VARIABLE VOLTAGE BATTERY PACK

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Final Report for ECE 445, Senior Design, Spring 2017

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03 May 2017

Project No. 26

Abstract

The variable voltage battery pack is a self-contained system of rechargeable batteries, power electronics, and measurement systems. It is flexible and portable energy storage device. The user can select from either an AC or DC voltage output and determine the output voltage magnitude. The system will provide the user with visual feedback on current and voltage from the system. Although we encountered system integration issues, we successfully demonstrated that a battery pack can be made into a flexible storage unit through the use of power electronics. Future iterations could increase the power output and reliability of the project and increase the functionality of the measurement subsystem.

Contents

1. Introduction

1.1 The purpose and Usefulness of the Project

As people come to depend more and more on electricity, industry must meet the growing need in two ways. First, access to the electrical grid must be expanded and made more reliable. This has been the focus of much effort and research but the second need is to provide more effective and flexible portable energy storage. Today, much of the portable electrical energy comes in the forms of batteries. The problem with using batteries is their inherent inflexibility. Batteries are usually designed to output a limited voltage range, and only at DC. Batteries are also “dumb.” They cannot control themselves. They cannot protect against overcurrents, or warn the user of low charge. If the user wants to check the state of the battery, they then must attach an external metering system for themselves.

Should a user require the use of different voltage ranges for different applications, then they would need to carry different batteries. This is inefficient. Since electrical energy is easily converted from one voltage to another, why not provide the user with one battery pack and then give them the tools to select the output they need for a particular application? Going a step further, why not also allow them to draw AC power? This lets the user carry one power source to meet a range of portable applications. We want our project to give the user control over their battery. That means giving them feedback on how they are using their battery. To do that, the variable voltage battery pack gives the user a visual display of important circuit measurements. They will be able to see for themselves how much voltage is on the batteries, what voltage their application is drawing, and what current they are drawing.

1.2 Summary of Project Function

Our mission statement is to produce a rechargeable battery pack with power electronics that allow the user to control the output voltage while also providing power measurements for display to the user. To fulfill these functions, our project is designed for the following high level objectives:

- Stores electrical energy in rechargeable batteries
- Generates a DC and AC voltage simultaneously
- Gives the user the ability to determine the output voltage magnitude
- Measures key current and voltages, and displays them to the user
- Can be placed in a portable, self-contained enclosure

1.3 Overview of Project Blocks and Subprojects

To fulfill our mission statement we require a system with an input power module, a control unit, an output power module, and rechargeable batteries. A high level block diagram is provided in Figure 1. The input power module is required to charge the batteries and provide power for the rest of the circuitry. The control unit is responsible for interfacing between the machine and the user. It interprets the user input through a control knob potentiometer, measures the battery and output power parameters, and displays those parameters to the LCD screen. Finally, it is responsible for directing the operation of the output power module based off user input. The output power module consists of a DC/DC buck-boost converter in series with an inverter and transformer. The user will be able to draw power from either the DC/DC converter or the transformer. The voltage level of both the DC and AC output is controlled by the output of the DC/DC converter, as directed by the control unit. The lead acid batteries store electrical energy from the input power module. The battery terminals provide power for the control unit and output power module.

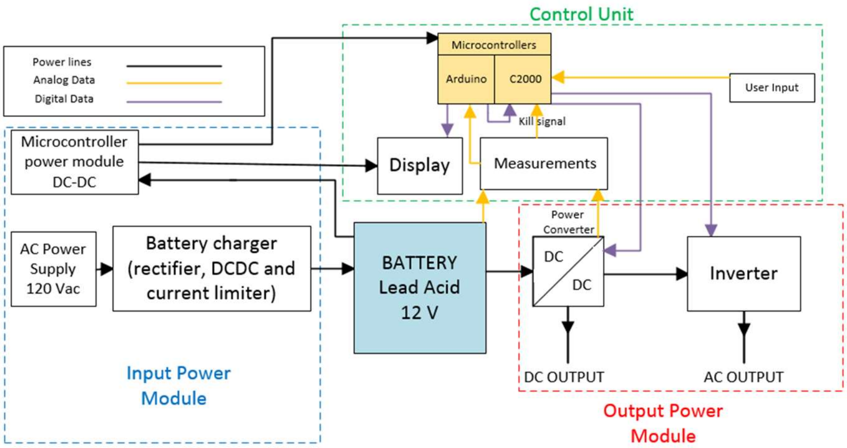

Figure 1: Block Diagram

Figure 2 shows the physical assembly of our project. All modules have been placed in an enclosure to demonstrate that our project can be portable and self-contained. The weight is approximately 20-30 pounds, which is light enough to be carried by a human adult. Most of the weight comes from the 2 lead acid batteries and the output transformer. Although this prototype uses a metal enclosure, a commercial version would come in a non-conductive container with fixed outlets for the input and output power terminals. The control knob and LCD screen would be mounted onto the container. The batteries, microcontrollers, and power electronics would be mounted into place. We judged that a industry-grade enclosure was beyond the scope of our project, given the time constraints and mission objectives. The transformer could also be smaller, given our chosen power requirements, and this would make the box lighter.

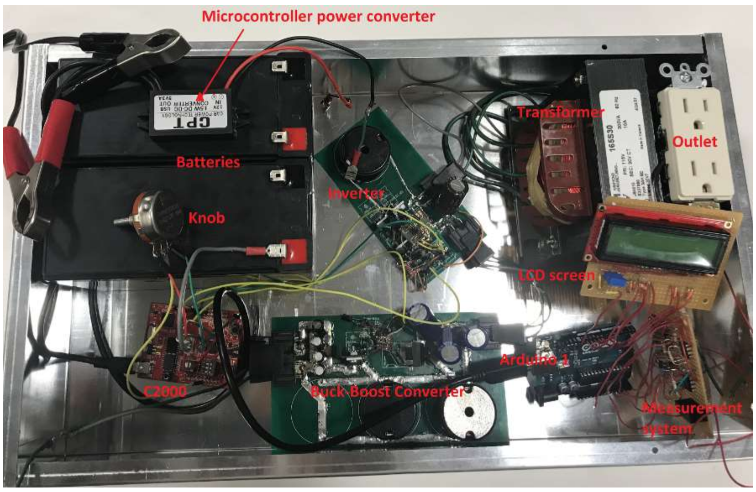

Figure 2: Finished product

2 Design

2.1 Input Power Module

The input power module is responsible for rectifying the grid AC voltage to supply the variable voltage battery pack. It is designed to connect from a standard U.S. wall outlet and provide a DC voltage to charge the battery and operate the microcontrollers. The input power module consists of commercial components, but we were responsible for integrating the purchased parts into the project. We selected commercial parts for safety reasons, and because commercial parts did not hinder the functionality of our input power module. Our project had sufficient hardware complexity in the measurements systems, control unit, and output power electronics. We judged that building parts whose job could easily be done by commercial parts would waste time and introduce more points of failure.

2.1.1 Battery Charger

Our battery charger is the Battery MINDer PLUS 1500 or BM1500. The battery charger is a purchased component that is specialized to correctly charge lead-acid 12V DC batteries. It connects to US wall power and charges the batteries in separate stages to prevent the shortening of operation life. We purchased this component for safety reasons. Lead acid batteries require a carefully controlled charging sequence [1]. Designed a good battery charger is a project in of itself, and it is important that it's done correctly because mischarging of a lead-acid battery is potentially hazardous [2]. Overcharging a lead-acid battery, for instance, poses an explosion hazard as the battery undergoes electrolysis, producing hydrogen gas.

