Smart USB-C Wall Plug for the DC House Project

California Polytechnic State University Electrical Engineering Department

Faculty Advisor: Dr. Taufik

Report Authored by: Dino Maslic, Ridge Lahti

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Abstract

DC operated devices and appliances powered by AC systems suffer inefficiencies resulting from the losses of converting AC energy into DC energy. At Cal Poly, the DC House Project aims to minimize the need for AC electricity in homes and encourage the use of renewable energy systems. The DC House uses a 48V DC bus that must be stepped down for use with increasing number of DC loads in a typical home. In this project, a Smart USB-C Wall Plug is designed to work with USB Power Delivery to provide a variable voltage output for use with these DC loads that operate at 5V, 9V, 15V, and 20V up to 3A. The Smart USB-C Wall Plug was implemented in hardware using a custom PCB and tested to show that it met requirements for 1% line regulation, 1% load regulation, 5% voltage ripple, 90% efficiency, and 60W maximum power. Further measurements demonstrated that the output voltages except for 5V met the 1% line regulation and 5% voltage ripple requirements.

Chapter 1: Introduction

Reliance on carbon emitting energy sources to meet demand remains a significant problem affecting the world. With global heating increasing at unprecedented rates, and the potential catastrophic impacts of climate change, it is more important than ever that technologies are developed to increase energy efficiency and decrease reliance on carbon emitting sources [1]. According to the Energy Information Association, nearly 80% of all energy consumed in the United States used coal, natural gas, or petroleum in 2020 [2]. The total breakdown of energy consumption in the US for 2020 is shown in Figure 1-1.

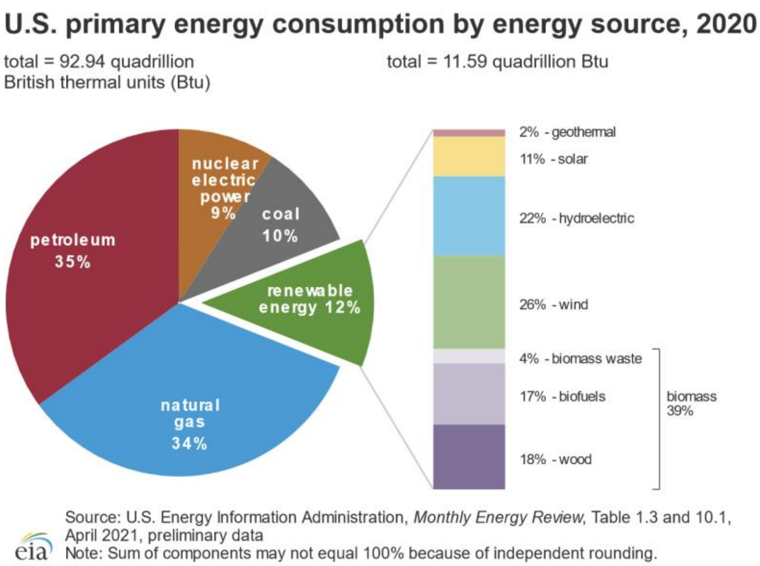


Figure 1-1: US Energy Consumption in 2020 [1]

Renewable sources need to take a larger share of the energy consumed in the US and the world at large. In order for renewables to become more efficient, improvements in power converting technologies are necessary. One area of power conversion technology is Power Electronics.

Power electronics are found throughout nearly all modern-day electronics, and in electrical power grid applications. One of the four key functions of power electronics is power conversion: AC to DC, DC to AC, AC to AC, and DC to DC [3]. From this list, we can see that one of the main conversion processes is AC to DC power, as many electronic devices are powered via DC, and the power grid is delivering mainly AC power. Practically, all power conversion within power electronics is done via converter circuits which have inefficiencies that cause power loss while processing electrical energy. For example, when using a DC device powered by an AC source, there will be power loss within the conversion process from AC to DC regardless.

One of the bigger issues involved with the present power conversion is the fact that renewable energy sources like residential solar panels are being used increasingly, and solar panels output DC power. In order to use the DC power from solar panels, power needs to be converted from DC to AC so it can be used by the houses, and then AC back to DC in order to use the energy for the devices that run off of DC power such as LED lightings. All of the conversion going DC-AC-DC may cause a large power loss throughout the system. This is because the conversion going from DC-AC-DC has one extra step that causes extra power loss that may not be necessary. One way to combat the conversion issues of a DC source powering DC devices is through the use of highly efficient DC-DC converters, rather than converting DC-AC-DC [4]-[7].

Aside from renewable energy systems, the applications of DC-DC converters include High Voltage DC (HVDC) power systems, microgrid systems, electric vehicles, and consumer electronics chargers [8]-[13]. Another reason for the increasing popularity of DC-DC converters has been due to the more prevalent use of small-scale renewable energy sources for off-grid applications. An example of how DC-DC converters may be applied for this type of application is to combine multiple renewable sources into a single DC bus [14]-[16].

The main benefits of DC-DC converters are their high efficiency and versatility in power conversion applications, and their small size when compared to traditional AC transformers. Various topologies of non-isolated DC-DC converters can be implemented depending on the desired application. For examples, buck converters are used to step down voltages, boost converters are used to step up voltages, and Buck-Boost converters are used to either step up or down a particular voltage [17].

Although there are numerous benefits to DC-DC converters, there are drawbacks as well. One example comes from the inductor commonly used in DC-DC converters as the main energy storage. While vital to the operation of converters, it also has drawbacks associated with it. Inductors are large components in comparison to the physical size of other components in the converters such as capacitors and resistors. This means that inductor will take up a large amount of space on any circuit board it is attached to. If one wants to reduce the size of the inductor, so not much space is taken up, they will have to use one with relatively small inductance value. However, when a small inductor is being used in DC-DC converters, the operating frequency needs to be increased to maintain superior performance of the converters. This will unfortunately cause another issue since the switching losses of the converter will get worsen with the increase in switching frequency [17]. Careful selection of the inductor and switching frequency is therefore important in the design of DC-DC converters to maintain the balance in the trade-offs caused by the inductor and switching frequency.

Another drawback with DC-DC converters is the inherent noise at the output of the converter. Consequently, this can cause issues in noise sensitive applications like RF and analog circuits [18]. With all power electronic converters, they need solid-state switches in order to process the energy. With the use of switches there will be some inherent noise at the output of the converter due to the periodic turning on and turning off of the switches. Therefore, power electronic converters are designed to have a very low output voltage ripple in mind; however, there will be ripple in the converters no matter what due to the switching nature of the converters. To overcome this, some power electronic converters employ what is called the resonant techniques to significantly reduce the switching noise [19]-[24]. Even with these aforementioned disadvantages of DC-DC converters, they are still great and highly efficient circuits to use in different applications of power electronics.

Chapter 2: Background

DC-DC converters are used in consumer electronics to power the devices people use on a daily basis. In a typical home, AC power is used for the wall outlets that devices are plugged into. Since most consumer electronics use DC power, the AC voltage needs to be converted to DC before it can be used by a typical device. After the AC voltage has been converted to DC, the DC voltage will then need to be stepped down to the specific voltage a device needs to operate. At each stage of power conversion, there are losses that decrease the efficiency of a device's power supply or charger.

At Cal Poly, the DC House Project is working to reduce power losses in a home by improving the prevalence of DC power in a home and encouraging the use of renewable energy sources to generate the DC power [4]-[7]. The DC House uses a 48V DC bus to power devices within the house. DC-DC converters will be useful when designing wall plugs for the DC House in order to step down the 48V DC bus to a voltage that can be used for a particular DC device.

There is a technical issue, however, related to the use of a fixed DC voltage bus in the DC House system. The DC loads are unfortunately not standardized. This means DC devices operate at different voltage levels. For example, USB connected DC devices typically need 5V input, laptop runs at around 19V, while others operate at other voltages such as 9V, 12V, and 24 V. Consequently, this implies the need for wall outlets that can provide multiple DC voltage levels. This will pose major challenges in adopting DC electricity since a system with such multiple wall plugs will be expensive and will be confusing to use by the users. Some type of a smart wall plug method will therefore be useful.

Without the use of "smart" control, as previously mentioned a different DC wall plug would be needed to power devices with different power requirements. Previous efforts have been conducted to design and construct smart DC wall plugs, but the results are not yet optimized for the most suitable use in powering various DC loads [25]-[29]. One technology that could potentially be utilized to enable a smart wall plug functionality is the USB-C. The USB-C standard provides a solution to the need for smart control through the use of USB Power Delivery (USB PD). With USB Power Delivery, the output power of a USB-C device can be changed to 5V, 9V, 15V, and 20V at up to 100W [30]. The USB PD device communicates to the USB PD supply through a communication protocol such as I2C, and a USB PD controller adjusts the voltage output of the supply. Through the use of USB PD, a wide range of devices can be powered from a single wall plug in the DC House. However, USB PD only works with devices that are compatible with the standard. Devices that are incapable of communicating with a USB PD controller will not be able to negotiate the power of the supply. Using USB PD will optimize the power delivery for devices in the DC House, improving efficiency.

USB PD is being used in a multitude of applications. Smartphones utilize the USB PD standard to decrease the amount of time it takes to charge the device, and their associated power supplies use the standard to optimize the fast charging through a flyback converter [3]. Charging optimization research has also been conducted for resonant converters and switched capacitor converters [31], [32]. A proof of concept has been developed for a 350V DC microgrid to utilize a smart DC-DC plug that takes advantage of USB PD to power consumer electronics devices [33].

Previous work on the USB PD power plug for the DC House Project was presented in [34]. The work involves the design of a two-phase buck converter with USB PD that can charge Galaxy Buds and a Nintendo Switch. The converter is able to deliver 100W at full load, have 96.27% efficiency, have 1% output voltage ripple, and 2% line and load regulation. However, further improvements need to be conducted to enhance its performance. The objective of this project is therefore to create a similar and improved design with on a single buck converter. The design should be able to supply power up to 60W for a variety of USB PD capable devices. Additional requirements also include 90% efficiency at full load, 1% load and line regulations, and no more than 1% output voltage ripple at all possible output voltages. Details of the design requirements will be described in the next chapter.

Chapter 3: Design Requirements

The level 0 and level 1 functional block diagrams show the overview of the Smart USB-C Adapter. The level 0 diagram details the overall inputs and outputs of the adapter. The level 1 block diagram shows the key components within the adapter that will enable the system to function properly. See Figures 3-1 and 3-2 for Level 0 and Level 1 diagrams respectively.

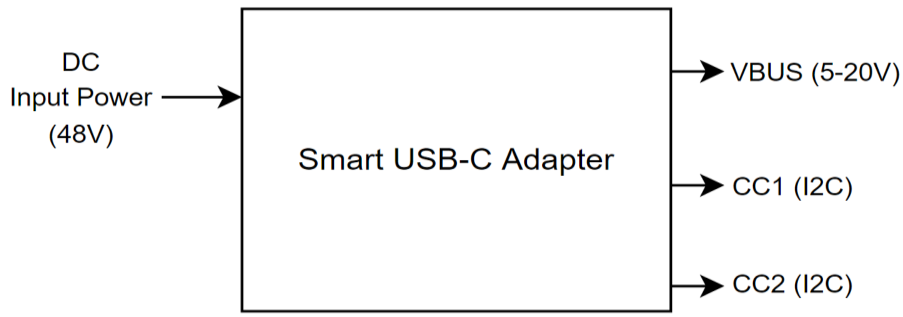


Figure 3-1: Level 0 Block Diagram

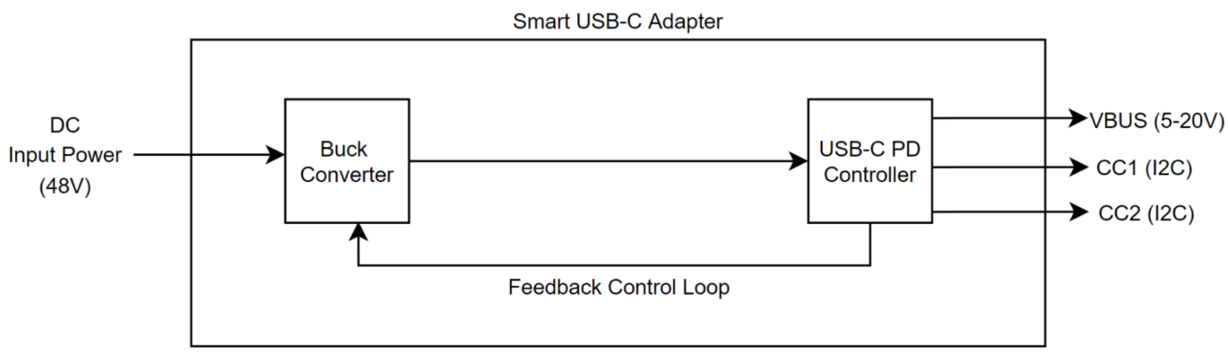


Figure 3-2: Level 1 Block Diagram.

The DC input power supplied will be at 48V DC. This will be used to power the system and will need to be stepped down in voltage to the required output voltage on VBUS. VBUS is a standard pin on a USB-C connector that contains the voltage being transferred on a cable. From the USB PD standards, VBUS will be set at one of the following voltage levels: 5V, 9V, 15V, or 20V. VBUS will be carrying a maximum current of 3A to supply to a connected device. CC1 and

CC2 are pins on standard USB-C connectors that will be the channels of communication between the load device and the adapter. I2C protocol is used on these pins to do the power delivery communication between the load and the adapter to determine the correct output voltage needed by the load device.

