Adaptive Fast Charger and Power Pack

Design Document

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1. Introduction

1.1 Objective

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. Additionally, existing power packs rarely include rapid charge functionality.

We will create an AC/DC wall adapter with an intelligent charge rate limit and a built in rapid charging battery. The device will have a button for the user to select a charge rate limit manually and indicators to display charge rate mode and an SOC of the internal battery.

1.2 Background

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 High-level Requirements

- The device shall be capable of automatically limiting USB charge current to 1.0A and have a maximum output of 2.7A.

- The device shall be capable of charging its internal battery from 20% - 70% SOC within 30 minutes.

- The device shall have a size constraint, with a maximum volume of 200 cm^3

2. Design

2.1 Block Diagram

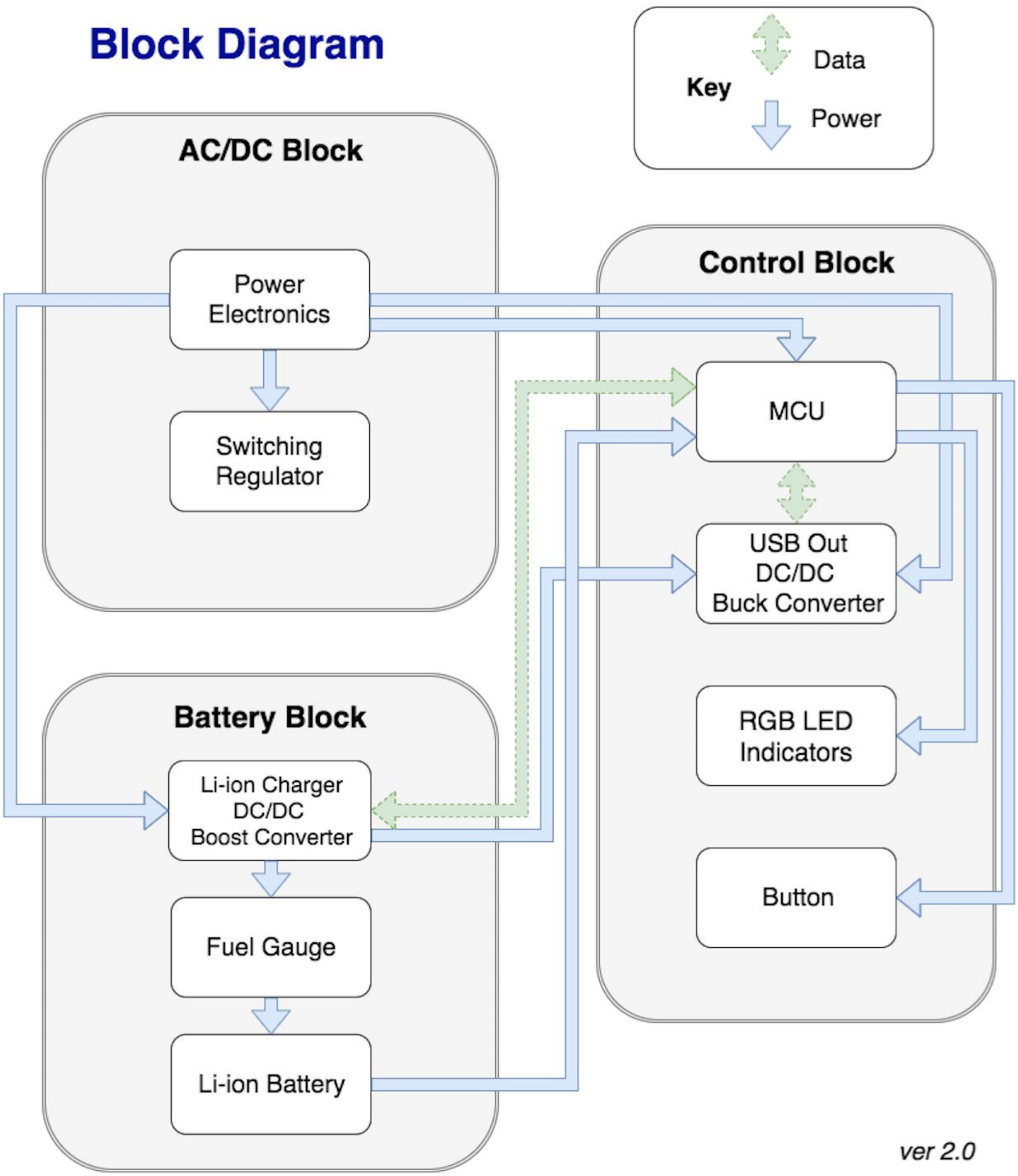


Figure 1. High Level Block Diagram

2.2 Physical Design

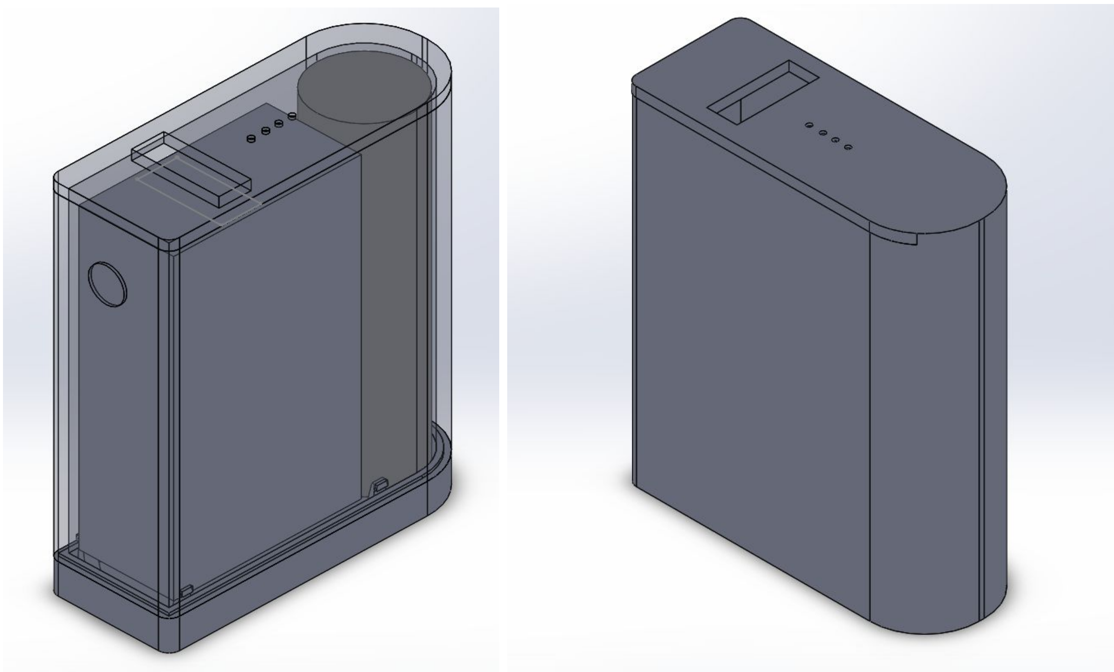


Figure 2. Preliminary CAD Mockup of Project

This device will resemble other common “charging cube” designs, having a rectangular shape and a single USB port output. There will also be LED indicators on the exterior and a single button to control charge mode. Our design requirement is to have a total exterior volume of 200 cm^3 or less.

2.3 Functional Overview

2.3.1 AC/DC Unit

This block will take 100-240V AC power from a wall outlet and convert it to 12V DC for the other blocks to use. The AC to DC conversion will be done by using a full wave rectifier to convert the incoming AC power to high voltage DC. The high voltage DC is lowered to low voltage DC, using a flyback topology. The high voltage DC is switched on and off by a MOSFET. The MOSFET's turn on and turn off is controlled by flyback controller IC. The chopped DC is sent through a flyback transformer that produces low voltage AC. The AC is then converted to DC and filtered a smooth regulated DC voltage.

2.3.2 Control Unit

This block will control the current output of the USB port. This will be achieved by a microcontroller and a current limiting circuit. Additionally, the control unit will contain LED indicators for charge mode and internal battery SOC. The only user input will be a single button that toggles fast and slow charge modes.

2.3.3 Battery Unit

This block will contain Li-ion battery cell(s) and a charge controller. The charge controller will charge the battery from the 12V power rail at a rate commanded by the control unit. There will be a 5V DC/DC boost converter to allow the battery to power the MCU and USB port.