2.1.2 Batteries

The energy storage of the system will be provided by two 12V, 10A rechargeable lead-acid batteries, each with 10 Amp-hour capacity, and connected in parallel to double the capacity and current. The voltage on each battery is about 12.5V when fully charged and 11.7V when depleted.

2.1.3 Microcontroller Power Module

The microcontroller power module is a commercial buck converter by CPT that is connected to the 12V battery power and steps down the voltage to 5V in order to power both microcontrollers. It has two USB outputs that connect directly to both the C2000 and the Arduino. It is rated for 15W which is sufficient to meet the power usage of both microcontrollers.

2.2 Output Power Module

The output power module consists of a DC/DC converter, an inverter, and a transformer. The output power module is responsible for taking the 12V battery power and converting into a range of DC and AC power for the user. It is controlled by the microcontrollers of the control module which changes the magnitude of the voltage through switching control.

The power stages of the output power module are shown in Figure 3. The power stages help to conceptualize voltage and current at each stage in the system. By knowing how much power the user intends to draw and then working backward through the converters, we can see how much power, voltage, and current is going through each stage and also how much power is being drawn from the batteries. For our project we wanted to be able to supply US wall power because most devices that would use AC power would need to be charged at that level. We also wanted to supply a large voltage range so we set 120 V_{rms} (wall voltage) as our maximum voltage for AC output at $1A_{rms}$ for maximum output power of 120W. We decided on 1A because most devices and equipment in the power ranges we wanted to be able to charge draw about 1A. We also wanted to supply 5V DC which is a common DC voltage many devices charge at so we set that as our minimum DC output voltage. We tried a number of voltage ranges and transformer turns ratios combinations before deciding on a maximum DC voltage of 40V which would invert into 30V AC rms. Then we only needed a 1:4 transformer to step up the voltage to hit our AC output max. The power stages shown in Figure 3 assume 100% efficiency for simplicity. We used this diagram to help choose our part sizes, duty cycle ranges, and current trace sizes.

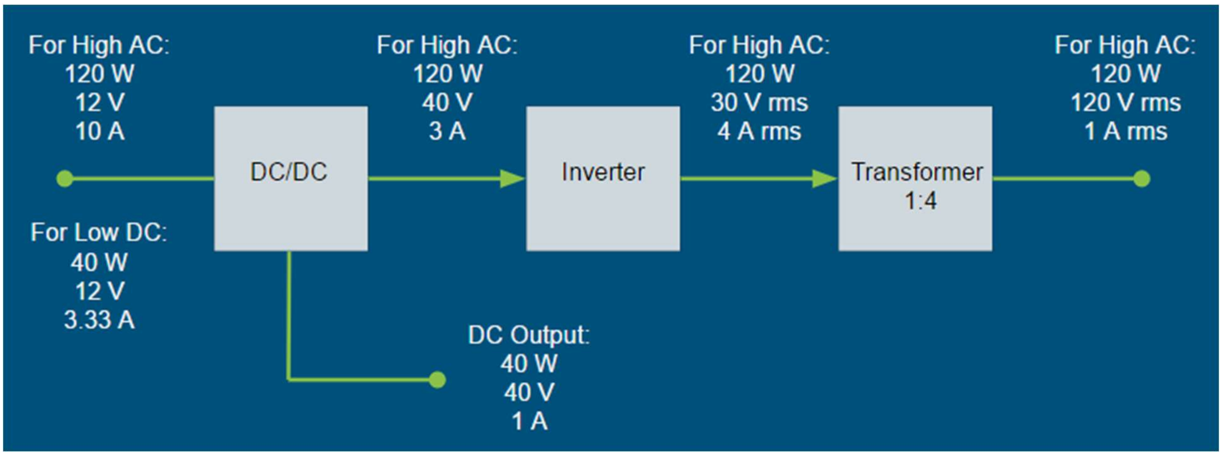

Figure 3: Idealized power stage flow diagram of the output power module assuming 100% efficiency.

2.2.1 DC/DC Converter: Buck-Boost

The DC/DC converter is responsible for taking battery power at 12V and converting the voltage to a different value at its output. Based on our specified range from our power stages, we need to convert 12V from the battery into 5V up to 40V. In order to do this we need to choose a converter topology that allows for reducing and increasing the input voltage. The standard for this is the buck-boost converter, which is what we chose [3]. The output of the buck-boost connects directly to DC output to provide DC power to the user. It also connects to the input of the inverter. The C2000 in the control module also connects to the buck-boost through sending PWM signals to the buck-boosts' gate driver which controls its switching action. This PWM signal effectively controls what output voltage magnitude the buck-boost will have.

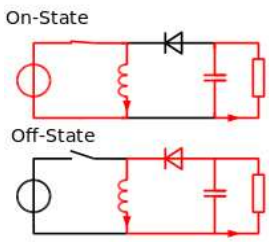

Figure 4: Buck-boost switching states [4]

The buck-boost converts an input voltage to a different magnitude through switching action and energy storage. Figure 4 shows the two stages of a buck-boost converter. In the first stage the switch is closed and the source stores energy in the inductor magnetically. In the second stage the switch is open and the inductor transfer the energy to the load at a different voltage magnitude. This magnitude is dependent on the input voltage magnitude and the duty cycle of the waveform controlling the switching action of the switch. The buck-boost converter also inverts the polarity of the voltage so if the input voltage is positive to some reference then the output voltage will be negative [3].

$$V_O = V_i * \frac{-D}{1-D} \tag{1}$$

Our voltage limits are 5V and 45V and let's assume that V_{DON}=0.92V and V_{DSON}=1.56V so the D will be:

$$-(45+0.92) = (11.5-1.56) * \frac{-D}{1-D} \rightarrow D = 0.82 \tag{2}$$

$$-(5+0.92) = (11.5-1.56) * \frac{-D}{1-D} \rightarrow D = 0.37 \tag{3}$$

We also are going to choose a current ripple in the inductor of 20% the output current which is:

$$P_{max} = I_{in\,max} * V_{in} = 12V * 20A = 240W \rightarrow$$

$$I_{out} = \frac{240W}{45V} = 5.33A \rightarrow \Delta I_{L\,max} = 0.2 * 5.33 \approx 1A \tag{4}$$

$$\Delta I_{L\,max} = \frac{V_{in} * D}{f_{sw} * L} \rightarrow L = \frac{12 * 0.82}{80 * 10^3 * 1} = 115.6\,\mu H \tag{5}$$

$$\Delta V_c = \frac{\Delta I_{L\,max}}{8 * C * f_{sw}} \rightarrow C = \frac{\Delta I_{L\,max}}{8 * \Delta V_c * f_{sw}} \tag{6}$$

If we take as ΔV_C=0.05*5V=0.25 V:

$$C = \frac{\Delta I_{L\,max}}{8 * \Delta V_c * f_{sw}} = \frac{1}{8 * 80 * 10^3 * 0.25} = 6.25\mu F \tag{7}$$

We will take both capacitors C_{IN} and C_{OUT} of this capacitance.