In the level 1 block diagram, there are two key components within the adapter that will be doing most of the work: the buck converter and the USB-C PD controller. The buck controller is responsible for efficiently stepping down the input voltage into the needed VBUS voltages that the load device needs. While the USB-C PD Controller will be handling the communication between the device and the adapter. The controller will communicate with the device over the CC1 and CC2 channels in order to properly determine what voltage the device needs. Once this voltage is determined, the controller will signal to the buck converter what voltage is needed, and the buck will adjust it accordingly. Power through VBUS will be going through the PD controller, in order to output power onto the VBUS pin.

See Table 3.1 for technical specifications, this table provides individual technical specifications for the Smart USB-C Adapter, as well as reasoning for each of the specifications.

Table 3.1: Technical Specifications

Technical Specification	**Reasoning**
System needs to operate with a 48V DC input voltage	In order to be compatible with the Cal Poly's DC House, the adapter needs to be able to take in a 48V input as that is the voltage that the DC House operates at.
The output voltage should be able to range from 5V to 20V	The output of the plug must be able to use the full range of voltage available on USB-C devices . This range of voltage will also allow for interfacing of renewable sources along with allowing high power output. This will be done using a buck converter.
Load regulation should be limited to < =1%	The load regulation needs to be less than 1% to ensure that the power output remains constant. Changing voltage will cause changes in the power output.
Line regulation should be limited to <= 1%	The line regulation needs to be less than 1% to ensure that the power output remains constant. Changing current will cause changes in the power output.
The maximum output power must be 60W	The maximum power of 60W is required as a proof of concept. USB-C is capable of 100W; however, it requires 5A to do so. 60W gives reasonable power without large amounts of current.
The efficiency should be no less than 90% at full load for power in versus power out.	The power efficiency must be no less than 90%, or the system will not be worth using. If the power out cannot closely match the power in, then the USB-C plug is accounting for too much loss, thereby increasing the power cost on the consumer.

In addition to the technical specifications listed above, there are also measurable specifications for the project. These specifications contain specific measurable values that can be taken from our final version of the project which consist of electrical, mechanical, and physical dimensions.

Table 3.2: Measurable Specifications

Measurable Specification	Value
Efficiency	Greater than 90%
Peak to peak output voltage ripple	Less than 5%
Line Regulation	Less than 1%
Load Regulation	Less than 1%
Output Current	Maximum 3A
Output Voltage Levels	5V, 9V, 15V, 20V
PCB Size	100x80 mm
PCB Layers	2 Layers
Total Size	15x15x5 cm enclosure

Chapter 4: Hardware Implementation and Testing

The key to our proposed design for the Smart USB-C Adapter is USB-C Power Delivery (USB-C PD). USB-C PD is a standard implemented in many of the modern consumer electronics being produced today in order to enable faster charging. USB-C PD works by using two pins on standard USB-C connectors called CC1 and CC2 to negotiate the needed power. On these pins, I2C communication is done between devices and power adapters to determine the ideal voltage and power that the device connected to the adapter needs. This enables faster charging as devices are able to communicate to adapters to change the voltage that is being outputted to the device in order to charge faster.

The solution designed to meet the requirements of the Smart USB-C Adapter will be talked about in detail in this chapter. The overall level 2 diagram, shown in Figure 4-1, shows a more detailed overview of the Smart USB-C Adapter. It includes all of the major components that make up the final design of the adapter.

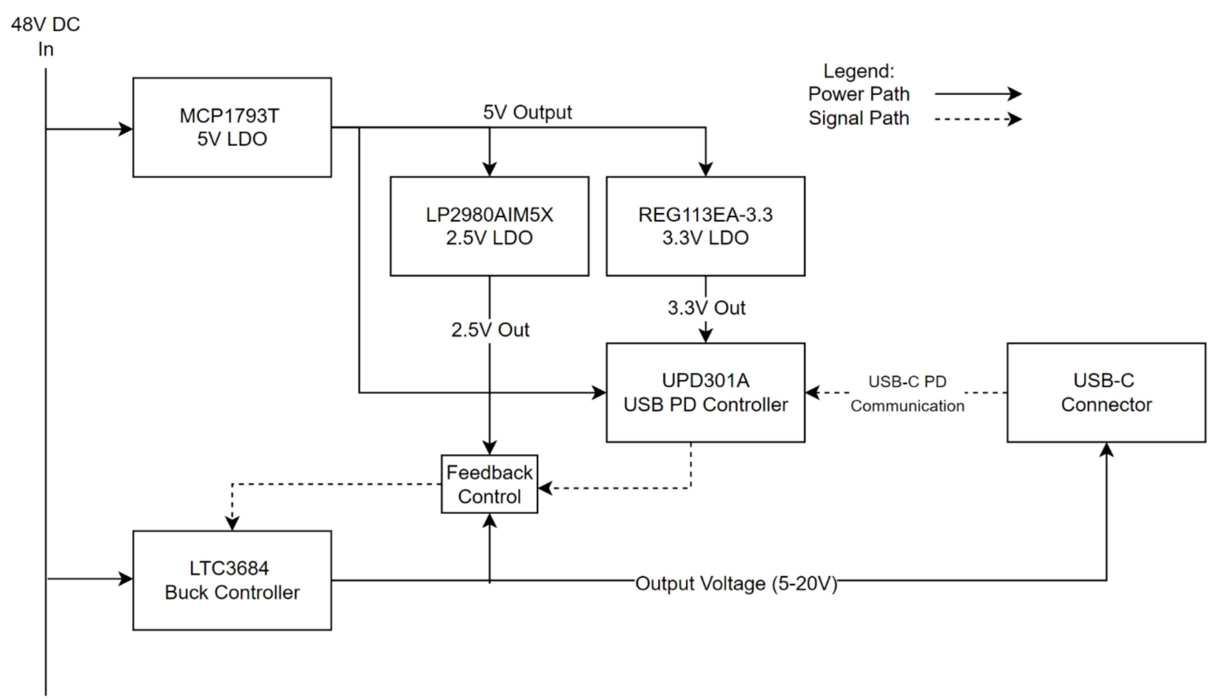


Figure 4-1: Level 2 Block Diagram

The solution uses a 48V DC input that powers the entire system. This power rail is connected to a MCP1793T, a 5V low-dropout linear regulator (LDO). The MCP1793T powers the two other LDO's used in the design, the REG113EA-3.3, a 3.3V LDO, and a LP2980AIM5X, a 2.5V LDO, as well as supplying voltage to a UPD301A, a USB-C Power Delivery controller. The LDO's provide steady voltage rails to the UPD301A and our feedback control in order to ensure that they can function properly. The two key components within the design are the UPD301A and the LTC3684, as these will be responsible for determining and outputting the correct voltage on the USB-C voltage bus. The UPD301A is responsible for determining the voltage that the device connected through the USB-C connector needs to properly function. This is done by taking in the CC1 and CC2 lines on the USB-C connector. Once the UPD301A determines what voltage is needed, it will output a voltage on a DAC output in order to change the voltage as needed. This DAC output voltage is then used in a feedback control loop that also takes in the current output voltage and a 2.5V power rail from the LP2980AIM5X LDO. This feedback loop is tied to the LTC3684 buck controller in order to properly change the output voltage. The LTC3684 is the main controller that will actually change the duty cycle of the switch in the buck controller in order to set the proper output voltage that the device connected to the adapter needs.

4.2: Buck Converter

The buck converter is the powerhouse of the USB-C adapter. Using the asynchronous topology, the design calculations for the buck converter were performed in MATHCAD for each possible output voltage of 5V, 9V, 15V, and 20V using the following set conditions:

$$Pmax = 60W$$

$$Vo = 5V, 9V, 15V, 20V$$

$$Vin = 48V$$

$$Vinmax = 52V$$

$$Vinmin = 44V$$

$$Vinrip = 8V$$

$$Ioutmax = 3A$$

$$Vrip\% = 5\%$$

$$PercentCurrentRipple = 30\%$$

$$\Delta IL = 0.9A$$

$$f = 535kHz$$

The steady-state duty cycle of a buck converter operating in continuous conduction mode is calculated as:

$$D = \frac{Vo}{Vin}$$

For each output voltage, the nominal, minimum and maximum duty cycles were calculated using the nominal, minimum and maximum input voltages. Next the critical inductances were calculated for each output voltage using the minimum and maximum input voltages as follows:

$$Lcrit = \frac{(Vin - Vo) \cdot D}{\Delta IL \cdot f}$$

The corresponding duty cycle was also used for the minimum and maximum input voltages. Values for the critical input and output capacitances were calculated in the same way as inductance using the following equations:

$$CcritOUT = \frac{1 - Dmin}{Vrip\% \cdot 8 \cdot Lcrit \cdot f^2}$$

$$CcritIN = \frac{Iswmax \cdot (1 - Dmin)}{Vinrip \cdot f}$$

where

$$Iswmax = Ioutmax \cdot Dmax$$

Finally, component sizing for the switch, diode, and capacitor RMS currents, were calculated:

$$Iswmax = Ioutmax \cdot Dmax$$

$$Idmax = Ioutmax \cdot (1 - Dmin)$$

$$OutputCapRMS = \frac{Vo(1 - Dmin)}{2 \cdot \sqrt{3} \cdot Lcrit \cdot f}$$

$$InputCapRMS = Ioutmax \cdot \sqrt{Dmax \cdot (1 + \frac{\Delta IL^2}{12 \cdot Ioutmax}) - Dmax^2}$$

Detailed calculations performed in MATHCAD for each output voltage are listed in the appendix, and the calculation results are listed in Table 4-1.

Table 4-1: MATHCAD Component Calculation Results for Buck Converter

Component	Calculation Result
Critical Inductance	25.56µH
Critical Input Capacitance	0.1961µF
Critical Output Capacitance	0.8411µF
Maximum Switch Current	1.364A
Maximum Diode Current	2.712A
Output Capacitor RMS Current	0.26A
Input Capacitor RMS Current	1.504A

For each calculated value, the largest value from the different input and output cases was chosen to represent the worst-case scenario. In choosing components, the values that are used have larger ratings than were calculated to make sure that the buck converter did not have problems handling the worst-case scenarios. The chosen components are listed in Table 4-2.

Table 4-2: Chosen Buck Converter Components

Component	Value	Description
B82559B0303A016 Inductor	30µH	The inductor was chosen for its high saturation current of 40A, much larger than the 3A required, and for the fact that its inductance is slightly larger than the required critical inductance
Si7469DP Switch	28A rating	The switch was recommended in the example schematic for the LTC3864 in LTSpice. It was chosen for its high current rating
PDS5100 Diode	Schottky Diode	The diode was recommended in the example schematic for the LTC3864 in LTSpice. It was chosen for current rating and forward voltage of 0.64V for the test conditions of our project.
A768MS476M1KLAE034 Capacitors	47µF, 80V	The capacitors meet the voltage requirement of the input and are large to help compensate for voltage ripple.

With the buck converter components chosen in Table 4-2, the LTC3864 was then configured to finish the converter.

4.3: LTC3864

The LTC3864 requires several key components to operate properly. First, per data sheet recommendations, a sensing resistor. Rsense, and power monitoring resistor, Rgood, are needed to enable the chip. Rsense is placed across the Vin and Sense pins on the device to monitor the current in the buck converter. If the current increases to dangerous levels, the chip will shut down to protect itself. A value of 10mΩ was chosen through simulation after the initial calculated value of Rsense was inoperable. The calculated value was determined with the following equation:

$$Rsense = \frac{95mV}{Ioutmax + \frac{\Delta IL}{2}}$$

The power monitoring resistor, Rgood, is attached to the Pgood pin of the LTC3864. A resistance of 100kΩ is chosen per datasheet recommendations in buck converter example schematics. The compensation filter attached to the Ith pin was determined experimentally using LTSpice to see which configuration produced a stable output for all possible output voltages. It consists of a 10nF capacitor in series with a 25kΩ, both of which are shunted by a 1pF capacitor. Finally, a small 0.47μF capacitor is attached from Vin to the Cap pin on the LTC3864 per datasheet recommendations. The remaining Run, SS, and Freq pins are left floating. With the Freq pin floating, the LTC3864 runs at a switching frequency of 535kHz.

In order to interface the LTC3864 with the UPD301A, a resistor network and difference amplifier are used to calculate the error between the DAC output of the UPD301A and a 2.5V reference from the 2.5V LDO. The amplifier is set up using all 100kΩ to achieve unity gain and is supplied using the 5V LDO for V+ along with ground for V-. Figure 4-2 displays the final schematic for the buck converter in LTSpice.

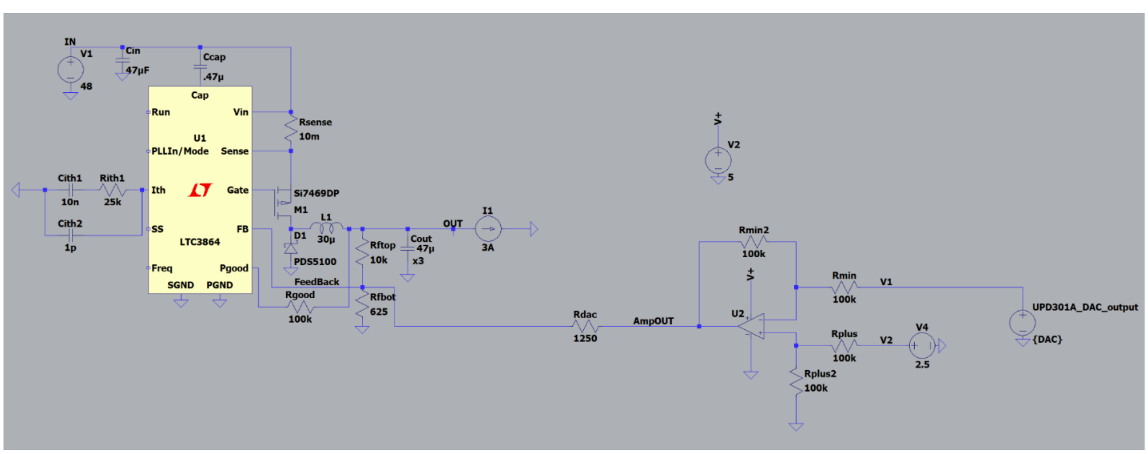


Figure 4-2: Buck Converter Schematic with the LTC3864 and Feedback Network

4.4: UPD301A

The UPD301A is one of the key components of the design as it takes care of all of the USB-C PD communication. The UPD301A will communicate with the device plugged into the USB-C connector on our adapter, through this communication the device will request a voltage from the adapter. The UPD301A will change the output on a DAC output pin that is connected to control circuitry to change the output on a buck through the LTC3684. Figure 4-3 shows the schematic of the UPD301A and how it is connected in the design.

