Hybrid Wall Outlet for AC or DC Power Delivery

Kerr Allan, Greg Perini, & Garrett Knoller

California Polytechnic State University, San Luis Obispo

Senior Project: 2022 - 2023

Advisor: Dr. Jason Poon

Date of Submission: 12/14/23

Abstract

The goal of this project is to develop hybrid DC and AC wall outlets for an efficient, flexible power interface. A DC plug standard is also proposed to allow DC devices to be safely powered by the outlet with the correct DC voltage for each device. The primary objective is to create a power outlet compatible with the proposed DC plug as well as NEMA 5-15 AC plugs, enabling the same outlet to power both types of load as needed. The outlet is intended for buildings and systems transitioning to an isolated DC grid to encourage DC development and adoption. Existing wall wiring will be given 48V DC and used to power these devices, avoiding expensive rewiring when retrofitting. The outlet uses an H-bridge topology to facilitate DC to AC conversion, a Boost topology to reach standard wall voltage, and a Buck topology for DC voltage applications.

Introduction

DC electricity is becoming more prevalent as the world seeks efficient power distribution and sustainable power generation. DC electricity inherently offers power transmission capacity benefits of up to 29.3% and a cost reduction of 33% compared to AC lines [1]. DC-DC voltage conversion also offers efficiency benefits over AC–AC or AC-DC at the cost of needing more sophisticated conversion equipment. In one paper, the authors found a potential 28% increase in the energy efficiency of a data center by switching their system from AC to DC [2]. These efficiency benefits make DC adoption appealing to power providers and consumers.

Additionally, the growing use of sustainable energy encourages DC adoption. Solar, wind, and other asynchronous renewable generation techniques inherently output DC, and so do the battery systems that correct for their intermittency. On the consumer's side, most loads, such as computers and lighting, require DC or are compatible with DC. This means that the DC output of renewables is converted to AC for distribution, only to be converted back to DC by the consumer.

The main issue that prevents the introduction of DC power systems is simply that existing electric infrastructure is set up to distribute AC power. Microgrids, however, are closed systems that can be proving grounds to develop renewables and DC technology without changing billions of dollars of infrastructure. Due to their significant emphasis on renewables and energy storage, microgrids have even more reason to switch to DC with the flexibility to do so. As such, fully DC microgrids are a topic of great interest but need help to be usable because most devices are designed to take AC. This presents the challenge of transitioning from devices that run on AC to those that run on DC. A hybrid environment that can output either AC or DC to devices as needed would enable a gradual transition to DC rather than an all-or-nothing choice.

Background

The American power grid is going through a change right now, as much of the infrastructure that has already been built needs to be replaced. Additionally, the push towards a net-zero energy system has replaced many traditional power stations with smaller, on-site generation methods such as solar power [3]. This movement towards solar power can also be seen in many Global Southern countries since power grids may not be reliable. Traditional AC systems require much larger equipment and maintenance due to their bulky transformers and higher monitoring needs [1]. Thus, the solution to both the aging and outdated power system in America and the less reliable systems in the Global South is smaller DC systems supplied by local generation: Microgrids.

Single-structure microgrids that experiment with DC infrastructure are active at Purdue and Cal Poly [4] [5]. Both projects are called DC houses, and they differ in their approaches, but they both have to contend with the ubiquity of AC technology. At Purdue, Jonathan Ore discusses the benefits of a “DC Nanogrid House” in his doctoral thesis [4]. He and his team conclude in the paper that the reduced energy losses of the newly constructed DC power system vastly improve the efficiency of residential buildings. With grids such as Ore’s showing promising results, consumers will need a way to use their devices designed for an AC system. The solution must be efficient, cost-effective, and capable of converting DC to AC and adapting to the input load of a DC device. This device must also meet the engineering and design standards of the pre-existing grid.

Design Requirements

Specifications

The purpose of the hybrid Wall Outlet is to supply either AC or DC voltage as required by the electronics plugged in. For the purpose of this project we were concerned primarily with the hardware and software of our design and not the casing or connection components. However, we propose a new socket that, for the safety of the consumer and their electronics, has a keyed design for the DC plug that will prevent it from plugging into a standard AC outlet. This keying is different from all current NEMA standard outlet patterns [6][7], meaning nothing can be plugged into the wrong socket accidentally. Our plug determines the power type and at what voltage the device requires. Both pieces of information are encoded into the shape and properties of the DC plug and AC plug, eliminating the need for expensive “smart” components such as the ARM processors found in USB-C smart outlets. There are sensors on each side of the pronged plug, which will determine the power type. More details for the outlet can be seen in Figure 1.

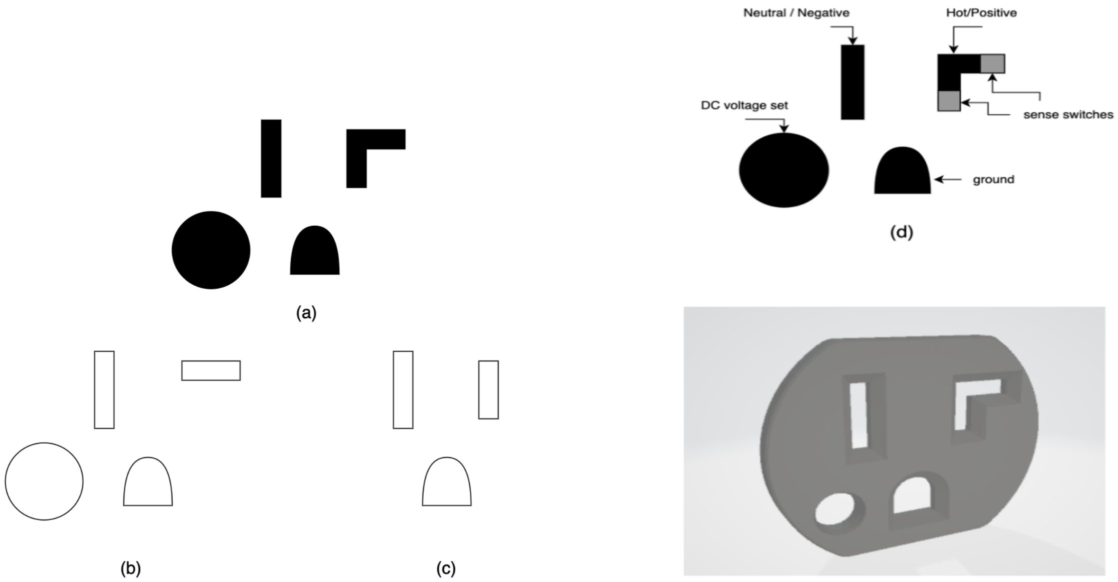


Figure 1: a) Hybrid receptacle (female) design. b) DC plug (male) design. c) AC NEMA 5-15 polarized plug design. d) labeled hybrid receptacle.

If only the lower sensor pair detects a prong, then it must be an AC plug that has been inserted, so the outlet will provide 120V RMS AC to it after a short safety delay. If only the upper sensor pair detects a prong, the socket will provide DC with the correct voltage according to the DC voltage set pin. The DC voltage set pin is a ¼” audio jack with a resistance between the tip and the ground section. This resistance will be chosen by the maker of the DC device so that the outlet provides the correct voltage according to our standard. If there is an open or a short circuit on the DC voltage set pin, the sensors in either pair disagree, or both sensor pairs detect a prong, then the outlet will light an LED and will not energize. This lets the user know that maintenance or replacement is required. Figure 2 shows an example of what the printed, 3d model of the outlet would look like with a standard NEMA 5-15 plug inserted into it. The added keying that has high voltage connected to it is blocked so it cannot be accessed.

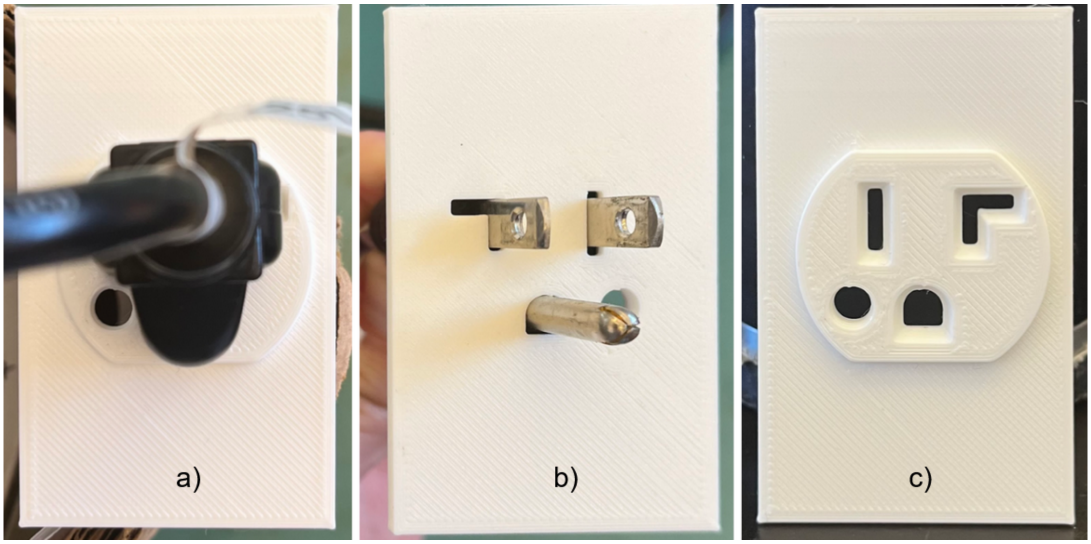


Figure 2: a) Front side of AC plug b) Back side of AC plug c) 3D model.

We focused on electronics that require smaller DC voltages and small to medium loads for testing purposes. We tested several household devices, such as chargers, soldering irons, fans, and TVs, with a Watt-meter and found that very few devices pulled more than 200 Watts. Therefore, at minimum, our outlet will be capable of providing 200 Watts. The devices that pulled more than 200 Watts were microwaves, fridges, and toasters [8]. These devices pulled 800 Watts or more. When running 48 Volts over wire rated for 15 Amps, the maximum power for that circuit is 720 Watts across any number of outlets. Max power can be increased by raising the voltage, but voltages above 50V require extra precautions according to OSHA regulations [9]. As such, we will use 48V; higher-power devices will be outside the project's initial scope.

In addition to the wattage that the outlet puts out, it has to do so in a timely manner. Namely, the delay between plugging in the device and receiving power should be as small as possible to not frustrate or confuse the user on whether the device is working based on the user's experience with other plugs. We found through our own testing [10] that this delay was around 1 second, so we gave ourselves 2 seconds to account for potential design trade offs as well as budget constraints.

Block Diagram

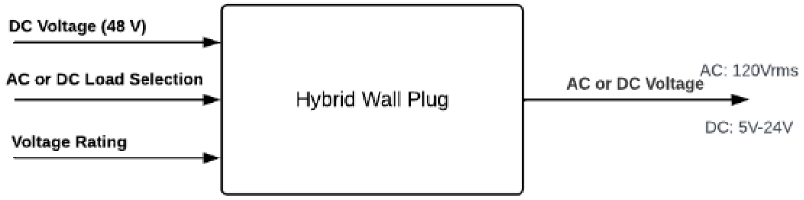


Figure 3: Hybrid Wall Outlet Level 0 Block Diagram

Level 0 Block Diagram

Level 0	Hybrid Wall Outlet
Inputs	● Power: DC(48V) ● Information: (for DC voltage, audio jack: Load Voltage) ● Information: (DC/AC switches: Type of Load)
Output	● Power: AC(120 Vrms) or DC(5-24V)
Functionality	● Determines load current requirement and outputs the appropriate current type to meet those needs ● Simplicity of the interface offers ease of use for end user

Table 1: Hybrid Wall Outlet Level 0 Functional Decomposition

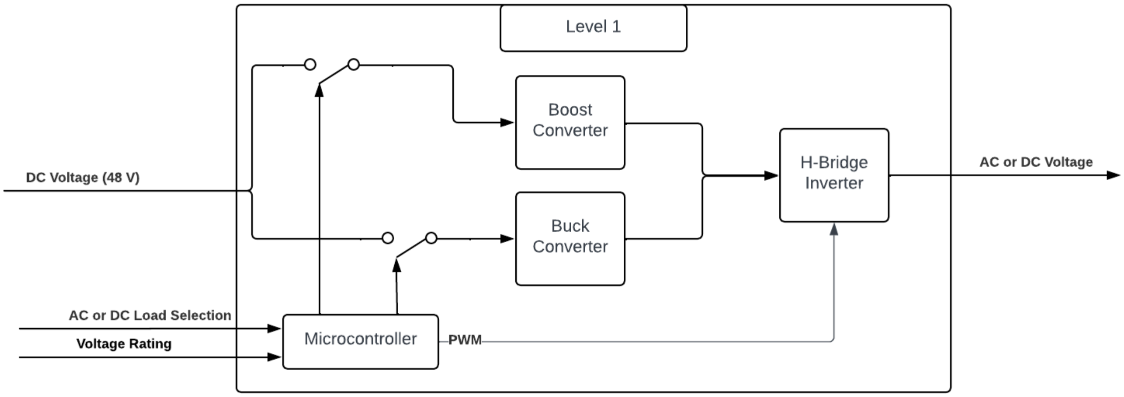


Figure 4: Hybrid Wall Outlet Level 1 Block Diagram

Level 1 Block Diagram	
Level 1	Hybrid Wall Outlet
Inputs	● Power: DC(48V)

	- Information: (for DC voltage, audio jack: Load Voltage) - Information: (DC/AC switches: Type of Load)
Output	- Power: AC (120 Vrms) or DC (5-24V)
Functionality	- Input voltage is supplied to either boost or buck converter, which is controlled by a microcontroller who makes the decision via the external control signals - A voltage bus is shared by both converters to supply power to the inverter, which then supplies the output power - Inverter switching is controlled by a PWM signal from the microcontroller [11]

Table 2: Hybrid Wall Outlet Level 1 Functional Decomposition

At a high level, the design has three stages. The first stage takes in 48 VDC from the external supply and adjusts it either up or down, depending on the needs of the load. This voltage is then fed into the second stage, which either feeds the voltage through unchanged or switches it into an AC waveform. The DC or AC waveform would then be fed to the third stage, which is the physical outlet receptacle. The receptacle has sensors to determine the type of plug inserted into it (see Figure 1), which will ultimately deliver power to the load. All of these three are governed by a microcontroller which looks at the system inputs and orchestrates proper functionality within and between each stage. For the purpose of our design, we used an Arduino UNO to control the selection output voltage of the buck and boost. A finished product would have an embedded microcontroller which manages these tasks and also reads the DC selection signal from the data pin to verify proper operation. An embedded solution may also directly manage the converter switching as well as the inverter switching.