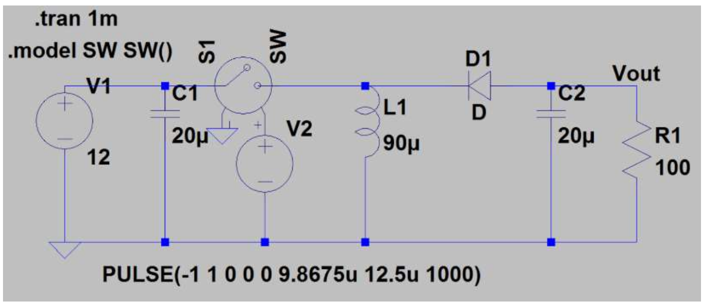

Figure 5: Buck-Boost Simulation Schematic

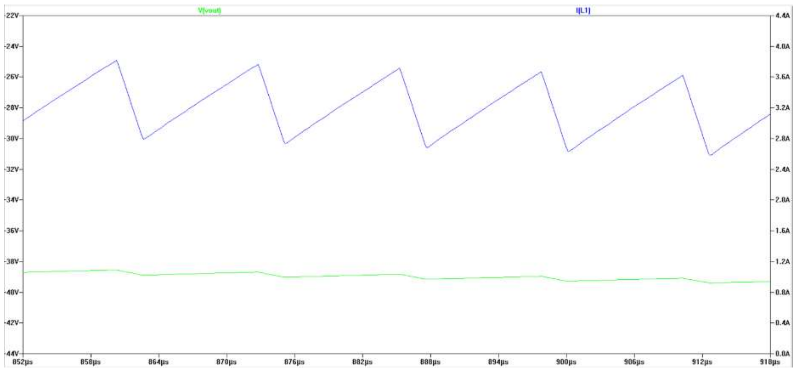

Figure 6: Buck-Boost Simulation of Output Voltage Waveform (Green) and Inductor Current (Blue)

In Figures 5 and 6 you can see the LTSpice simulation schematic and graphs we used in order to make sure we were getting proper output voltage magnitude as well as checking for output voltage ripple and inductor current ripple. This simulation was run at a duty cycle of 80%, which were the conditions for the largest ripples. In our final design, we ended up using even larger inductance and capacitance values than shown in this simulation in order to minimize ripples because there was no large inconvenience in doing so. After simulating and confirming the design we created the schematic in Eagle and made the PCB layout. Figure 7 shows our circuit schematic in Eagle.

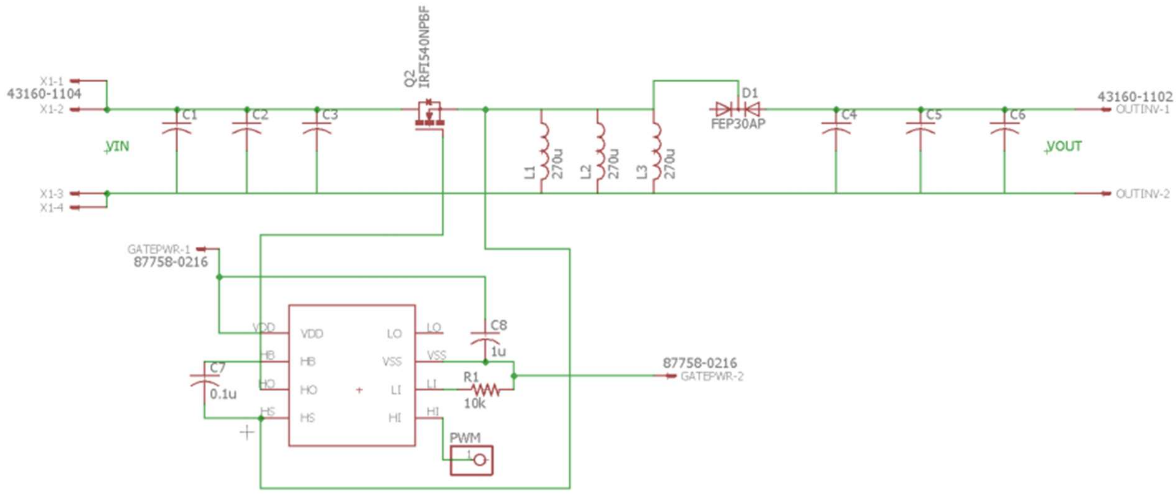

Figure 7: Buck-Boost Converter Circuit Schematic

Among the components of our project, the DC/DC converter was the one with the most time spent on redesign. When we first put everything on the PCB we realized that the gate driver was not outputting the PWM waveform from the C2000 correctly. We figured out that because the buck-boost inverts the output voltage polarity, there was a problem with the ground of the gate driver. The gate driver needed its VSS pin to be ground at the negative output voltage terminal of the buck-boost which is the top output terminal in Figure 7. This ground also became the ground for the inverter and its gate drivers. Another issue we had was with negative voltage spikes appearing on the gate drivers at higher currents and duty cycles. This broke a lot of our original gate driver chips [5]. We later fixed this problem by placing a schottky diode from the ground up to the HB pin which effectively limited the negative voltage spikes to the 0.7 V drop of the diode. We also placed a gate resistor between the HO pin and the gate of the switch as well as a resistor between the HS pin and the tapping of the circuit as the source node of the switch. These all led to much more functional gate driving action.

The only other major problem we had which limited our entire projects maximum AC power output was the buck-boost not being able to maintain 40 V at high power. When more current was put through the circuit it would begin to drop voltage at increasingly lower duty cycles. To output 1 A from the AC output of the project the buck-boost needed to output about 3 A. At this level the buck-boost could not boost the voltage enough to get 120 V_{rms} on the final output. This was because the gate driver would start to “skip” periodically. This is shown in Figure 8. This skipping action was when the gate driver wave-form would not go high for one cycle which would cause the inductor to lose current and therefore the output voltage magnitude to drop. The problem seemed to be from input power negative voltage spikes to the gate driver causing it to shut off for brief periods, causing the skipping. It was mitigated slightly by the shorter wires on the PCB and using the battery instead of the bench power supply as well as reducing the gate driver power voltage from 12 to 10 V via a resistor. The problem still persisted at the required output power rating of 120 W however.

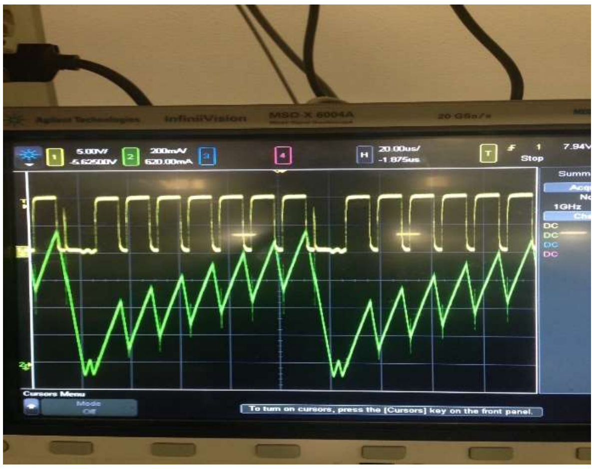

Figure 8: Skipping Gate Driver Waveform

2.2.2 Inverter

For our inverter design we chose a full bridge topology using 4 switches. We need the switching variation and flexibility of 4 switches, instead of the 2 in a half bridge inverter. A half bridge inverter has the disadvantage of halving the input voltage, and being unable to produce the zero crossing dead-time that is required for harmonic elimination. We desire harmonic elimination in order to reduce the total harmonic distortion (THD) of our AC waveform. THD refers to the amount of higher order harmonics present in the output wave-form included with the fundamental harmonic [6]. It is a measure of how sinusoidal a waveform is at the fundamental frequency. The input of the inverter is the output of the DC/DC buck-boost converter. The output of the inverter is connected to the transformer. The inverter does not have a feedback loop because the output voltage will be controlled by the buck-boost converter output magnitude. The switches in the inverter will be controlled by enhanced PWM modules from the C2000.