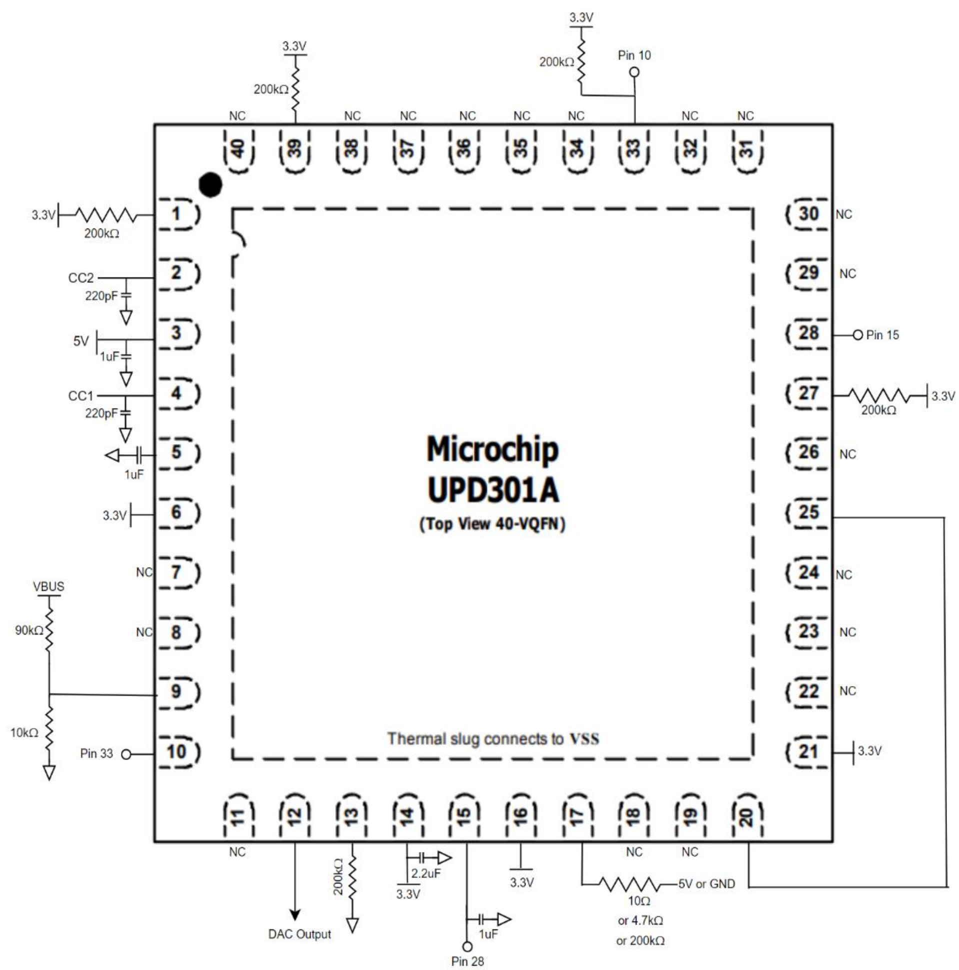


Figure 4-3: UPD301A Schematic

On each of the input and output voltage sources of the UPD301A, there are 1uF to 2.2uF bypass capacitors connected. This was done due to recommendations by the datasheet of the

UPD301A to ensure proper operation of the chip. In addition to this, multiple pins throughout the board have varying pull-up and pull-down resistors, this was also done because of datasheet recommendations in order to ensure that the UPD301A would function properly. One pin that will be varied depending on what power profile is being tested is pin 17, PDP_SEL. This pin controls which power delivery profile will be used depending on what kind of resistor configuration is connected to the pin; there is a choice between 10Ω, 4.7kΩ, and 200kΩ pull-up/ pull-down resistors. Each of these different configurations will give different maximum power/voltage limits. See Table 4-3 for these different profile values, taken from UPD301A datasheet.

Table 4-3: Power Delivery Profiles for the UPD301A [1]

PDP_SEL Value	PDP	PDO 1	PDO 2	PDO 3	PDO 4
200kΩ Pull-Down	7.5W	5V@1.5A	-	-	-
200kΩ Pull-Up	15W	5V@3A	-	-	-
4.7kΩ Pull-Down	27W	5V@3A	9V@3A	-	-
4.7kΩ Pull-Up	45W	5V@3A	9V@3A	15V@3A	-
10Ω Pull-Down	60W	5V@3A	9V@3A	15V@3A	20V@3A

4.5: LDO Selections

For the proposed design, 3 steady voltage rails besides the input voltage are needed in order to ensure that all the components function properly: 5V, 3.3V, and 2.5V. A 5V and 3.3V input are needed for the UPD301A as input voltage supplies, and to ensure that the feedback control would work as designed a 2.5V voltage rail was needed to be inputted into the terminal of the subtraction op-amp. For the 5V LDO, the MCP1793T-5002H/OT was chosen as it could handle large input voltages up to 60V, for the proposed design the input will be 48V. The 3.3V LDO is the REG113EA-3.3V, this will take in 5V as the input voltage and will supply the UPD301A with a 3.3V rail. Lastly, the 2.5V LDO is the LP2980AIM5X-2.5V and will also take in the 5V LDO output as its input voltage. Each of these LDO's have input and output capacitors connected to them to ensure proper operation, this was done because of datasheet recommendations from the manufacturers.

4.6: Simulations

The buck converter was simulated using the LTSpice schematic shown in Figure 4-4:

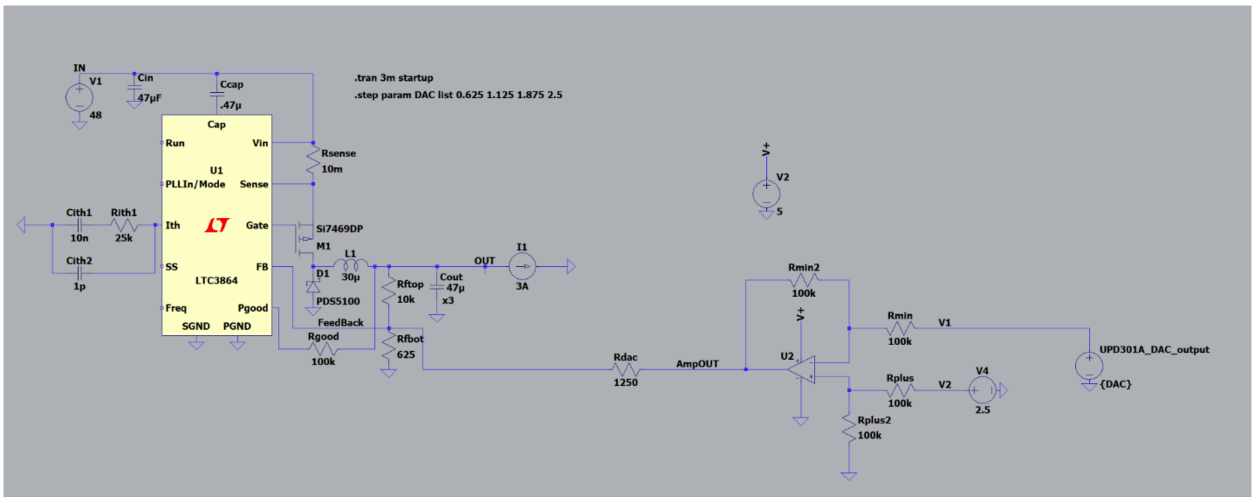


Figure 4-4: LTSpice Schematic for Buck Converter

The UPD301A DAC output is modeled using the voltage source DAC in order to change the output voltage of the buck converter. Each output voltage waveform, for the nominal 48V input, is plotted in Figure 4-5:

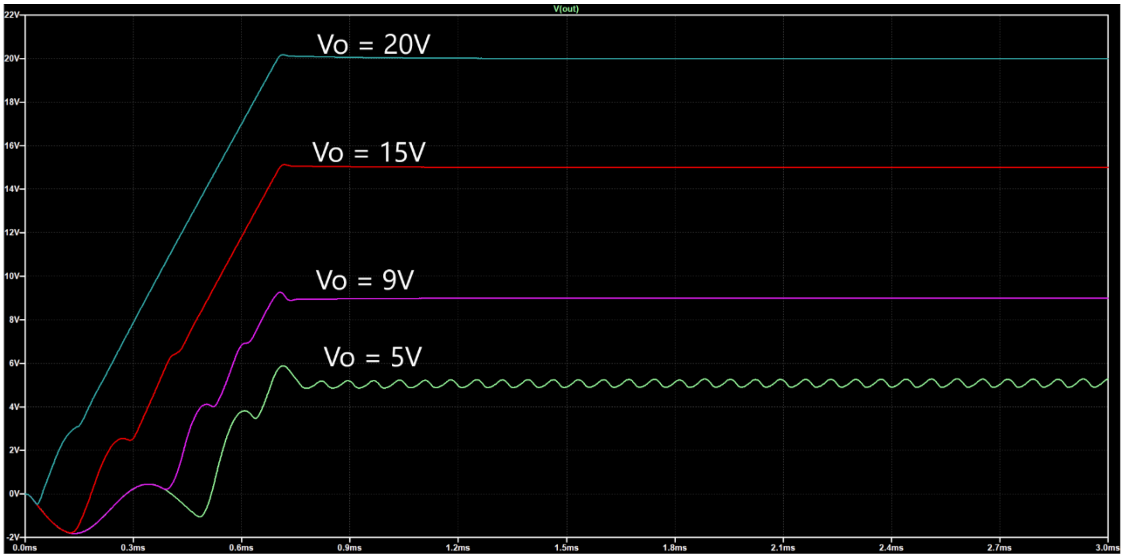


Figure 4-5: Simulated Output Voltage Waveforms

Within Figure 4-5, the blue waveform represents a 20V output, the red a 15V output, purple a 9V output, and green a 5V output. The peak-to-peak ripple of each waveform is recorded in Table 4-4:

Table 4-4: Simulated Peak to Peak Ripple

Output Voltage	Peak to Peak Ripple
5V	337mV
9V	0V
15V	0V
20V	0V

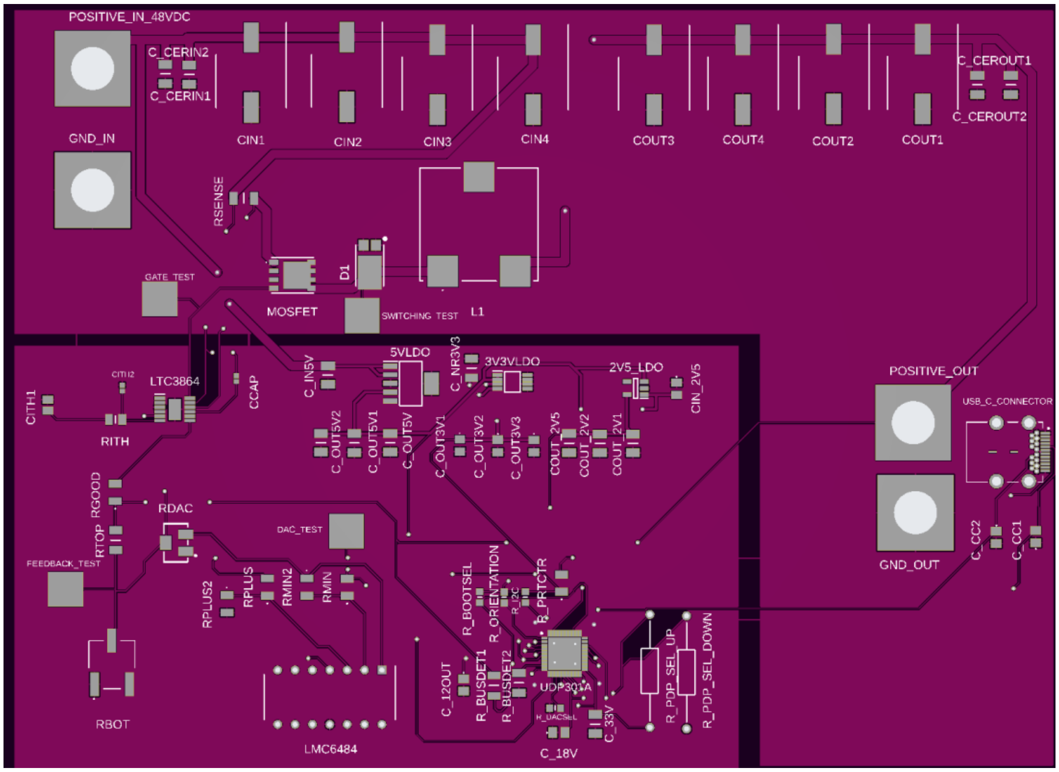
The only problematic case is 5V, where the peak to peak is 337mV. The compensation filter on the Ith pin was adjusted until 5V had a stable output voltage, and once the voltage was stable the design moved forward. Unfortunately, the 337mV ripple had to be accepted for the project. Each output voltage was simulated for efficiency, and the results are shown in Table 4-5 for steady state efficiency:

