Adaptive Fast Charger and Power Pack

Final Paper

Group #25

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Abstract

The device is an energy storage and conversion device that contains a powered USB port intended to be used for charging smartphones. A high voltage AC wall plug acts as the power source for charging the internal battery as well as powering the USB port. The internal battery acts as a secondary power source for the USB port when AC power in unavailable. The USB port is capable of sourcing up to 2.1 A in “fast mode” and 1 A when the device is in a “slow mode”. A button input and LED output allow a user to see and select the charging mode.

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1. Introduction

1.1 Overview

Rapidly charging smartphone batteries leads to unnecessary battery degradation due to increased heat during charge and a greater amount of time spent at 100% SOC (State of Charge). Additionally, existing power packs rarely include AC charging functionality.

We have created an AC/DC wall adapter with a selectable charge rate limit and a built in battery. The device has a button for the user to select a charge rate limit manually and indicators to display charge rate mode.

1.2 Background and Purpose

All iPhones in the US and other countries have shipped with 5W wall chargers, however iPhones since at least the 8th generation (iPhone 6, september 2014) support increased charge currents that can be delivered by higher power chargers. Although the iPhone supports faster charging, this isn't without detrimental effects to the battery. Increased charge currents of around 2.4A charge that battery at a rate approaching 1C, which can cause increased wear on the battery according to Battery University [1].

Additionally, faster charging causes increased power dissipation from the phone's internal charge electronics, resulting in increased heating to the device. This can be shown to increase the device's temperature beyond the manufacturer's recommended charge temperature, especially when cooling is physically restricted by a phone case or pillow. According to Apple, battery degradation will occur when devices are exposed to ambient temperatures about 95F (35C) [2].

We have found in our personal experience that consumers are generally aware that fast charging degrades battery health and would respond positively to a solution such as this one.

1.3 Block Introduction

Our design consists of 4 independently verifiable blocks that each play a distinct role in device functionality. The AC/DC Unit converts a wide range of input voltages and frequencies and outputs 12V DC. The Control unit converts power from 12V to 5.1V for output to the USB block and contains a microcontroller to send control signals to the other blocks. The Battery unit charges a lithium ion battery from the 12V rail and then outputs 5.1v power the the USB port via a Boost Converter. Finally, the USB Unit limits current to the USB port in response to inputs from the Control Unit.

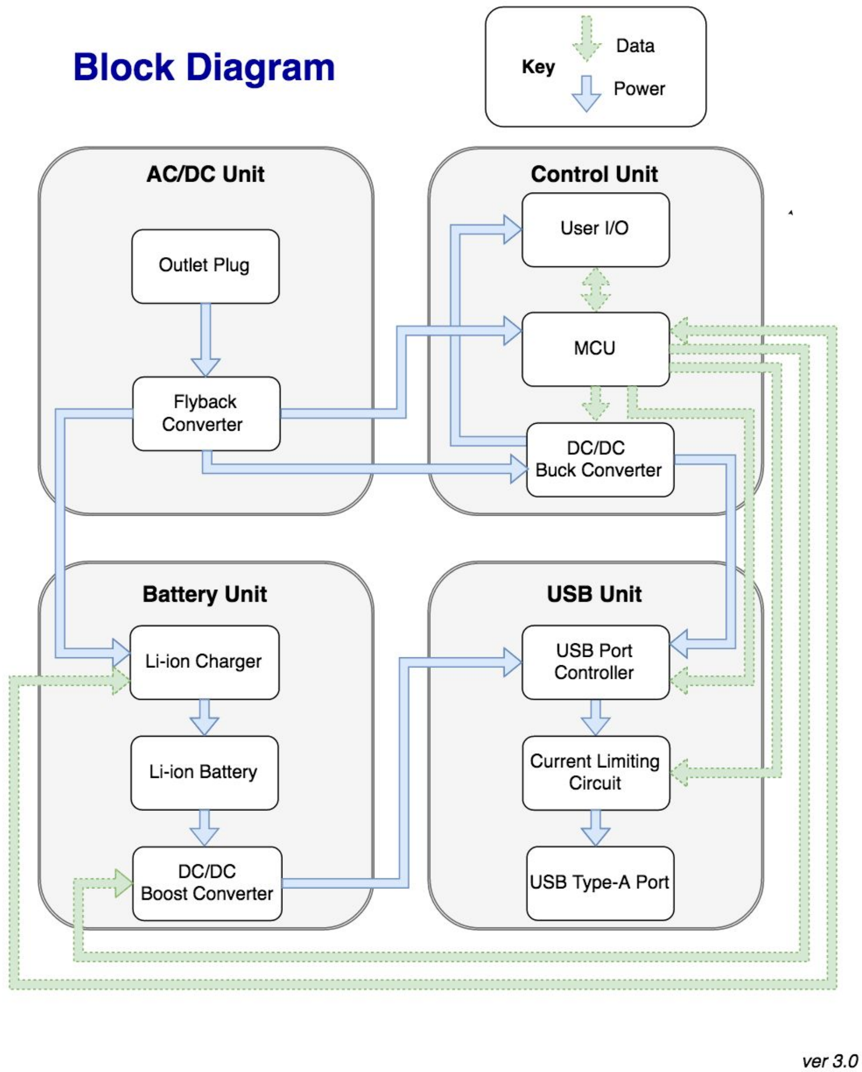


Figure 1. High Level Block Diagram

2. Design

2.1 Design Procedure

The largest engineering tradeoffs we were forced to make were in the AC/DC specification and the USB port controller design. We chose to create an intermediate 12V rail in our device to minimize the current output requirements of the AC/DC and allow for a smaller transformer size. The alternative would have been to convert directly to 5V, which would have required much wider traces and larger components to handle the increased current for a given power requirement. For current limiting in the USB port, we decided to use a dedicated USB port controller as this allows for maximum device compatibility at the expense of component cost. A custom USB port controller would have been tailored to Apple or Samsung phones due to the complexity involved in making a custom universal design and given the time limitations.