As most of the components that will be connected at the output of out battery pack have a rectifier in the input, we are not overly concerned about the THD. That is why we will use harmonic elimination in order to remove the third harmonic, which will reduce the THD of our project to a 30 percent. This percentage could be even less by filtering the output wave.

$$V_{1rms} = \frac{4V_{DC}}{\sqrt{2}\pi}\cos(\delta) \tag{8}$$

$$V_{rms} = \sqrt{\frac{1}{\pi}\left[\int_{\pi/6}^{5\pi/6} V_{DC}^2\, dwt\right]} = \sqrt{\frac{V_{DC}^2}{\pi}\left(\frac{5\pi}{6} - \frac{\pi}{6}\right)} = \sqrt{\frac{2V_{DC}^2}{3}} \tag{9}$$

$$THD = \sqrt{\frac{V_{rms}^2 - V_{1rms}^2}{V_{1rms}^2}} = 0.31\ V_{DC} \tag{10}$$

$$V_1 = \frac{4V_{DC}}{\pi}\cos(\delta) \rightarrow our\ V_{DCmax}\ will\ be\ 45V\ and\ \delta = \frac{\pi}{6} \rightarrow$$
$$\rightarrow V_1 = 49.6\ V_{pk-pk} = 35.1\ V_{rms} \tag{11}$$

$$V_1 = \frac{4V_{DC}}{\pi}\cos(\delta) \rightarrow our\ V_{DCmin}\ will\ be\ 5V\ and\ \delta = \frac{\pi}{6} \rightarrow$$
$$\rightarrow V_1 = 5.51\ V_{pk-pk} = 3.9\ V_{rms} \tag{12}$$

$$V_3 = \frac{4V_{DC}}{3\pi}\cos(3\delta) = \frac{4V_{DC}}{3\pi}\cos(90) = 0 \tag{13}$$

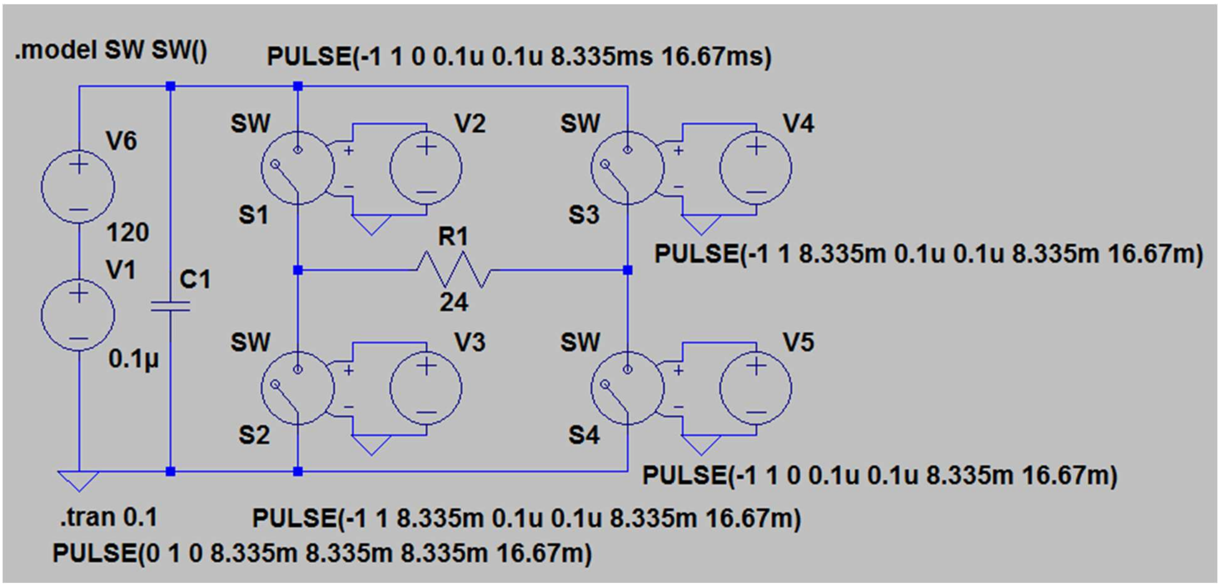

Figure 9: Inverter Simulation Schematic

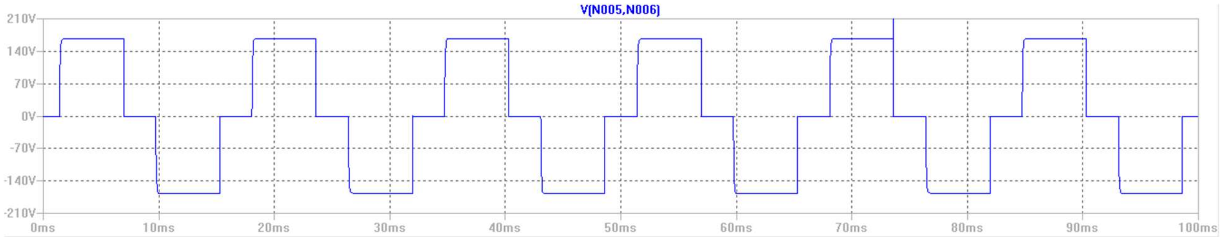

Figure 10: Simulation of inverter output with 3rd harmonic elimination.

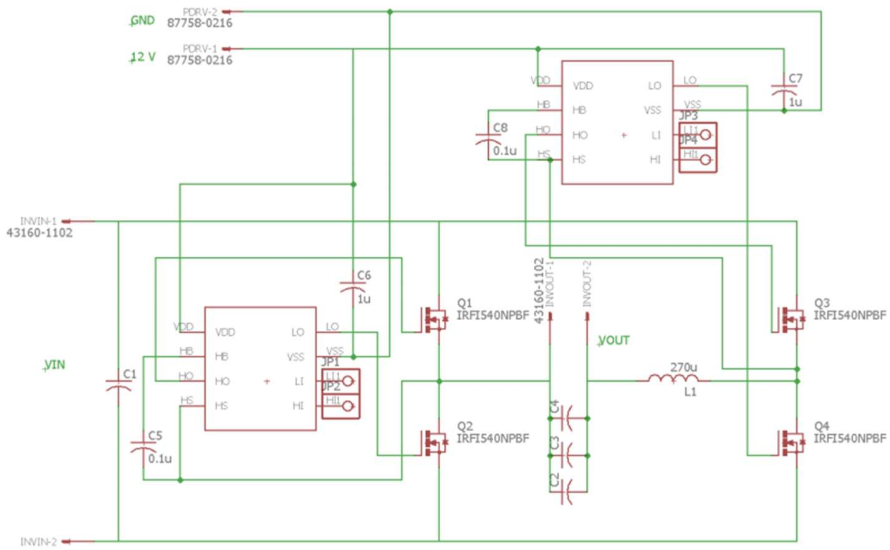

Figure 11: Inverter Circuit Schematic

There were no significant high level design changes made to the inverter design through the course of the project but there were some changes we made after we placed it onto the PCB. The gate drivers were replaced, as mentioned before, so we have to abandon the original board traces for those and use 2 tiny external chips to attach the new gate drivers, which had different pin layouts than the ICs the PCB was designed for. We also realized the LC filter we had planned for would not work unless the inductor had a much higher inductance value, but since an LC filter was not required to fulfill our mission statement, we just did not use those parts on the PCB.