Table 4-5: Efficiency Simulation Results

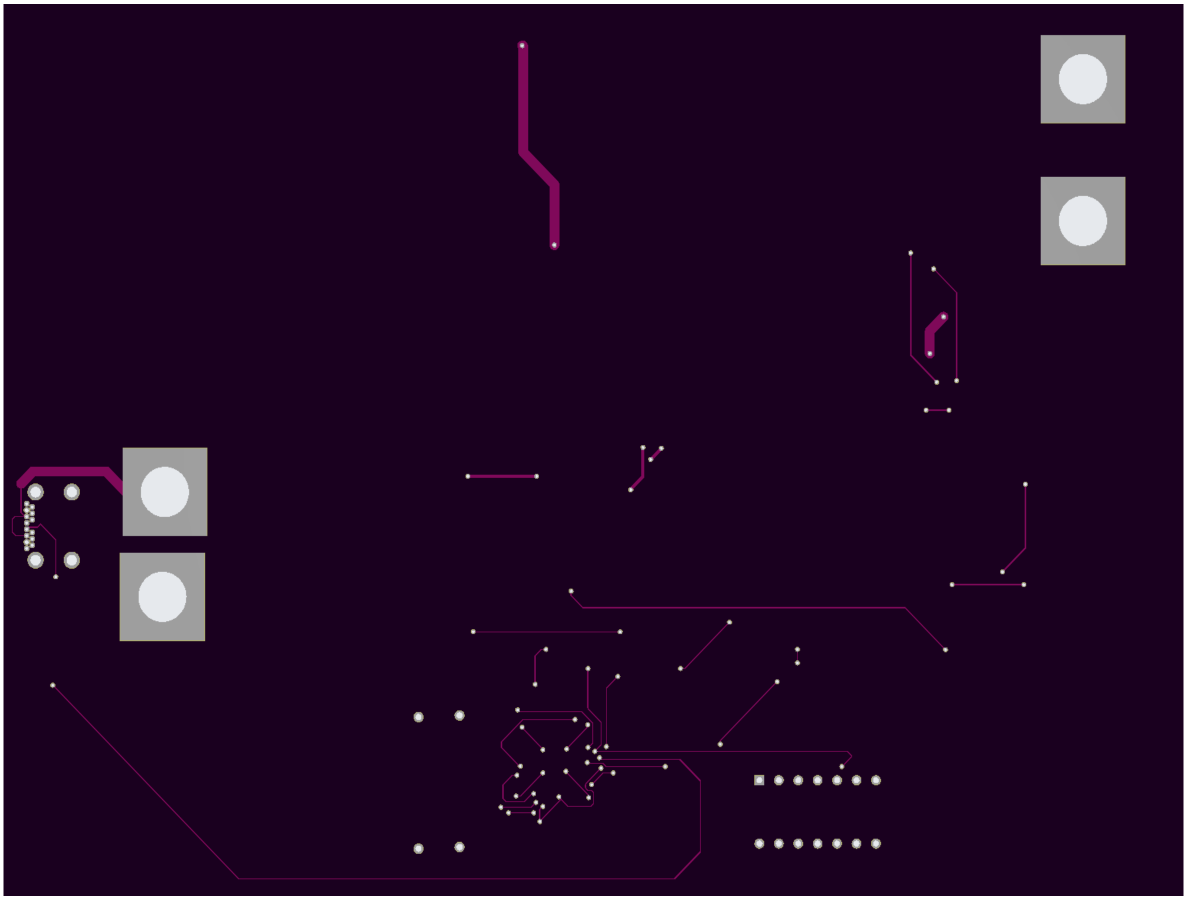
Output Voltage	Efficiency
5V	68.4%
9V	74.5%
15V	83.3%
20V	87.1%

4.7: Layout

Figure 4-6 shows the final PCB layout that will be used in assembling the final design for testing. For the PCB, layout considerations were taken into account to limit noisy grounds and to have an efficient and decluttered design. The PCB is a two-layer PCB, with the top layer containing all of the components needed along with ground planes, and the bottom layer containing a multitude of signals that are routed to efficiently connect to components on the top layer. Two separate ground planes were created, one used purely by the buck converter and the USB-C connector, this will be referred to as power ground. The other ground plane was created for controllers and LDO's, this is referred to as signal ground. These ground planes were electrically connected via very small traces to ensure that grounds are connected, but to limit the effect of the amount of noise generated by the large switching power components onto the control components, like the UPD301A and the LTC3684. The board was made in such a way that the top portion and right side of the board house the power components on the power ground plane, and the bottom left side of the board contains the signal ground with all of the control components. Test points were added throughout to make testing and possible debugging of the design easier, on the board there are test points on the gate signal of the MOSFET, the switching node of the buck converter, the feedback voltage of the LTC3684, and the DAC output of the UPD301A. Also, there are large banana plug ports created to easily connect an input power supply and measure the output voltage and current of the adapter.


POSITIVE_IN_48VDC
C_CERIN2
C_CERIN1
GND_IN
CIN1
CIN2
CIN3
CIN4
COUT3
COUT4
COUT2
COUT1
C_CEROUT1
C_CEROUT2
RSENSE
D1
MOSFET
L1
GATE_TEST
SWITCHING_TEST
5VLDO
3V3VLDO
2V5_LDO
C_NR3V3
C_IN5V
CIN_2V5
CCAP
LTC3864
CITH1
CITH2
RITH
C_OUT5V2
C_OUT5V1
C_OUT5V
C_OUT3V1
C_OUT3V2
C_OUT3V3
COUT_2V5
COUT_2V2
COUT_2V1
POSITIVE_OUT
USB_C_CONNECTOR
GND_OUT
C_CC2
C_CC1
RGOOD
RTOP
RDAC
DAC_TEST
FEEDBACK_TEST
RPLUS2
RPLUS
RMIN2
RMIN
R_BOOTSEL
R_ORIENTATION
R_PRTCTR
R_BUSDET1
R_BUSDET2
C_12OUT
UDP301A
R_PDP_SEL_UP
R_PDP_SEL_DOWN
C_33V
C_18V
RBOT
LMC6484

(a)



(b)

Figure 4-6: Final PCB Layout, (a) is top layer and (b) is bottom layer

The PCB layout represents the footprints of the components listed in the Bill of Materials, which is found in the Appendix.

Chapter 5: Hardware Test and Results

5.1: Build Procedure

The PCB shown in Chapter 3 and the components listed in the bill of materials were used to construct the USB-C wall plug project. Since most of the components are surface mount devices, reflow soldering was used to attach parts to the PCB. Some parts, including the operational amplifier, the select resistors, and the USB-C port required through hole soldering using a soldering iron. The bench setup for soldering is shown in Figure 5-1.

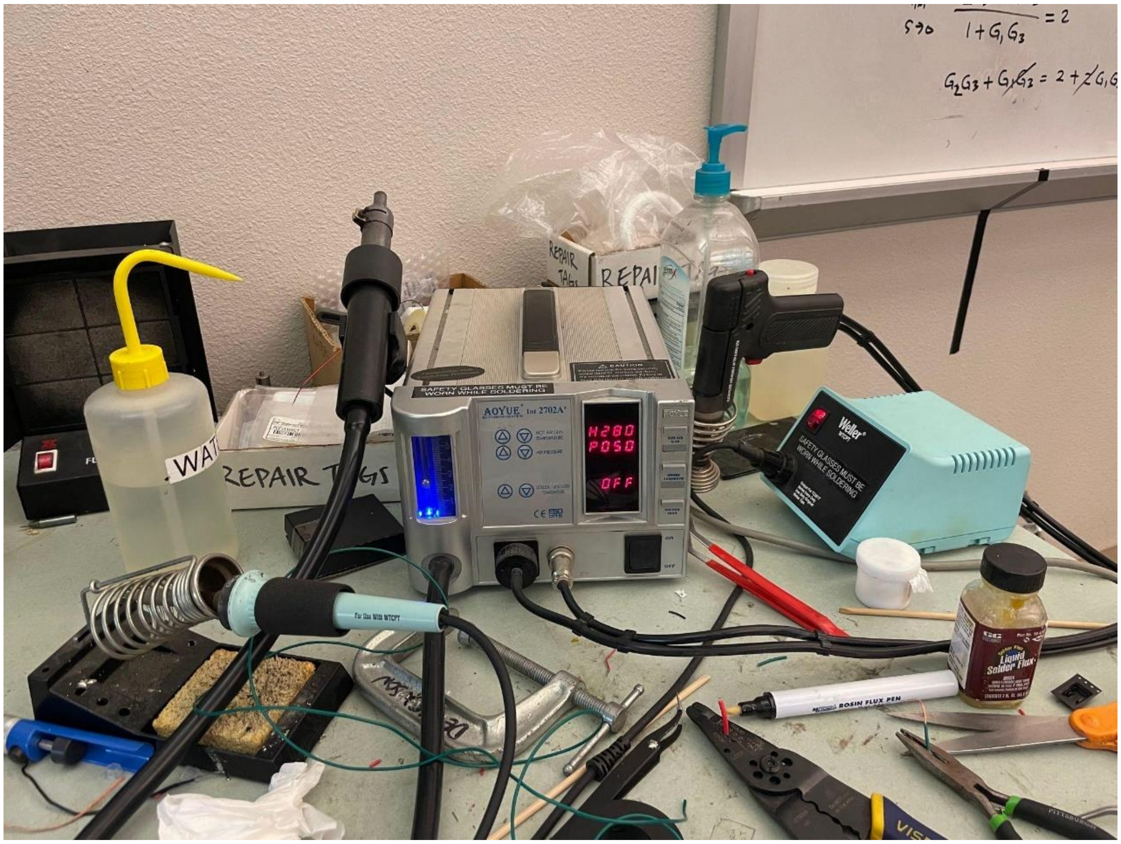


Figure 5-1: Soldering Station with Heat Gun and Soldering Iron

5.2: Test Procedure

With the construction of the PCB completed, hardware testing began using the lab bench shown in Figure 5-2:

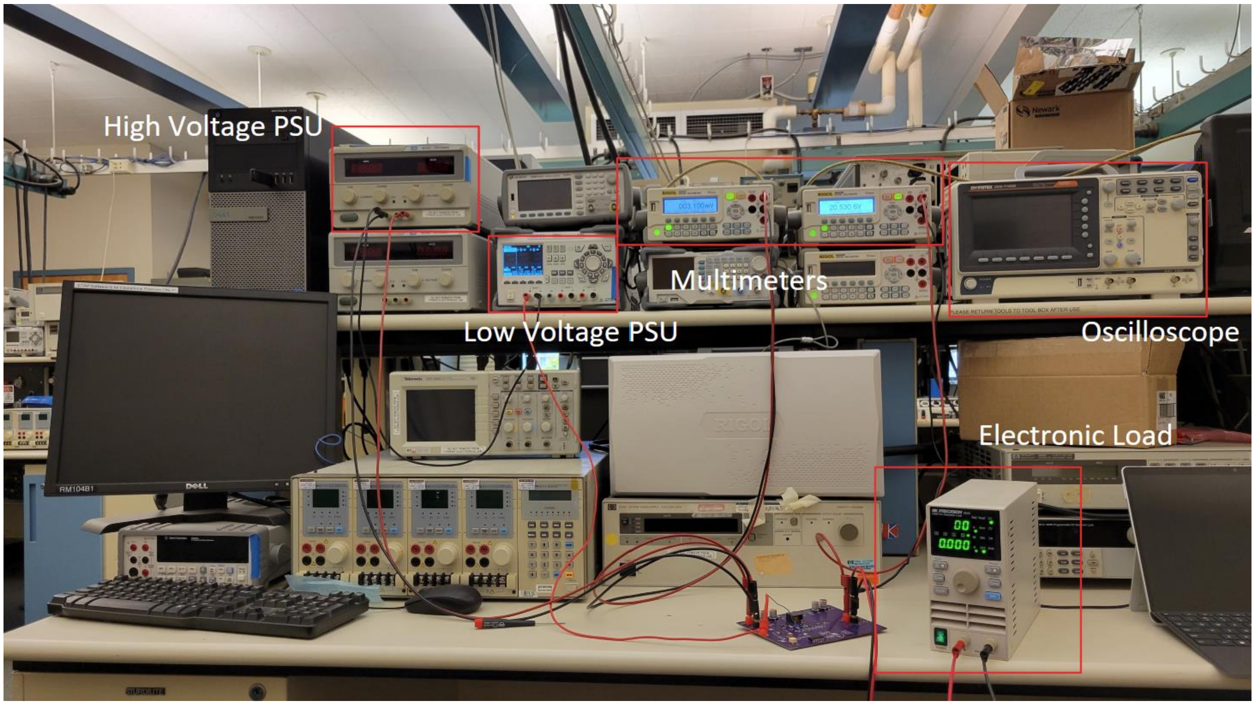


Figure 5-2: Lab Bench Setup

A 360W power supply was used to simulate the 48V input from the DC House, with a voltmeter attached to the input terminals of the PCB. The input voltmeter is necessary to ensure that losses along the wires leading from the source to the PCB input do not result in a lower voltage at the input of the PCB. A multimeter on the output is used to measure the average output voltage, along with an electronic load to simulate possible load currents. While the electronic load does have voltage measurements, the output voltmeter is needed for the same reason as the input voltmeter. Losses from the output of the PCB to the electronic load will result in an inaccurate voltage measurement. An oscilloscope is used to measure the voltage output ripple and any other waveforms that need to be observed when troubleshooting. Finally, a second voltage supply is used to simulate the output from the UPD301A power delivery controller. For testing purposes, the power converter was analyzed before the UPD301A was used to communicate power negotiations via I2C. The block diagram of the lab bench is shown in Figure 5-3.