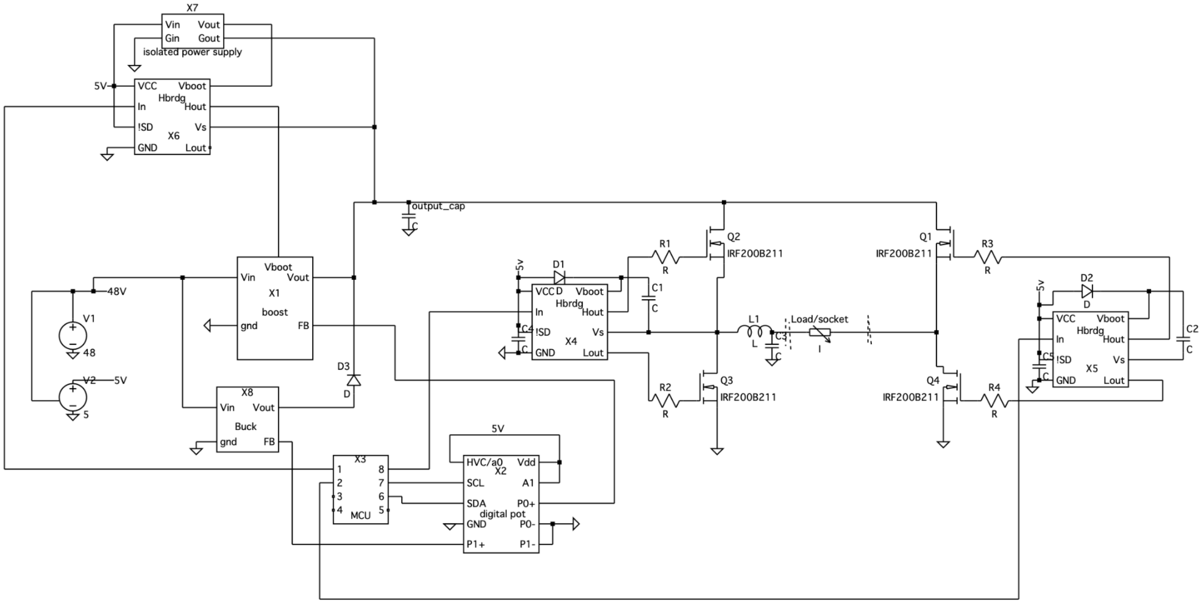


Figure 5: High Level Wiring Diagram

Design Choices

The first step in designing the inverter stage is to choose a topology. We chose a transformerless topology since it avoids bulky low-frequency transformers. There are two main ways to implement this type of inverter; One uses a H-bridge fed with a single 170V input and the other which has a half bridge fed with +170V and -170V [12]. The latter solution would result in a circuit that is compatible with polarized AC devices, however we decided to implement a H-bridge since it would be much easier to create and regulate a single 170V input. In addition, there are challenges that arise from needing to send control signals to two circuits that have different ground voltages.

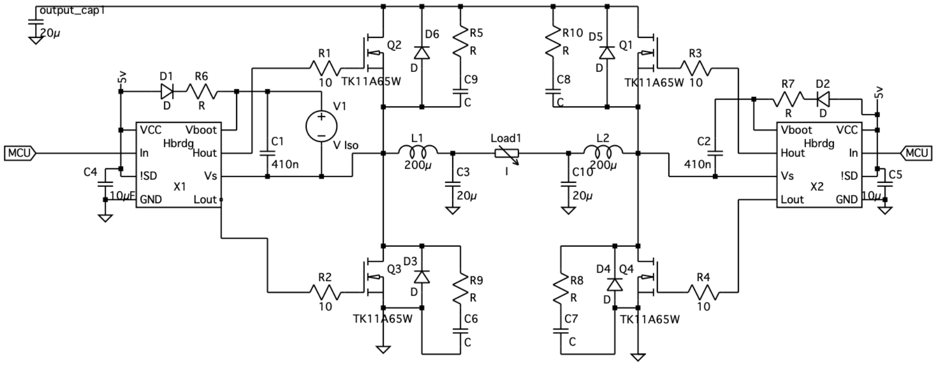


Figure 6: H-bridge Schematic

We started the H-bridge design by picking out a driver. Since our design required a chip that could handle 170 V_{peak} and 120 V_{rms}, our options narrowed significantly. We ended up selecting the IRS2302SPBF made by Infineon, which made it easy to simulate our H-Bridge using their online simulation tool. We would use two of these half bridge drivers to create an H-bridge. Our initial design followed the recommended typical application, but we eventually made some changes to tune it to suit our needs better. Firstly, we chose the decoupling capacitors to be 10µF since that is the largest surface mount capacitor we have readily available, and swapping to an electrolytic capacitor would be more hassle with little benefit.

Unlike normal inverters, our inverter needs to also be capable of delivering DC. Practically, this means that one half of the H-bridge needs to remain switched high, and the other side low indefinitely. This poses a problem because of the bootstrapping that we are using to actuate the H-bridge switches [13]. When outputting AC, the bootstrapping capacitors for either half bridge are charged up when driving that side low and then use that charge to turn on the high side during the other part of the cycle [12]. If the half bridge was in the high state continuously, the bootstrapping capacitor would eventually drain and the MOSFET would turn off. To get around this we placed a small isolated power supply module in parallel with the bootstrapping capacitor that provides a continuous voltage to keep the MOSFET on for an unlimited amount of time [14]. This essentially makes other parts of the bootstrapping circuitry obsolete, but the components were not removed for redundancy. The bootstrapping could still be used if the isolated power supply fails at some point, using a high duty cycle to keep the capacitor charged, but with efficiency losses.

We are using varying PWM to drive the H-bridge in order to better reproduce a sine wave [11] (see Figures 12 and 13). In order to make our sine wave as pure as possible, we included an LC filter. The reason for this type of filter is that it is much more efficient than an RC filter where the resistor will dissipate some power, and its low pass characteristics allows us to filter out the 32 kHz switching frequency of the PWM signal. During our research, we learned that as a rule of thumb for this type of filtering, the cut off frequency should be one decade below the switching frequency [15]. This cutoff sufficiently filters the output while keeping the components small. For a given cutoff frequency there is a continuum of possible L and C values.

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

Figure 7: LC Filter Cutoff Equation

When selecting values for these components, we had to keep in mind that practically speaking, the values for both our inductors and capacitors had to be reasonably balanced to keep both components small and easy to get. After running through a few iterations, we found that 200uH and 20µF would fit the application and were easily available. The final design element that we added to improve our design is called a “snubber”, which is essentially a resistor in series with a capacitor, and both are in parallel with the freewheeling diode and switch. There are two functions that a snubber can achieve in the circuit depending on the component values used. The first is to increase efficiency by providing a better path for current during the time when the MOSFETs are transitioning from on to off. The second function is to dampen the transient spikes that often occur when switching an inductive load. These spikes ordinarily pass through the freewheeling diodes onto the rails, but they can introduce noise in the process which can be reduced by the use of snubbers [16].

For the layout of the PCB, one of the most important aspects was making sure that the board could handle the load current. Since this board was meant to be used for a relatively low power appliance in a demonstration, we set the max current draw as 4.5A. Using a PCB trace width calculator, we ran into the problem that with a standard 1 oz copper pour, the required trace width would need to be 161 mils, which is an abnormally large size. To reduce this trace size, we changed the copper pour to 2 oz, and by allowing the temperature to rise by 20°C, we ended up with a trace width of about 81 mils. To prevent noise from ruining signal integrity, we moved the signal components to the left half of the board, and placed the power components on the right half of the board, giving about an inch and a half of space between the 2 groups. To further isolate the groups, we made 2 ground plane polygons pours. The purpose being that the MOSFETs create a lot of noise when switching high voltage and current, so by putting them on their own ground plane it helps to isolate the noise and keep it from interfering with the sensitive signal components. Since these ground planes must still connect electrically, a thin trace was used to electrically connect the two planes. The last design consideration was that due to our budget, we had to make the board's area as small as possible to keep the fabrication costs down. While this didn't play a major role in the board's final dimensions, it does explain why the signal components are placed together in such a high density.

We decided to split the functionality of the DC to DC conversion into two parallel converters for a few reasons. Firstly, we wanted to avoid using an isolated converter to maximize efficiency and minimize size. We also decided to rule out inverting topologies among the non-isolated topologies because of potential issues with the H bridge and the DC converter stage needing two separate grounds but having the same controller. Initially, we intended to use a 4-switch buck-boost due to its versatility and compact size overall. However, we were unable to find a driver that could tolerate 170V. The same difficulty arose with other topologies that use a high-side switch. Ultimately, it would be easiest to design a buck converter and a boost converter and use a few extra components to allow them to operate in parallel [17][18]. These components included a diode in series with the output of the buck converter to prevent the boost voltages from damaging the lower-rated buck components. It also included a series switch and driver in the same configuration as on the H-Bridge to block the 48V rail from leaking straight through the boost converter and prevent the buck from outputting lower voltage properly (see Figure 8). This split design allows us to reach our output parameters without using expensive specialty chips or a complicated topology. To choose components, we used an LTspice simulation along with some hand calculations to determine and test the ideal components. Multiple iterations were needed to find values that met our requirements yet were still easy to get. The inductor was particularly challenging in this respect. Several other components such as the MOSFETS and filtering capacitors were chosen due to them already being used on the H-Bridge. It was also decided that it would be too complicated to have a microcontroller manage the buck or boost switching at the same time as it manages the inverter, so we decided to find off-the-shelf driver ICs for the converters. The way we set the voltage is to modify the resistance in the feedback voltage divider that sets the output voltage. This is done by sending values over I2C to a digital potentiometer which sets its resistance and thus the output voltage. The digipot holds the resistance given to it so the microcontroller does not have to do anything after the initial set command. The buck and boost feedback voltage dividers are both connected to a dual output digital potentiometer. The digital potentiometer has a volatile and nonvolatile memory register for both outputs. The nonvolatile value is loaded when first powered which allows for both the Buck and the Boost to have a default value that can be set in the case of a power cycle. For safety these will be set to the maximum resistance, forcing the converters to their minimum output to prevent overvoltage damage. In normal operation, when a device is plugged in and needs a certain voltage, the volatile memory for the relevant converter's voltage divider will be written to and the digipot adjusts its value. Then the converter will be enabled and the correct voltage will be sent to the load.

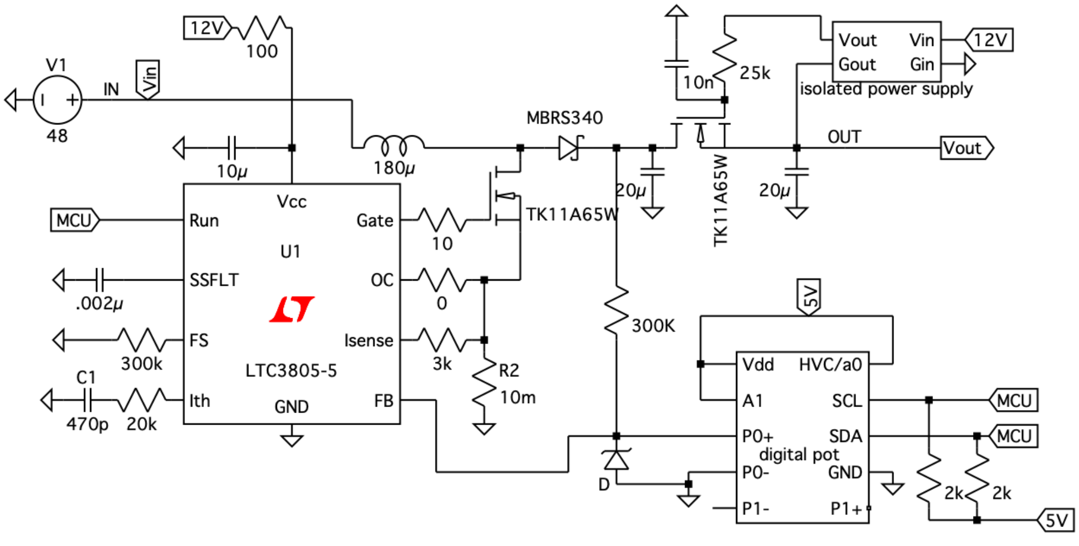


Figure 8: Boost Converter Schematic

Many buck converter models are available on the market, the first step was finding one that matched our specifications. The buck converter needed an input of 48V with a wide output range adjustable by a voltage divider. There needed to be an integrated switch to help with efficiency, simplify the board design, and an enable pin. After considering different chips such as the MAX17576, LT8620, and the TPS54561Q1, the TPS54561Q1 was chosen for the project due to its wide input range, soft-start mode, and PowerGood pin, which protects the rest of the circuit if the output of the buck falls out of regulation for any reason [18].

With the buck chosen, the WEBENCH Power Designer created multiple layouts for a circuit that outputs 5V, 12V, and 24V. Each was designed for a maximum of 2% voltage ripple, a nominal output current of 5A, and a possible input voltage difference of 48V±1V. The design was prioritized for a 12V output range, with inductor values chosen for 24V to allow for better compensation. The feedback resistor was chosen based on the dual channel 1-10kΩ digital potentiometer shared between the buck and the boost in order to supply a stable 5V-24V output as the digipot swings from 1-10kΩ.

The boost converter chip was easier to find because it only uses a low side switch, so it is capable of driving any input or output voltage using an NMOS. We chose the LTC3805-5 driver IC because it has a good balance between customizability and design complexity at a relatively low price [17]. The chip had the necessary enable pin and also allowed us to set frequency, inductor current limit, soft start properties, and transient compensation. An LTSpice simulation model existed for the part, which made it much easier to verify that our calculations would have the desired effect in the final circuit.

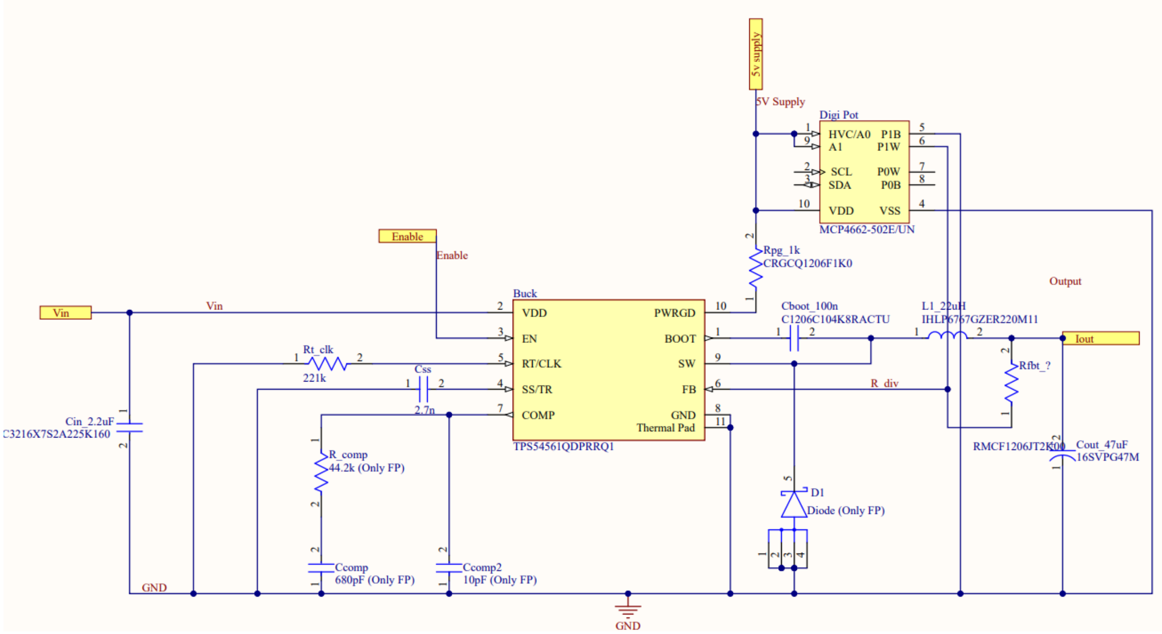


Figure 9: Buck Converter Schematic

Hardware Test and Results

Preliminary testing of the hardware has consisted of creating the H-Bridge circuit on a breadboard as well as a PCB milled using an Othermill Pro. This circuit was used to test the functionality of the isolated power supply bootstrapping and to prototype our PWM control methodology and output filter. We decided to use a slightly unusual PWM methodology because it was convenient to set up on the arduino, and had been used in similar projects. With these prototypes we found that the circuit could output a clean sine wave to a load of 50Ω up to the maximum voltage that could be handled by the diodes we had at the time of 50V. The circuit could also pass DC to the load indefinitely.