2.2.3 Transformer

The transformer is located at the output of the inverter and its function is to step up the output AC voltage [7] in proportional to the turns ratio. The transformer is what allows the AC voltage to reach the desired maximum value of 120 V_{rms}, which corresponds to what may be expected out of a grid outlet. We designed for a 1:4 transformer turns ratio, but lab tests showed that the actual transformer turns ratio was 1:3.5. This made it more difficult to reach the maximum AC output than we expected

2.2.3 Original/Alternative Design

Our original design had a different power stage flow. It used a flyback converter instead of a buck-boost. A flyback has a transformer where the inductor would be so it has the ability to significantly boost up the output voltage given an appropriate turns ratio [8]. We thought we needed to get the output DC voltage to 170 V before going into the inverter to produce 120 V rms. This meant we also needed a second output on the transformer in the flyback that had a less extreme turns ratio in order to produce lower DC voltages at the DC output. This three winding transformer was very specific and trying to search for one similar turned up no results. Doing that severe of a step up in the DC/DC converter stage also put large voltage and current stresses on the converter components. In the end we moved the voltage step up to the end of the inverter because it was only important for the AC output anyway and streamlined our power stages. We replaced the flyback with a buck-boost which was easier to build, reduced component stresses and more easily outputted low voltage DC power.

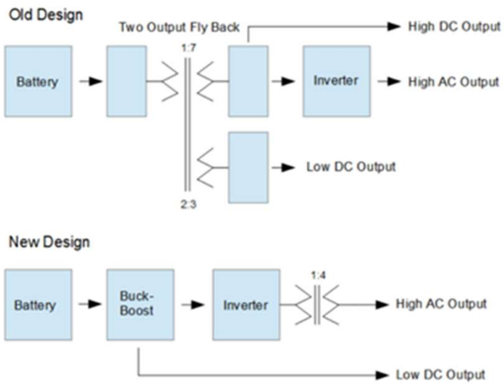

Figure 12: Diagram of Change of Design

2.3 Control Module

The control unit handles communication with the user by a turn knob, through which the user can vary the duty ratio of the buck-boost converter, and as a consequence the output, voltage magnitude of our project. The user will know the output voltage and current, as these will be shown on the LCD screen. This screen will be controlled by the Arduino. The microcontrollers will be powered by the input power module across the microcontroller power converter that will step down the output voltage of the batteries from 12V to 5V USB. The control unit will be in charge of controlling the switching functions for both output converters.

2.3.1 Microcontrollers

We selected two different microcontrollers for our project, each with its own advantages and disadvantages. The Arduino is excellent for interfacing with the LCD screen thanks to an existing software library. It also has an easily implemented ADC functionality that, combined with its LCD driver library, makes it the natural choice to process and display our circuit measurements. The main disadvantage of the Arduino is its limited PWM capability. The Arduino does not permit precise control over the frequency and has no functionality for phase shifting different PWM signals. For that, we need a specialized microcontroller like the C2000 Piccolo. The C2000 is optimized for feedback control of power electronics. It permits us to select a PWM frequency more carefully, and at higher frequencies, than allowed by the Arduino. With the C2000, we produce a switching frequency of 98 kHz for the buck-boost power MOSFET. The advantage of higher switching frequency is lower inductor current ripple and output voltage ripple. In theory, the C2000 could have allowed us an even higher switching frequency, but we judged that unnecessary. The C2000 permits multiple PWM outputs that can be phase shifted from one another. This feature permits the switching timing required for the inverter's control scheme. The main disadvantage of the C2000 is code complexity. Compared to the Arduino, it has a complicated ADC procedure and no LCD driver library. By using both microcontrollers, we resolve their limitations and exploit their capabilities.

2.3.2 User input

The user input is done through a rotary potentiometer connected across the 3.3V and ground terminal of the C2000. The potentiometer output voltage is read by the C2000. The C2000 software scales the buck-boost switching duty cycle in proportion to the magnitude of the potentiometer voltage, up to a limit of 82%. This is done because the buck-boost converter is unstable at high (near 100%) duty cycles.

2.3.3 Measurement Circuitry

The measurement circuitry was implemented on a perfboard, apart from the PCBs but connected to them through breakout wires. It was comprised of two voltage dividers coupled with LM358 op-amp buffers, and three ACS712 Hall Effect sensor chips. The resistive dividers were to scale the voltages down to 5 volts or less, the magnitude that can be read into the Arduino. The op-amp provides a unity gain buffer to prevent the Arduino from presenting a load onto the voltage divider [9]. In the case of the buck-boost voltage, the op-amp was wired into an inverting configuration to account for the negative output voltage. The ACS712 Hall Effect sensor chips were acquired in two varieties, a 5A version and a 30A version. The 5A version was for the output currents. The 30A version was for the battery current. They each operated the same: generating an analog voltage between 0-5 depending on the input current. The exact relationship between current and analog voltage is specified on the ACS datasheets [10] and is accounted for within software.

2.3.4 LCD Display

A 16 by 2 LCD operated by an Arduino microcontroller displays the voltage and current values read by the Arduino

2.4 Software

2.4.1 Arduino Software

The Arduino code is comprised of an ADC section and a display section that runs in a continuous loop. In the ADC section, the code reads in the analog voltages that represent the voltage and current measurements on the system and stores them as a digital value from 0 to 1023[11] . The digital value is divided by 1023 then multiplied by a scale factor. For voltage readings, this scale factor is determined by the resistive divider. For current readings, this scale factor is provided by the ACS712 datasheet. The AC current is measured by sampling over 1 second to get the peak to peak value, then multiplying by .707 and the scale factor to get the rms current. The LCD section takes the values generated by the ADC section and updates the display.

2.4.2 C2000 Software

The C2000 is responsible for providing PWM outputs to feed the power electronics' gate drivers. The functionality can be divided into two parts: the buck-boost control and the inverter control. The buck-boost control involves reading in an analog voltage from the control knob, and updating the duty cycle of an ePWM module in proportion to this voltage. Each ePWM module controls two, independent PWM outputs, A and B, which run off the same counter [12]. The frequency is determined by a period constant. Unlike the Arduino, the C2000 generates a digital reading up to 4096, which gives it 4 times the ADC resolution of the Arduino. This digital value is scaled down to the period time scale, and then set at the compare value for the PWM module. A counter module counts up and down constantly. When the counter reaches the compare value, the PWM module either outputs a high signal or a low signal, depending on the action qualifier setting. This is how the duty cycle is controlled within the C2000. By implementing complementary action qualifier settings, we can make A and B be exactly 180 degrees out of phase. This becomes useful in the inverter control, which involves 2 ePWM modules. Each ePWM module has an A and B output, which are set to be 180 degrees out of phase, with 2 us of dead-time between rise and fall times. This is to prevent a direct power to ground short within the H-bridge. Each ePWM module controls either the left or right pair of inverter switches and they are phase shifted for 3rd harmonic elimination. The second ePWM module is phase shifted 120 degrees from the reference ePWM module by entering the corresponding parameter for the PWM_setPhase() function.

3. Design Verification

3.1 Input Power Module

3.1.1 Battery Charger
The battery charger works as required. It is able to charge the batteries back to a nominal voltage of around 12.5V.

3.1.2 Batteries
The batteries are able to source the current and voltage required in our project. They are both around 12.5V when fully charged and together can source more than the required amount of amps to meet the power requirements.