2.4 Circuit Schematics

2.4.1 Battery Unit Schematic

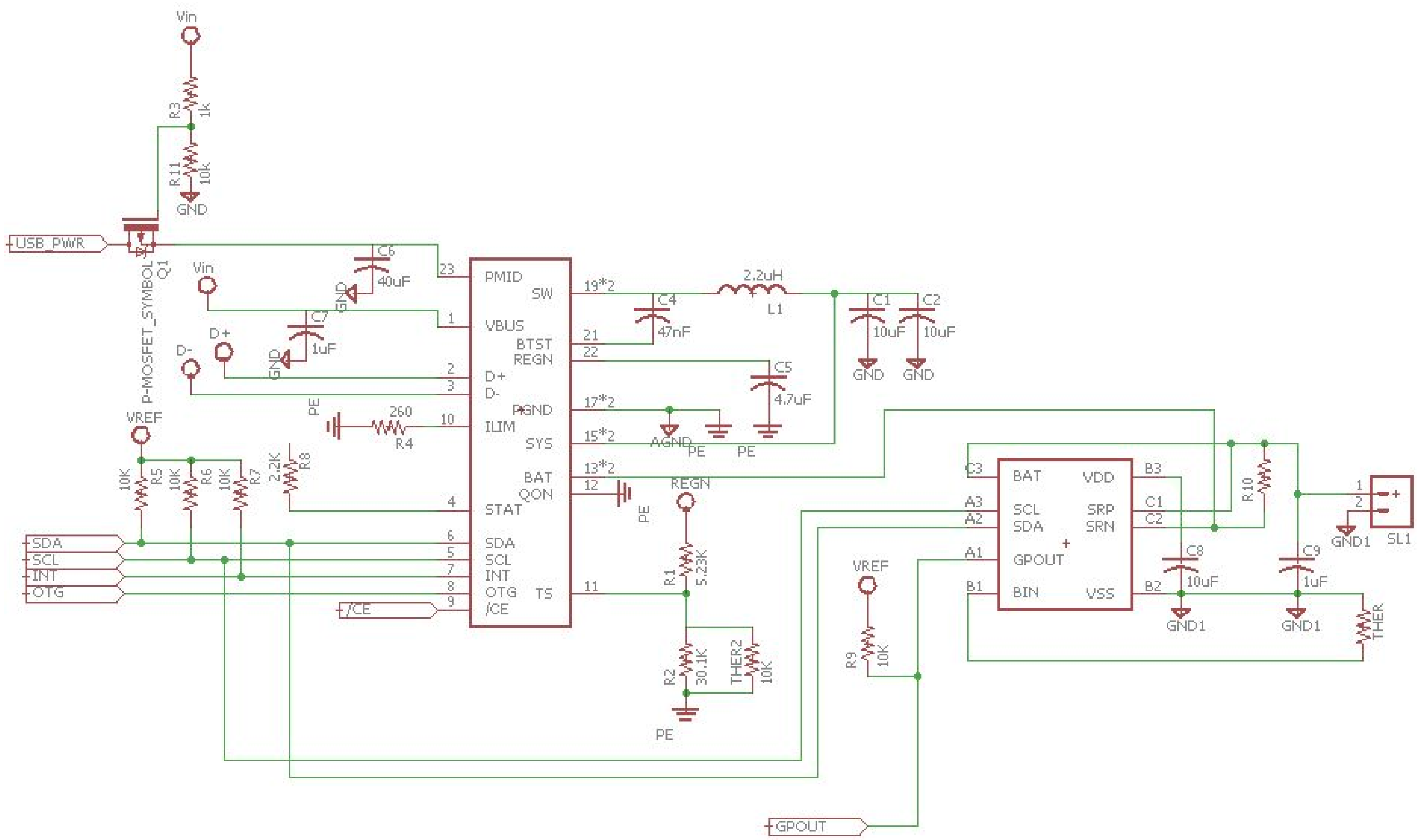


Figure 3. Battery Unit Schematic

2.4.2 AC/DC Unit Schematic

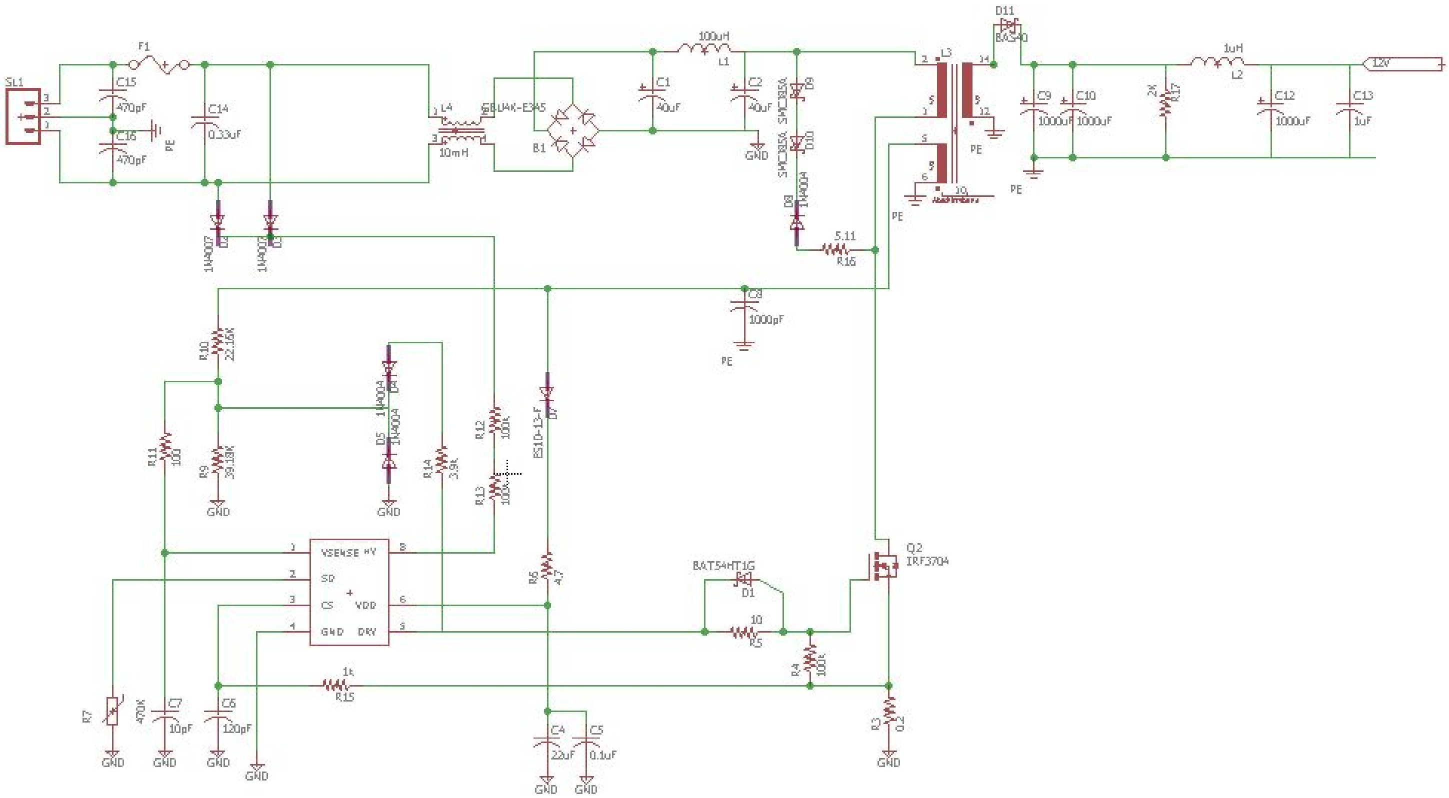


Figure 4. AC/DC Unit Schematic

2.4.3 Control Unit Schematic

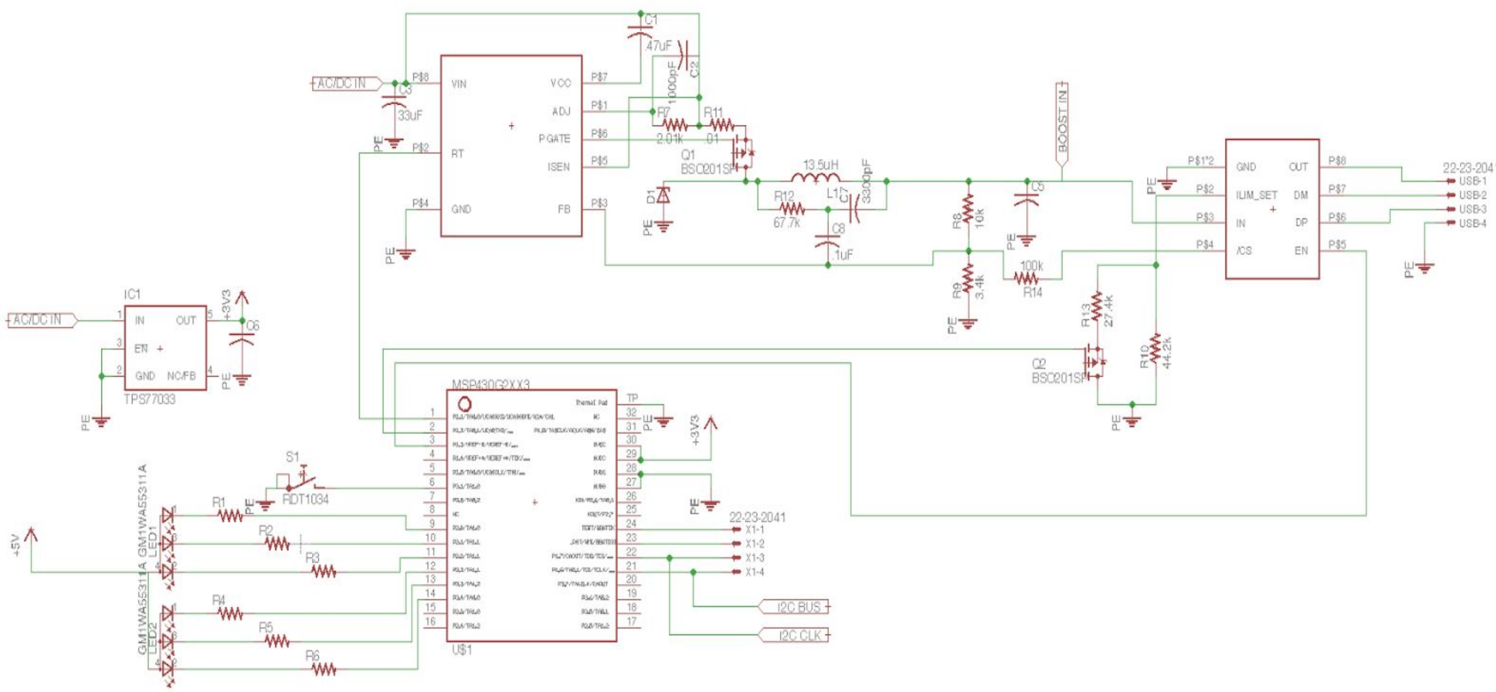
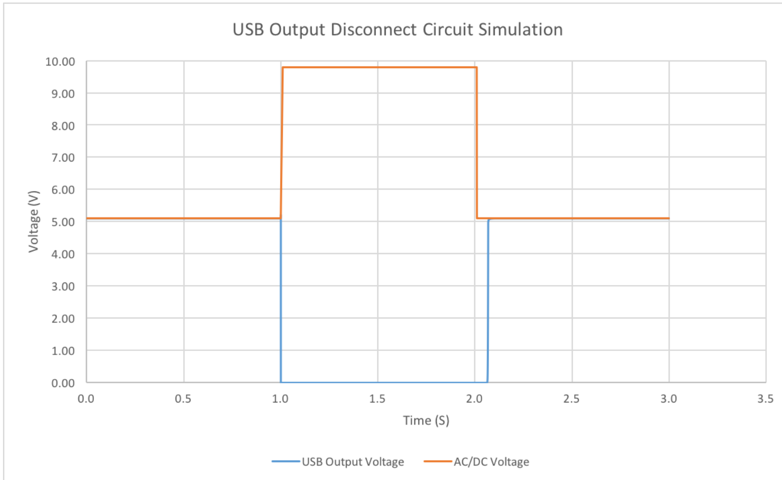
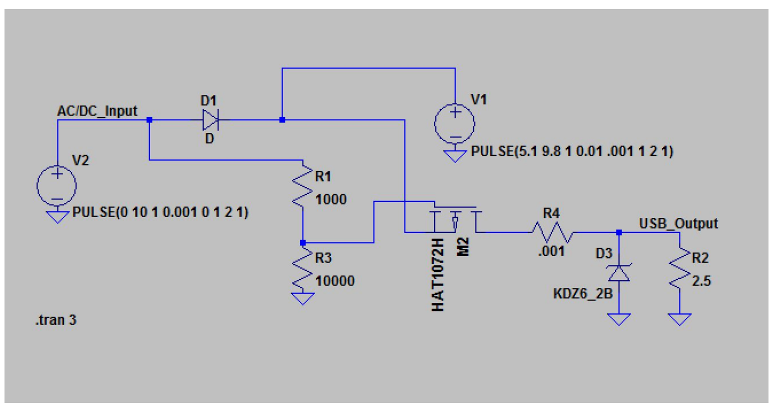


Figure 5. Control Unit Schematic

2.5 USB Output Circuit Simulation



Plot 1: USB Output Simulation



Schematic 1: 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.

Included above is a schematic and simulation of this circuit. 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 AC/DC Calculations

In the conversion of AC grid voltage to smooth DC output voltage, specific calculations must be performed on the flyback converter to ensure the design requirements can be efficiently met. The goal of the conversion is to convert between different voltage types and levels, with high efficiency. Trade-offs between efficiency, cost, and component sizing must be factored in designing.

A simplified schematic of the AC/DC flyback controller is shown in (fig. 6). The UCC28630 is a high power flyback controller that regulates the output voltage and current, by using primary-side regulation to change the switching frequency and duty cycle of the MOSFET. The flyback transformer contains three windings, a primary, secondary, and auxiliary.

The flyback transformer steps down the rectified grid voltage. Careful design steps must be taken with the flyback transformer, such as winding ratios, magnetizing inductance, and maximum peak current.

