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Power Supply for Driving High Power LEDs with Wireless Control

Computer Engineering Senior Project

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Introduction

Project Overview

This project is the design of a power supply for driving high power light emitting diodes (LEDs) with wireless control. The project is divided into two sections, the power supply for driving the LED lights, and the wireless control and fan power supply.

The power supply for driving the LEDs is a AC to DC current mode power supply with linear and pulse width modulation (PWM) dimming capabilities rated at 40 Watts of output at 60 Volts. Its primary function is to power two 20 W LED chips, each composed of nine 3 W white LEDs in series.

The wireless control and fan power supply board contains a Bluetooth Low Energy (BLE) module for communicating with a smartphone or laptop, a real time clock (RTC) module for keeping time, an analog to digital converter (ADC) for linear dimming of the LED power supply, and two 12 V fan outputs. This board has all of the above components and three AC to DC voltage mode power supplies to power the components.

Stakeholders

The target market for this product is high tech consumers who want to outfit their home or office with smart lighting that can be used to mimic the natural transition in the sun's color. Another market for this type of lighting could be in a showroom, gallery, or retail environment where lighting with a high Color Rendering Index (CRI) is desired to highlight the vibrant colors of items on display. Using LED lights in a warehouse or workplace can also help save businesses money directly by reducing the energy consumption of their lighting and save money indirectly by reducing the cost of cooling their environment. Traditional lights produce heat through wasted electrical energy (the energy that is not converted to light), as well as through infrared light emission (which heats whichever surface absorbs its rays). Since LED lights do not produce infrared light and they are more efficient at producing light from electrical energy, they operate without generating as much heat as traditional CFL and incandescent light bulbs.

Project Goals and Objectives

The goal of this project was to create a current mode power supply that can be controlled wirelessly over Bluetooth to adjust the output intensity of LED lights.

Goals

- Create a power supply capable of powering high power LED lights up to 700 mA at 60 V.
- Create a wireless control mechanism capable of full range dimming of the LED lights.
- Integrate wireless control mechanism with a clock module capable of adjusting the lights based on the time of day.
- Create a platform capable of adapting this technology to a variety of applications.
- Learn the fundamentals of power electronics and LED lighting.

Objectives

1. Determine a power supply topology capable of:
    a. Powering LED strings over 30V at 700 mA.
    b. Full range linear dimming (0 – 100 % brightness).
    c. Easy current limit adjustments. Either programmable or through the replacement of a minimal number of interchangeable components on the board.
    d. Operating at a wide range of input voltages from 85 – 265 V_{AC}.
    e. Operating at 80% efficiency or better.
    f. While minimizing cost and number of components in the Bill of Materials.
2. Determine a method for controlling power supply capable of:
    a. Accepting control signals from a smartphone or tablet.
    b. Running independently of a smartphone or tablet.
    c. Persistent state in case of a power failure.
    d. Pulse width modulation (PWM) dimming.
    e. Linear dimming or current limiting.
    f. Notifying user is the system gets too hot or overheats.
    g. Activating cooling fans if the temperature of the system gets too hot or overheats.
3. Gain exposure to topics and theory in:
    a. Power electronics.
    b. AC – DC power conversion.
    c. LED lighting.
    d. Embedded system design.
4. Design a power supply that meets above criteria.
5. Design a PCB for the power supply.
6. Design a PCB for control interface.
7. Assemble power supply and control interface.
8. Determine efficacy of power supply and control scheme.

Outcomes and Deliverables

Throughout the development on this project I learned many important engineering lessons and gained a solid understanding of concepts in power electronics, lighting, and embedded system design. The deliverables for this project include. EAGLE PCB layouts for the control interface board and power supply, EAGLE schematics for the control interface board and power supply, a Bill of Materials, results of design, and future considerations. The finished design is meant to be the base of a platform of future designs in the area of LED lighting and power electronics, and during the design of this system I have learned many important lessons that I will apply to future designs.

Background

During the processes of writing my initial proposal for my senior project I had many goals in mind for what I wanted my senior project to entail. Since my first year in college I had been interested in LED lighting systems, but it was not until after my third year of school that I felt I had the fundamental skills necessary for undertaking a project in the design of an LED system.