2.2 Physical Design

Figure 2. CAD Mockup of Project Enclosure

Our device resembles other common “smartphone charging cube” designs, having a rectangular shape and a single USB port output. Our final enclosure design is above (Fig. 2). There are blue and orange LED indicators on the exterior and a single button to control charge mode. The Blue LED indicates slow charging and the Orange LED indicates fast charging.

2.3 Unit Design and Circuit Schematic

2.3.1 AC/DC Unit

This block takes 100-240V AC power from a wall outlet and converts it to 12V DC, which is sent to the control unit and battery unit. The AC/DC first rectifies the AC input to a high voltage DC. The high voltage DC is lowered to low voltage DC, using a flyback converter topology. The high voltage DC is chopped using a MOSFET, which is driven by flyback controller UCC28630 [6]. This chip was chosen, because it uses an auxiliary winding on the flyback transformer to monitor voltage regulation on 12V DC output. This eliminates the need for an optocoupler on the output, saving space on the PCB. The UCC28630 also has high efficiency over different loads, which was need for our circuit, since the load varies as the batteries are charged. The AC/DC Unit schematic can be seen below (Fig. 3).

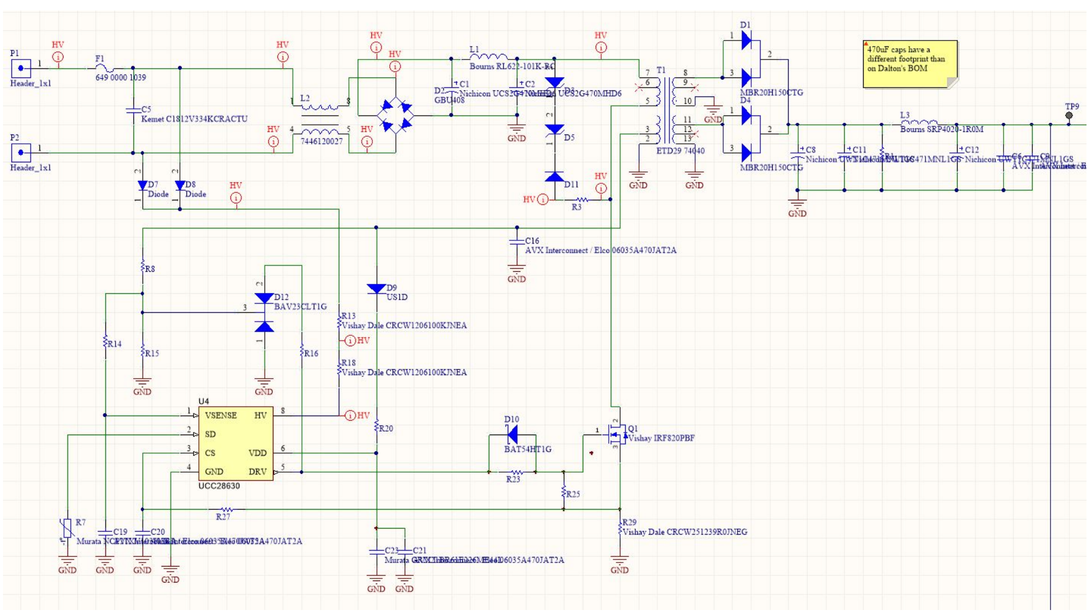


Figure 3. AC/DC Unit Schematic

2.3.2 Control Unit

This block controls various signals in the device based on the current state of the device. This is achieved by TI's MSP430 Microcontroller [8]. The microcontroller is powered by a 3.3V linear regulator from the 12V rail. This block also contains a buck converter which converts the 12V rail to a 5V rail for use by the USB Unit. Additionally, the control unit contains LED indicators for the current mode of charge (fast or slow) . The only user input is a single button that toggles fast and slow charge modes. The Control Unit schematic can be seen below (Fig. 4).