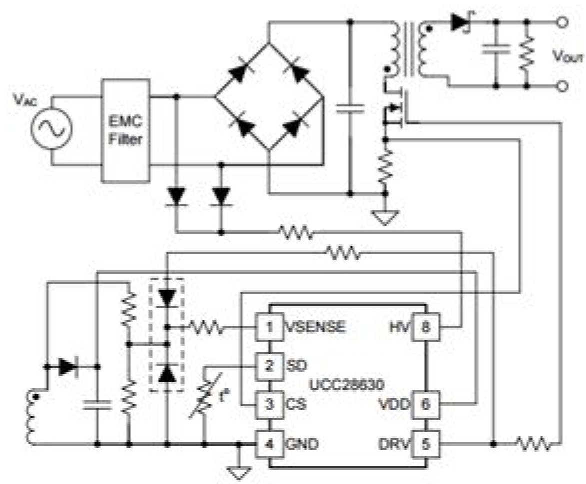


Figure 6: Simplified schematic of a AC-DC converter [6]

For the adaptive fast charger and power pack the desired design parameters are shown below (table 1). The circuit needs to provide 12 V, up to 4.16 A continuous, to the other modules in the design. The calculation of the rated continuous output power, is shown below (equation 1).

A target efficiency of 88 percent was selected for the AC/DC converter, and the expected efficiencies of the other modules were used. So the circuit must be able to provide at least 45.87W, so 50W rated was used in case of lower actual efficiencies.

The UCC28630 controller tests the voltage across the bulk capacitor to determine if the level is high enough to allow the power stage to start. The bulk capacitor is the capacitor after the diode bridge in figure 6. The minimum bulk voltage required is for this is 82 V, specified by the UCC28630 data sheet [6].

$$P_{rated} \geq \frac{V_{battery(max)} * I_{battery(max)}}{\eta_{AC-DC} * \eta_{battery}} + \frac{V_{charger(max)} I_{charger(max)}}{\eta_{AC-DC} * \eta_{charger}} = \frac{4.2V * 5A}{0.88 * 0.8} + \frac{5V * 2.4A}{0.88 * 0.85} = 45.87W \quad (1)$$

(eq. 1)

Design Parameters	Target Value
Output Voltage	12 V
Rated (continuous) output power	50W
Peak (transient) output power	100W
Peak (transient) output power duration	2 ms
Input AC voltage range	88 VRMS to 264 VRMS
Typical efficiency	88%
Minimum bulk voltage at 88 VAC/47Hz and rated (continuous) output power	82 V

Table 1: Adaptor Design Parameters and Targeted Values

The required bulk capacitance of the circuit depends on the target minimum bulk capacitor ripple voltage at minimum line frequency and rated maximum output power. The bulk capacitance can be accomplished by using two 50 µF capacitors in parallel.

$$C_{BULK} = \frac{\frac{P_{out}}{\eta} * \left(0.5 + \frac{1}{\Pi} * sin^{-1}\left(\frac{V_{BULK(min)}}{\sqrt{2} V_{AC(min)}}\right)\right)}{\left(2 * V_{AC(min)}^2 - V_{BULK(min)}^2\right) * f_{LINE(min)}} = \frac{\frac{50\,W}{0.88} * \left(0.5 + \frac{1}{\Pi} * sin^{-1}\left(\frac{82V}{\sqrt{2} * 88V}\right)\right)}{(2 * (88V)^2 - (82)^2) * 47\,Hz} = 100\mu F \quad (2)$$

(eq. 2)

The turns ratio on the transformer is also determined by the input voltage, output voltage, and the voltage drops across diodes. The UCC28630 suggests using 85% for the derating on the rectifier reverse voltage stress. The turns ratio, between the auxiliary and the secondary winding is given by equation 3. It is important to note that actual ratio used will be slightly different, since integer value turns must be used on the windings.

$$\frac{N_P}{N_S} = \frac{V_{AC(pk\_max)}}{(V_{REV(rated)} * \%Derating) - (V_{out} + V_{rect})} = \frac{264 * \sqrt{2}V}{(60V * 0.85) - (12V + 0.5V)} = 9.69 \quad (3)$$

$$\frac{N_B}{N_S} = \frac{V_{BIAS(target)} + V_F}{(V_{out} + V_{rect})} = \frac{12V + 0.7V}{12V + 0.5V} = 1.016 \quad (4)$$

(eq. 3, eq. 4)

The switching frequency of the MOSFET in figure 6 changes depending on the load, but the circuit was designed that the MOSFET would nominally switch at 60 kHz. This limits power loss in the circuit from high switching, and is fast enough to limit losses in the transformer.