While the market for color LED lights has been growing steadily since their introduction in the 1960's, it wasn't until the invention of the blue LED light in 1994 that LED lights were capable of accurately producing white light [1][2]. Blue LED lights are capable of producing white light though a blend of color from a red green and blue light, or when they are coated with a phosphor material that bends the narrow spectrum of blue light produced by the LED into a full spectrum white light [3]. It is this careful blend of phosphor materials that allows a materials engineer to design a white LED with different light color temperatures from cool, blue dominant white to warm, yellow dominate white[3].

Originally I began designing a system around a four color LED chip with embedded red, green, blue, and white LEDs that would be able to produce a wide range of colors in the visible light spectrum. However, after exploring the feasibility of the design I determined that it would very difficult to design a power supply capable of operating at the low voltages required for red lights and the high voltages required for blue and white light without significantly modifying the design of the power supply outputs for each color channel. In order to simplify the design I opted to create a system that powered white lights with the same voltage and current characteristics but with different color temperatures.

With different color temperature white LED lights I can create a system that emulates the color of sunlight in the morning, afternoon and evening. During dawn and dusk periods the sun is at a low incident angle to the earth and the light is a warm color temperature. As the sun moves overhead the color temperature cools, until the sun is directly overhead and the light begins to slowly warm until sunset. Using a cool white 5300K light I am able to produce light that is analogous to the color profile of the sun when overhead[4]. With a warm white 3000K LED I can produce light that mimics the color profile of morning and evening sunlight[4]. An LED light system that changes in time with the natural cycle of the sun can be designed by blending the color output of the two lights throughout the day.

Engineering Specifications

The goal of this project is to design a platform for controlling high power LED lights of using a wireless interface that can adjust the light output of multiple strings of LEDs.

#	Description	Requirement	Tolerance	Risk
1	Per channel power output	40 W	Min	L
2	Per channel current output	700 mA	Max	L
3	Number of output channels	2	Min	L
4	AC input voltage range	85 – 256V	+/ 15V	M
5	Wireless range	10 ft.	Min	L
6	Linear dimming	0% - 100%	+/- 5%	H
7	Current limiting	0 mA – 700 mA	+/- 10%	H
8	Wireless protocol	BLE	N/A	L

End User Personas

Catherine

Catherine is a software developer in California's Silicon Valley; she is always looking for ways to improve her productivity and her energy levels at work. Catherine works from her home office most days and has recently decided to look into ways to make her office a more comfortable working environment. Catherine has heard from a friend that the light in her workspace can help her stay more alert during the day and that having bright white light with a cool color temperature in her workspace may make her more productive. Since Catherine is always looking for ways to increase her productivity she decides to investigate different lighting options.

When Catherine heard about new color adjusting lights she was excited to try them out at home. After purchasing a daylight LED system Catherine synchronized the system with her phone and immediately began to notice that her work environment looked more vibrant and her energy levels were more consistent throughout the day. Catherine also noticed that when she works late she has an easier time falling asleep at night.

Joseph

Joseph is an aquarium enthusiast in Las Vegas, Nevada; he loves building new aquarium environments for his home and tweaking his existing setups. He currently has three aquariums each with blue and white lights illuminating them. Every year he spends thousands of dollars upgrading and maintaining his setup. Joseph is always looking for the newest technology to outfit his tanks with.

After hearing about color adjusting lights on an online forum he was interested to see how his fish would look under some new lights. After installing and configuring his new daylight LED system Joseph noticed his fish were more active during the day and looked more vibrant under the new lights.