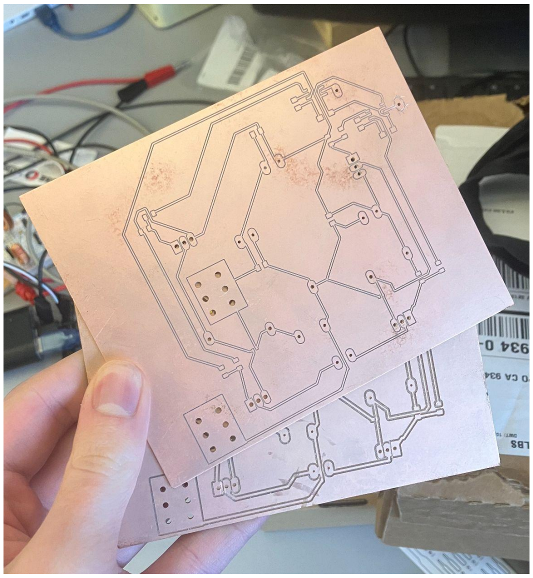


Figure 10: Milled PCBs Unpopulated

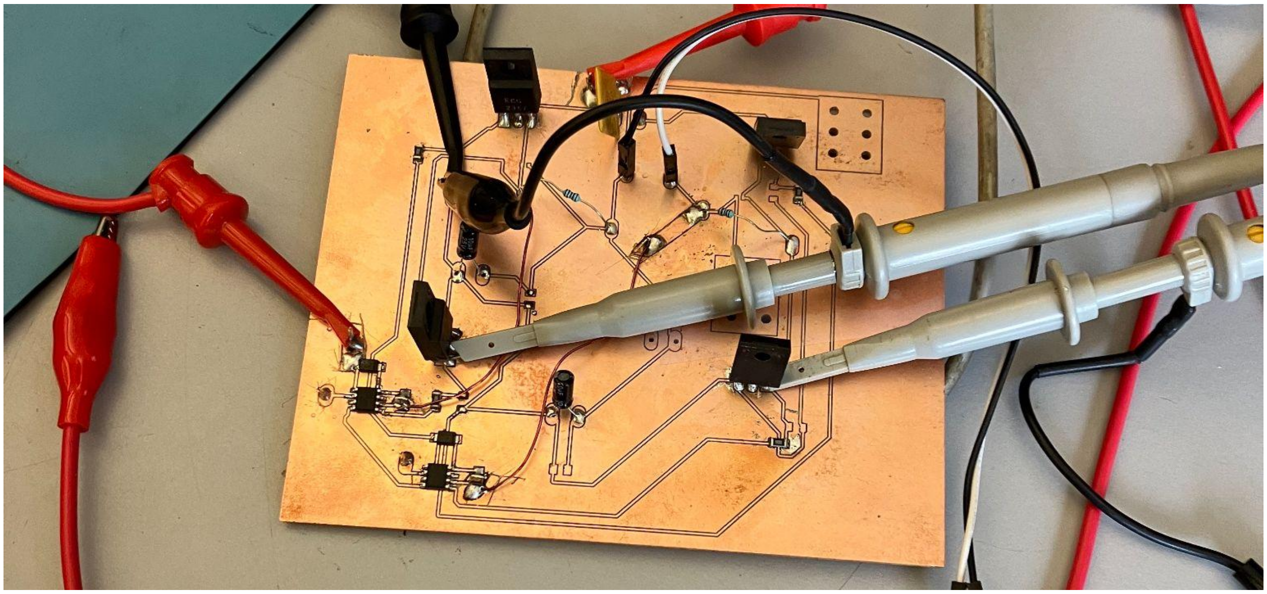
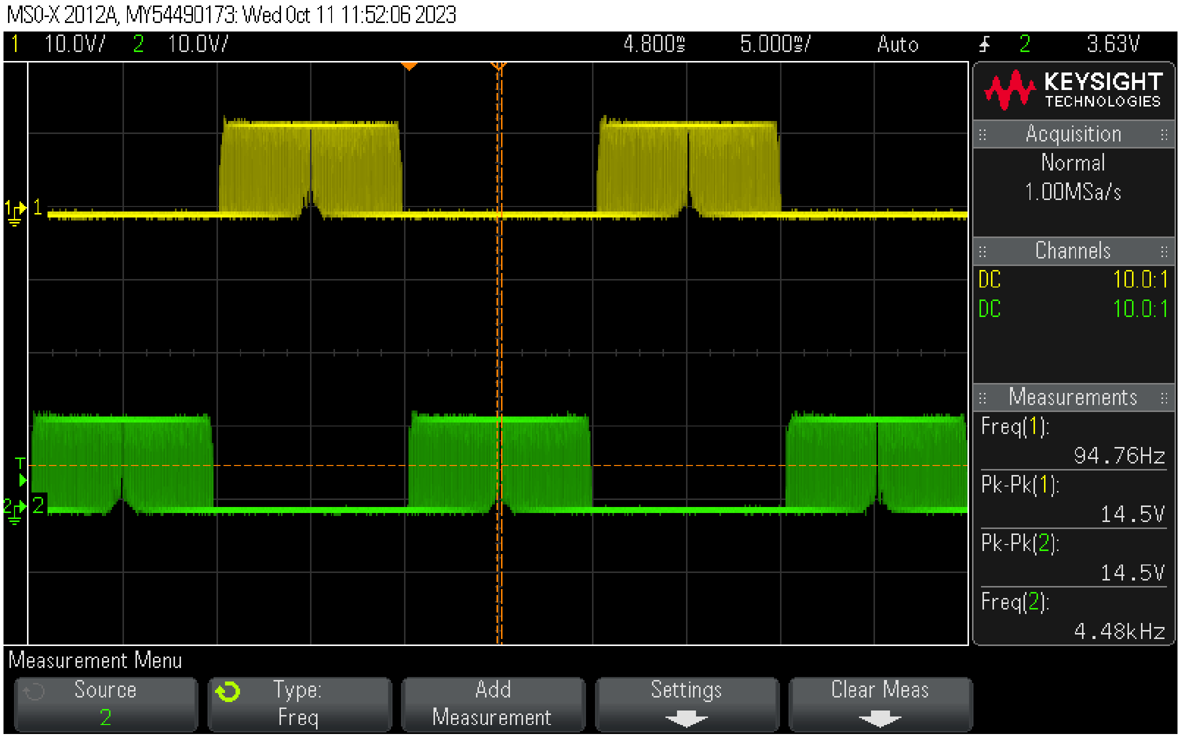


Figure 11: Milled Prototype Undergoing Testing



MSO-X 2012A, MY54490173: Wed Oct 11 11:52:06 2023

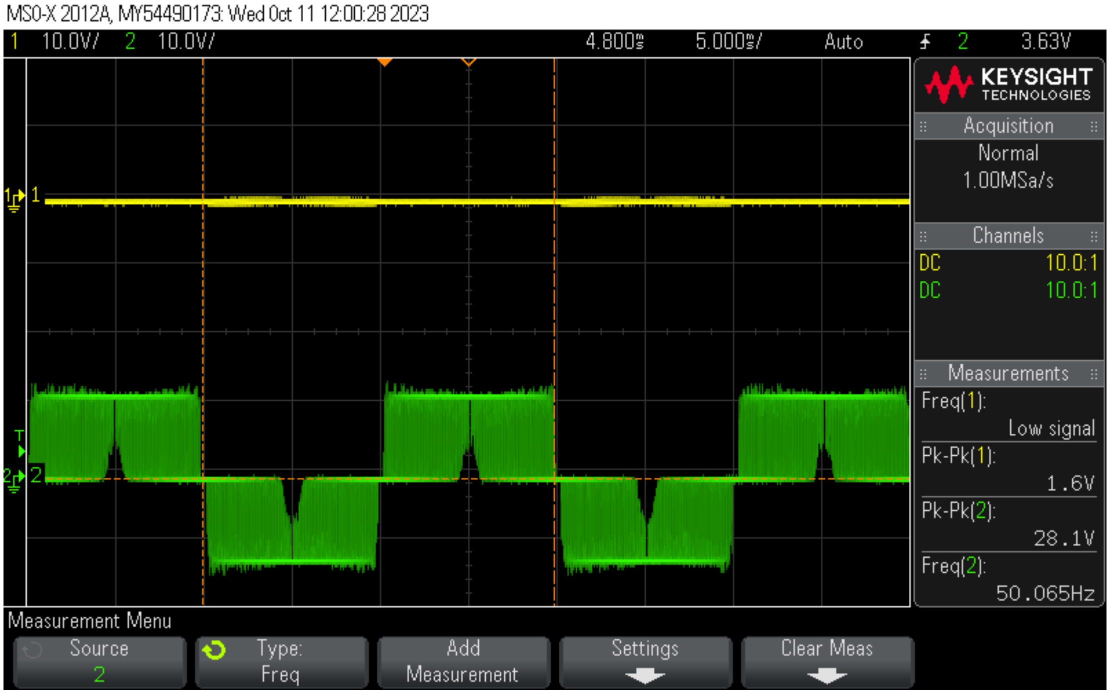
1 10.0V/ 2 10.0V/ 4.800s 5.000s/ Auto 2 3.63V

Acquisition
Normal
1.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): 94.76Hz
Pk-Pk(1): 14.5V
Pk-Pk(2): 14.5V
Freq(2): 4.48kHz

Figure 12: Inverter Output Per Half Bridge



MSO-X 2012A, MY54490173: Wed Oct 11 12:00:28 2023

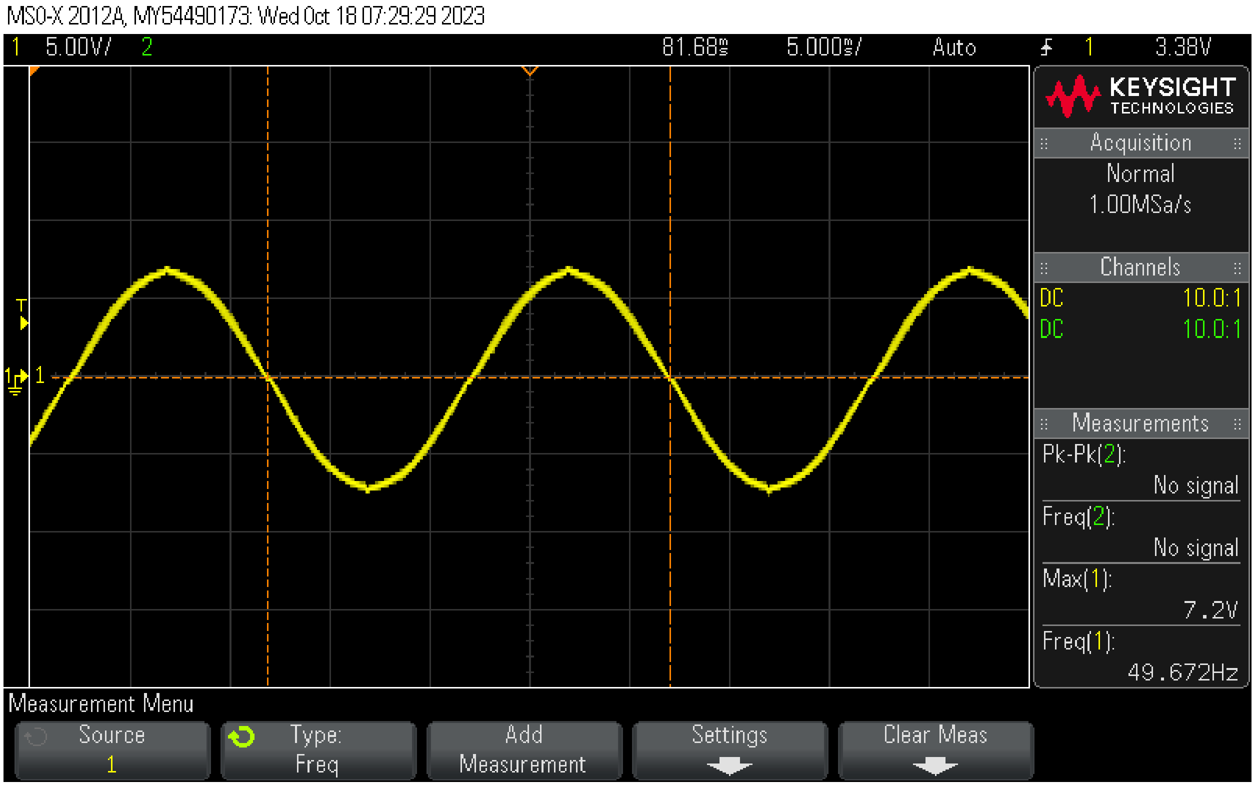
1 10.0V/ 2 10.0V/ 4.800s 5.000s/ Auto 2 3.63V

Acquisition
Normal
1.00MSa/s

Channels
DC 10.0:1
DC 10.0:1

Measurements
Freq(1): Low signal
Pk-Pk(1): 1.6V
Pk-Pk(2): 28.1V
Freq(2): 50.065Hz

Figure 13: Unfiltered Inverter Output As Seen By The Load


MSO-X 2012A, MY54490173: Wed Oct 18 07:29:29 2023

1 5.00V/ 2 81.68ms 5.000ms/ Auto 1 3.38V

Acquisition: Normal 1.00MSa/s

Channels: DC 10.0:1, DC 10.0:1

Measurements

Pk-Pk(2): No signal

Freq(2): No signal

Max(1): 7.2V

Freq(1): 49.672Hz

Measurement Menu

Source: 1

Type: Freq

Figure 14: Filtered Inverter Output As Seen By The Load

After the initial testing of the H-bridge on the milled board, the circuit was redesigned so that it can be sent to JLCPCB and be professionally manufactured and we could assemble and test again. Figures 15 -17 show the final design and fabricated inverter board. The Buck and Boost board was also designed as can be seen in Figures 19-22. These converters were designed to share the same output wires and operate one at a time depending on the desired output.