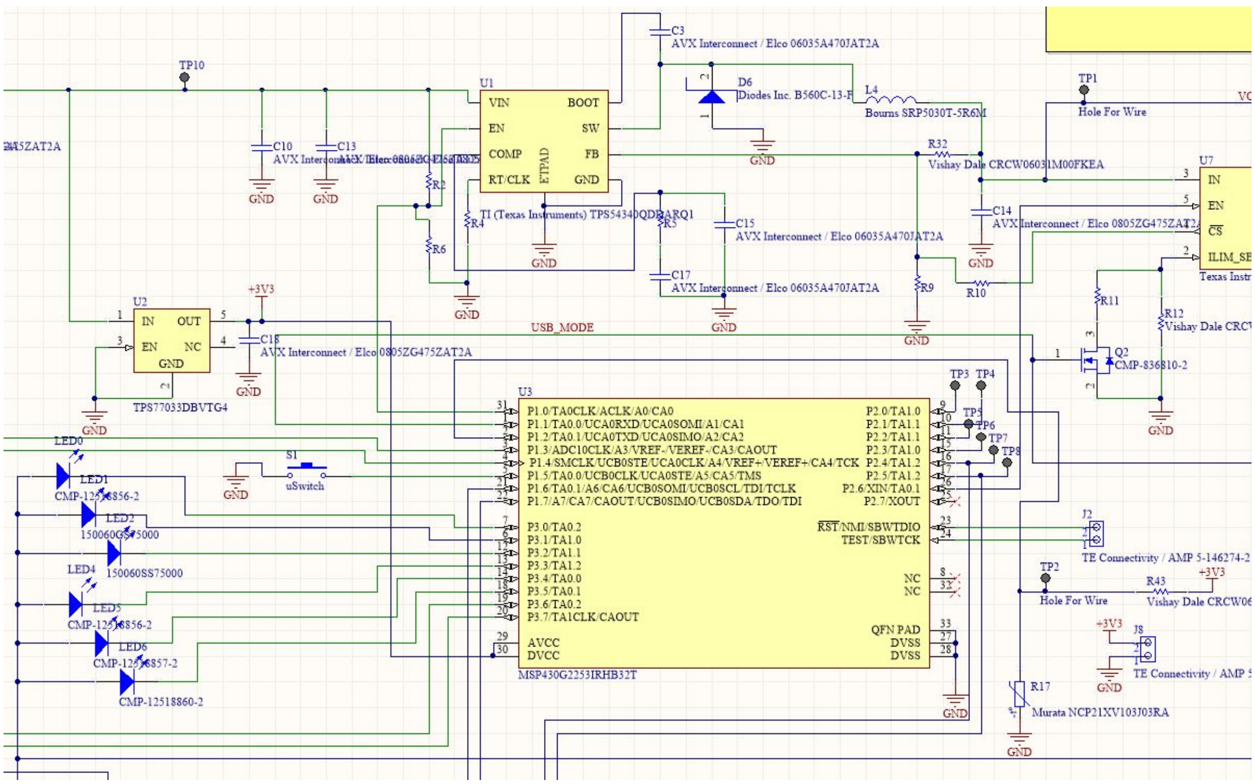


Figure 4. Control Unit Schematic

2.3.3 Battery Unit

This block contains an 18650 Li-ion battery cell and a charge controller. The charge controller charges the battery from the 12V power rail at a rate commanded by the Control Unit. There is a 5V DC/DC boost converter to allow the battery to power the MCU and USB port. Both the charging and Boost functionality are implemented with the TI BQ25895 Chip. Most component values are based on the application notes in the product datasheet [9]. The chip on the bottom right is a fuel gauge and is not required to meet our requirements but was included in our design for future functionality. The Battery Unit schematic can be seen below (Fig. 5).

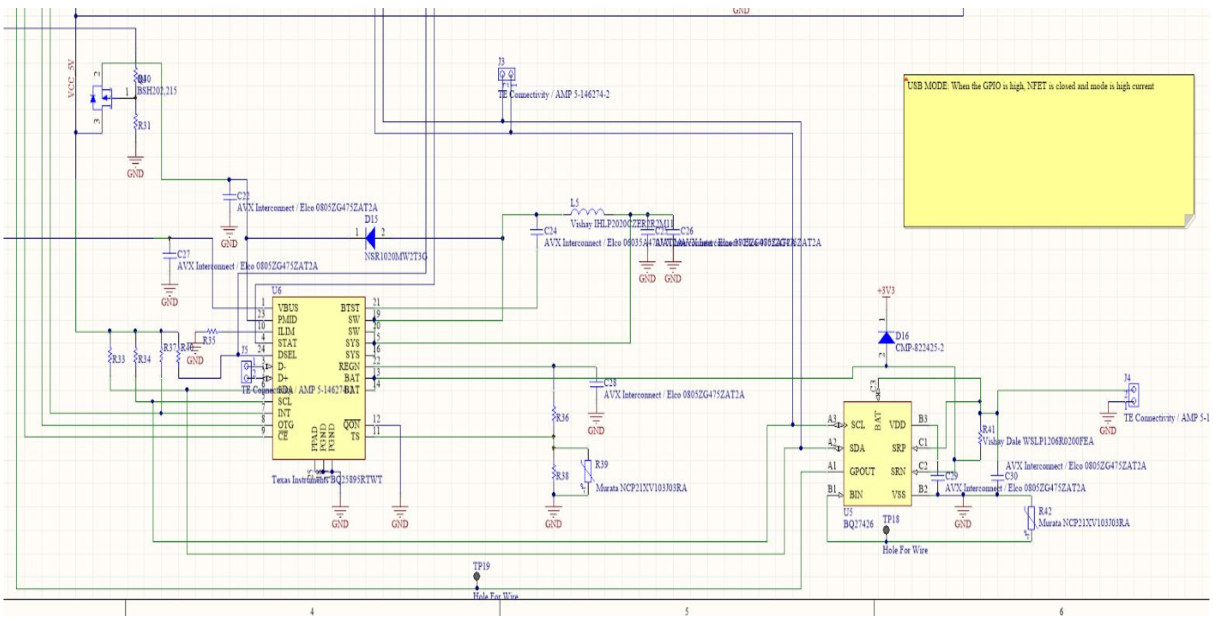


Figure 5. Battery Unit Schematic

2.3.4 USB Unit

This block controls the current output of the USB Type-A port. This is achieved by adjusting the current limit resistor on the ILIM_SET pin of the TI TPS 2511. Additionally, the mechanical relay RLY1 swaps the data pins to the USB port to allow the device to be recognized as a 5W or 12W charger. These current selection features are based on configuration instructions detailed in the product datasheet [11] Both of these changes are made in response to a logic output from the Control Unit. The USB Unit schematic can be seen below (Fig. 6).