Final Detailed Design

EAGLE Schematics and Board Layouts

40W Power Supply

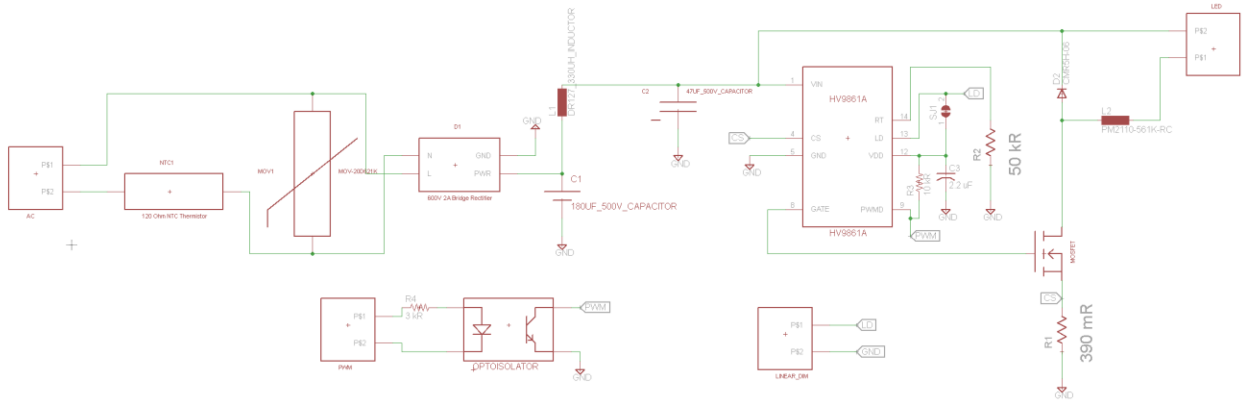

Figure 1: 40W Power Supply Schematic

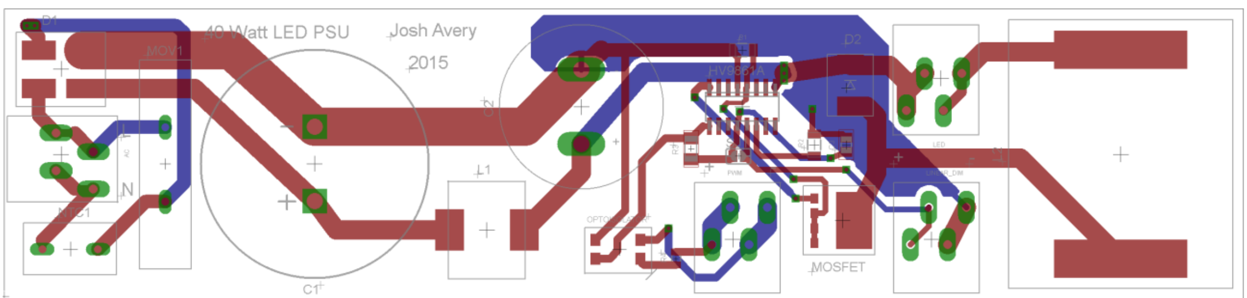

Figure 2: 40W Power Supply PCB Layout