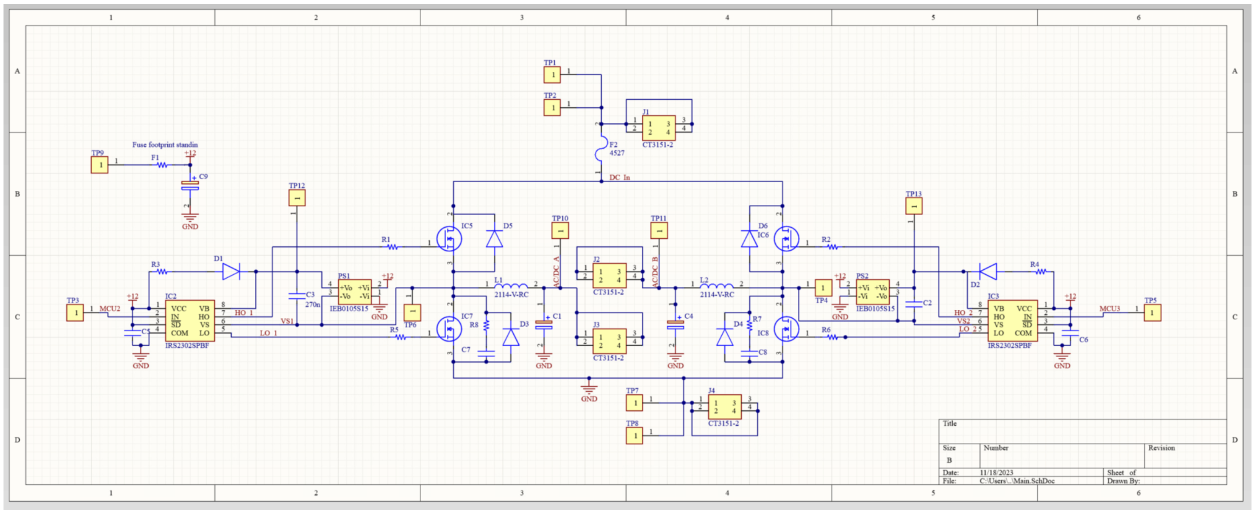


Figure 15: Inverter Schematic

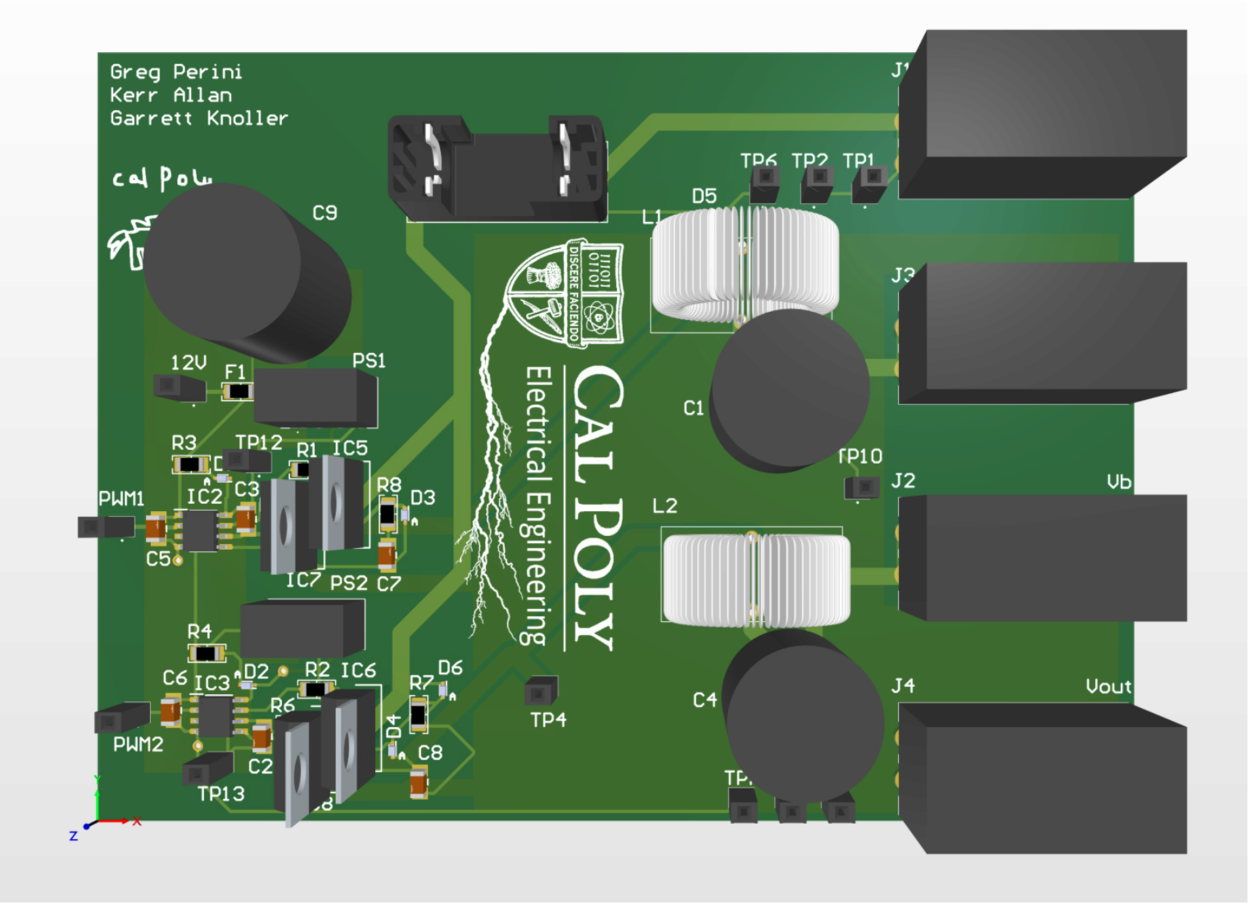


Figure 16: Simulated Top View of Inverter

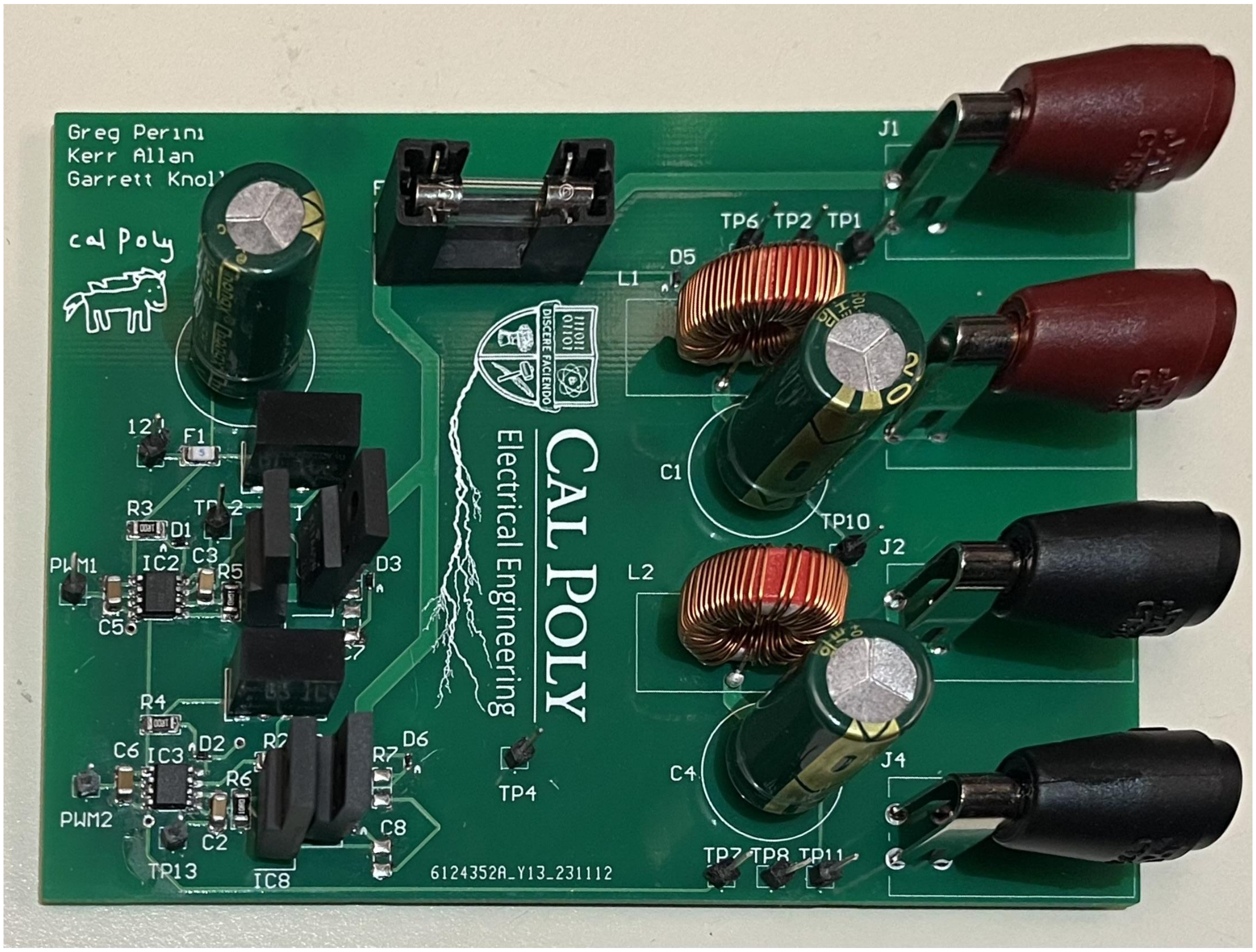


Figure 17: Top View of Assembled Inverter

For our inverter testing, it was especially important to make sure that the testing started with low voltage and load conditions, in order to spend the least amount of time remaking boards. For this reason, we took most of our measurements at a 30V input while varying our load. For our load resistance, we used the panel mounted resistors in the power lab in place of the DC electronic load because the DC load can't be reverse polarized. To increase the output load current, we put the panel mounted resistors in parallel to lower the equivalent resistance. To calculate the efficiency, we used a multimeter in parallel with the dc power supply to find the actual input voltage since the power supply isn't as accurate. However, when using an ammeter, the power supply did display the correct value so we used its reading for input current. To find the output power on the load side, we hooked up the AC power meter which is able to determine voltage, current, and power at the output.

Using this information, we were able to determine the efficiency for a load current of 110 mA up to 600 mA, which gave us the efficiencies found in Figure 18. From this data, it appears that when the load exceeds 110 mA, the efficiency is around 90%, which aligns with our goals we came up with in EE460.

For the last portion of the inverter testing, we attempted to reach our max output goal of 120V at a 4 amp load. As we increased the voltage past 75V, we heard a pop sound, which we later determined to be a cracking in one of the diode's plastic cases, but this was determined to be an anomaly as the diode still worked and never got warm on the thermal camera. As we continued to increase the voltage, we got up to 120 V at 260 mA before one of the half bridge drivers failed.

Despite the failure, the board didn't appear hot which would indicate that the issue was too much current being drawn. The FETs seemed to be undamaged and the low side of the output driver still functioned but the high side did not. The driver is rated to go up to 600V and says it is immune from dv/dt damage, and we are very skeptical that we could have produced a 600V+ spike at all, and if we did, it would likely have done more damage than we are seeing. While the exact cause of the failure is unknown, the lack of proper ESD protection could possibly be responsible. It is also possible that the very high duty cycle at the edges and center of our switching waveform interacts poorly with the driver, as it was told to turn on before being told to turn off just a little before it is all the way on. The rise time is 130ns and our minimum duty cycle would have an on time of 120ns. Although we predicted this just meant the chip would not turn all the way on during that part of the cycle, it may have been damaging to the chip. Another possible consideration is that PCB layout is a skill that many people make a career out of due to its complexity, and therefore it is possible that some complicated form of behavior we did no anticipate fried the driver.

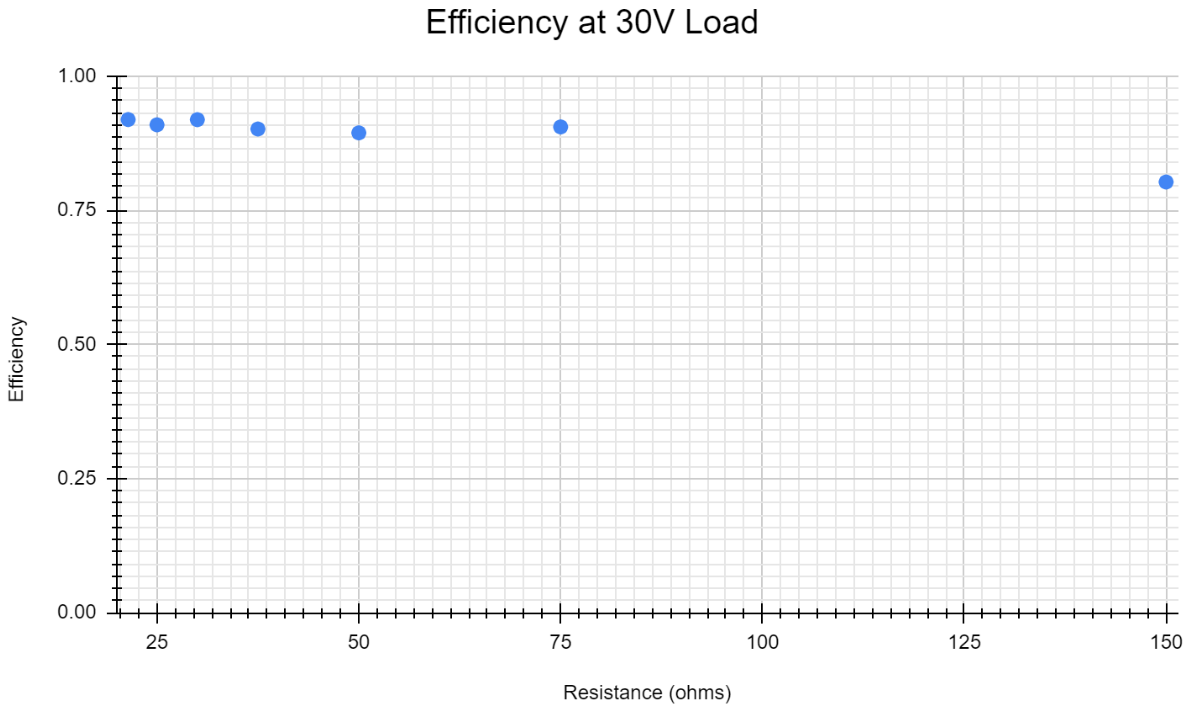


Figure 18: Inverter Efficiency

Testing the Buck and Boost Board

Much of the initial testing for the Buck/Boost Board was diagnosing usually simple faults in the soldering and assembly of the board. Firstly, the big polarized capacitors C5 and C6 at the top of the board were soldered in the wrong direction which was leading to no signal getting through to the output. We replaced those capacitors in the correct direction and continued testing. We then realized that we still received zero output and some of our components were overheating. We realized that the Vin+ and Vin- and we were feeding the wrong ends into the board, so we replaced the casing on those ports. At this point we started to receive the expected values for the Buck converter and were able to vary the voltage from 5V to 20V and analyze its efficiency as can be seen in figures 23 and 24.