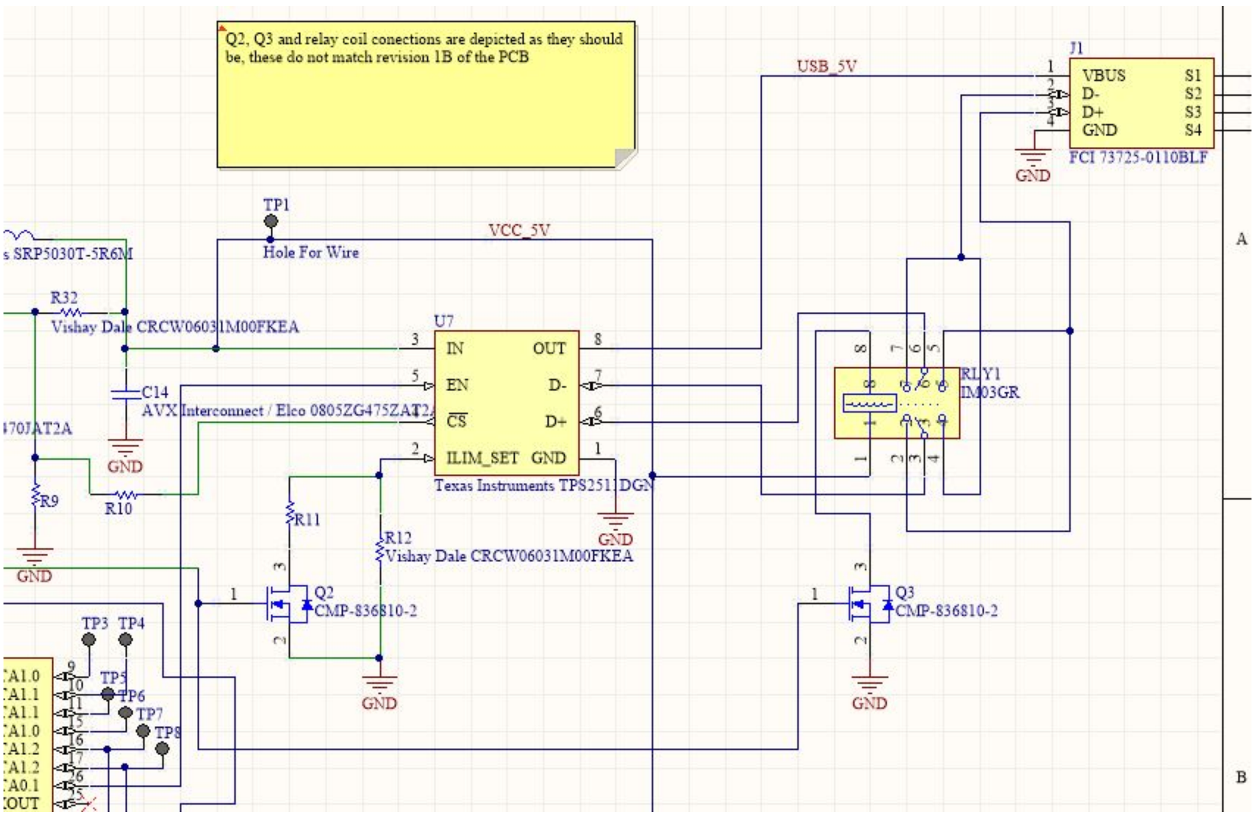


Figure 6. USB Unit Schematic

2.5 USB Output Circuit Simulation

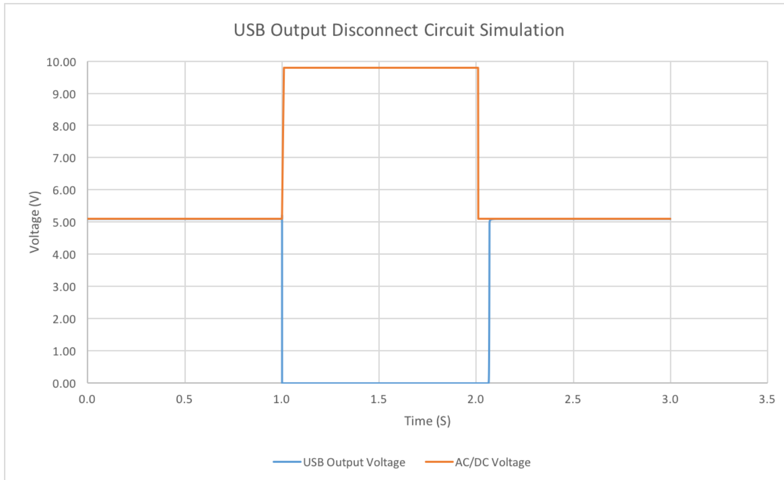


Figure 7: USB Output Simulation

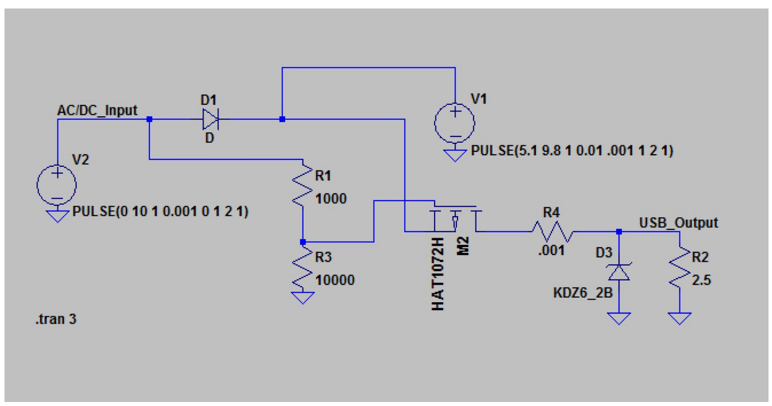


Figure 8: USB Output Simulation

Due to the topology of the TI bq25895M charge IC and boost converter, the 5V boost converter output may be driven to Vin when the Vin rail is above the 5.1V boost converter output voltage. To prevent this voltage from reaching the USB port, we created a circuit with a PMOS FET that disconnects the PMID pin from the USB port when Vin is active (Fig. 8).