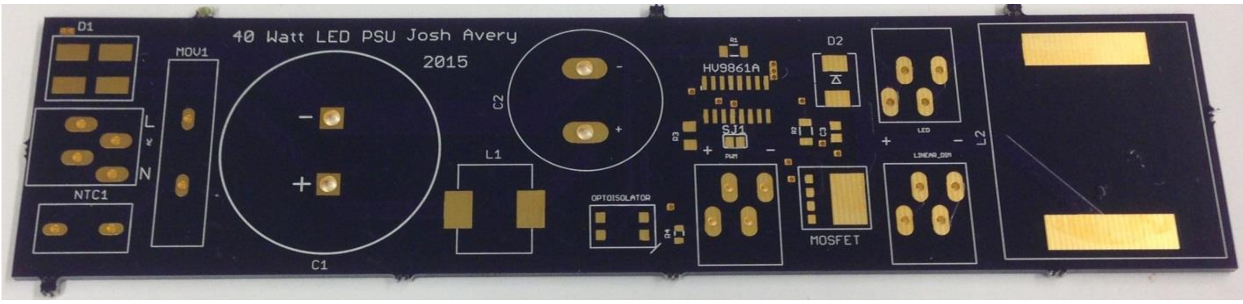

Figure 3: 40W Power Supply before Assembly

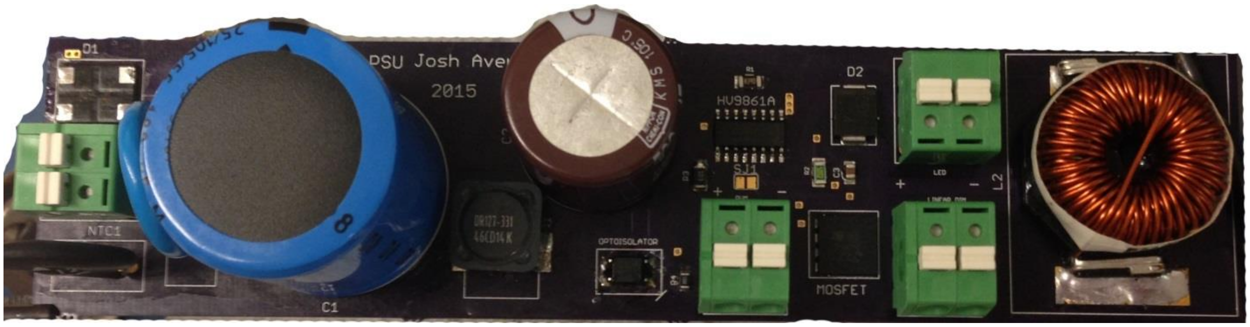

Figure 4: 40W Power Supply after Assembly

Cooling and Control Board

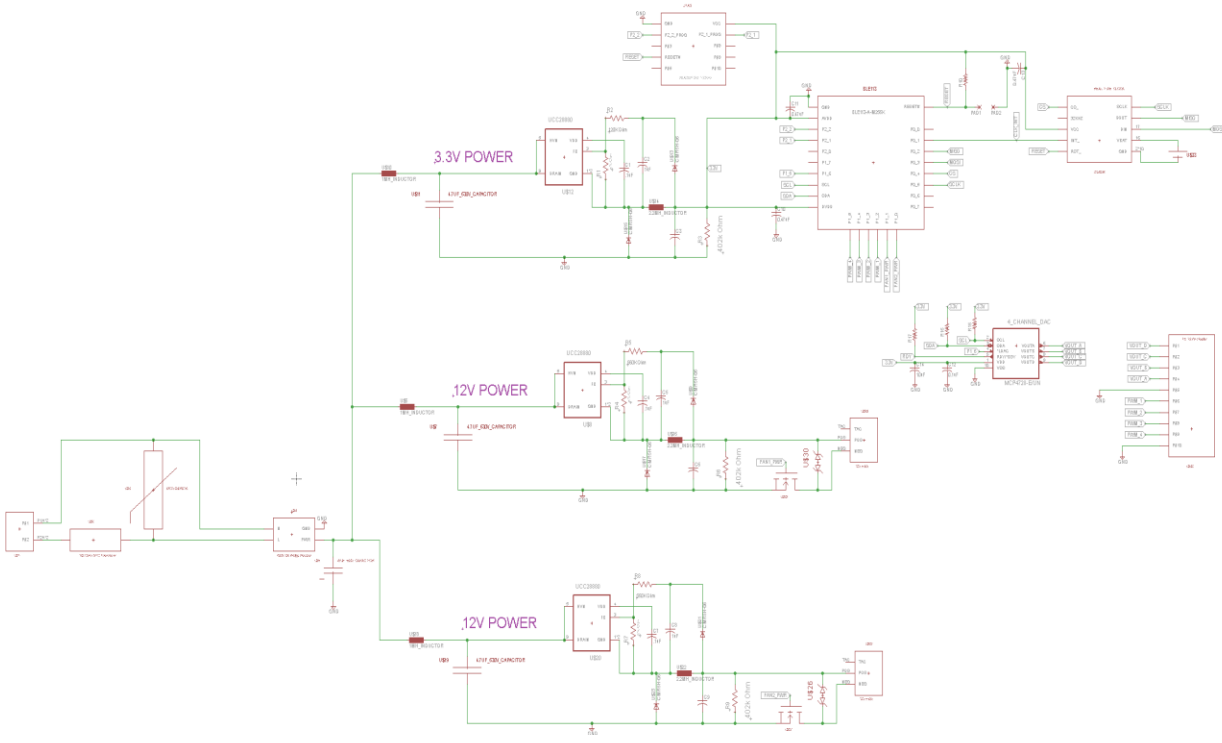