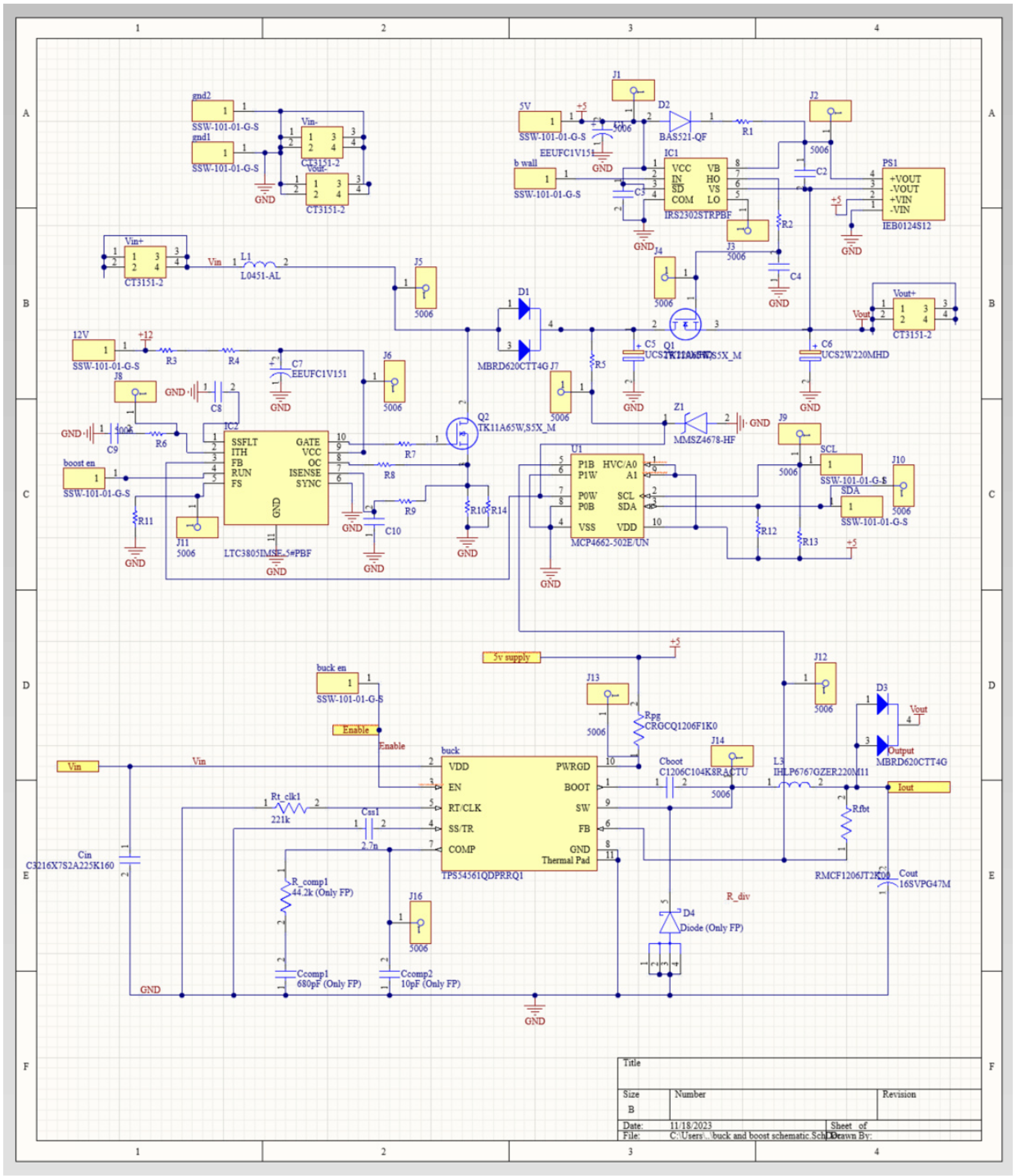


Figure 19: Buck And Boost Board Schematic

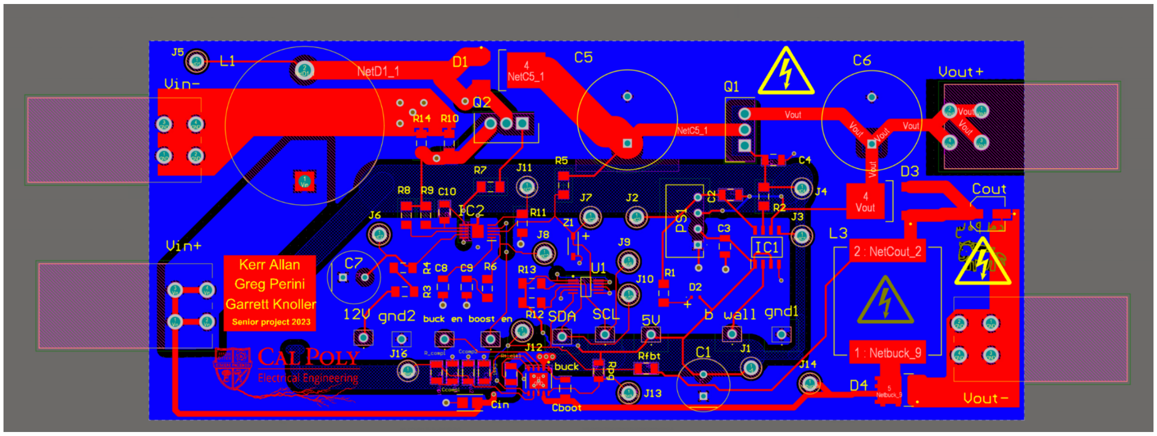


Figure 20: Buck And Boost PCB Layout

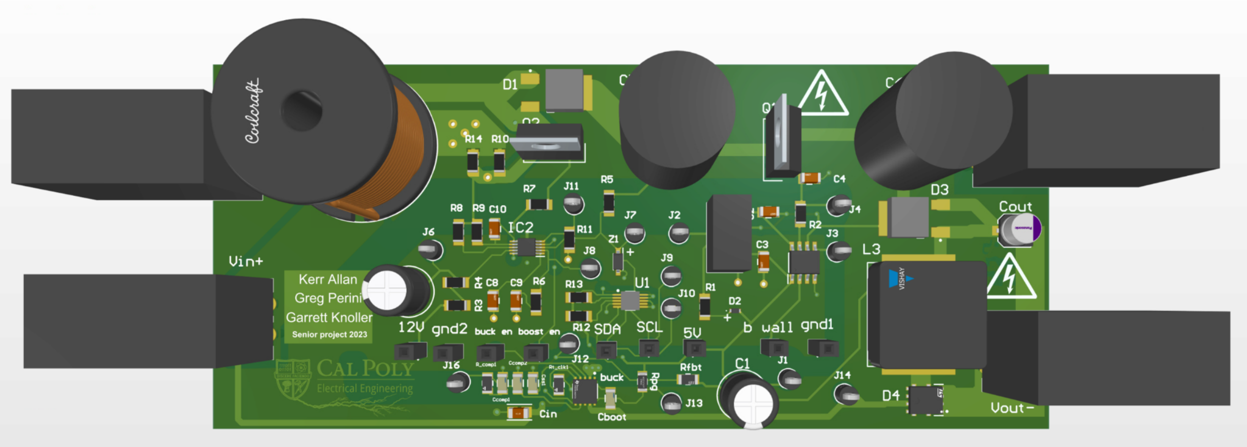


Figure 21: Buck And Boost PCB Layout In 3D

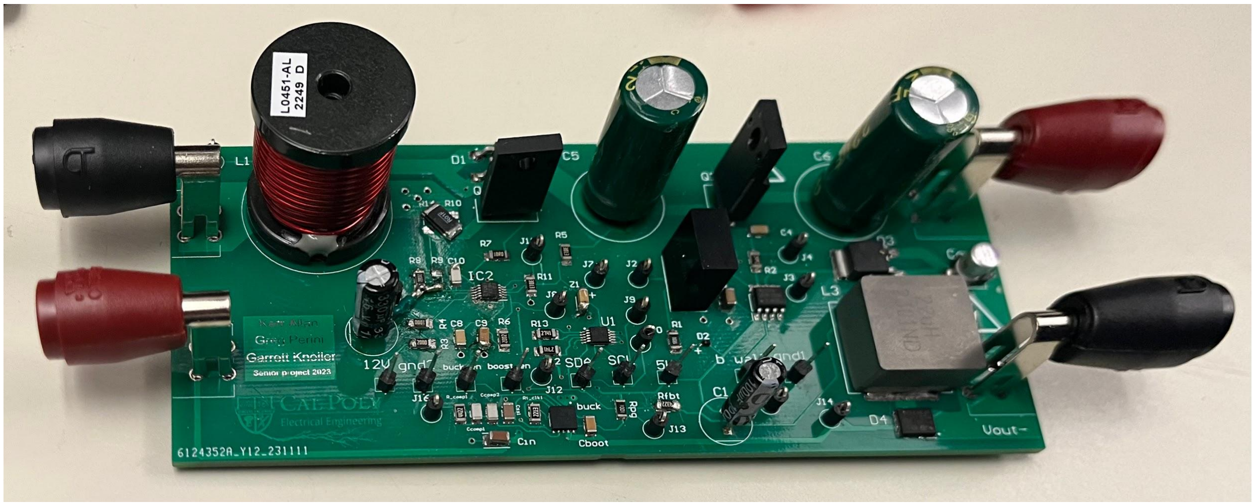


Figure 22: Fully Assembled Buck And Boost PCB

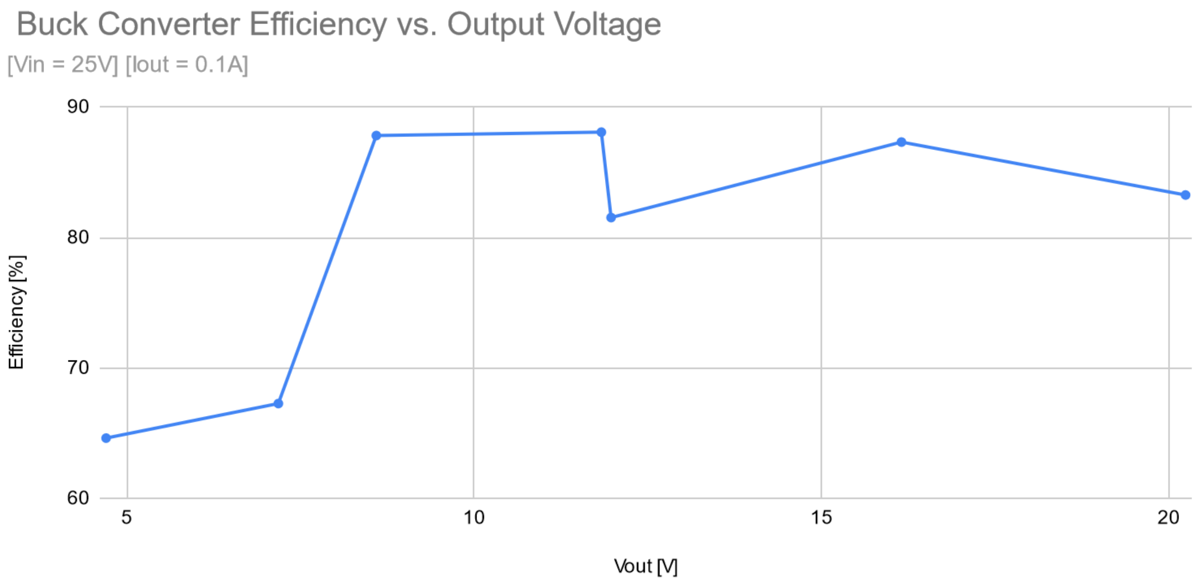


Figure 23: Buck Converter Efficiency at Light Load

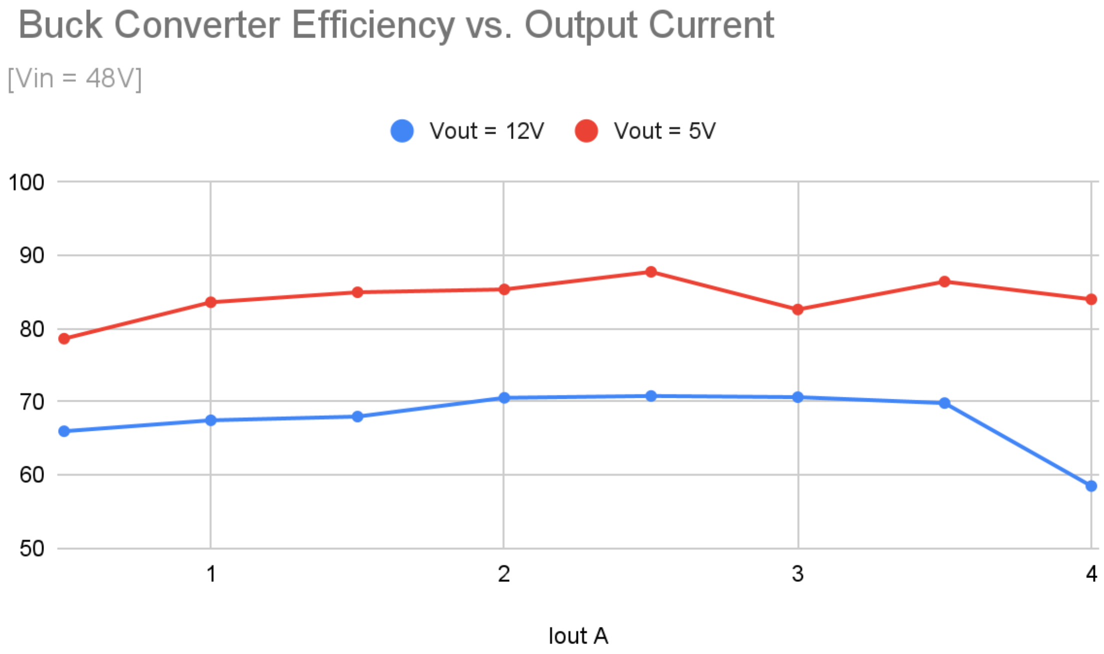


Figure 24: Buck Converter Efficiency at Different Loads

Testing of the Boost converter then continued. The first issue was the switching on the chip was stopping at one cycle and turning off. We concluded that the overcurrent protection pin was being triggered on the very first switch. The datasheet told us that shorting the IOC to the sense resistor would set the overcurrent limit to trip only at the minimum duty cycle of 6%, but it was tripping immediately. This was possibly due to noise coupling to the line causing the 100mV threshold to be exceeded early or from parasitic resistance influencing the sense resistance. We created a voltage divider for that pin with a 2Ω resistor and a short to the ground and lowered the sense resistance value, this caused the boost converter to power on as expected without shutting down, but there were still some issues with its behavior. This modification can be seen in Figure 22.

After the overcurrent protection issue was fixed, the circuit was running well under light loads. We measured efficiency under these loads as shown in Figure 25, but as we got to higher loads the inductor started to make an audible noise. This could not be from normal operation since the switching frequency is 84kHz, far above what the ear could hear. Upon looking at the switching node we found that there were subharmonics where the switch duty cycle would go from low minimum to maximum for one cycle every few cycles depending on the load as seen in Figure 26.