3.1.3 Microcontroller Power Module
As required, the microcontroller power module steps down the battery voltage to around 5V and when hooked up, the microcontrollers both turn on and operate successfully. The variation in battery voltage is not large enough to cause a variation from 5V that stops the powering the microcontrollers.

3.2 Output Power Module

3.2.1 DC/DC Buck-Boost Converter
The buck-boost converter met all module requirements. It is able to produce the required output range of 5 to 40 V with an input voltage from the battery. Figure 13 shows the ideal vs. measured output voltages of the buck-boost versus the duty cycle range we calculated. The graphs mirror each other very closely with expected voltage drops in the measured results due to the power diode and losses. Figure 14 shows the efficiency test results. Our requirement of 75% efficiency while supplying 1 A at every voltage range point was exceeded. Testing showed that we were able to achieve 80-90% efficiency. This test also shows that the buck-boost is able to supply 1 A at all voltage ranges which was another requirement. The last requirement of the buck-boost was to have a voltage ripple of less than 5%. Our calculations showed we needed less than 100 µF of output capacitance to achieve this but we ended up using about 1 mF of output capacitance because we had room on the PCB and why not reduce the ripple even more. The ripple was basically impossible to see on the oscilloscope, as the scope noise exceeded the actual ripple, so we were able to meet this requirement.

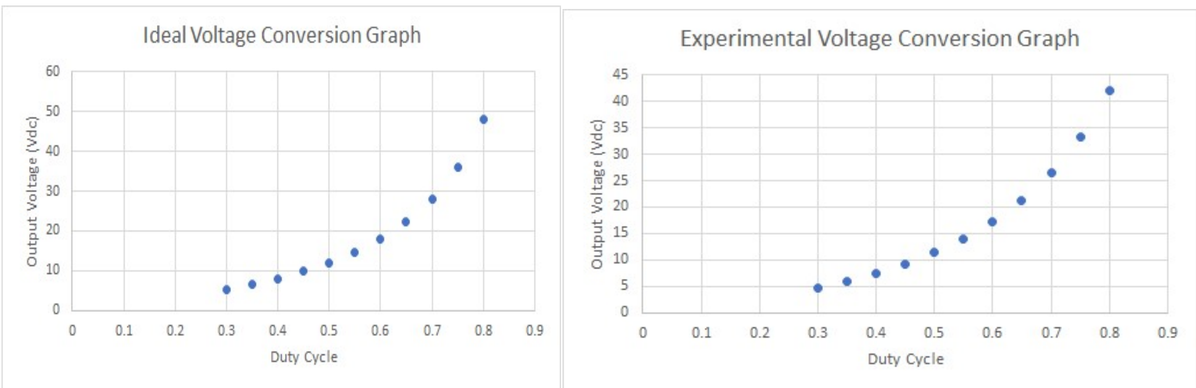

Figure 13: Buck-Boost Voltage Conversion Test Results

D (%)	Rload(Ω)	Vin(V)	Iin (A)	Vo(V)	Io(A)	η(%)
30	4.5	12	0.423	4.29	0.98	82.8
35	6	12	0.516	5.57	0.96	86.3
40	7	12	0.69	7.02	1.03	87.3
45	9	12	0.822	8.76	1.02	90.6
50	11.5	12	0.974	10.85	1	91
55	13.5	12	1.245	13.32	1	90.9
60	17	12	1.5	16.43	1	91.3
65	21	12	1.866	20.33	1	90.8
70	26	12	2.367	25.29	1	89
75	33	12	3.01	31.91	1	88.3
80	40	12	3.94	38.3	0.99	78.1

Figure 14: Buck-Boost Efficiency Test Results

3.2.2 Inverter and AC Output

The inverter met all its modular requirements as well. It needed to be able to successfully create an AC wave-form output that removed the third harmonic. Figure 15 shows the output of the transformer. The shape of the waveform is exactly what we predicted given the removal of the third harmonic. The figure also shows the rms of the voltage waveform to be about 116 V. This was at a duty cycle of 80% for the buck-boost. We were able to reach the required 120 V_{rms} for our AC output at slightly higher than 80%. This is shown in Figure 16 where the output AC rms is graphed versus the buck-boost duty cycle. We were not able to meet the 1 A_{rms} requirement however. The voltage magnitude would drop before we could successfully source 1 A. This was due to the skipping and voltage drop problem in the buck-boost. Since the voltage magnitude of the output is directly based on the output voltage magnitude of the buck-boost, it was the bottleneck to our project not meeting the 120 W AC output power requirement.

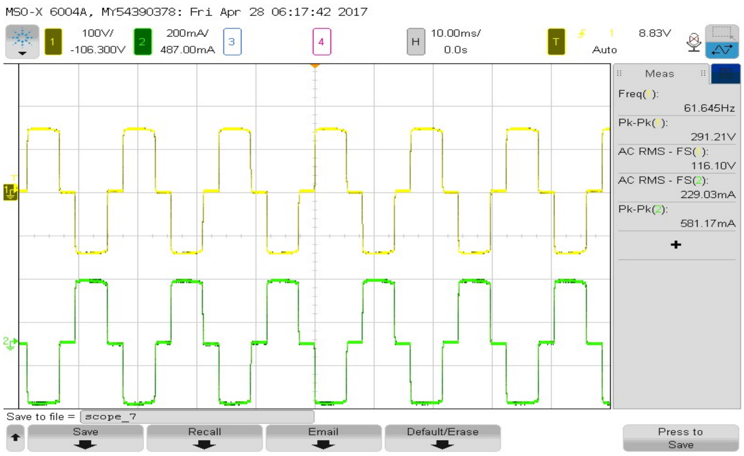

Figure 15: Output AC Wave-form Results (Voltage-Yellow, Current-Green)

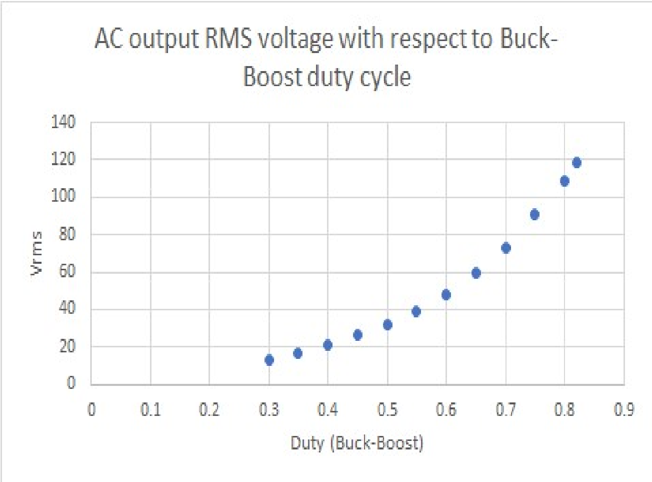

Figure 16: AC Output Voltage Test Results

3.3 Control Module

In Figure 17, we have a simulation of what the inverter control scheme should be. Switches A and B are complementary. Switches C and D are complementary. The key to 3rd harmonic elimination is the phase difference between A and C, or B and D. For a value of 30 degrees, the phase difference is +240 or -120 degrees. In Figure 18, we display the actual switching waveforms produced by the C2000. Note that yellow and blue are 180 degrees out of phase. Yellow and red are 120 degrees out of phase. The fourth waveform, which is not shown for lack of more voltage probes, would be 180 degrees out of phase with respect to red. The complementary PWM waveforms have a small dead time between rising and falling edges that prevented the high and low switches on one side of the H-bridge from conducting simultaneously in the turnoff/turn-on transition periods. If simultaneous conduction was allowed to happen, a power to ground short would cause a massive current spike and break the MOSFETs. Throughout testing, this never occurred.