Figure 5: Cooling and Control Schematic

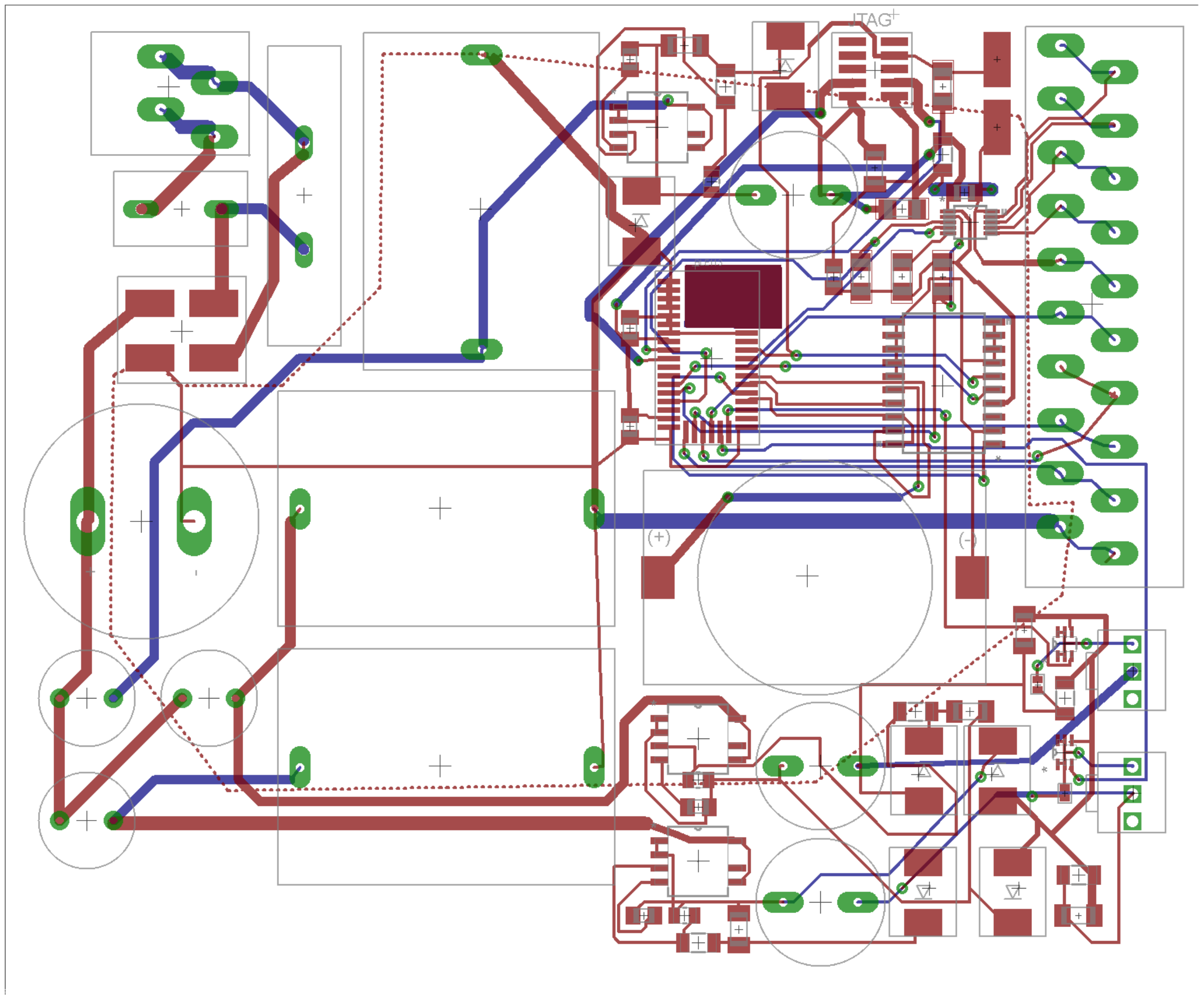

Figure 6: Cooling and Control PCB Layout

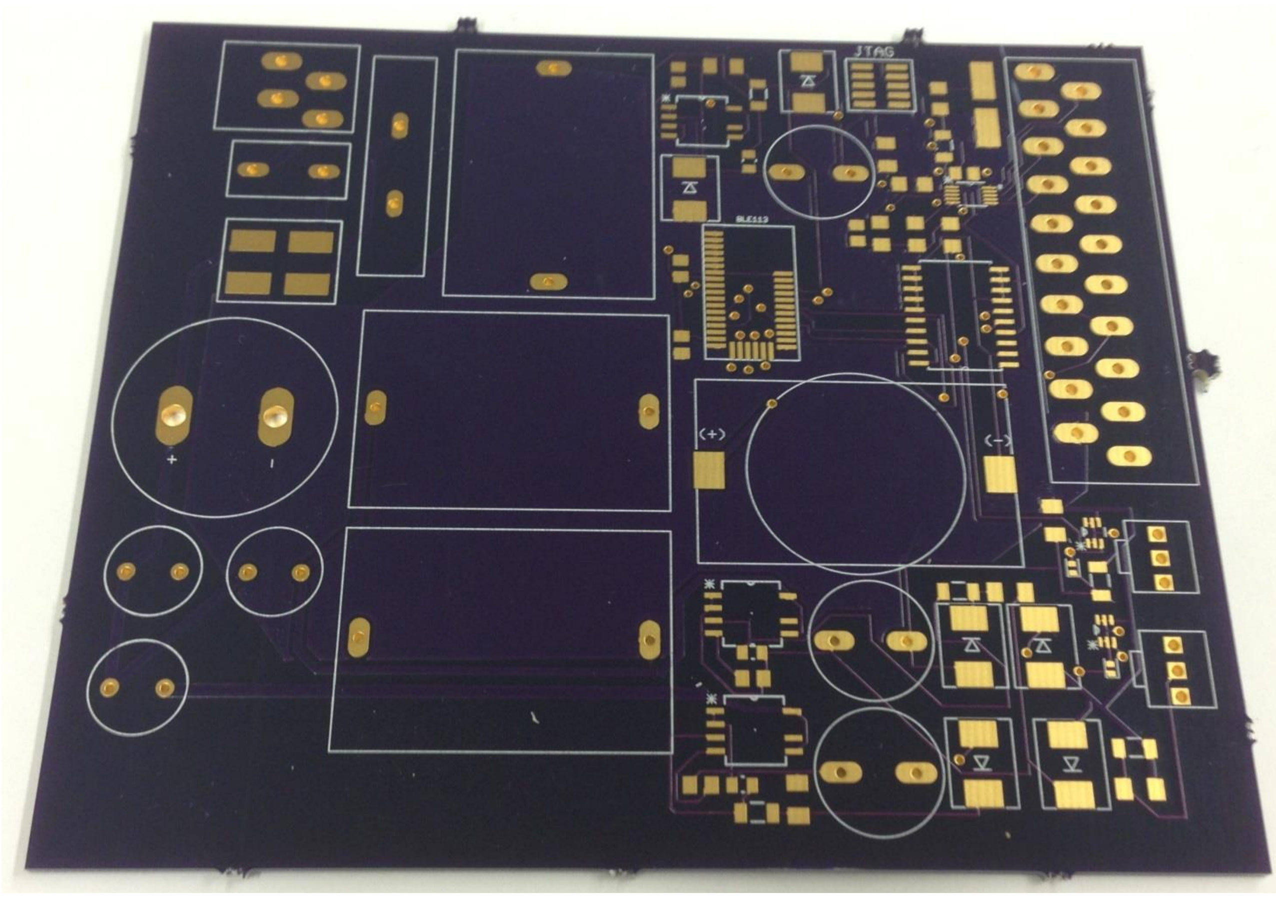

Figure 7: Cooling and Control Board before Assembly