The primary magnetizing inductance of the transformer is shown in equation 5. This process of calculation was continued for different requirements of the transformer, as well as for calculation of other components in the circuit to achieve the design parameters. The equations in the UCC28630 can be used to see how the values of components in AC/DC schematic were
calculated.

$$L_{PRI} = \frac{1}{2 * \left(\frac{P_{RATED}}{\eta}\right) * \left(\frac{1}{V_{BULK(min)}} + \frac{1}{\frac{N_P}{N_S} * (V_{out} + V_{rect})}\right)^2 * f_{sw(nom)}} = \frac{1}{2 * \left(\frac{50V}{0.88}\right) * \left(\frac{1}{82V} + \frac{1}{9.69 * (12V + 0.5V)}\right)^2 * 60kHz} = 353\mu H \quad (5)$$

(eq. 5)

2.6.2 Battery Charge Time Calculation

We have made a calculation in order to confirm one of our three overall design requirements. These calculations have been performed with our current specifications in the Battery Unit. The requirement was as follows:

- *The device shall be capable of charging its internal battery from 20% - 70% SOC within 30 minutes.*

The following calculations confirmed our requirement:

- ❏ 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)

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

$$C_x = \left(\frac{x}{100}\right)(C_{tot}) \qquad \textbf{(Eq. 6)}$$

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

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

$$C_{desired} = \left|C_{x_1} - C_{x_2}\right| \qquad \textbf{(Eq. 7)}$$

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

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

$$t_{tot} = \frac{C_{desired} * 60}{I_{battery}} \qquad \textbf{(Eq. 8)}$$

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

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

3. Block Requirements and Verifications

The following are specific requirements and verifications that pertain to each sub-block outlined by the Block Diagram (Fig. 1). These requirements will be adhered to throughout the design process.

3.1 AC/DC Unit

Requirements	Verification
Switching regulator: This regulator must output 11.5V to 12.5V DC up to 4.16A from a 100-240V AC source.	A. Connect a load to the switching regulator and measure the voltage
Power Electronics: Low power consumption - <100mW	A. Test across 100-240V RMS and test power consumption

3.2 Control Unit

Requirements	Verification
MCU: Must have at least one input from the button and at least 3 outputs for LEDs, regulator shutdown, and current limiting. Must be capable of communicating with the charge controller(s). Must be capable of driving LEDs from GPIO pins.	A. Confirm LEDs are driven by outputs B. Change color of LED based on button input C. Read and write data registers from devices on the I2C bus.
LED Indicators: Must be visible by a user in a bright environment.	A. Take device outside during the day and make sure the LED is visible
Button: Must be capable of triggering on input on the MCU.	A. Change LED color in response to button input to verify operation
DC/DC Buck Converter: Must output 5.25V to 4.55V DC at up to 2.7A or 1A to the USB port, depending on MCU input.	A. Connect a resistive load to the output to verify that current does not exceed selected values B. Measure voltage at output currents between 0 and 2.7A and verify that output voltage is between 5.25 and 4.55V C. Connect a smartphone and verify that current does not exceed selected values

3.3 Battery Unit

Requirements	Verification
Li-ion Charger: Must be capable of charging a Lithium ion battery at up to 5A and must limit charge current in response to MCU inputs. Must accept 12V DC from the AC/DC block.	A. Set a battery charge current and verify that the battery input current does not exceed this value B. Verify that the Charge IC operates at the maximum and minimum output voltage of the AC/DC
Li-ion Battery: Must be capable of charging at 5A.	A. Charge the battery at rates between 3.4A and 5A and ensure that temperature does not exceed 45C.
DC/DC Boost Converter: Must output 5.25V to 4.55V DC at up to 2.7A or 1A to the USB port, depending on MCU input.	A. Connect a resistive load to the output to verify that current does not exceed selected values B. Measure voltage at output currents between 0 and 2.7A and verify that output voltage is between 5.25 and 4.55V C. Connect a smartphone and verify that current does not exceed selected values

4. Tolerance Analysis

We performed a tolerance analysis on a very key part of our circuit in the Control Unit. This circuit (Fig. 7) is a Current Limit Selector

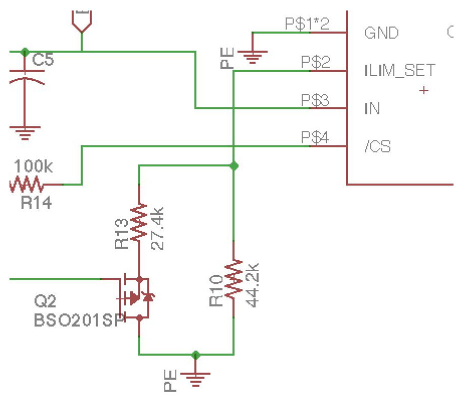


Figure 7. Current Limit Selector

We are using 1% resistor for this selector to control the maximum typical current that the TPS2511 will allow 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 will be 44.642 and 43.758 kOhms, respectively. For the 16.915 kOhm parallel combination, the maximum will be 17.084 kOhms and the minimum will be 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. 9)**, 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 2.7A in fast mode or 1A in slow mode are met.

