycle of the square wave sent to the buck converter. For example, if the frequency of the alternator drops to 55Hz, the encoder's PWM signal will have a frequency corresponding to 55Hz, recorded by the MSP. In response, the MSP will increase the duty cycle of its output PWM so that the motor driver increases its output voltage and thus increases the speed of the motor; finally, this pushes the alternator's frequency up to 60 Hz. The degree of modulation depends on how close or far from 60 Hz the alternator is at each sample.

The MSP constantly samples 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.

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 Figure 4.3.

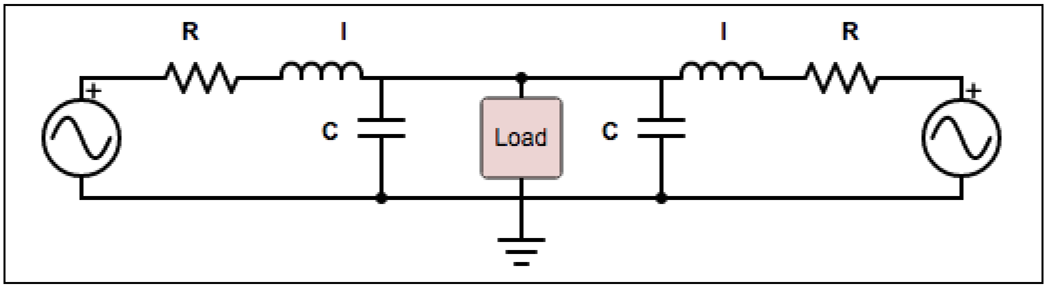

Figure 4.3 – In this figure the load is connected at a point between the two generation points and transmission lines as it would be on a real power grid. This configuration causes the load to be seen as a parallel path to ground.

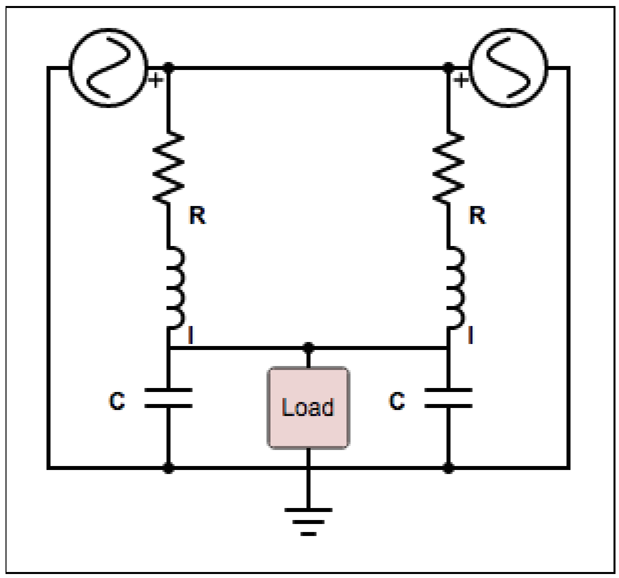

Figure 4.4 - This figure is an adjustment of the circuit in Figure 4.3. It operates under the assumption that the two generators are phase locked, which makes the calculation less complex.

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 a given load.

Power

The test facility's primary objective is to supply power to the loads through the transmission lines. Because different loads can be different combinations of resistance, capacitance, and inductance, the power supplied changes as the voltage and current stay out of phase.

There are three kinds of power: reactive power, real power, and apparent power. Reactive power is the power that is consumed by inductive and capacitive loads. Real power is the load power consumed by resistive loads. Apparent power is the combination of reactive and real power. Seen by the graphs below, the IV characteristics change depending on the load.