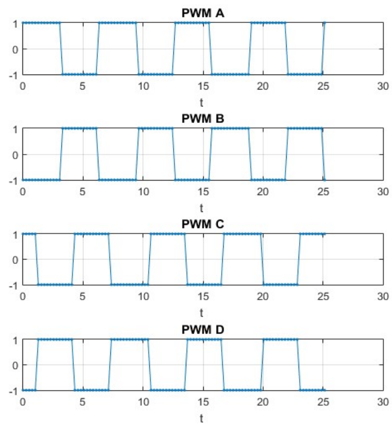

Figure 17: Simulation of the inverter switching scheme.

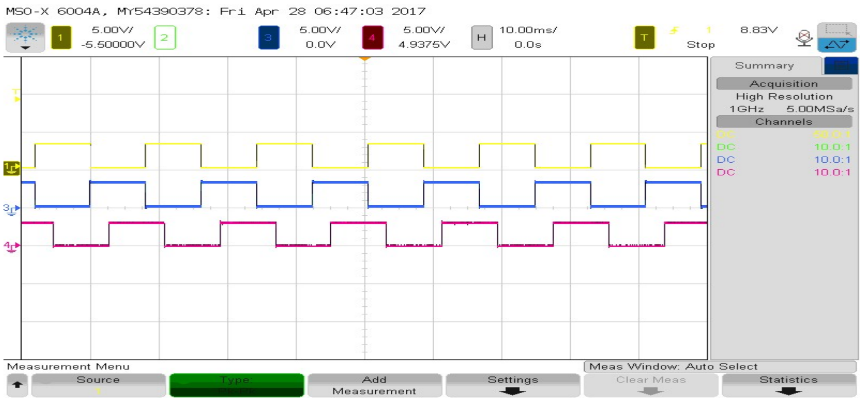

Figure 18: Sample PWM waveforms generated by the C2000 used to drive the H-bridge.

3.3 Measurement Circuit

The measurement circuit was constructed and tested. The LCD display was working, but prior to the demonstration it broke during a test, and a replacement was not on hand. The voltage and current measuring systems were tested, but the outputs were incorrect and we did not have sufficient time to troubleshoot them. We made the decision to discontinue verification of the measurement circuit, after testing of the measurement circuit resulted in a short that blew a power MOSFET in the buck-boost.

4. Costs

4.1 Parts

In table 1 we can see the prize of all the parts used in the project.

Table 1

Item	**Quantity**	**Total Cost ($)**
C2000 Piccolo	1	17.05
16x2 LCD	1	13.95
Rotary potentiometer	1	9.77
IRFB4137 Power MOSFET	5	22.65
IRFS21867 Gate Driver	3	4.62
Arduino Uno	1	33.45
Battery charger	1	52.6
Outlet	1	14.8
Hall effect sensors	3	27.4
12-12 DC converter	1	11.5
4 270 uH Inductor	4	30.60
Power Diode	1	4.12
Transformer	1	75.60
12 Volt Battery	2	35.99
Connectors	4	4.64
LM358 Op-Amps	2	.94
12v to 5v buck converter(microcontroller power module)	1	6.51
Box enclosure	1	40.00
Completed prototype	**1**	**406.19**

4.2 Labor

The breakdown of labor costs for this project is shown in the table 2. At an hourly rate of $ 30 for each group member the total cost for the course of this semester would be $

Table 2

NAME	HOURLY RATE	HOURS INVESTED	TOTAL=HOURLY RATE* HOURS INVESTED*2.5
Mason	$35	150 h	$13125
Javier	$35	150 h	$13125
Jeffrey	$35	150 h	$13125
Group	$105	450h	$39375

We can see the total cost of the project in table 3.

Table 3

SECTION	COST
Labor	$39375
Components	$406.19
TOTAL	$39781.20

5. Conclusion

5.1 Accomplishments

We were able to successfully accomplish most of our high level objectives, as laid out in the introduction. Our battery pack can safely store electrical energy from a standard AC wall outlet. It can source both DC and AC power. The user can turn a knob to control the magnitude of the output. Finally, we showed that such a system could be made portable. The only objective we did not achieve was to measure and display voltages and currents. However, we did have the measurement circuitry constructed. Time limited the implementation and integration of the measurement system.

5.2 Uncertainties

We do not know for certain what is limiting the current output of our buck boost converter. We understand that there is a skipping issue with the gate drive signal, but we do not fully understand what specifically is causing them. If we had more time, we could resolve this issue with more research, testing, and more improved PCB layouts. Another mystery is the LCD failure we experienced. The LCD was working properly during initial test. We did not change its wiring or software drive, but in the following test it failed midway. We were unable to resolve the issue, even after much effort, and we believe that the LCD is broken. We suspect that a short caused the unit to fail, but we cannot know for sure what caused that short. Perhaps we could have prevented the problem by having neater solder joints and using electrical tape to isolate the connections from external shorts. The final uncertainty is what went wrong with our measurement perfboard. We had it built and integrated into the system. However, the analog voltages being produced were erroneous, and while troubleshooting the measurement board we somehow caused a catastrophic short in the buck-boost power MOSFET. We did not have time to resolve the issue with the measurement perfboard.

5.3 Ethical considerations

The IEEE code of ethics outlines a set of ethical guidelines that we sought to follow throughout our project design process and final demonstration.[13]. For the sake of integrity, we demonstrated the verified capabilities of our project and provided full disclosure for the reasons our project did, or did not, meet previous established specifications. We sought to test in a modular, incremental procedure that limited the risk to equipment and personal. We did not perform riskier tests until prerequisite tests were performed. For instance, we did not test with the lead-acid batteries until we verified circuit operation with controlled, and current limited, power supplies. We performed breadboard tests with the new gate drivers before integrating them into the PCB. When issues arose with lead-acid battery testing, we discontinued testing pending the resolution of the issue. We sought to verify the performance and stability of individual project components before integrating them with other components. We did not move forward with integration until individual component risks were resolved, and when design issue were discovered, we did not proceed with construction until the flaws were resolved. For instance, in our original design with the flyback, our calculations revealed high voltage stresses that could damage our circuit components. We did not continue to build until we found a safer design.

5.4 Future work

In the future we would like to redesign our PCBs in order to integrate all the measurement systems as well as the new gate drivers on them. The new gate driver ICs have different pinouts then the ones that the PCB was designed for. This forced us to float the new gate drivers above the PCB. This fix worked for our demonstration, but it is not ideal. We had a similar situation with the measurement system. The voltage dividers and Hall Effect sensors were separate from the PCBs, forcing us to run extra wires through the system and increasing system integration complexity. We could have reduced this unnecessary complexity by having the Hall Effect sensors, voltage dividers, and buffers on the same PCBs as the output power converters.

Given more time, we would have liked to fix the skipping problem of our buck-boost converter in order to be able to source the required power. This would require additional testing and research to uncover the cause of the problem.

If we want to make this project affordable, we should be able to reduce both cost and size by using more reliable components as well as a more compact design.

We would like to test our project with actual devices, such as computers or mobile phones. In our lab, we only tested with purely resistive loads. In the future we could experiment with inductive and capacitive loads.