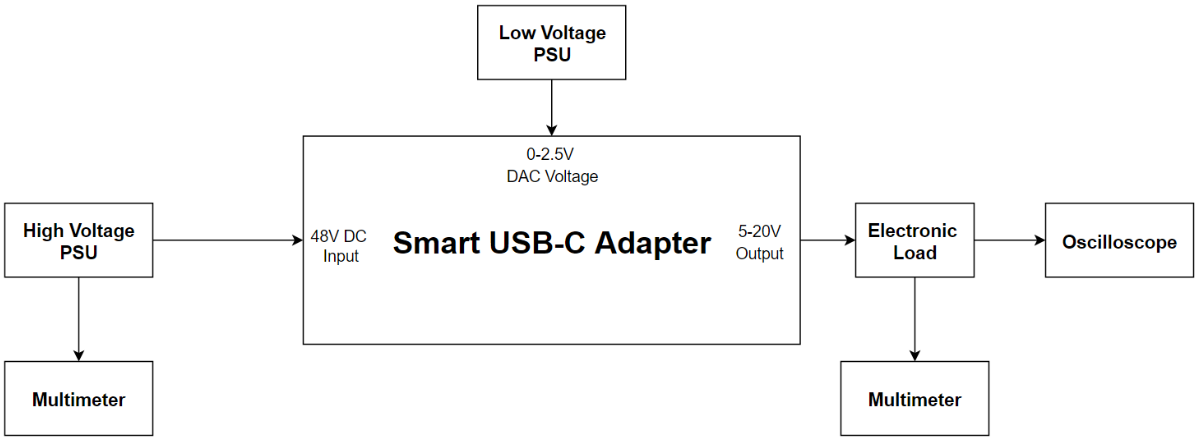


Figure 5-3: Lab Bench Block Diagram

A Charger Lab Power Z tester, shown in Figure 5-4 was planned to be used for testing the USB Power Delivery.

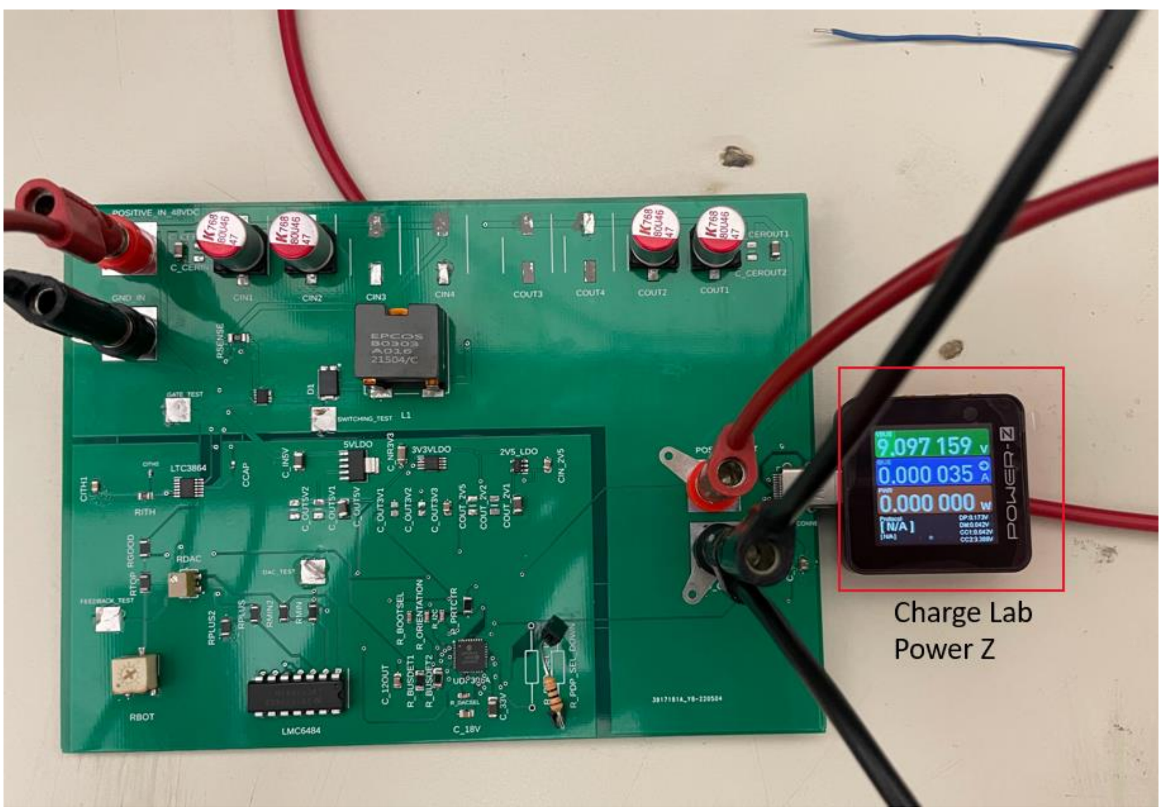


Figure 5-4: Charge Lab Power Z Tester

However, due to time constraints and issues with the power components the USB PD circuitry and controller were not able to be properly tested. When plugged in, the tester was unable to detect the USB PD communication protocol. While the layout surrounding the controller was designed per datasheet recommendations, the communication signals for I2C could not be detected on the CC1 and CC2 pins of the smart wall charger.

5.3 Testing Results

The power components were tested using the procedure outlined in section 5.2, using the voltage supply to emulate the DAC output voltage for the UPD301A. Line regulation was tested at +/- 4V on the 48V bus. The low input voltage was 44V and the high voltage was 52V. Line regulation was tested for all of the possible output voltages of the USB-C wall charger. The results are listed in Table 5.1:

Table 5.1: Line Regulation

Output Voltage [V]	Output Voltage At Low Input [V]	Output Voltage At High Input [V]	Output Voltage At Nominal Input [V]	Percent Line Regulation
5	5.137	4.958	4.936	-3.63%
9	9.256	9.191	9.227	-0.70%
15	15.548	15.482	15.492	-0.43%
20	20.474	20.53	20.54	0.27%

For all of the output cases except for 5V, the line regulation measurements meet the requirement of +/-1%. While it is disappointing that the 5V case measured well over 1% line regulation, it is not surprising given the simulation results shown in Chapter 4 where the 5V had a simulated ripple of 334mV.

Peak to peak voltage ripple was also measured for each output voltage, at no load, using an oscilloscope. Screenshots of each output voltage on the oscilloscope are shown in Figures 5-5 through 5-8.