Included above is a schematic and simulation of this circuit (Fig. 7, Fig. 8). V2 represents the 12v input Vin, and V1 simulates the 5.1v PMID pin output. Diode D1 represents the topology of the TI chip. Resistors R1, R3 and FET M2 comprise our added protection circuit. R2 simulates the load of a smartphone charging on the USB port. R4 is used as a fuse and D3 is used as a crowbar diode to quickly blow the fuse. D3 will also clamp the USB output to 6.1v for the protection of the smartphone if the protection circuit fails.

2.6 Calculations

2.6.1 Current Limiting Circuit Calculations

We performed calculations and analysis on a key part of our circuit in the USB Unit. This circuit (Fig. 9) is a Current Limit Selector Circuit.

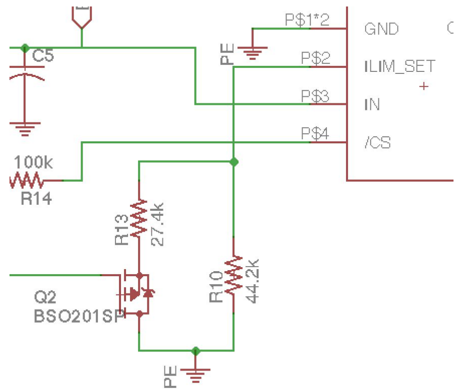


Figure 9. Current Limit Selector Circuit

We are using 1% resistor for this selector to control the maximum typical current that the TPS2511 sources to the USB port. A FET will control the change this resistor value between a typical 44.2 kOhms and 16.915 kOhms. The upper and lower bounds on these values for the 44.2 kOhm resistor are 44.642 and 43.758 kOhms, respectively. For the 16.915 kOhm parallel combination, the maximum is 17.084 kOhms and the minimum is 16.746 kOhms.

$$44.2k\Omega + 44.2k\Omega * .01 = 44.642k\Omega$$

$$44.2k\Omega - 44.2k\Omega * .01 = 43.758k\Omega$$

$$16.915k\Omega + 16.915k\Omega * .01 = 17.084k\Omega$$

$$16.915k\Omega - 16.915k\Omega * .01 = 16.746k\Omega$$

$$51228/44.642k\Omega = 1171mA$$

$$51228/43.758k\Omega = 1148mA$$

$$51228/17.084k\Omega = 2999mA$$

$$51228/16.746k\Omega = 3059mA$$

By the equation $I_{OS\,TYP} = 51228/R_{ILIM}$ **(eq. 1),** the typical current in fast mode will range from 2999mA to 3059mA. The typical current in slow mode will range from 1148mA to 1171mA. With these current outputs from the device, our requirement of sourcing at least 2.1A in fast mode or 1A in slow mode are met.

3. Requirements and Verifications

For reference, our final Requirements & Verifications table is located in Appendix A.
The following are our test results during verification and testing of our project.

3.1 AC/DC Unit

The requirements for the AC/DC unit were to provide 12V± 0.5 V DC to the control and battery block, up to rated power of 45W. The calculation of rated power for the charger is shown below in equation 2. Also, the unit should be able to output 12V from 100-240 V AC input, since the charger was designed to be a universal charger. Another requirement for the AC/DC unit was to draw less than 100 mW during no load operation, when nothing is being charged.

$$Prated > \frac{Vusb*Iusb}{\eta trans*\eta buck} + \frac{Vbat*Ibat}{\eta trans*\eta bat} = \frac{5V*2.1A}{(0.88)*(0.86)} + \frac{4.352V*5A}{(0.88)*(0.90)} = 41.35W$$

(eq. 2)

For the project the AC/DC unit was never able to output the desired 12V. The purchased Myrra 74040 flyback transformer contained a different primary inductance value, than listed on the datasheet [12]. The measured primary inductance was 383.4 uH, which resulted in a 23.3% difference from the specified 500 uH value on the datasheet. This difference caused the flyback controller to never leave start up mode, and begin driving the MOSFET. The AC/DC unit was able to rectify the AC input and filter it to create a smooth DC on the primary side of the transformer. Attempts to rewire the transformer changing the turns ratio in order to the get the flyback controller to drive the MOSFET were attempted, but unsuccessful.

3.2 Control Unit

The requirements for the Control Unit were to provide digital signals to other blocks and to convert 12V to 5.1V at up to 2.1A. This block also has a low voltage operation requirement and a requirement for LED visibility. The first two requirements were tested by applying 12V to the 12V rail and monitoring the logic levels and power output of the DC/DC. The output voltage and current of the DC/DC are well within our design requirements (Fig. 10).

To test the low voltage requirement of the Control Block, we removed power from the DC/DC and monitored logic levels to ensure that the MCU was still operating. Verifying the LED brightness requirement was accomplished by using the device in a bright environment and making sure the LEDs are visible.