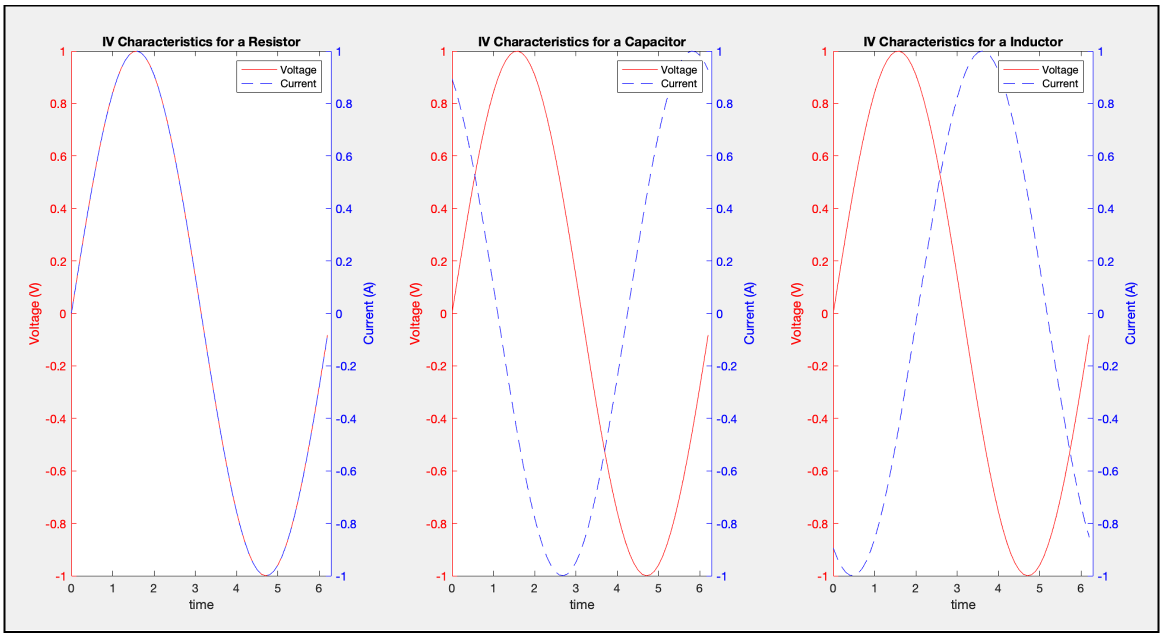

Figure 4.4 - The IV characteristics for a resistor, capacitor, and inductor. For a resistor, current and voltage are in phase. For a capacitor, current leads voltage by 90˚. For an inductor, current lags voltage by 90˚.

In electrical energy systems, the problem with current and voltage being out of phase is that the electrical grid consumes reactive power. Because the grid is alternating current (AC), reactive power is not utilized but rather oscillated back and forth by capacitors and inductors and dissipated in the resistance of the transmission lines. As a result, power is wasted. Ideally, the phase is zero, which would make the power factor, defined as the $cos(phase)$, one. By changing the transmission lines' natural impedance, capacitance, and resistance of the test facility, students can visualize how different combinations change the power factor and phase.

5 Relevant Engineering Standards

Electric Safety Codes

For the electrical grid, IEEE sets a variety of applicable standards. The National Electric Safety Code (NESC) sets guidelines for how to properly work with electrical systems and electrical grids. This code is maintained and distributed by IEEE for all pertinent personnel. Although this project did not consult NESC, NESC regulates many of the test facility's components such as power generation, transmission lines, and synchronization.

IEEE Standard 1547 discusses the interconnection of energy sources. Standard 1547 is used to build up infrastructure for integrating renewable energy technology. Although the test facility does not have any renewable energy sources, the generators could serve to represent renewable sources such as a wind turbine.

IEEE Standard 2030 outlines a foundation of knowledge for Smart Grids and how they can be implemented into different power systems. The test facility is not a Smart Grid, but it could be converted into one by a future team.

Communication Standards

IEEE standard RS-232 describes how data is sent along a serial connection. MATLAB views the DAQ and PicoScope as objects for programming. Behind the software, this standard, as well as USB3, describes how the data will actually be carried along the wire connecting the devices to the computer.

6 Cost Breakdown

Though the current test facility is already a modified version of an original design, the next unit could still be optimized for production cost. Due to the system's modular nature, there are extra unused PCBs, which could be used in future versions. Additionally, many of the minor costs for the model's original construction could be purchased in bulk to reduce the price per model. It's also important to note that the client provided the PicoScope and DAQ devices and were not purchased for this project.

Project Costs for Production of Beta Version (Next Unit after Prototype)				
Item	Quantity	Description	Unit Cost	Extended Cost
Smart Grid Test Facility	1	Alpha version of Smart Grid project	$1,906.57	$1,906.57
PicoScope Series 2204A	1	Mini Oscilloscope with 2 Channel Probes	$149.00	$149.00
NI myDAQ	1	Data acquisition board	$550.00	$550.00
USB-B cable	2	Connects PicoScope and myDAQ to a computer	$8.81	$17.62
ECL30UD02-S	1	Replacement for bench-top power supply	$89.62	$89.62
			Beta Version-Total Cost	$2,712.81

7 Appendices

7.1 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	

7.2 Appendix B – Team Information

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I am a senior in electrical engineering from Denver, Colorado. Following graduation, I will be moving to Washington D.C to be a Naval Reactors Engineer working with the Nuclear Reactors used on submarines and aircraft carriers.

Aidan McCall
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I am a senior in electrical engineering, also from Denver, Colorado! I have not committed to anything yet, but I plan to do testing and research in optics for either quantum computing or telecom applications.