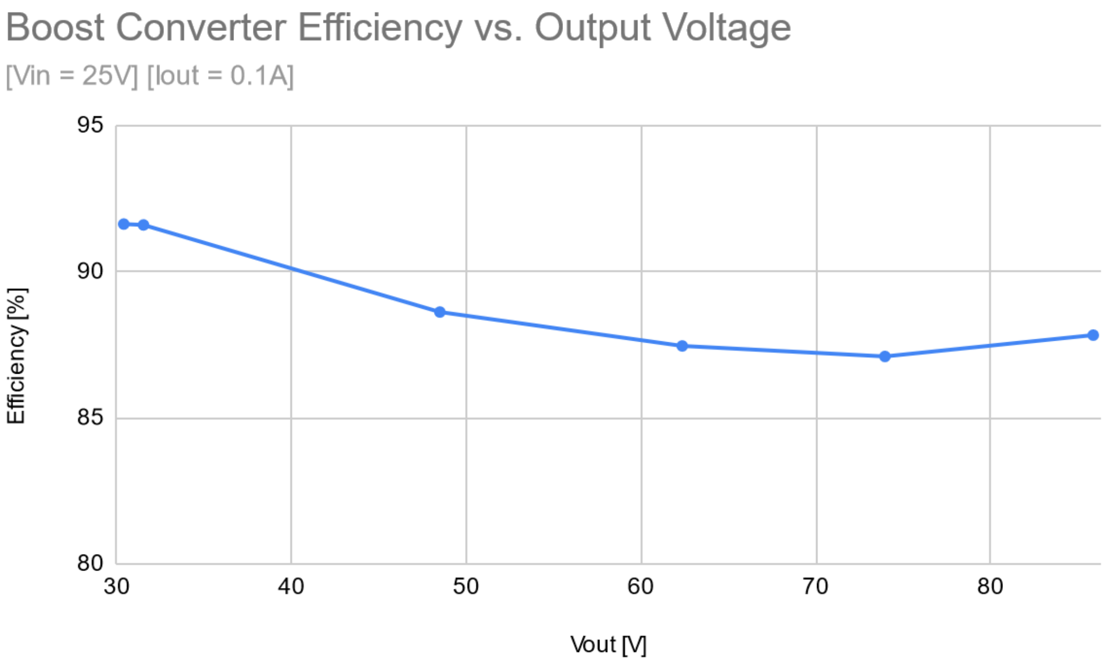
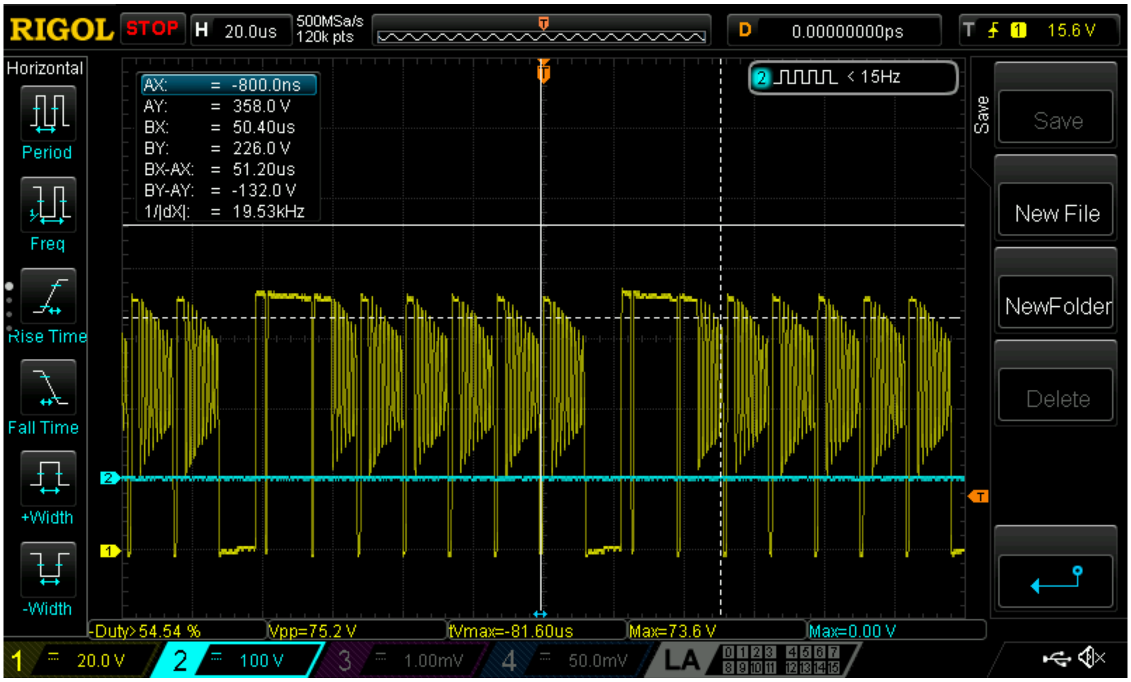


Figure 25: Boost Converter Efficiency

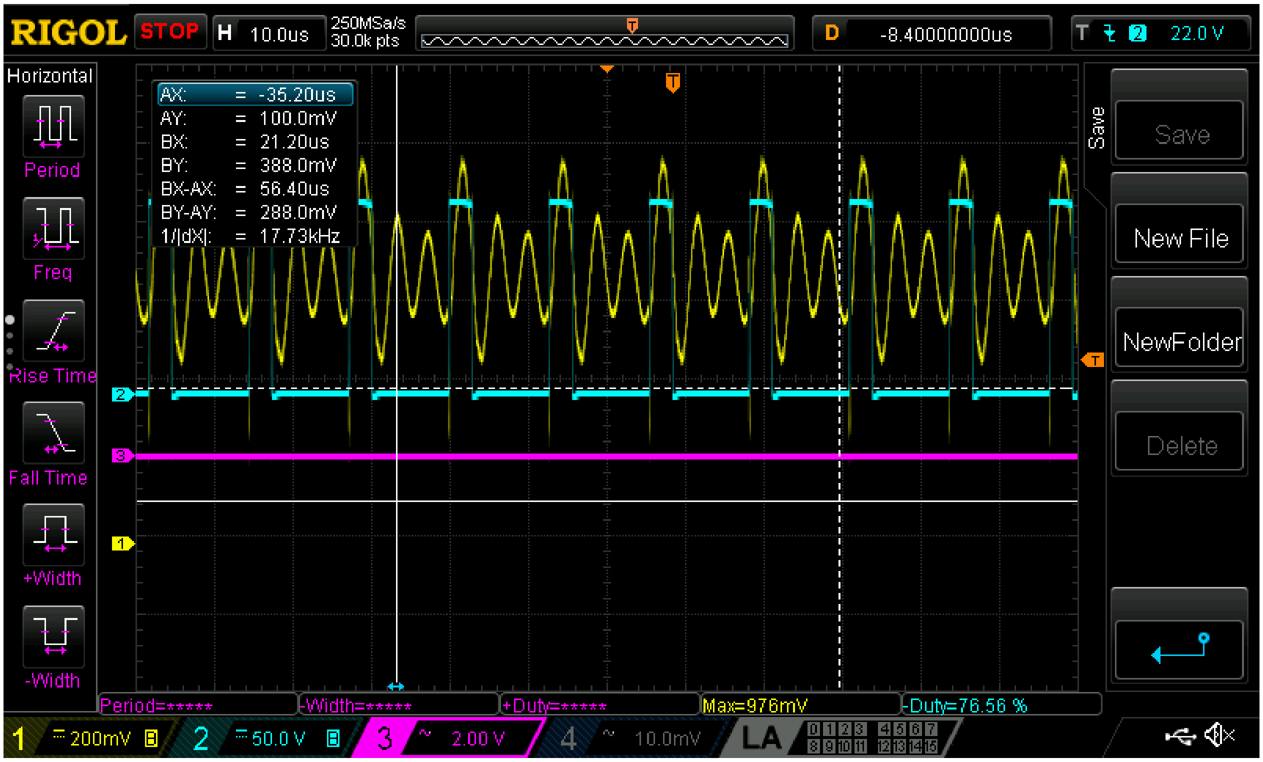


```
AX:      =  -800.0ns
AY:      =  358.0 V
BX:      =  50.40us
BY:      =  226.0 V
BX-AX:   =  51.20us
BY-AY:   =  -132.0 V
1/|dX|:  =  19.53kHz
```

```
-Duty>54.54 %   Vpp=75.2 V   tVmax=-81.60us   Max=73.6 V   Max=0.00 V
```

Figure 26. Boost switching node at 25V in, 75V and 100mA out.

This created a large amount of electrical noise and output ripple. In order to fix this, several attempts were made to modify the transient behavior and to stabilize the output, but the fixes that worked in simulation did not fix the real circuit's behavior. At heavy loads the circuit was capable of stabilizing out of the subharmonics, but at the cost of somewhat poor ability to maintain the output voltage. There was also a large amount of ringing on the feedback pin as seen in figure 27 which we tried to fix with some extra capacitance to no avail. This ringing could have been due to the behavior of the digipot, the electronic load, or some resigning internal to the circuit. That being said, the boost converter was highly efficient in every situation we tested it in, never deviating from around 90% efficient. The boost converter almost worked to our goals, it was able to reach 130V (the DC electronic loads could only tolerate 150V so we left a safety margin of 20V) up to about 600mA of current before the voltage dropped by more than 10%. Under light loads it maintained the output voltage accurately but made a buzzing noise and had large output ripple. And under heavy loads it was quiet and was able to deliver 260W at around 100V before overheating, but had trouble maintaining output voltage. Ultimately an odd control loop error was seemingly the only thing preventing the boost circuit from working to our stated goals.



H 10.0us
250MSa/s
30.0k pts
D -8.40000000us
T 22.0 V

AX: = -35.20us
AY: = 100.0mV
BX: = 21.20us
BY: = 388.0mV
BX-AX: = 56.40us
BY-AY: = 288.0mV
1/|dX|: = 17.73kHz

Period=*****
-Width=*****
+Duty=*****
Max=976mV
-Duty=76.56 %

1 200mV
2 50.0 V
3 2.00 V
4 10.0mV

Figure 27. Switching node (blue) and feedback pin (yellow) at 30V in, 118V and 600mA out.

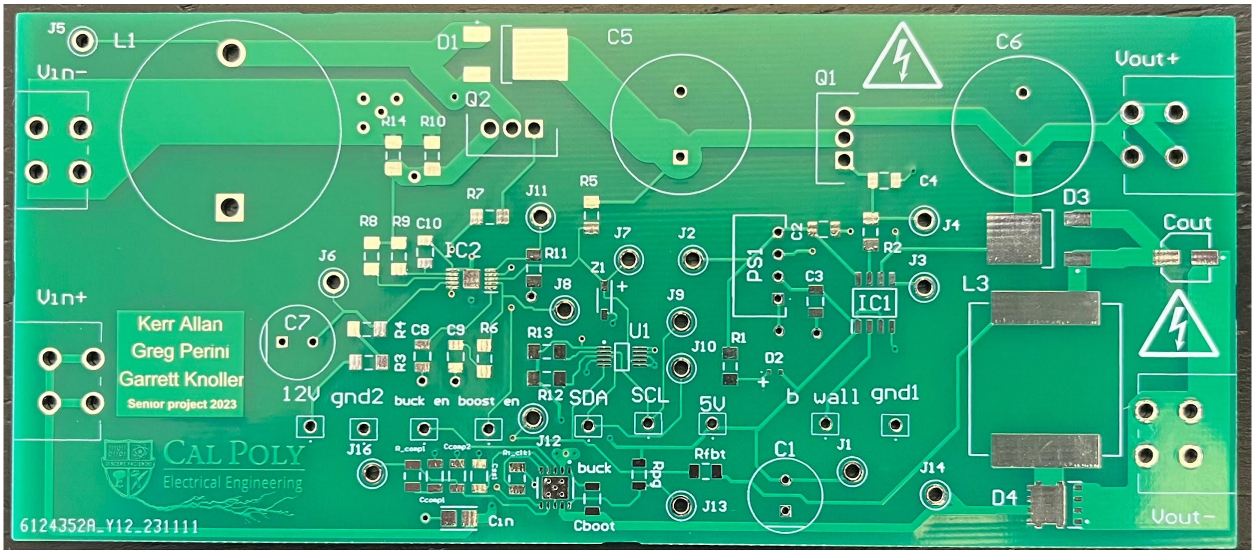


Figure 28: Pre-soldered Converter Board

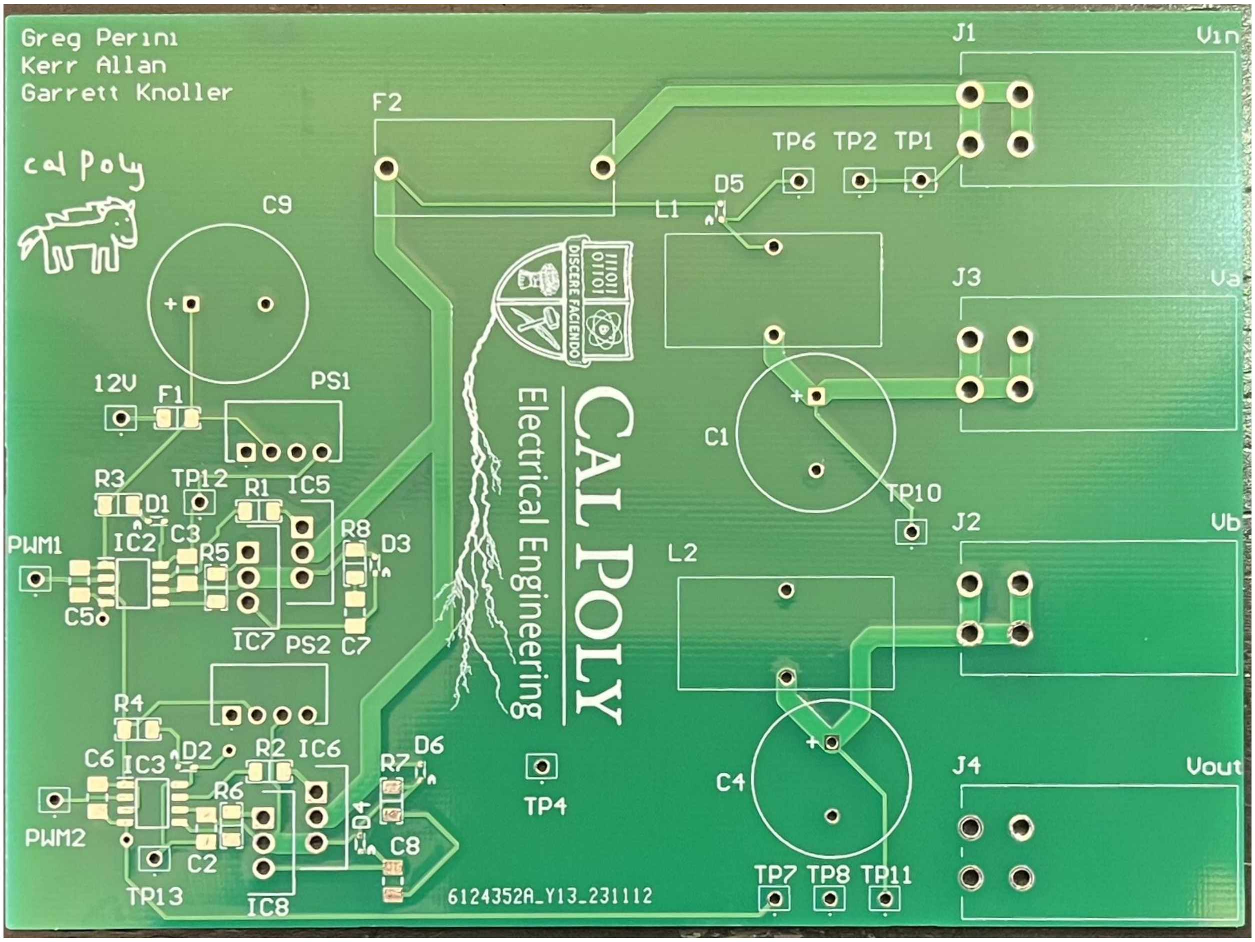


Figure 29: Pre-soldered Inverter Board

Conclusion

At the conclusion of this project, the design accomplished what our group set out to achieve. It could successfully accept a 48VDC input, and provide either a DC or AC output. The circuit just struggled to handle the high voltages and currents that we were hoping it would. Those voltage and current requirements were fairly high for our budget and level of experience so we are still very proud that our circuit was capable of functioning successfully at slightly reduced voltages and currents. As a result, this circuit is a great proof of concept. A second revision could be used in a house such as the conceptual Cal Poly DC house to supply power to either a legacy AC type plug or a standardized DC plug.