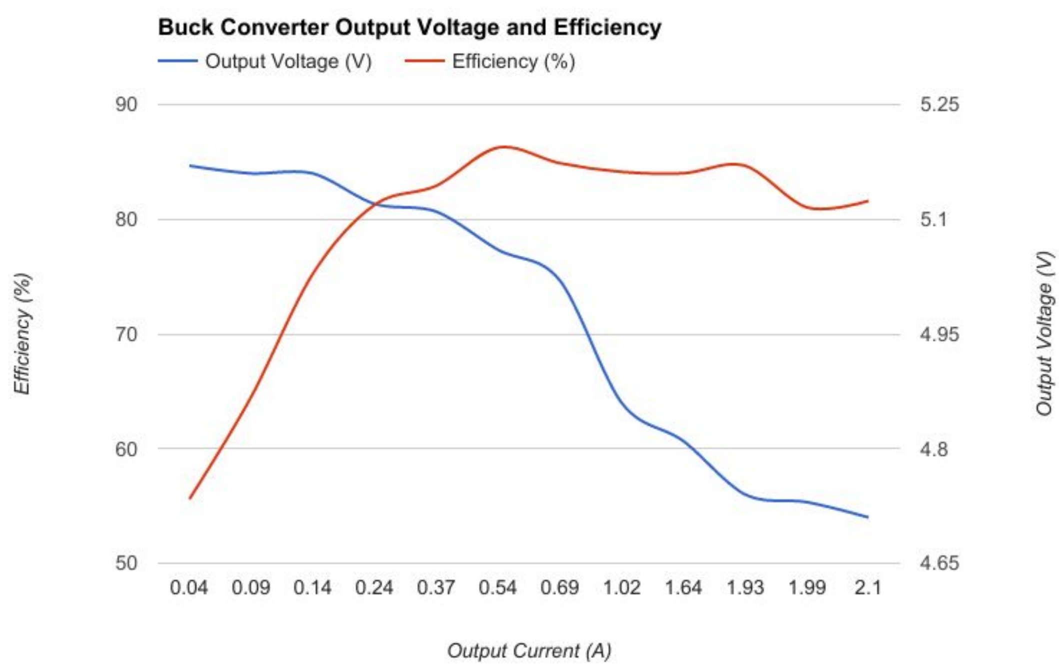


Figure 10: Buck converter test results

3.3 Battery Unit

The requirements of the Battery Unit consist of charging rate requirements and output voltage and current requirements. The charge rate requirement was verified by powering the 12V rail, connecting the battery, and monitoring charge current to confirm that it exceeds 1A to the battery. Unfortunately, we were not able to verify the operation of the Boost Converter. We suspect that bugs in the hardware layout caused the boost converter to fail to begin operation. We were unable to debug this in time for final demonstration.

3.4 USB Unit

The USB unit requirements include current limiting on the output as well as the ability to be recognized by a smartphone as a fast or slow charger depending on mode. The recognition requirement was verified by connecting a smartphone and using an app called Battery Percentage by Hien Mai to see what the charger is recognized as. The charger was successfully identified as a 5W charger in slow mode and a 12W charger in fast mode. The current limit was verified by connecting a load on the USB output and ensuring that the output is limited to 1A in slow mode and can provide at least 2.1A in fast mode.

4. Cost

4.1 Cost of Parts and Labor

Our fixed development costs for labor are estimated to be \$40/hour, with 10 hours/week for three people and 16 weeks. Though we worked more hours near the end of the semester, we averaged about 10 hours/week. The labor estimate is \$48,000, and is shown in equation 10. The cost per 1k unit is estimated to be \$28.15. The total price of the parts and labor is **\$76,150** (Table 1)**.**

$$3 \cdot \frac{\$40}{hr} \cdot \frac{10\ hr}{wk} \cdot 16wk \cdot 2.5 = \$48,000 \quad \text{(Eq. 3)}$$

Part	**Cost ($USD)**	**Cost (1k Units, $USD)**
1x 18650 Panasonic Li-ion Battery XBX01016	6	6
Passive components (Resistors, capacitors, diodes, transformer etc.)	7	5
PCB	12.30	6.15
Enclosure and mechanical components	7	2
ICs (Charger, AC/DC Controller, DC/DC boost and buck)	Sample	8
MCU MSP430G2553	1	1

Table 1: Cost of Parts

5. Conclusion

5.1 Outcome

At the time of our Final Demonstration, our team had succeeded in creating a functional USB charging interface, a high current buck converter, and a battery charging system. These components of our system were tested to exceed our system level requirements. Even with these successes, more work remains to be done in order to meet our requirements, most notably gaining functionality in our DC/DC Boost Converter and our AD/DC unit.

5.2 Uncertainties

Due to the condensed nature of this project timeline, certain aspects of the design that relate to longevity, cost optimization, and extreme operating conditions remain uncertain. The most major of these considerations is heat dissipation from our power conversion components. We aimed to maximize efficiency in our converters as a general rule in an effort to minimize heat in our device.

Due to limitations in our mechanical design and analysis capability, we were unable to create a production representative PCB layout and mechanical enclosure. As such, it is an open question as to whether or not our components will overheat when fully enclosed and exposed to high ambient temperature. We were able to mitigate this uncertainty during prototyping by creating a larger enclosure that is not sealed and allowing ambient air to cool our components.

5.3 Future Work

Future work for the project includes finishing the AC/DC unit functionality, and integrating with the rest of the project units. In order to help ensure required design specifications are met a custom flyback transformer will be purchased. Also a predictive algorithm will be programmed and implemented on the MSP430 to increase utility in this device. This algorithm predicts the desired charge rate based on usage patterns of the user and can be overridden by pushing a button. Additionally, we will continue to revise the design of the PCB and enclosure for manufacturability as well as select lower cost components wherever possible.