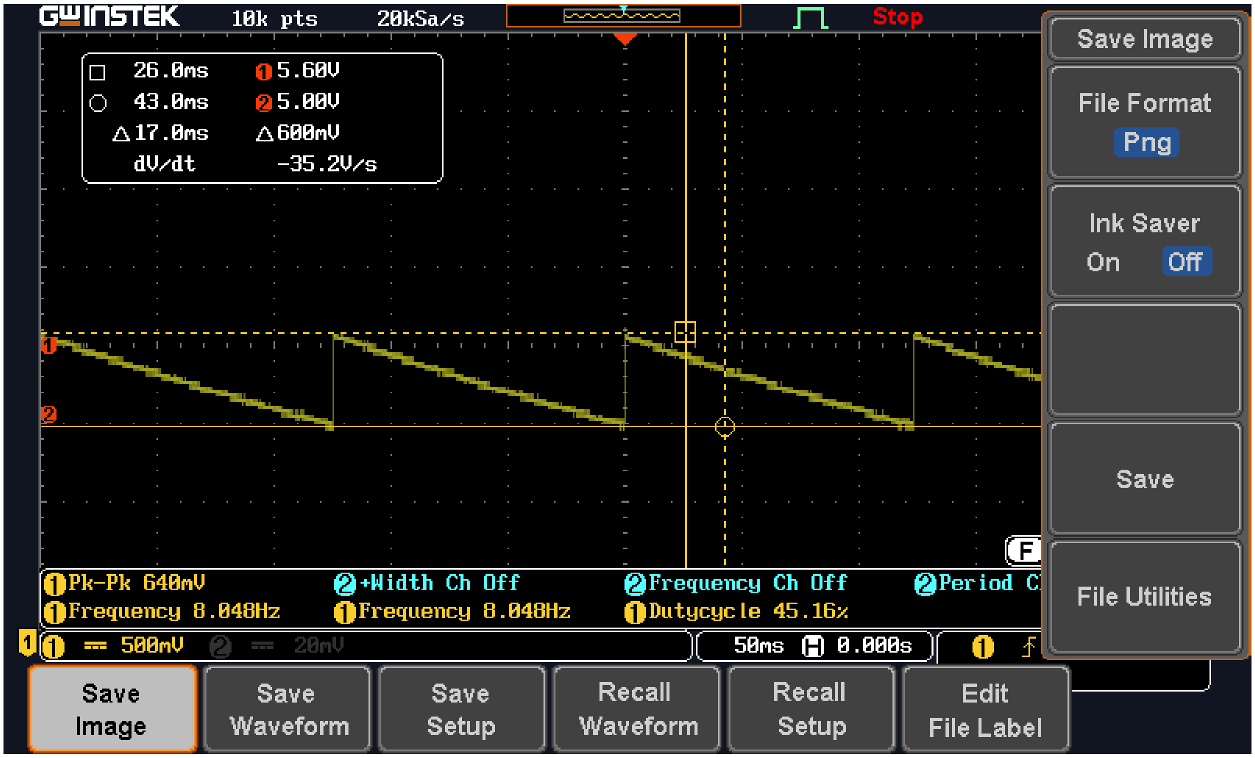


Figure 5-5: Output Voltage Ripple for 5V

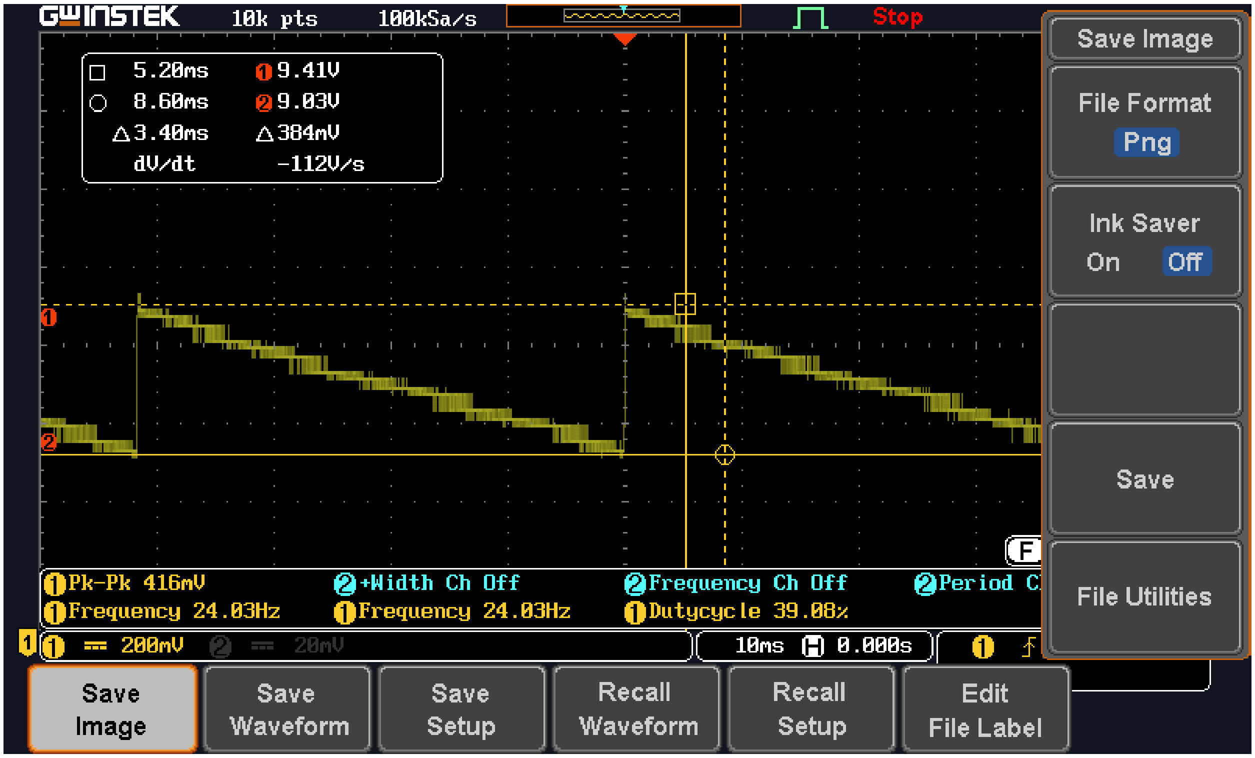


Figure 5-6: Output Voltage Ripple for 9V

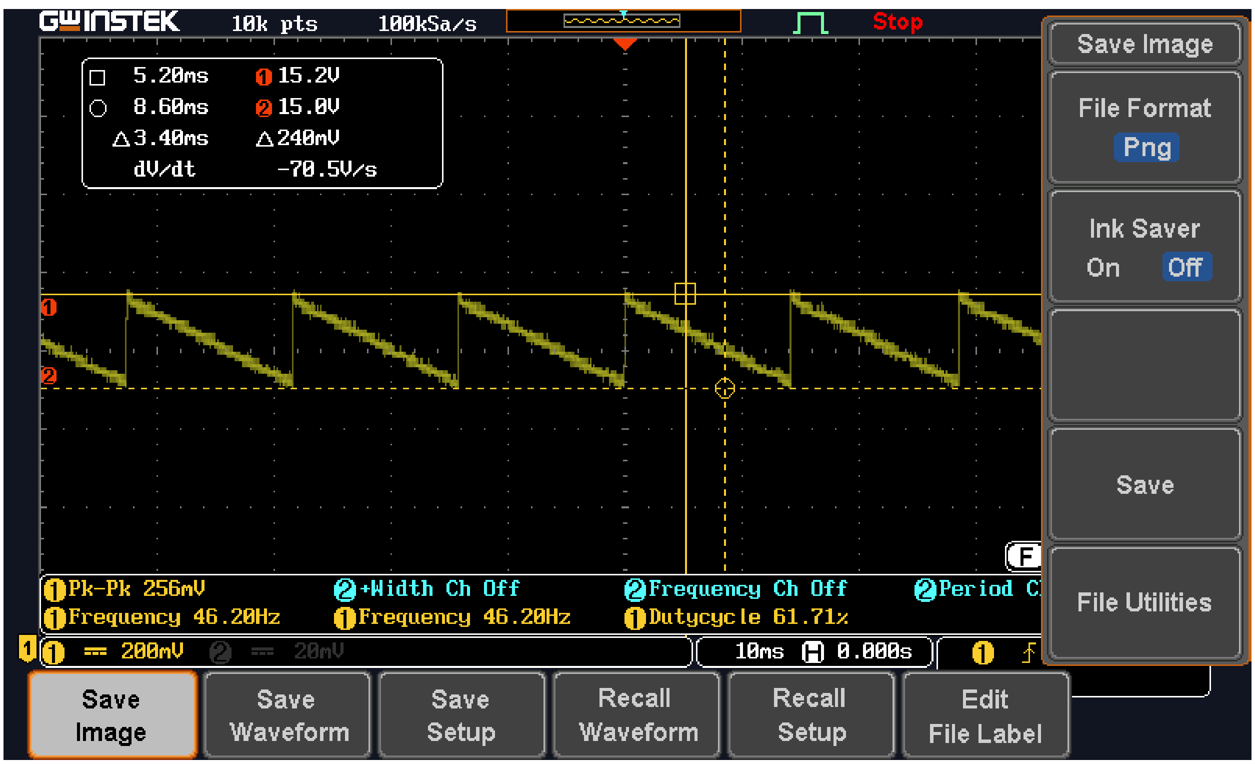


Figure 5-7: Output Voltage Ripple for 15V

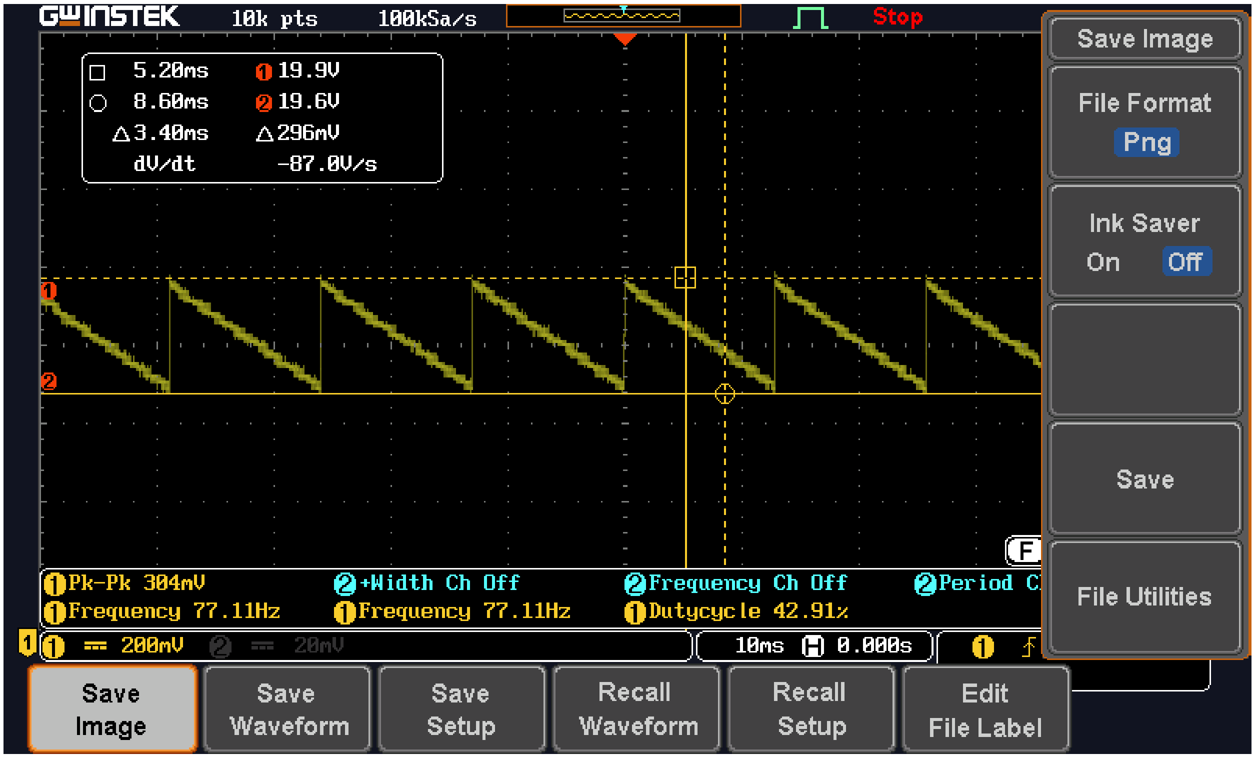


Figure 5-8: Output Voltage Ripple for 20V

The resulting peak to peak ripple voltages at no load are listed in Table 5.2.

Table 5.2: Measured Peak to Peak Voltages

Output Voltage	Measured Voltage Ripple	Percent Voltage Ripple
5V	600mV	12%
9V	384mV	4.3%
15V	240mV	1.6%
20V	296mV	1.5%

All of the output cases except for the 5V case met the requirement for less than 5% voltage ripple on the output. However, the higher voltage ripple for the 5V case was expected from the simulations shown in Chapter 4.

5.4 Other Troubleshooting Techniques and Measurement Problems

Throughout testing the PCB design multiple issues were encountered that required extensive troubleshooting. One of the biggest issues encountered was the buck controller IC, the LTC3684, failing and shorting pins internally. With the initial design of the PCB the controller ended up shorting internally 3 times on 3 separate IC's. Two of the times the IC shorted, it also blew the P-Channel MOSFET that was used initially, the Si7469DP. Upon closer inspection, it was found that one of the capacitors being connected from 48V to the CAP pin on the LTC3684 was rated for a much smaller voltage than what it was being implemented onto. This is what is believed to have caused the issue. Upon the second rendition of the PCB, the specific design changes of the PCB will be discussed below, a new switch and updated capacitor was used. Once the whole design was soldered the circuit would not regulate to any voltage, but once the capacitor connecting the CAP pin and 48V was removed, the circuit would regulate to the voltages it was designed for. Only issue is that it would only regulate under load, anything above 100mA was being drawn, the circuit would stop regulating entirely. The reason for this is still unknown as much troubleshooting was done and the root cause of the issue has still not been found.

5.5 Redesign of the PCB:

Upon receiving the first version of the PCB, issues were found with the layout. Namely with the footprint orientation of the USB-C connector. The first version of the PCB had the footprint of the connector off by 180°, the connector was pointing into the board rather than off the edge of the board. This was a big issue due to the connector having to sit flush onto the board, and it would be impossible to connect USB-C cables to the connector in this orientation. Another issue was that both of the MOSFETS that were previously purchased blew up, and all online distributors were out of stock on the specific component used, so a new MOSFET had to be chosen, and the PCB design altered slightly to accommodate the new footprint of the MOSFET. The new MOSFET was the RQ7L050AT. One positive about this new MOSFET is that it provided better overall efficiency of the circuit, improving upon the previous design by 3% to

4% depending on the output voltage. However, the 5V output case had decreased efficiency by about 3%. The new simulation results are listed in Table 5.3:

Table 5.3: Simulated Efficiency of Smart Charger with RQ7L050AT MOSFET

Output Voltage	Simulated Efficiency
5V	65.9%
9V	80.4%
15V	87.5%
20V	90.5%

Unfortunately, the charger with the new MOSFET was unable to be tested due to issues with the converter regulating under load as outlined in section 5.4.

Chapter 6. Conclusion

At Cal Poly, the DC House project is working to reduce home reliance on AC power systems to reduce inefficiencies in powering residential DC loads, and to encourage further use of renewable energy systems. In order for the project to be successful, DC wall plugs are needed to step down the 48V bus to a usable output for consumer electronics. Since different DC devices require different voltages, USB Power Delivery is an attractive option for creating DC-DC converters that can have multiple output voltages depending on what the connected device requires.

In this project, a buck converter was designed to use USB Power Delivery to achieve a variable step-down output from the 48V bus. The UPD301A from Microchip was selected as the USB Power Delivery Controller because it is pre-programmed for I2C communication by the manufacturer. Following the data sheet, the UPD301A was configured to have 3A maximum output current at an output voltage of 5V, 9V, 15V, and 20V. The buck converter itself was designed around the LTC3864 controller. This device was chosen for the buck converter because it met the voltage and current requirements of the system. It was also readily available to purchase from Mouser.

Component calculations were performed in MathCAD and the components were sized according to the worst case calculations found in the Appendix. The converter was simulated in LTSpice, and a PCB layout was designed in Fusion 360. After the components had been selected and purchased from Mouser, the PCB was sent to JLCPCB for manufacturing.

Testing the project yielded few results. The converter could not regulate voltage under load and the Power Delivery controller was unresponsive. Line regulation data was able to be gathered by simulating the Power Delivery controller control signal using a voltage source, but no other data with loading could be taken.

6.2: Project Results Summary

Measurable results from this project are the line regulation and peak to peak voltage ripple measurements listed in Chapter 5. From the line regulation results, it can be seen that the designed buck converter can hold a stable output for all of the possible output voltage without any load connected to the output of the converter. While the 9V, 15V, and 20V outputs were able to remain under 1% line regulation, the 5V case was measured at -3.63%. This was expected from the simulations outlined in Chapter 4 where the 5V case had the most voltage ripple when compared to the other outputs. Output ripple voltage was also measured at no load, with the 9V, 15V, and 20V outputs maintaining ripple below 5%. As expected, the 5V output had a much higher ripple of 12%.

Issues with the 5V output were likely due to the compensation filter on the Ith pin of the LTC3864. In simulation, there was no possible combination of capacitors and resistors that stabilized the 5V output within 5% ripple. In the end, the decision was made to move on with the project since the other output voltages were performing well for the engineering requirements.

When the converter was put under load, the output voltage failed to regulate. With as little current as 100mA on the electronic load, the converter's output voltage would go to zero. Sometimes, the capacitor connected to the CAP pin of the LTC3864 would burn up, or the MOSFET would burn up. If neither component burnt up, then it became clear that the LTC3864 was entering a shutdown state with some pins being shorted. Looking through the datasheet, and probing various test points on the PCB, it was unclear as to why the LTC3864 was shutting down when a load was attached to the output of the buck converter.

6.3: Cost Breakdown

The total cost for designing and building the project was $379.43 with detailed breakdown of the cost of components shown in the Bill of Materials section of the Appendix. The money spent on the project was primarily used for buying circuit components, PCB orders, and to cover shipping costs. Additionally, a USB-PD tester was also purchased in order to test the USB-PD portion of the project.

Cal Poly's power electronics lab was used abundantly throughout the project, especially when it came time to physically assemble the design. Soldering irons and heat guns in the lab were used to mount components to the PCBs. Also, a multitude of test equipment, high and low voltage power supplies, electronic loads, and oscilloscopes, in the lab were used to test the metrics of the assembled design.

6.4: Project Challenges

Throughout the duration of the project many issues were encountered. The three main challenges that had to be worked through were PCB design issues, component ratings, and loading issues on the final design.

PCB design issues were one of the first issues realized when assembling the first PCB, after placing in the USB-C connector into the appropriate through holes, it was realized that the footprint of the connector was placed backwards. Meaning the connector was facing into the board, rather than facing outwards. This proved to be a critical issue since the USB-C connector that was used for the design sits flush to the PCB, which means that no USB-C cables could be connected to the connector since the connector was flush to the board. Once this issue was found, an updated PCB layout was created to fix this issue with the orientation of the USB-C connector. In addition to this, the original MOSFET that was used for the design was no longer in stock, so no more of those switches could be purchased. During testing two of the MOSFETs blew and only 2 were purchased, so there were none left. It was decided to then find a new MOSFET and implement that onto the new layout and get multiple switches in case some blew up during testing. The RQ7L050ATTCR P-Channel was chosen, and through simulations actually made the design more efficient. With these design changes, a new set of PCBs were ordered that had all the proper layout orientations and updated components.

On the first rendition of the PCB, the initial testing three LTC3684 buck controllers and two Si7469DP P-Channel MOSFET blew while loading the adapter. Each time a component blew, extensive troubleshooting and checking over proper component placement was done, with finding that nothing was off from the design that was created. After the last switch blew, heavy digging was done into each of the components mounted onto the PCB. It was found there was a capacitor connected across the 48V DC input and the CAP pin of the LTC3684 that was thought to have been rated for 100V, but looking into the datasheet the capacitor was actually rated for only 10V. The location where it was mounted would have a much larger voltage drop than what the capacitor was actually rated for. This capacitor was the main culprit for why the original design could not work. For the second version of the PCB, a new capacitor was found that could replace the original capacitor, and handle the large voltage drop across.

Upon mounting all the components onto the new PCB, including the new switch and capacitor testing was done to see how the new version of the design would work. When all the components were placed onto the board, the new design would not regulate at all, and the LTC3684 would enter a “shut off” stage. If the capacitor was removed and left an open on the CAP pin of the controller, the design would regulate the voltage under no load, but if anything over 100mA would be drawn from the load, the controller would again enter the “shut off” stage. Upon looking through the datasheet, and probing different pins on the controller and various test points on the PCB, and doing extensive troubleshooting it was unclear as to why the LTC3864 was entering a “shut off” state when a load was attached to the output of the buck converter.