While this design was successful, there are some key areas where the design could be further improved in later iterations. We think that it may end up being much more compact to swap the dual buck and boost topologies out for a single 4 switch buck-boost if one can be made to handle the voltages. If two parallel topologies are to be used we recommend changing the outputs that the circuit provides to be from 5-48V and 170V rather than 5-170V. This would allow the boost to be swapped out for a circuit that uses transformers or coupled inductors to reach 170V much more easily. The majority of devices are going to demand 5-48VDC or 170VAC so the new circuit would have easier requirements with little lost functionality. The next steps for anyone wishing to continue building on this design would be to identify the source of the two issues that hindered our existing circuits, and either repair or redesign them. Also, a functional outlet cover should be further designed and built so that real devices can be tested as loads. With more refinement this device can hopefully be made practical enough to line the walls of the DC house.

Works Cited

[1] Taufik, *Advanced Power Electronics*, vol. Rev. 6, Rev. 6 vols. [203-207] San Luis Obispo, CA: Lulu, 2023.

[2] .G. AlLee and W. Tschudi, "Edison Redux: 380 Vdc Brings Reliability and Efficiency to Sustainable Data Centers," in IEEE Power and Energy Magazine, vol. 10, no. 6, pp. 50-59, Nov.-Dec. 2012, doi: 10.1109/MPE.2012.2212607

[3] N/A, “Reimagining and Rebuilding America’s Energy Grid,” Energy.gov, https://www.energy.gov/articles/reimagining-and-rebuilding-americas-energy-grid (accessed Nov. 17, 2023).

[4] Ore, Jonathan (2021): The DC Nanogrid House: Converting a Residential Building from AC to DC Power to Improve Energy Efficiency. Purdue University Graduate School. Thesis. https://doi.org/10.25394/PGS.14519604.v1

[5] P. Granieri, “Smart DC Wall Outlet Design with Improved Load Voltage Detection,” thesis, Cal Poly Digital Commons 2019.

[6] C. H. McGregor, “Plug & socket types,” *WorldStandards*, 09-Aug-2022. [Online]. Available: https://www.worldstandards.eu/electricity/plugs-and-sockets/. [Accessed: 16-Mar-2023].

[7] ""What is Nema"", “What is Nema,” *Home*. [Online]. Available: https://www.ascopower.com/us/en/resources/articles/what-is-nema.jsp#:~:text=NEMA%20provides%20a%20standard%20ratFing,communication%20between%20purchaser%20and%20manufacturer. [Accessed: 16-Mar-2023]

[8] S. Smith, “Power Consumption Chart of Household Appliances,” *Power Stuffs*, 23-Feb-2021. [Online]. Available: https://powerstuffs.com/power-consumption-of-household-appliances/. [Accessed: 16-Mar-2023].

[9] Occupational Safety and Health Association, Davenport, IA: Mancomm/Mangan Communications, 2009, p. 1910.303(g)(2)(i).

[10] G. Knoller, G. Perini, and K. Allan, “Delay between plug-in and charge start time.” California Polytechnic State University, San Luis Obispo, 16-Feb-2023.

[11] B. Jajodia, A. Mahanta, and S. Ahamed, “Energy-efficient DAC switching technique for single-ended SAR adcs,” *Energy-efficient DAC switching technique for single-ended SAR ADCs*, 06-Jul-2020. https://doi.org/10.1016/j.aeue.2020.153334

[12] International Rectifier, “Half-Bridge Driver,” IR2302 datasheet, Aug. 2004

[13] Diallo, M. (2018, August). Bootstrap Circuitry Selection for Half-Bridge Configurations. Dallas, TX; Texas Instruments. Available: https://www.ti.com/lit/an/slua887a/slua887a.pdf?ts=1700142498341&ref_url=https%253A%252F%252Fwww.google.com%252F

[14] Mornsun, “1W isolated DC-DC converter Fixed input voltage, unregulated single output,” B1212S-1WR3 datasheet, Dec. 2021

[15] C. Yikai, “Cutoff Frequency - an overview | ScienceDirect Topics,” *www.sciencedirect.com*, 2021. https://www.sciencedirect.com/topics/computer-science/cutoff-frequency

[16] C. D’Anna, “Snubber Circuit - an overview | ScienceDirect Topics,” *www.sciencedirect.com*, 2021. https://www.sciencedirect.com/topics/engineering/snubber-circuit

[17] Linear technology, “Adjustable Frequency Current Mode Flyback DC/DC Controller,” LTC3805 datasheet, 2006

[18] Texas Instruments, “4.5-V to 60-V Input, 5-A, Step-Down DC-DC Converter With Eco-mode™,” TPS54561-Q1 datasheet, Sep. 2014 [Revised Jan. 2017]

ABET Senior Project Analysis

Project Title: Hybrid Wall Outlet for AC or DC power delivery

Student's Name: Garrett Knoller, Greg Perini, Kerr Allan

Advisor's Name: Jason Poon

1. Summary of Functional Requirements

The Hybrid Wall Outlet aims to provide an easy-to-use and efficient power interface for buildings and systems transitioning to an isolated DC grid. It takes in a 48V DC power supply and offers various kinds of power to the device. The device will be installed in a building with a pre-established DC generation grid supplying its power. The purpose of the Wall Outlet is to act as a transitional technology as power generation and power delivery transition to DC, as well as the needs of the customer's devices that might take in either AC or DC. Because of this, our smart plug needs to determine which type of electricity and at what voltage the device requires.

2. Primary Constraints

The first requirement is that the Wall Outlet works with both AC and DC-powered electronics. This means it must have a 1:1 compatibility with existing charging technology. The Wall Outlet should supply the maximum AC or DC voltage needed for smaller devices such as computer chargers, curling irons, and TVs; these devices all sit at or below 200W.

The second requirement would be a power delivery within 2 seconds of plug-in. After experimentation, it was determined that a standard plug delivers power to a laptop after 0.76-0.98 seconds after plug-in. An additional second could be allowed for the charger to reach the waveform required, but any longer could cause the user to doubt if the outlet is working. The third requirement is that AC power should not be able to be accessed by a DC plug or vice versa. This requirement is essential as the wrong power delivery could be extremely dangerous to the user and catastrophic to the device. Finally, the device must be easy to install. The device will fit in a standard NEMA outlet box to meet this requirement. This makes the technology highly likely to be adopted and prevents misuse and confusion.

3. Economics

After a thorough cost analysis, a pessimistic, likely, and optimistic projection for the materials required to create the Wall Outlet were created. After considering the parts needed, such as a capacitor, resistor, and inductor kit, MOSFETs, diodes, the fabrication of the container, a DC converter driver, and a PCB, the likely total cost was \$122.63. A pessimistic value of \$181.61 and an optimistic value of \$89.32 was also found in order to give a possible range of cost. This is without considering the labor cost which for the past quarter was \$253.33 per week per engineer with a Low and High true Cost of \$316.67 and \$354.66. The Yearly salary for each of these engineers was \$85,000.

These are the immediate costs of developing the Wall Outlet that would be accounted for through materials and work alone. According to initial estimates, this step should take 30 weeks to complete. However, there are other considerations regarding this technology throughout its life cycle. Once the product is developed, there is a need for adoption for the product to be used continuously. This could occur through its use in a microgrid experiment such as the one at Purdue. Throughout the Growth and Maturity stages of the product's life, the benefits of its efficiency will be the main draw of the product. As consumers see a drop in energy spending, it is more likely that the Wall Outlet will continue to be used. Finally, the Wall Outlet will fail at some point, like most outlets, and must be replaced.

4. If manufactured on a commercial basis:

If this product were to be manufactured on a commercial basis, there would need to be facilities geared in PCB assembly, and plastic molding acquired for assembly. This product can be considered an additional kind of outlet with some of the framework of a traditional outlet staying intact. Due to this, a more cost-effective path could be to introduce an already existing outlet factory—this way the same machinery can be used with minor adjustments.

Currently, The cost for each outlet can be based on the materials needed to make the prototype which is $122.63. This, however, is based on purchasing large kits of capacitors, resistors, and inductors. Once the design is adjusted, the cost could be closer to $92.42 for production. This price will decrease dramatically once bulk orders of PCBs can be obtained and containers are produced on-site. With these concessions, the production would look closer to $51.33. With a 50% markup, the purchase price for this product is $77. This price point would allow for steady product production until more sales start. Based on this markup and that about 129.4 million electrical outlets were sold in the US last year, and that approximately one-twentieth of those could have currently used this technology, the yearly profits could be 16.6 million dollars a year with full adoption. There is no user cost since the device will operate only when a device is plugged into it.

5. Environmental

Every new product poses the risk of introducing another use of resources that contributes less to its environment than it uses. However, the Hybrid Wall Outlet actively replaces existing technology that is less efficient and located at the device level instead of the distribution level. This means that the current system requires several converters to be plugged into an outlet to power a single device. Instead, you could have a single converter in the wall that can be used for multiple technologies. The increase in efficiency provided by the Hybrid Wall Outlet means there is a significant decrease in power loss and a positive effect on the number of materials needed to provide the same amount of power necessary to charge a device in the current system.

This device's environmental costs are mainly caused by the manufacturing and sources of materials needed for the outlet. If this device were to be available in a larger market, molds would have to be cast to create the shell of the outlet. PCBs and electronic components would also need to be sourced. This is an unavoidable part of developing new electronic equipment, but it affects mostly global southern countries.

6. Manufacturability

The constraints placed on this device make it reasonably simple to manufacture it on a large scale. Outlet boxes are already mass-produced so those can be adapted for this device. The plastic face of the Wall Outlet will need to be designed, and a mold will have to be made in order to produce many of the devices. As for the internal workings of the device, the entire circuit should fit onto a PCB board located behind the face; the assembly of the PCB does not pose an issue. Additionally, the components used in this design are standard and readily available. Considering the above facts, manufacturing this device on a large scale seems very attainable.

7. Sustainability

Using the triple bottom line as a framework, the sustainability of this product can be assessed by looking at each of the three aspects of this principle. The three aspects discussed are economic, social, and environmental sustainability.

This product uses resources with already established supply chains, electrical components that are cheaper than current, comparable technologies, and could be sold to the consumer at a reasonable markup. All of these factors prove this product to be economically sustainable. From a social perspective, this device can also be called sustainable as it will save the consumer money on their power bill every month. Less wasted energy means more people can afford to use electricity, especially those in low-income areas. Finally, this product is also environmentally sustainable as a large adoption of this Wall Outlet will lower the fuel spent to provide a given area power. Overall, the Hybrid Wall Outlet is a sustainable product.

8. Ethical

As a new technology that is being proposed and sold for people mainly in the global north, any raw materials will most likely be sourced from areas of the world that will experience the effects of the harvesting process. At the same time, this technology helps many people to be able to use more power and improve their quality of life. This is the ethical dilemma of the full adoption and development of this technology.

In order to solve this ethical dilemma, many in this field will go to the IEEE Code of Ethics. While the first canon, which deals with the safety and welfare of the public, seems to contradict the development of this product, it is not clear how the concern for the public extends. Transitivity also supports this perspective as a developer of this technology might not want to live in a place where these raw materials are being harvested. However, this technology provides more benefits than drawbacks. These supply chains are already in place, and given that issue, the Hybrid Wall Outlet provides people access to more efficient and cost-effective energy.

9. Health and Safety

There are two concerns regarding this product that might pose some risk to the users. Firstly, the installation of any outlet poses some risk if not completed in the proper steps. While the goal of this design is to be easily installed, it is possible to hurt yourself if the power is not turned off before installation. While this is a practice that every installation of electrical equipment should follow, there does exist risk if not done properly.

Secondly, the misuse of the Hybrid Wall Outlet could also result in harm to the consumer. Much like any other electrical outlet, this device has live contacts at the back of the socket, which could be bridged and cause many problems. Creating a bridge between two electrical terminals could cause a wall fire in the building if the correct breakers are not used or electrocute the consumer.

10. Social and Political

This project impacts both direct and indirect stakeholders, such as consumers, manufacturers, and the environment. The direct stakeholders include individuals or organizations who directly interact with the product, such as consumers who use the Hybrid Wall Outlet, and manufacturers who produce and distribute the device. Indirect stakeholders would include individuals or organizations who are indirectly affected by the product, such as the environment and the global southern countries that provide the materials needed for its production.

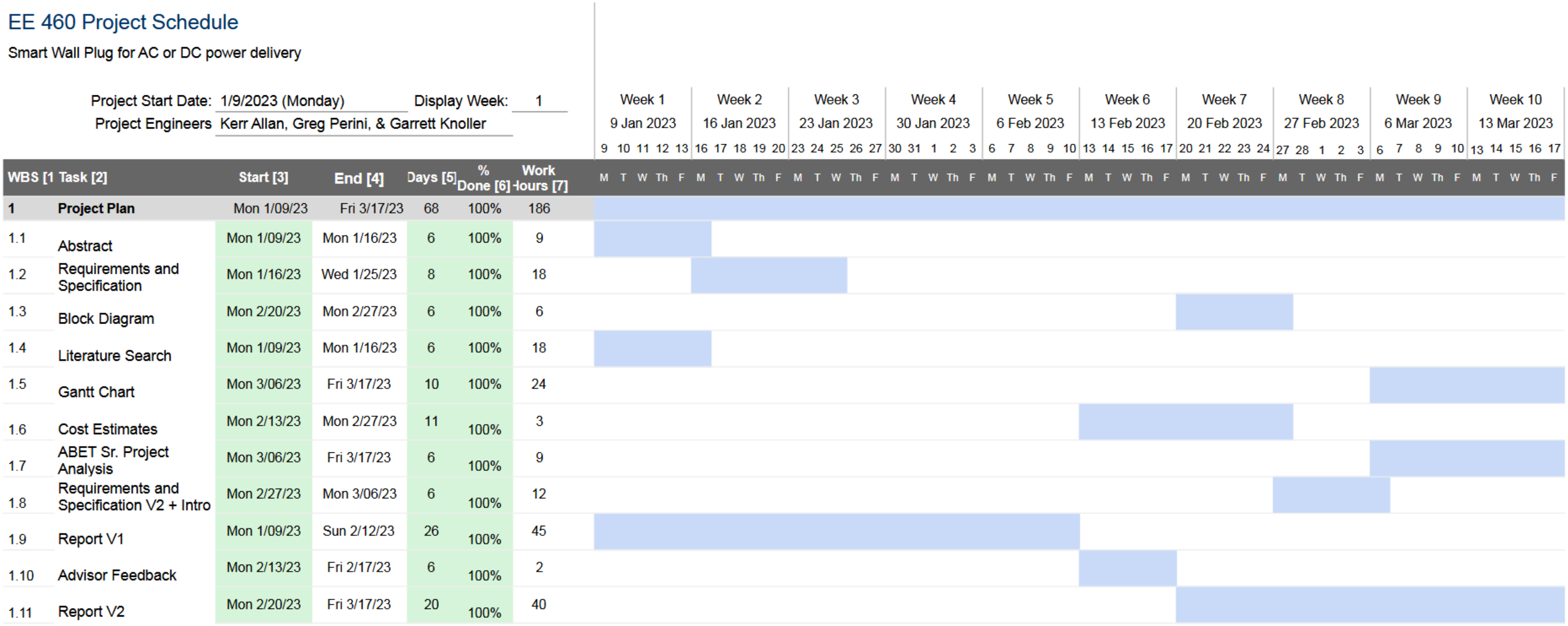
The Hybrid Wall Outlet project benefits various stakeholders, including consumers who will benefit from the increased efficiency of the device. This results in a decrease in power loss and a positive effect on the amount of materials needed to provide the same amount of power. However, the introduction of new technology could also create new inequities. For example, individuals in low-income areas may have limited access to the product, creating a digital divide. Also, the sourcing of raw materials from global southern countries could result in the exploitation of workers and the environment. Therefore, it is essential to consider various stakeholders' locations, communities, access to resources, economic power, knowledge, skills, and political power.