5.4 Ethical Considerations

On the purely ethical side of this project, we considered it important that we make a safe product and follow general safety regulations. Because we are dealing with li-ion batteries and fast charging, safety is a critical factor in our project, and the ethics surrounding every decision concerning safety are very clear. It is the duty of the engineer, as stated in the IEEE Code of Ethics, #1: “to accept responsibility in making decisions consistent with the safety, health, and welfare of the public...” [5].

Additionally, since the basis of our project is rooted in the belief that we can make a more adaptive and modern charger, specifically one that may solve issues of battery degradation, it is important that we report our findings without any omission for the sake of furthering our own points. This is detailed in the IEEE Code of Ethics, #3: “to be honest and realistic in stating claims or estimates based on available data;” Whether or not our data supports our hypothesis, we must report our findings from experiments factually.

Appendix A: Requirements and Verifications Table

The following are our final revised requirements and verifications that pertain to each sub-block outlined by the Block Diagram (Fig. 1). These requirements were referenced and adhered to throughout the design process.

I. AC/DC Unit

Requirements	Verification	Status (Y/N)
Converter Output voltage and Current: The AC/DC unit must rectify and then convert the 100-240V AC source to output 12 V ± 0.5 V. It must also be able to handle up to 3.75A on the secondary side of the Flyback transformer.	A. Connect an ammeter in parallel to a programmable electronic load. B. Connect a DC current meter in series with the programmable electronic load. C. Disconnect the battery unit, so it draws zero power. D. Connect the programmable load to the output of the flyback converter. E. Attach an oscilloscope across the load. F. Set the AC source voltage between 100-240V AC, and connect to the input of the charger. G. Set the electronic load to 45W. H. Monitor the output voltage and output current to insure it meets the requirements.	**N**
Converter Low Power Consumption: The AC/DC unit must draw less than 100mW, during no load operation.	A. Disconnect the charger from any load, and turn the battery unit off B. Connect a power meter at the input of the charger. C. Set the AC source voltage between 100-240V AC, and connect to the input of the charger. D. Monitor the input power on the power meter, while varying the input voltage source.	**Y**

II. Control Unit

Requirements	Verification	Status (Y/N)
MCU Low Voltage: The MCU must be capable of operating with the 5V and 12V power rails unpowered and the battery connected.	A. Ensure that a battery is connected and charged to at least 2.7V. B. Power the 12V and 5V rails to program the chip. C. Program the chip to repeatedly toggle an output pin. D. Measure the output to verify that the voltage is being switched. E. Remove power from the the 12V and 5V rails. F. Measure the output to verify that the voltage is being switched.	**Y**
LED Indicators: Must be visible by a user in a bright environment.	A. Take device outside during the day or place it in a bright environment. B. Power the 5V rail and the microcontroller with 5.1V and 3.3V, respectively. C. Program the microcontroller to turn on all of the LED outputs. D. Look at the LEDs and ensure that red, green and orange are distinctly visible.	**Y**
MCU Logic: Logical high corresponds to Vout = 3.3V +/- 0.3V, and Logical Low corresponds to Vout <= 0.5V	A. Power the microcontroller with 3.3V. B. Program the microcontroller to configure all pins used in the system to logic low. C. Measure the voltage of each output pin and ensure that it is less than or equal to .5V. D. Program the microcontroller to configure all pins used in the system to logic high. E. Measure the voltage of each output pin and ensure that it is greater than or equal to 3.0V.	**Y**

DC/DC Buck Converter: Must output 5.25V to 4.55V DC at up to 2.1A the USB port.	A. Apply 12V to the input of the DC/DC power converter B. Connect a programmable load to the output of the DC/DC C. Set the load to draw 2.1A from the DC/DC. D. Measure voltage at output currents between 0 and 2.1A and verify that output voltage is between 5.25 and 4.55V	**Y**

III. USB Unit

Requirements	**Verification**	**Status (Y/N)**
USB Interface: The device must provide a USB interface that can be recognized by a smartphone as a high power (>1A) charge source, or a standard charge source (~1A) as selected by the MCU.	A. Connect a USB to lightning or USB to micro-usb cable to the USB output. B. Install the smartphone app “Battery Percentage” by Hien Mai that displays to the user the detected charge source capabilities. C. Activate the USB output by applying 5.1V to the 5V rail. D. Toggle the button to set the device in “Fast Charge” mode, as indicated by an orange LED. E. Verify that the USB charge source is recognized as a >1A charge source. F. Toggle the button to place the device in “Slow Charge” mode as indicated by a green LED. G. Verify that the USB charge source is recognized as a <=1A charge source.	**Y**
USB Current Limit: The USB interface must limit output current to less than 1.5A when the device is in “Slow Charge” mode, and will limit to 2.1A in “Fast Charge” mode.	A. Power the 5V rail and the microcontroller with 5.1V and 3.3V, respectively. B. Connect a programmable load to the USB port power and ground pins. C. Toggle the button to place the device in “Slow Charge” mode as indicated by a green LED. D. Attempt to draw 1.5A or greater from the USB port and verify that the output current	**Y**

	is limited. E. Toggle the button to place the device in "Fast Charge" mode as indicated by an orange LED. F. Attempt to draw 2.1A or greater from the USB port and verify that the output current is limited.	