6.5: Recommendations for Future Work

Upon implementing the design for the Smart USB-C adapter, many issues and problems arose with the design. With these issues and problems though, recommendations can be made for what to do for similar projects in the future.

For the PD controller, the UPD301A was used for the design, but this controller was not the first choice for the design. The UPD301A had many more external sources and components that needed to be connected to the controller in order to function properly. Also, it had a DAC voltage output that went 0-2.5V as the voltage on the output needed 0-20V, this was backwards from every other controller that was researched and caused the need for much more control circuitry to be implemented in order to get the proper output voltage. It is recommended to get simpler, and more user-friendly chips like the STMicro STUSB4700, this was the first choice for the design of this project, but due to supply chain issues, this chip was unable to be purchased.

When selecting components for the project, we need to make sure that all of the ratings are well above what the expected voltage or current through the component will be. With capacitors especially, it is important to choose voltage ratings that are two times or greater than the expected voltage over the capacitor. Being mindful of component ratings would eliminate some of the issues faced in this project.

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Appendix A: Bill of Materials

Reference Designator	Component Value	Description	Quantity	Part Number	Supplier	Per Unit Cost	Quantity Cost
M1	External Switch	MOSFET	3	SI7469DP-T1-E3	Mouser	$2.78	$5.56
D1	Shottky Diode	Shottky Diode	2	PDS5100-13	Mouser	$1.52	$3.04
Cout and Cin	47uF	Capacitor	10	A768MS476M1KLAE034	Mouser	$1.05	$10.50
Cth1	10nF	Capacitor	2	08055C103KAT2A	Mouser	$0.14	$0.28
Cth2	1pF	Capacitor	2	GCM1555C1H1R0CA16D	Mouser	$0.17	$0.34
Ccap	0.47uF	Capacitor	2	C0402C474K8RACTU	Mouser	$0.50	$1.00
Rsense	10mΩ	Resistor	2	CFN1206-FZ-R010ELF	Mouser	$0.60	$1.20
Rmin and Rplus and Rgood, R_PRCTR	100kΩ	Resistor	8	RCC1206100KFKEA	Mouser	$0.32	$2.56
Rftop	10kΩ	Resistor	2	CRMA1206AF10K0DKEF	Mouser	$0.68	$1.36
Rfbot	1kΩ potentiometer	Resistor	2	3361P-1-102GLF	Mouser	$1.20	$2.40
L1	30uH	Inductor	2	B82559B0303A016	Mouser	$5.55	$11.10
Rith	25kΩ	Resistor	2	CPF-A-0805B25KE	Mouser	$0.55	$1.10
RDAC	2kΩ potentiometer	Resistor	2	3214W-1-202E	Mouser	$2.97	$5.94
LMC6484	LMC6484	Operational Amplifier	1	LMC6484	Mouser	$0.00	$0.00
LTC3684	LTC3684	Buck Controller	5	LTC3684	Mouser	$6.21	$31.05
USBC Connector	n/a	Female USB-C Connector	2	SS-52400-002	Mouser	$2.42	$4.84
UPD301A	USB-PD Chip	USB-PD Chip	3	UPD301A	Mouser	$2.92	$8.76
R_Orientation, R_I2c, R_BOOTSEL, R_DACSEL	200kΩ	Resistor	8	CHV0603-FX-2003EST	Mouser	$0.53	$4.24
C_12out, C_18V, C_5V, C_OUT3V3, C_IN5V	1uF	Capacitor	10	C0805X105K8RAC7210	Mouser	$1.13	$11.30
R_Busdet1	90kΩ	Resistor	2	RT1206DRE0790KL	Mouser	$0.52	$1.04
R_Busdet2	10kΩ	Resistor	2	CRMA1206AF10K0FKEF	Mouser	$0.74	$1.48

Reference Designator	Component Value	Description	Quantity	Part Number	Supplier	Per Unit Cost	Quantity Cost
C_33V, C_IN5V, C_OUT5V	2.2uF	Capacitor	8	HMR316BC7225KL-T	Mouser	$0.72	$5.76
R_PDP_SEL	200kΩ	Resistor Through Hole	2	MF1/2CCT52R2003F	Mouser	$0.10	$0.20
R_PDP_SEL	4.7kΩ	Resistor Through Hole	2	MBB0207VC4701FC100	Mouser	$0.00	$0.00
R_PDP_SEL	10Ω	Resistor Through Hole	2	CCF0710R0GKE36	Mouser	$0.00	$0.00
C_CC1, C_CC2	220pF	Capacitor	4	C0805C221J8RACTU	Mouser	$0.53	$2.12
REG113EA-3.3V	LDO Chip	LDO	2	REG113EA-3.3V	Mouser	$4.24	$8.48
C_IN3V3, C_NR3V3	0.1uF	Capacitor	4	C1206C104K3GACAUTO	Mouser	$2.01	$8.04
MCP1793T_5V	LDO Chip	LDO	2	MCP1793T-5002H/OT	Mouser	$1.09	$2.18
LP2980AIM5X-2.5V	LDO Chip	LDO	2	LP2980AIM5X-2.5V	Mouser	$0.94	$1.88
PCB	N/A	Printed Circuit Board	1	N/A	JLCPCB	$18.30	$18.30
Shipping Costs							$57.66
PCB 2	N/A	Printed Circuit Board	1	N/A	JLCPCB	$11.30	$11.30
Shipping Costs 2							$41.78
Power Lab Charger Z	Charger Lab	Power Delivery Tester	1	N/A	Power Lab	$108.74	$108.74
Ccap	0.47uF	Capacitor	3	UMK105ABJ474KV-F	Mouser	$0.20	$0.60
New MOSFET	External Switch	MOSFET	3	RQ7L050ATTCR	Mouser	$1.10	$3.30
Total Cost							$379.43

Appendix B: MathCAD Calculations

MATHCAD Calculations for the Buck Converter:

Equations for the Buck Converter

Constants for All Cases

$P := 60\ \mathbf{W}$ $\quad f := 535\ \mathbf{kHz}$ $\quad PercentCurrentRipple := 0.3$ $\quad Vrip := 0.05$

$Vin := 48\ \mathbf{V}$ $\quad Vinmax := Vin + 4\ \mathbf{V} = 52\ \mathbf{V}$ $\quad Vinmin := Vin - 4\ \mathbf{V} = 44\ \mathbf{V}$

$Vinrip := Vinmax - Vinmin = 8\ \mathbf{V}$

Vo = 5V Case

$Vo := 5\ \mathbf{V}$ $\quad Ioutmax := 3\ \mathbf{A}$

$$D := \frac{Vo}{Vin} = 0.104 \qquad Dmin := \frac{Vo}{Vinmax} = 0.096 \qquad Dmax := \frac{Vo}{Vinmin} = 0.114$$

$\Delta IL := PercentCurrentRipple \cdot Ioutmax = 0.9\ \mathbf{A}$

$$Lcrit1 := \frac{(Vinmax - Vo) \cdot Dmin}{\Delta IL \cdot f} = \left(9.386 \cdot 10^{-6}\right)\ \mathbf{H}$$

$$Lcrit2 := \frac{(Vinmin - Vo) \cdot Dmax}{\Delta IL \cdot f} = \left(9.204 \cdot 10^{-6}\right)\ \mathbf{H}$$

$$CcritOUT := \frac{1 - Dmin}{Vrip \cdot 8 \cdot Lcrit1 \cdot f^2} = \left(8.411 \cdot 10^{-7}\right)\ \mathbf{F}$$ **<----- Use This One**

$VDmax := Vinmax = 52\ \mathbf{V}$

$Vswmax := Vinmax = 52\ \mathbf{V}$

$Idmax := Ioutmax \cdot (1 - Dmin) = 2.712\ \mathbf{A}$

$Iswmax := Ioutmax \cdot Dmax = 0.341\ \mathbf{A}$

$$CcritIN := \frac{Iswmax \cdot (1 - Dmin)}{Vinrip \cdot f} = \left(7.199 \cdot 10^{-8}\right)\ \mathbf{F}$$

$$OutputCapRMS := \frac{Vo \cdot (1 - Dmin)}{2 \cdot \sqrt{3} \cdot Lcrit1 \cdot f} = 0.26\ \mathbf{A}$$

$$InputCapRMS := Ioutmax \cdot \sqrt{Dmax \cdot \left(1 + \frac{\Delta IL^2}{12 \cdot Ioutmax^2}\right) - Dmax^2} = 0.956\ \mathbf{A}$$

Vo = 9V Case

$Vo := 9\ V \qquad Ioutmax := 3\ A$

$D := \frac{Vo}{Vin} = 0.188 \qquad Dmin := \frac{Vo}{Vinmax} = 0.173 \qquad Dmax := \frac{Vo}{Vinmin} = 0.205$

$\Delta IL := PercentCurrentRipple \cdot Ioutmax = 0.9\ A$

$$Lcrit1 := \frac{(Vinmax - Vo) \cdot Dmin}{\Delta IL \cdot f} = \left(1.546 \cdot 10^{-5}\right)\ H$$

$$Lcrit2 := \frac{(Vinmin - Vo) \cdot Dmax}{\Delta IL \cdot f} = \left(1.487 \cdot 10^{-5}\right)\ H$$

$$CcritOUT := \frac{1 - Dmin}{Vrip \cdot 8 \cdot Lcrit1 \cdot f^2} = \left(4.673 \cdot 10^{-7}\right)\ F$$

$VDmax := Vinmax = 52\ V$

$Vswmax := Vinmax = 52\ V$

$Idmax := Ioutmax \cdot (1 - Dmin) = 2.481\ A$

$Iswmax := Ioutmax \cdot Dmax = 0.614\ A$

$$CcritIN := \frac{Iswmax \cdot (1 - Dmin)}{Vinrip \cdot f} = \left(1.186 \cdot 10^{-7}\right)\ F$$

$$OutputCapRMS := \frac{Vo \cdot (1 - Dmin)}{2 \cdot \sqrt{3} \cdot Lcrit1 \cdot f} = 0.26\ A$$

$$InputCapRMS := Ioutmax \cdot \sqrt{Dmax \cdot \left(1 + \frac{\Delta IL^2}{12 \cdot Ioutmax^2}\right) - Dmax^2} = 1.216\ A$$

Vo = 15V Case

$Vo := 15\ V$ $\qquad Ioutmax := 3\ A$

$D := \frac{Vo}{Vin} = 0.313 \qquad Dmin := \frac{Vo}{Vinmax} = 0.288 \qquad Dmax := \frac{Vo}{Vinmin} = 0.341$

$\Delta IL := PercentCurrentRipple \cdot Ioutmax = 0.9\ A$

$$Lcrit1 := \frac{(Vinmax - Vo) \cdot Dmin}{\Delta IL \cdot f} = \left(2.217 \cdot 10^{-5}\right)\ H$$

$$Lcrit2 := \frac{(Vinmin - Vo) \cdot Dmax}{\Delta IL \cdot f} = \left(2.053 \cdot 10^{-5}\right)\ H$$

$$CcritOUT := \frac{1 - Dmin}{Vrip \cdot 8 \cdot Lcrit1 \cdot f^2} = \left(2.804 \cdot 10^{-7}\right)\ F$$

$VDmax := Vinmax = 52\ V$

$Vswmax := Vinmax = 52\ V$

$Idmax := Ioutmax \cdot (1 - Dmin) = 2.135\ A$

$Iswmax := Ioutmax \cdot Dmax = 1.023\ A$

$$CcritIN := \frac{Iswmax \cdot (1 - Dmin)}{Vinrip \cdot f} = \left(1.7 \cdot 10^{-7}\right)\ F$$

$$OutputCapRMS := \frac{Vo \cdot (1 - Dmin)}{2 \cdot \sqrt{3} \cdot Lcrit1 \cdot f} = 0.26\ A$$

$$InputCapRMS := Ioutmax \cdot \sqrt{Dmax \cdot \left(1 + \frac{\Delta IL^2}{12 \cdot Ioutmax^2}\right) - Dmax^2} = 1.43\ A$$

Vo = 20V Case

$$Vo := 20\ V \qquad Ioutmax := 3\ A$$

$$D := \frac{Vo}{Vin} = 0.417 \qquad Dmin := \frac{Vo}{Vinmax} = 0.385 \qquad Dmax := \frac{Vo}{Vinmin} = 0.455$$

$$\Delta IL := PercentCurrentRipple \cdot Ioutmax = 0.9\ A$$

$$Lcrit1 := \frac{(Vinmax - Vo) \cdot Dmin}{\Delta IL \cdot f} = \left(2.556 \cdot 10^{-5}\right)\ H$$ **<----- Use This One**

$$Lcrit2 := \frac{(Vinmin - Vo) \cdot Dmax}{\Delta IL \cdot f} = \left(2.266 \cdot 10^{-5}\right)\ H$$

$$CcritOUT := \frac{1 - Dmin}{Vrip \cdot 8 \cdot Lcrit1 \cdot f^2} = \left(2.103 \cdot 10^{-7}\right)\ F$$

$$VDmax := Vinmax = 52\ V$$

$$Vswmax := Vinmax = 52\ V$$

$$Idmax := Ioutmax \cdot (1 - Dmin) = 1.846\ A$$

$$Iswmax := Ioutmax \cdot Dmax = 1.364\ A$$

$$CcritIN := \frac{Iswmax \cdot (1 - Dmin)}{Vinrip \cdot f} = \left(1.961 \cdot 10^{-7}\right)\ F$$ **<----- Use This One**