The Hybrid Wall Outlet project aligns with the sustainability framework's triple bottom line principles, which assess the product's sustainability by examining economic, social, and environmental factors. From an economic perspective, the product uses resources with established supply chains and could be sold to consumers at a reasonable markup. From a social perspective, the device can save consumers money on their power bill, making it more accessible, especially for those in low-income areas. Finally, from an environmental perspective, the product is more efficient than the current system, resulting in a decrease in power loss and a positive impact on the environment.

11. Development

During the course of this project, we have gained a deep understanding of the current framework surrounding the device side of power delivery and where the industry is going in the future. The proposed design and the tested circuitry provide a possible path forward that could bridge a gap between the power systems we have tested, and our current framework. Additionally, this project has built our understanding of power electronics through calculation and trial and error testing. The days spent debugging each of the three sections of this project allowed all members to fully grasp each part of the design. Overall, this project showed the potential of this technology and the points where it can be improved in the future.

Gantt Charts



EE 460 Project Schedule

Smart Wall Plug for AC or DC power delivery

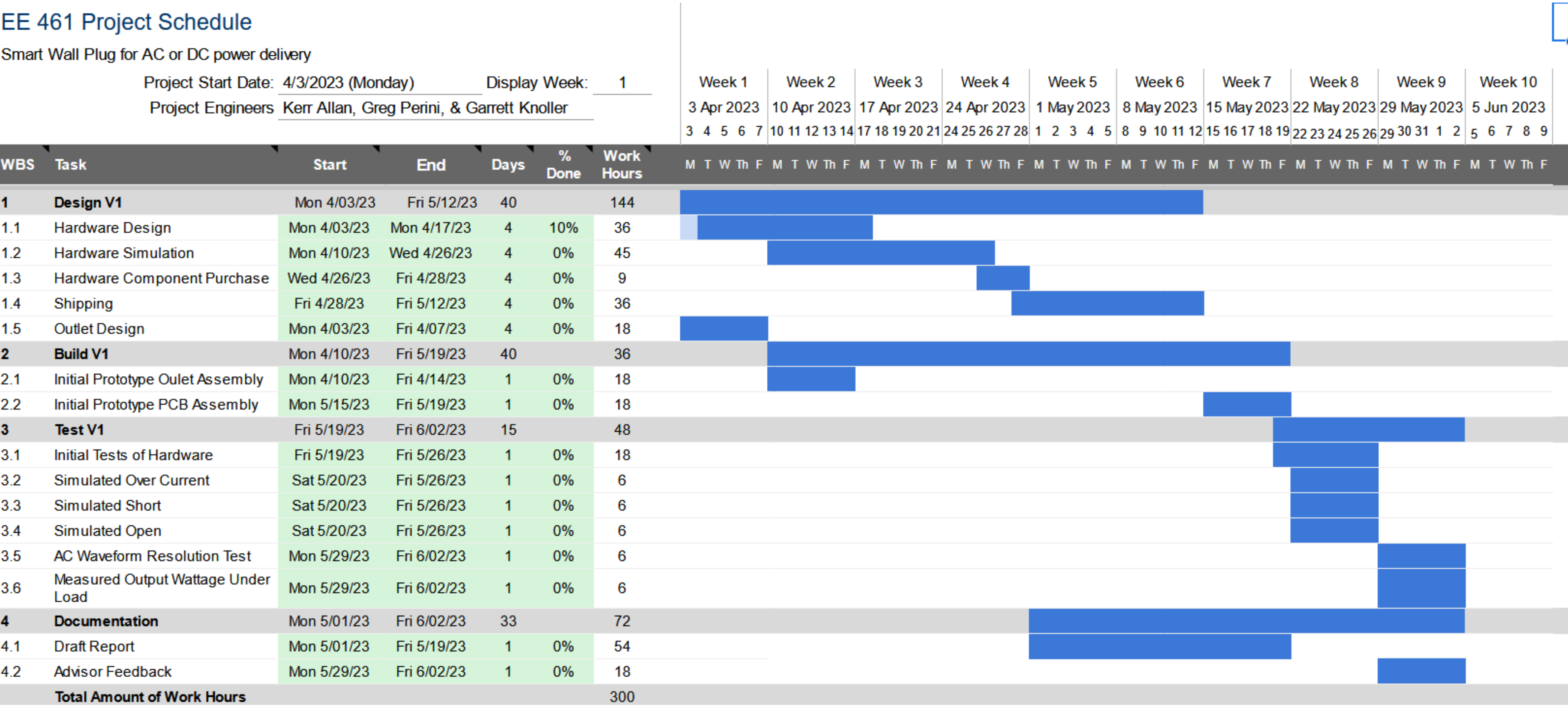
Project Start Date: 1/9/2023 (Monday) Display Week: 1

Project Engineers Kerr Allan, Greg Perini, & Garrett Knoller

Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
9 Jan 2023	16 Jan 2023	23 Jan 2023	30 Jan 2023	6 Feb 2023	13 Feb 2023	20 Feb 2023	27 Feb 2023	6 Mar 2023	13 Mar 2023

WBS [1	Task [2]	Start [3]	End [4]	Days [5]	% Done [6]	Work Hours [7]
1	**Project Plan**	Mon 1/09/23	Fri 3/17/23	68	100%	186
1.1	Abstract	Mon 1/09/23	Mon 1/16/23	6	100%	9
1.2	Requirements and Specification	Mon 1/16/23	Wed 1/25/23	8	100%	18
1.3	Block Diagram	Mon 2/20/23	Mon 2/27/23	6	100%	6
1.4	Literature Search	Mon 1/09/23	Mon 1/16/23	6	100%	18
1.5	Gantt Chart	Mon 3/06/23	Fri 3/17/23	10	100%	24
1.6	Cost Estimates	Mon 2/13/23	Mon 2/27/23	11	100%	3
1.7	ABET Sr. Project Analysis	Mon 3/06/23	Fri 3/17/23	6	100%	9
1.8	Requirements and Specification V2 + Intro	Mon 2/27/23	Mon 3/06/23	6	100%	12
1.9	Report V1	Mon 1/09/23	Sun 2/12/23	26	100%	45
1.10	Advisor Feedback	Mon 2/13/23	Fri 2/17/23	6	100%	2
1.11	Report V2	Mon 2/20/23	Fri 3/17/23	20	100%	40

Figure A: EE 460 Gantt Chart



EE 461 Project Schedule

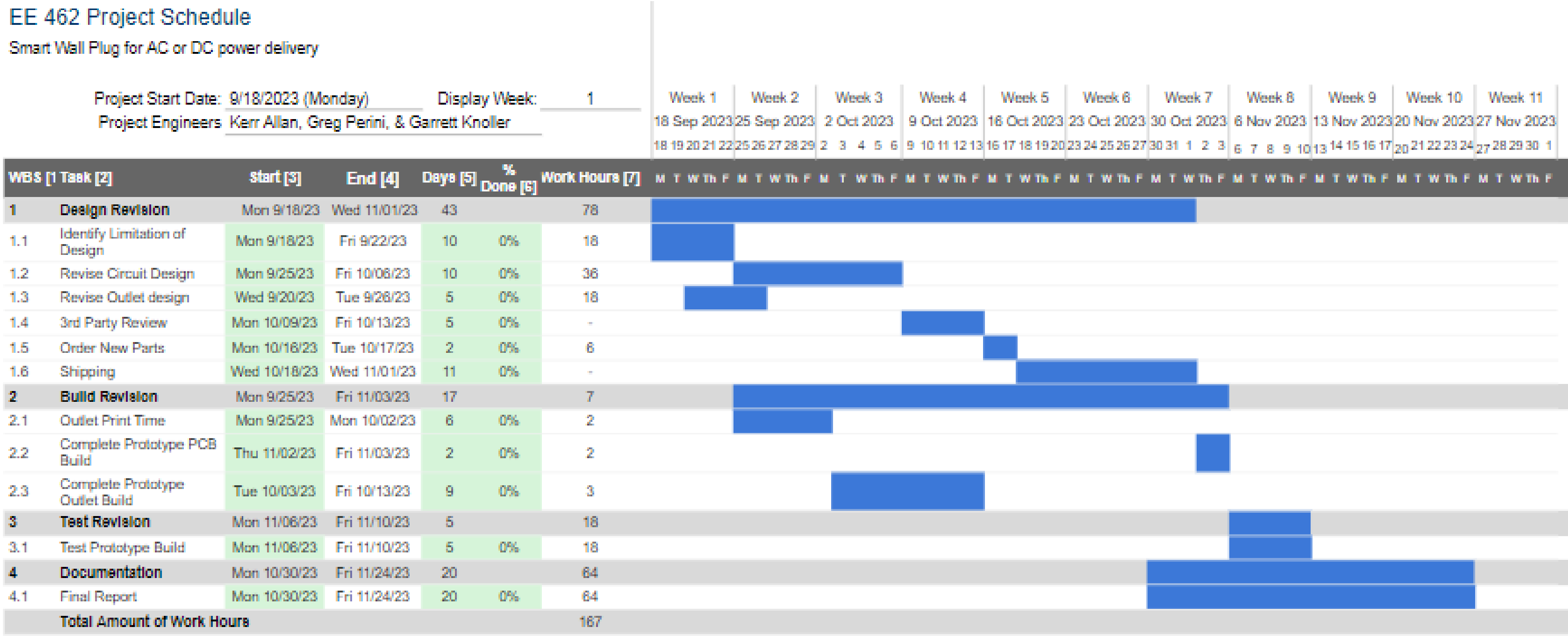
Smart Wall Plug for AC or DC power delivery

Project Start Date: 4/3/2023 (Monday) Display Week: 1

Project Engineers Kerr Allan, Greg Perini, & Garrett Knoller

WBS	Task	Start	End	Days	% Done	Work Hours
1	**Design V1**	Mon 4/03/23	Fri 5/12/23	40		144
1.1	Hardware Design	Mon 4/03/23	Mon 4/17/23	4	10%	36
1.2	Hardware Simulation	Mon 4/10/23	Wed 4/26/23	4	0%	45
1.3	Hardware Component Purchase	Wed 4/26/23	Fri 4/28/23	4	0%	9
1.4	Shipping	Fri 4/28/23	Fri 5/12/23	4	0%	36
1.5	Outlet Design	Mon 4/03/23	Fri 4/07/23	4	0%	18
2	**Build V1**	Mon 4/10/23	Fri 5/19/23	40		36
2.1	Initial Prototype Oulet Assembly	Mon 4/10/23	Fri 4/14/23	1	0%	18
2.2	Initial Prototype PCB Assembly	Mon 5/15/23	Fri 5/19/23	1	0%	18
3	**Test V1**	Fri 5/19/23	Fri 6/02/23	15		48
3.1	Initial Tests of Hardware	Fri 5/19/23	Fri 5/26/23	1	0%	18
3.2	Simulated Over Current	Sat 5/20/23	Fri 5/26/23	1	0%	6
3.3	Simulated Short	Sat 5/20/23	Fri 5/26/23	1	0%	6
3.4	Simulated Open	Sat 5/20/23	Fri 5/26/23	1	0%	6
3.5	AC Waveform Resolution Test	Mon 5/29/23	Fri 6/02/23	1	0%	6
3.6	Measured Output Wattage Under Load	Mon 5/29/23	Fri 6/02/23	1	0%	6
4	**Documentation**	Mon 5/01/23	Fri 6/02/23	33		72
4.1	Draft Report	Mon 5/01/23	Fri 5/19/23	1	0%	54
4.2	Advisor Feedback	Mon 5/29/23	Fri 6/02/23	1	0%	18
	Total Amount of Work Hours					300

Figure B: EE 461 Gantt Chart



EE 462 Project Schedule

Smart Wall Plug for AC or DC power delivery

Project Start Date: 9/18/2023 (Monday) Display Week: 1

Project Engineers Kerr Allan, Greg Perini, & Garrett Knoller

WBS [1	Task [2]	Start [3]	End [4]	Days [5]	% Done [6]	Work Hours [7]
1	**Design Revision**	Mon 9/18/23	Wed 11/01/23	43		78
1.1	Identify Limitation of Design	Mon 9/18/23	Fri 9/22/23	10	0%	18
1.2	Revise Circuit Design	Mon 9/25/23	Fri 10/06/23	10	0%	36
1.3	Revise Outlet design	Wed 9/20/23	Tue 9/26/23	5	0%	18
1.4	3rd Party Review	Mon 10/09/23	Fri 10/13/23	5	0%	-
1.5	Order New Parts	Mon 10/16/23	Tue 10/17/23	2	0%	6
1.6	Shipping	Wed 10/18/23	Wed 11/01/23	11	0%	-
2	**Build Revision**	Mon 9/25/23	Fri 11/03/23	17		7
2.1	Outlet Print Time	Mon 9/25/23	Mon 10/02/23	6	0%	2
2.2	Complete Prototype PCB Build	Thu 11/02/23	Fri 11/03/23	2	0%	2
2.3	Complete Prototype Outlet Build	Tue 10/03/23	Fri 10/13/23	9	0%	3
3	**Test Revision**	Mon 11/06/23	Fri 11/10/23	5		18
3.1	Test Prototype Build	Mon 11/06/23	Fri 11/10/23	5	0%	18
4	**Documentation**	Mon 10/30/23	Fri 11/24/23	20		64
4.1	Final Report	Mon 10/30/23	Fri 11/24/23	20	0%	64
	Total Amount of Work Hours					167

Figure C: EE 462 Gantt Chart