References

[1] Charging Lead Acid Batteries. 2017, Available: http://batteryuniversity.com/learn/article/charging_the_lead_acid_battery [Accessed 4-April-2017]
[2]Health Concern about batteries. 2016, Available: http://batteryuniversity.com/learn/article/health_concerns [Accessed 4-April-2017]
[3] Design Calculations for Buck-Boost Converters. 2015, Available: http://www.ti.com/lit/an/slva535a/slva535a.pdf [Accessed 25-March-2017]
[4] My technology world: buck-boost converters. 2017, Available: http://mytechwrld.com/buck-boost-converter/ [Accessed 25-March-2017]
[5] *Design and Application Circuit for High Voltage Gate Drive IC*,]. Fairchild Semiconductor., 2008. Available: https://www.fairchildsemi.com/application-notes/AN/AN-6076.pdf
[6] Essential basics of Total Harmonic Distortion. 2016, Available: http://electrical-engineering-portal.com/essential-basics-of-total-harmonic-distortion-thd [Accessed 28-March-2017]
[7] Ideal Transformers, 2014. Available: http://whites.sdsmt.edu/classes/ee322/class_notes/322Lecture14.pdf [Accessed 27-March-2017]
[8] *The Flyback Converter,* University of Colorado, ECEN417. Available: http://ecee.colorado.edu/ecen4517/materials/flyback.pdf .
[9] AN-20 An Applications Guide for Op Amps. 2012, Available: http://www.ti.com/lit/an/snoa621c/snoa621c.pdf [Accessed 2-April-2017]
[10] Allegro Microsystems, LLC ACS712ELCTR. 2015, Available: https://www.digikey.com/product-detail/en/allegro-microsystems-llc/ACS712ELCTR-05B-T/620-1189-1-ND/1284606 [Accesed 2-April-2017]
[11] Arduino Libraries. 2017, Available: https://www.arduino.cc/en/Reference/analogRead [Accessed 30-March-2017]
[12] TMS320x2802x, 2803x Piccolo Enhanced Pulse Width Modulator (ePWM) Module. 2016, Available: http://www.ti.com/lit/ug/spruge9e/spruge9e.pdf [Accessed 30-March-2017]
[13]“*7.8 IEEE Code of Ethics*, IEEE. 2017[Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html [Accessed:27-Mar-2017].

Appendix A Requirement and Verification Table

Battery Charger

Requirements	Verifications	Verification status (Y or N)
1. Safely charge a Lead-Acid battery. 2. Charges a Lead-Acid battery to at least 90% maximum capacity, given a standard wall outlet source.	1,2. Connect the battery to the charger. Check that the charger is indicating correct operation by its status LEDs.	Y

Microcontroller Power Module

Requirement	Verifications	Verification status (Y or N)
Provide a voltage source for the microcontrollers within the supply voltage range indicated by their datasheets. Both can be powered via USB. • C2000: $4.6V_{max}$, 3.3V operating [6] • Arduino: 7-12V raw input or 3.3V supplied directly to power pin [7]	Connect power module to the battery terminals. Verify that it can power both microcontrollers through USB.	Y

Battery Measurement

Requirements	**Verifications**	**Verification status (Y or N)**
1. Measure DC voltages within a range of 5V-40V with 10% accuracy 2. Measure DC and AC currents with 10% accuracy	1,2. A. Ensure the maximum voltage output level of the voltage divider does not exceed 5V, to protect the microcontroller B. Measure the relevant voltages and currents with a multimeter. C. Confirm that the microcontroller is reading the same value, either by having the microcontroller print to console or to an LCD screen.	Y Y N

Microcontroller

Requirement	**Verification**	**Verification status (Y or N)**
1. C2000 requirements. A. Can simultaneously output four different PWM signals to control the inverter switches. PWM1 must shifted 120 degrees off PWM 2. PWMA and B of each PWM module must be 180 degrees shifted, with sufficient (~2µs) deadtime to protect the full bridge. B. Can control a PWM duty cycle via ADC input for the buck-boost control. 2. Arduino Requirements A. Measures the output of the voltage measurement and current sensor circuits B. Can drive the LCD screen	1. To verify that the C2000 can execute its required role: A. Using an oscilloscope, verify the 120 degree phase shift from PWM 1 to 2. Verify the 180 degree phase shift from PWM A and B of each PWM module B. Vary the input voltage into the ADC pin and verify that the PWM output that controls the duty cycle is proportional to the ADC input voltage. 2. To verify the Arduino can execute its required role: A. Insert a variable DC voltage between 0-5V into an analog input pin. Use print() statements to verify the measurements B. Display text on a LCD	 Y Y Y N

LCD Display

Requirement	Verification	Verification status (Y or N)
Must display the voltage, charge level, current, temperature, and power values dictated by the microcontroller.	A. Isolate the display and microcontroller. B. Program dummy test values for voltage, charge level, current, temperature into the microcontroller. C. The display should match the dummy values.	Y Y Y

User Input

Requirement	Verification	Verification status (Y or N)
Turning the knob create a visible change in the output voltage displayed by the LCD.	Rotate the potentiometer knob, while the control unit and output power module are integrated. Verify that turning the knob results in a linear change in displayed voltage level.	Y

Output AC Power

Requirement	Verification	Verification status (Y or N)
The output of the transformer at maximum ratings should be $120V_{rms}$ at $1A_{rms}$	Measure the output waveform of the transformer when fed by the inverter and see if it is at the required power rating.	N

DC-DC Power Converter (Buck-Boost)

Requirement	Verification	Verification status (Y or N)
1. The converter must be able to deliver an output DC voltage from 5V to 40 V. 2. The converter must be designed to survive a maximum current of 1 Amps. 3. The converter must have at least 75 % efficiency. 4. The converter must have a voltage ripple of 5% or under.	A. Test the converter in open-loop configuration, with a 12V source and a C2000 microcontroller producing a PWM frequency at least 80 kHz switching frequency. B. Sweep the duty ratio to confirm that the output voltage can range from 5-45V. C. Check that the output voltage does not vary by more than 5 percent in steady state operation. D. Operate with a 1 A load. E. Measure average power input and average power output. Verify that the output power is at least 75% the magnitude of the output power.	Y Y Y Y Y

Inverter

Requirement	Verification	Verification status (Y or N)
1. The inverter will be able to output an AC voltage waveform 80 V_{pp} and 30 V_{rms}. 2. The inverter control eliminates the 3rd harmonic.	A. Operate the inverter with any DC input voltage between 5-40V with a harmonic elimination control algorithm. B. Measure the inverter output on an oscilloscope. Visually verify that the 3rd harmonic is eliminated.	Y Y

Points Summary:Variable Voltage Battery Pack

Module Name	High Level Requirements	Points
Input Power Module	• The input power module successfully steady power to the microcontrollers • The input power module successfully charges the battery safely to capacity from a US wall outlet	5
Control Unit Module Display Measurement/User Input Gate driving-Buck boost Gate driving-Inverter	• The microcontrollers can successfully drive the display • The microcontrollers can perform ADC voltage and current measurements • The microcontrollers correct a PWM signal with a closed loop feedback algorithm • The microcontrollers successfully output PWM signals to drive the inverter with no third harmonic	5 5 5 5
Output Unit Module Buck-Boost Converter Inverter	• From an input of 12V, the converter can successfully output 5-40V DC • Given a DC voltage and correct gate drive signal, successfully outputs an AC waveform with no third harmonic	15 10