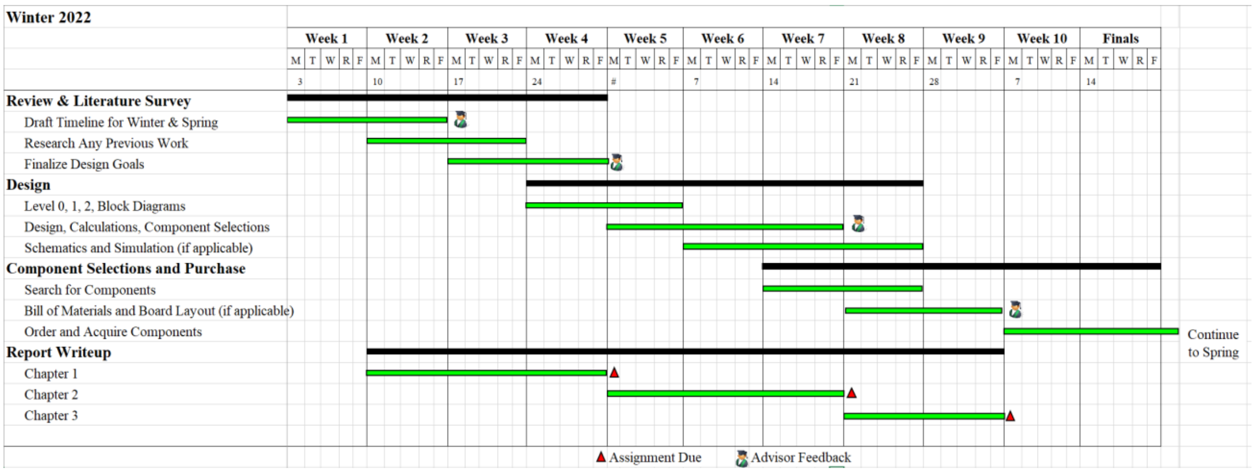
$$OutputCapRMS := \frac{Vo \cdot (1 - Dmin)}{2 \cdot \sqrt{3} \cdot Lcrit1 \cdot f} = 0.26\ A$$

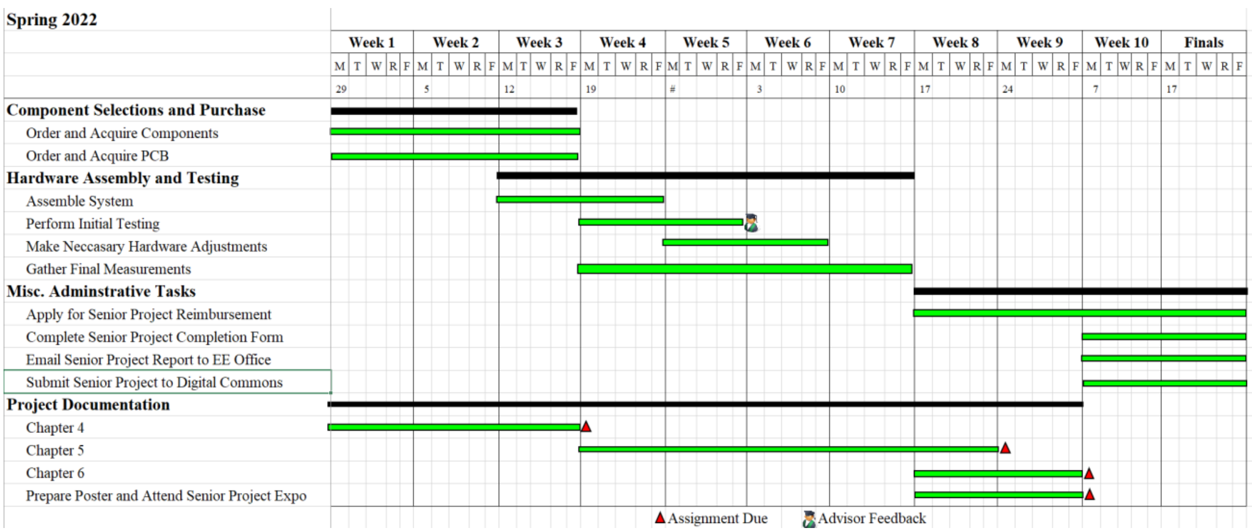
$$InputCapRMS := Ioutmax \cdot \sqrt{Dmax \cdot \left(1 + \frac{\Delta IL^2}{12 \cdot Ioutmax^2}\right) - Dmax^2} = 1.504\ A$$

Controller Specific

$$Rsense := \frac{95\ mV}{Ioutmax + \frac{\Delta IL}{2}} = 0.028\ \Omega$$ <---- Will change since ideal equation

Appendix C: Timeline of Tasks





Appendix D: Analysis of Senior Project Design

Summary of Functional Requirements

The Smart USB-C Wall Plug provides power to multiple types of devices using the USB Power Delivery standard. Devices communicate with the wall plug using the I2C protocol to negotiate the output voltage and total power delivered to the device. The plug takes 48V DC input from the DC House and converts the input to a 3-20V DC output with a maximum power of 10W, with a peak-to-peak voltage output ripple of +/-5%. Load regulation and line regulation are limited to +/-1%, and efficiency at full load is 90%. The output power and voltage of the device ranges from 3-20V at a maximum power of 10W depending on what a particular device connected to the wall plug communicates that it needs via the I2C protocol.

Primary Constraints

The Smart USB-C Wall Plug needed to have 90% efficiency at full load of 10W. Anything less than 90% efficiency wastes too much power for device charging applications. Load regulation and line regulation also needed to stay within +/-1% to retain the quality of the power being output by the wall plug. For maximum compatibility with the most devices, the 3-20V range needed to be met. More generically, the product needs to be easy to manufacture and assemble at low cost. The components used must be solderable to a printed circuit board.

Economic

Production of the Smart USB-C Wall Plug will require human capital in the form of electrical engineers with knowledge of power electronics, and people working to manufacture the device. Human capital will also be generated as people gain the skills to produce the device and redesign aspects of it. Commercial success of the project will generate financial capital in the form of revenue obtained by selling the device to customers with DC power systems, but significant financial capital will be required upfront to cover initial manufacturing costs. Once the manufacturing process develops, real capital will be created in the form of manufacturing sites and tools that are used to create the plug. To produce the device, natural capital will be required to produce components for the plug. Silicon needed for the chips used in the design, metal for the traces and some components, and water to manufacture the electronics are among the many non-replenishable resources required.

Following the product lifecycle, significant financial costs will be brought in the manufacturing phase. Use of the product will reduce cost as it limits losses from AC-DC conversion and allows for the use of more renewable energy sources in the average home. The device will also be able to be used for significant amounts of time, similar to the wall AC wall plugs found in the average home. The estimated design cost of the project is $60.94 and will be reimbursed by the EE Department at Cal Poly, and no extra test equipment beyond what is found at Cal Poly is required for completion of the project. Using the Gantt chart, the estimated time to complete the entire project is 118.8 hours.

If Manufactured on a Commercial Basis

The Smart USB-C Wall Plug will cost $60.94 per unit to produce in parts alone. Estimating manufacturing and shipping costs of $50 per unit, the total price is $110.94 per unit. The price of the plug will be marked up by $70 per unit, bringing the total price paid by the consumer to $180.94. While the $180.94 is the ideal price point, it is important to note that the cost of parts can become variable. If supply of the components dwindles while demand continues or increases, then the cost of the plug could increase if the $70 mark up remains a fixed cost for the consumer.

Homes powered by only DC power are rare. Most users of the product, in the near future, will be people with solar systems on their homes who are wanting to bypass the power inefficiencies of using an inverter to convert the solar DC output to AC, and then converting the AC back to DC for use in their electronic devices. With this in mind, the total accessible market for the Smart USB-C Wall Plug will be small at first. The total number of units estimated to be sold in a given year is 4000. With 4000 units sold, the total revenue will be 4000x180.94 = $723760. Considering the cost to produce the product, the total profit will be 723760 – (50+60.94)x4000 = $280000 per year. It is important to note that employee salaries and other labor costs will reduce the profits further.

The cost to the consumer will come in the form of wear and tear on their own power system by using the plug to charge their devices. Assuming a $15000 renewable energy system that has a lifespan of 30 years, and considering the fact that the DC-DC converter in the wall plug will always be stepping down the input voltage with or without a connected charging device, the cost becomes:
$150k/(30yearsx365days) = $13.7 per day to operate the system.

Environmental

The impact of the Smart USB-C Wall Plug environmental is beneficial to the environment in its application, however manufacturing the device itself if harmful. Beginning with the benefits of the wall plug, it is a device designed with fully renewable energy systems in mind. The DC House Project, which the plug is designed for, seeks to improve the use of DC power systems in homes in order to encourage the use of renewable sources and diminish inefficiencies in converting AC power to DC power. While in the use phase of its life cycle, the plug will help reduce the use of fossil fuels to generate electricity, and it will reduce the amount of power wasted in energy conversions.

While the use phase of its life cycle will see benefits for the environment, the manufacturing and disposal phases of its life cycle represent potential for significant harm. Electronics manufacturing requires many natural resources to create the pure silicon, pure metals, plastics and laminates that are needed to produce useable devices. Many of the process also utilize harmful chemicals that can be released in to the environment during the manufacturing process.

Once the device has ended its use phase, disposal represents another environmental issue. As with most consumer electronic devices, the components in the plug cannot be easily recycled. Instead, the replaced wall plug will be sent to a landfill or some other electronic disposal site where the harmful materials used to manufacture the device may be released into the environment.

Manufacturability

The Smart USB-C Wall Plug uses parts that are already manufactured in bulk in the electronics industry. Silicon, plastic, and metals are needed to manufacture the components used in the design. Metals, such as copper for traces, and laminates, such as PCB, are needed to manufacture the printed circuit board that the components lie on. The wall plug is assumed to be used inside a home, meaning that the operating temperature of the device will not be varied to extremes in a typical circumstance. With this in mind, no extra considerations need to be made for temperature tolerances beyond the given tolerances of the components used to make the device. Component value tolerances will need to be met by manufacturers, however the tolerances chosen in the plug design are within the scope of what is already being manufactured by semiconductor companies.

Sustainability

Maintenance of a complete Smart USB-C Wall Plug will be minimal. The device is designed to be plugged into a DC power system and remain until the components in the power converter fail years later. However, once the components fail, the device will need to be replaced. This negatively impacts the sustainability of the product's life cycle since it cannot easily be repaired and reused. Disposal represents an issue with the sustainability with the device. Since electronics are not easily recyclable, the plug will end up in a landfill where disadvantaged communities suffer the worst consequences of the negative environmental impact.

While the device is in use, it will promote the use of sustainable energy sources and increase the efficiency of a home power system, reducing strain placed upon the environment to generate electricity. The system could be redesigned to be more modular in replacing defective components. Easily reparable design will allow the typical consumer to replace parts on their own to increase the life cycle of the overall device. Upgrading the design will increase the labor cost, increasing the cost per unit that the consumer must pay.

Ethical

The main ethical dilemma of the Smart USB-C Wall Plug is its eventual disposal. Electronic devices use many materials, including plastics and PCB, that are toxic when released into the environment. Without significant advances in how electronics can be recycled, the end of the wall plug's life cycle will violate the first element of the IEEE code of ethics as it will endanger the environment upon disposal [1]. Also, the effect of toxic waste is not felt equally. Disadvantaged communities that are near disposal sites will be faced with the majority of the environmental harm. The issue of disposal can also be viewed with Consequentialism. Since the action of creating the wall plug results in the negative consequence of electronic waste and the positive consequence of improving energy efficiency and sustainability, analysis of the net environmental consequence can determine the morality of the project with relation to its environmental impact.

Health and Safety

Following the product life cycle, the Smart USB-C Wall Plug has safety concerns in the manufacturing and disposal phases of the project. Electronics manufacturing requires many natural, nonrenewable resources, and releases toxic materials to the environment. Communities that are near the manufacturing plants will be greatly impacted by the release of toxic materials in the manufacturing process. Especially with materials such as PCB using in creating circuit boards, the health risks of manufacturing the plug are significant.

Along with manufacturing, the disposal of the plug into a land fill or electronic waste facility will also release dangerous materials to the environment. Similar to manufacturing, communities that are established near waste facilities will be impacted by the toxic materials being released into the environment near them. Without better electronic recycling procedures or extended reuse, disposal will continue to represent a significant health risk associated with the Smart USB-C Wall Plug.

Social and Political

The Smart USB-C Wall Plug does not violate any political requirements such as safety regulations. Component sourcing and design requirements are all well within the bounds of federal and local regulations. The project's focus on enabling the success of renewable energy systems contributes positively to the political goals of reducing fossil fuel emissions to zero by 2045 in California, and the social benefit of having a clean environment [2].

The burden created by this project is felt unequally between communities. The environmental cost of the manufacturing and disposal phases of the product's life cycle will be focused on the communities present at the manufacturing and disposal facilities. While the negative impacts may not be felt by many consumers of the plug or the design engineers, it is important to consider the impact of the project on those who may have no say in how cost is distributed. Environmental injustice against communities near disposal facilities takes away from the overall benefit of improving renewable energy systems using the wall plug.

Development

Completion of the Smart USB-C Wall Plug required research on the use of USB Power Delivery and I2C to interface the communication module with the DC-DC converter and connected devices. USB Power

Delivery is a standard that is not mentioned in any of the classes taken before the senior project begins. The standard is well documented and reputable reference material to learn how to best use the technology was readily available. Skills with DC-DC converter design were also self-taught to complete the project on time. Long term project management is another skill that was essential to complete the project in EE460/461/462. Learning how to set realistic deadlines, stick to them, and adapt, when necessary, allowed for the project to be completed without timeline issues.

References

[1] “IEEE code of Ethics,” IEEE. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 15-Nov-2021].

[2] “Table of 100% clean energy states,” Clean Energy States Alliance, 18-Aug-2021. [Online]. Available: https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/. [Accessed: 15-Nov-2021].