IV. Battery Unit

Requirements	**Verification**	**Status (Y/N)**
Li-ion Charger: Must be capable of charging a Lithium ion battery at a minimum of 1A from the 12V rail.	A. Apply 12V to the 12V power rail. B. Connect a Li-ion battery with an open circuit voltage of less than 4.0 to the charger output. C. Enable the charger by programming the MCU to toggle the charge enable pin. D. Measure the voltage across the series shunt resistor on the PCB. E. Calculate the current by using the known shunt resistance and the measured voltage; verify that it is above 1.0A.	**Y**
DC/DC Boost Converter: Must output 5.25V to 4.55V DC at up to 2.1A.	A. Connect a Li-ion battery with an open circuit voltage of at least 3.7V. B. Connect a programmable load to the boost converter output. C. Enable the boost converter by programming the MCU to activate the boost converter enable pin. D. Measure voltage at output currents between 0 and 2.1A and verify that output voltage is between 5.25 and 4.55V.	**N**

Appendix B: Battery Charge Time Calculation

We made calculations in order to confirm our parts met one of our design goals. The device should be capable of charging its internal battery from 20% - 70% SOC within 30 minutes.

- TOTAL CAPACITY SPECIFICATION of Panasonic 18650 3.7V Li-ion cell: 3400mAh
- Battery Charge Current is defined at 5A in our design specification.
- State of Charge (SOC) is analogous to a "fuel gauge" for a battery.

Variable Definitions:

$I_{battery}$ = Charge Current for Battery (A)

C_{tot} = Total Capacity (mAh)

x = State of Charge (SOC) %

$C_{desired}$ = Desired Capacity (mAh)

t_{tot} = Total Time of Charge (min)

$$\mathbf{x_1 = 20,\ x_2 = 70}$$

$$C_x = \left(\frac{x}{100}\right)(C_{tot})$$

$$C_{20} = \left(\frac{20}{100}\right)(3400) = 680 \text{ mAh}$$

$$C_{70} = \left(\frac{70}{100}\right)(3400) = 2380 \text{ mAh}$$

$$C_{desired} = \left|C_{x_1} - C_{x_2}\right|$$

$$C_{desired} = \left|C_{20} - C_{70}\right|$$

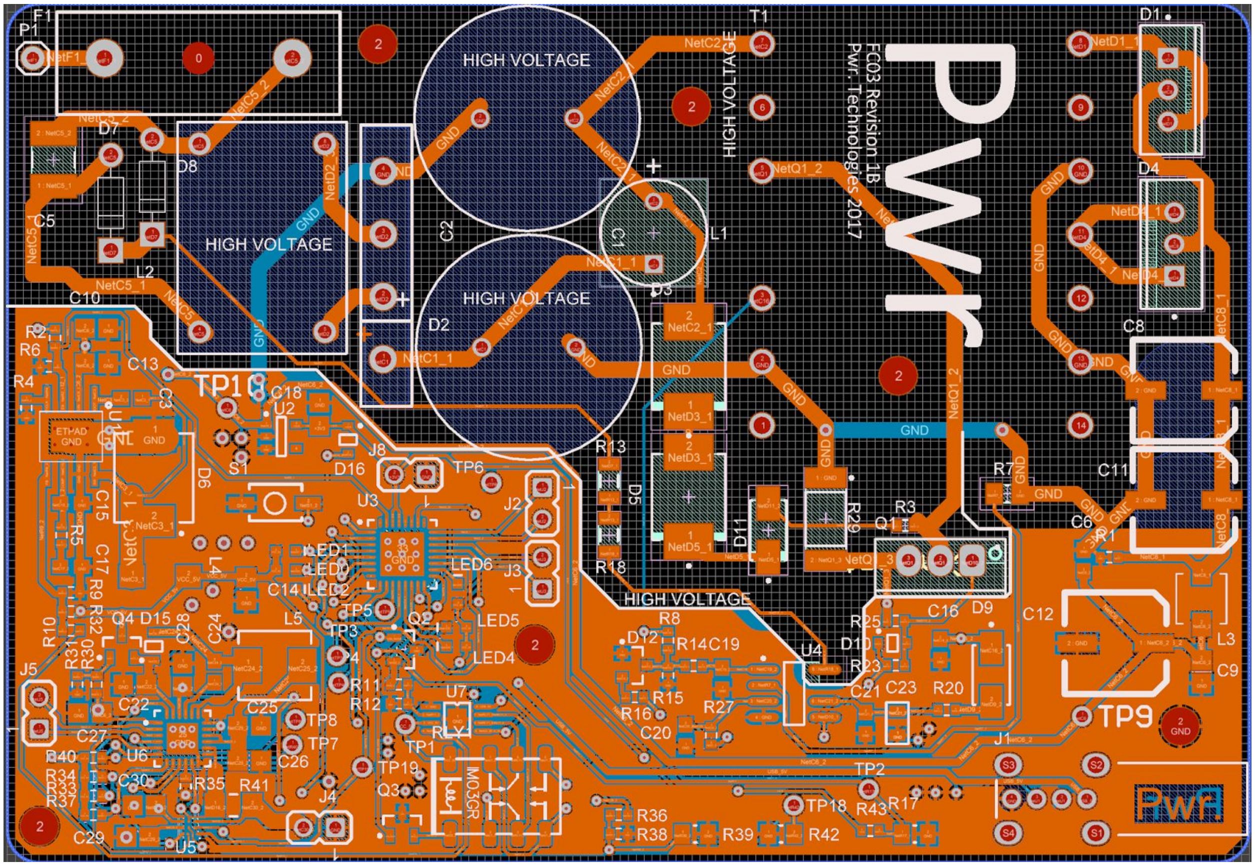
$$C_{desired} = \left|680 - 2380\right| = 1700 \text{ mAh}$$

$$t_{tot} = \frac{C_{desired} * 60}{I_{battery}}$$

$$t_{tot} = \frac{1700 * 60}{5} = \mathbf{20\ min}$$

The charge time of 20 minutes to go from 20% SOC to 70% SOC is well within our requirement of 30 minutes.

Appendix C: PCB Layout



Appendix D: References

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