5. Cost and Schedule

5.1 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. The labor estimate is $48,000, and is shown in equation 10. The cost per 1k unit is estimated to be $28.15. The grand total price of the parts and labor is **$76,150.**

$$3 \cdot \frac{\$40}{hr} \cdot \frac{10\ hr}{wk} \cdot 16wk \cdot 2.5 \ = \$48,000 \tag{10}$$

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

The following chips are currently being used in our design and are cited throughout the doc:

UCC28630, bq27426, MSP430G2x53, bq25895M, LM25085, LP2985, TPS2511

5.2 Schedule

Week	Brian	Nikhil	Dalton
2/20	Work on Design Document. Create schematic for battery block and Control block. MCU Design	Work on Design Document. Update intro, block diagram, overview, calculations, safety, ethics. MCU	Work on Design Document. Create schematic for AC/DC block

		Design	
2/27	Reverse engineer 2.4A charger. PCB Board Layout.	Reverse engineer 2.4A charger. I2C interfacing with MSP430.	Create BOM for AC/DC, ensure correct packaging in EAGLE
3/6	Order PCB Rev. 1 and BOM components.	Continue I2C work, RTC Implementation	Test blocks, by assembling them on a board
3/13	Bring up PCB and revise design. Order Rev. 2 (if necessary)	RTC Implementation, Algorithm/Machine Learning code	Test the PCB, and revise design. Order Rev. 2 (if necessary)
3/20	*Spring Break*	*Spring Break*	*Spring Break*
3/27	Bring up PCB Rev. 2 and write initial software.	Continue algorithms/code for the MCU unit	Bring up PCB Rev. 2 and begin validation tests
4/3	Validate algorithms with hardware under varying conditions.	Enclosure design, heat sink design and characterization	Enclosure Design, Design LED Array
4/10	Conduct safety tests, monitor thermal performance during rapid charging.	Continue heat sink design and characterization, verify volume requirement	Conduct safety tests, monitor thermal performance during rapid charging.
4/17	Revise enclosure design and finish system integration. Work on final presentation.	Test LED Array with Color Switching and Button. Finish system integration. Work on final presentation.	Revise enclosure design and finish system integration. Work on final presentation.
4/24	Demo	Demo	Demo
5/1	Finish Final Report	Finish Final Report	Finish Final Report

6. Ethics and Safety

6.1 Safety

As our project deals primarily with charging and batteries, there are significant potential safety hazards that could present themselves in our project. Because of this, it is important to take the necessary safety precautions to properly and safely test all of our modular blocks in the project. As we continued our project past our proposal, many of the safety concerns remained the same.

The battery unit will be the most volatile part of our project in terms of safety. We will adhere to all best practices found in the Battery Safety manual, last edited by our very own TA Jackson Lenz!

We will be dealing with Lithium-ion batteries, which can potentially explode if overcharged or are subject to undue stress from heat. Because our project will be testing the behavior of these batteries at higher temperatures (>35C), it will be paramount to ensure that we are working in a safe environment for testing. The health of the battery is also important in our project, so these precautions work both ways for us.

In order to prevent short circuiting of the batteries, we will store it in a secure location with terminals partially insulated, as recommended by the battery safety document. We will also make sure that we use Charging ICs in our design in order to make sure we are using li-ion batteries safely. Industry standards and safety regulations surrounding products that include batteries and charging are quite stringent, and rigorous safety testing will be followed to make our project a viable product.

In terms of federal and state regulations, Title 40 of the code of Federal Regulations (CFR), part 273, deals with universal waste regulations, including provisions for batteries. Because li-ion batteries are a volatile chemical device, if we must dispose of them we will do so in a safe manner [3].

Additionally, because we will implement fast charging circuitry in our project, it is important that we do not ruin any batteries by overcharging or overheating (not to mention any smartphones). While working with live higher voltage circuits, we will be sure to take the necessary precautions to mitigate risk. Basic examples include having multiple people in the lab at one time, properly grounding any test experiments, and limiting currents to lower values when possible [4].

6.2 Ethics

On the purely ethical side of this project, it is very important that we make a safe product and follow safety regulations. As we continued our project past our proposal, many of the ethical concerns remained the same. 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].

Providing for a safe work environment during development and testing is the right and ethically correct thing to do. 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.

In summation, our project has safety precautions that must be taken, primarily concerning use of a li-ion battery cell and high voltages. Taking these safety precautions is the wise and ethical thing to do in this project.

7. Citations

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