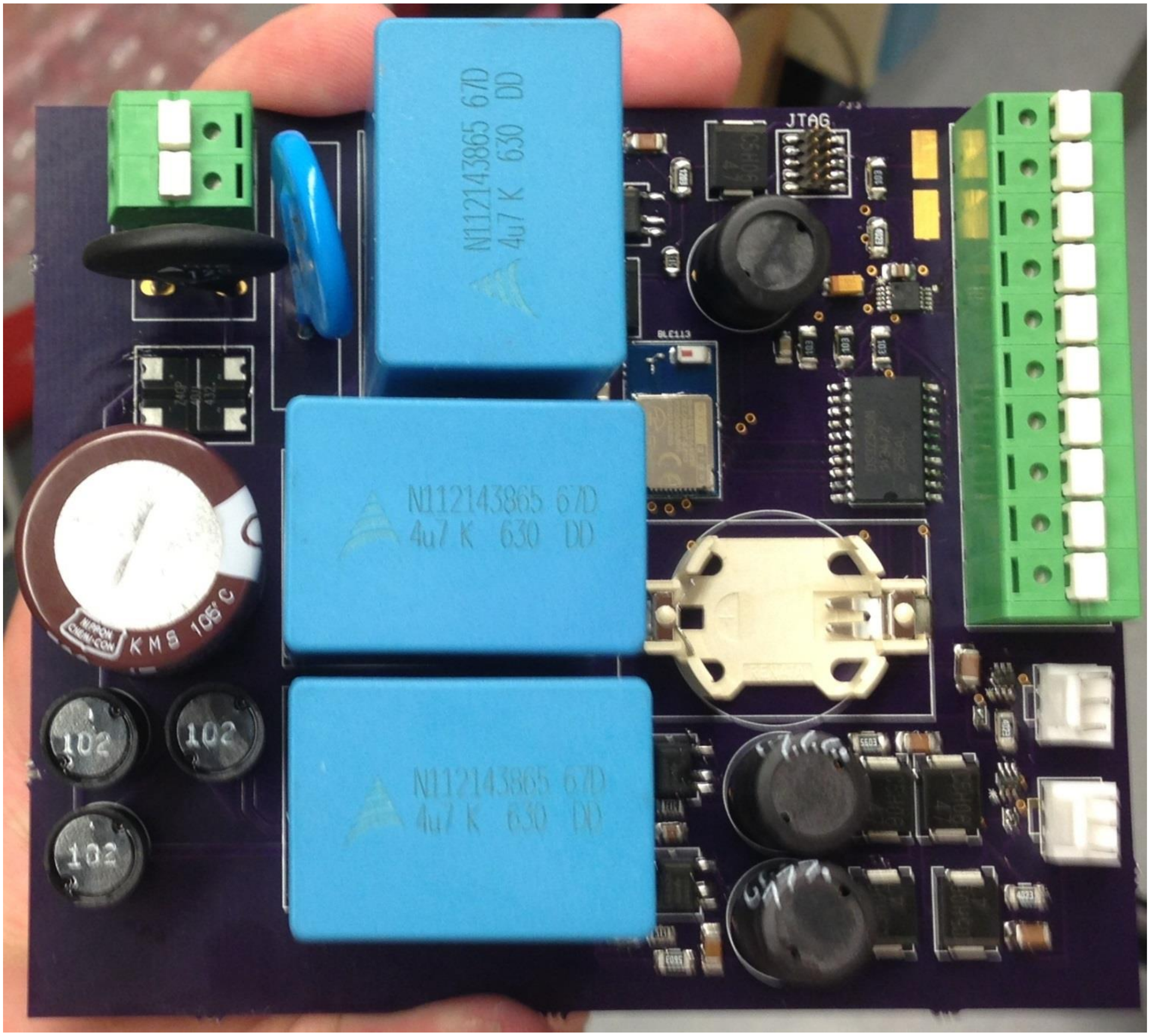

Figure 8: Cooling and Control Board after Assembly

Bluetooth/Microcontroller Software Flowchart

This section describes the process for the setting the light output of the LED system.

LED system:

1. Power up.
2. Check for saved light schedule.
3. Set light output to 100% if no schedule set.
4. Wait for Bluetooth Low Energy Connection
5. If connection made check for updates to light schedule and light output.

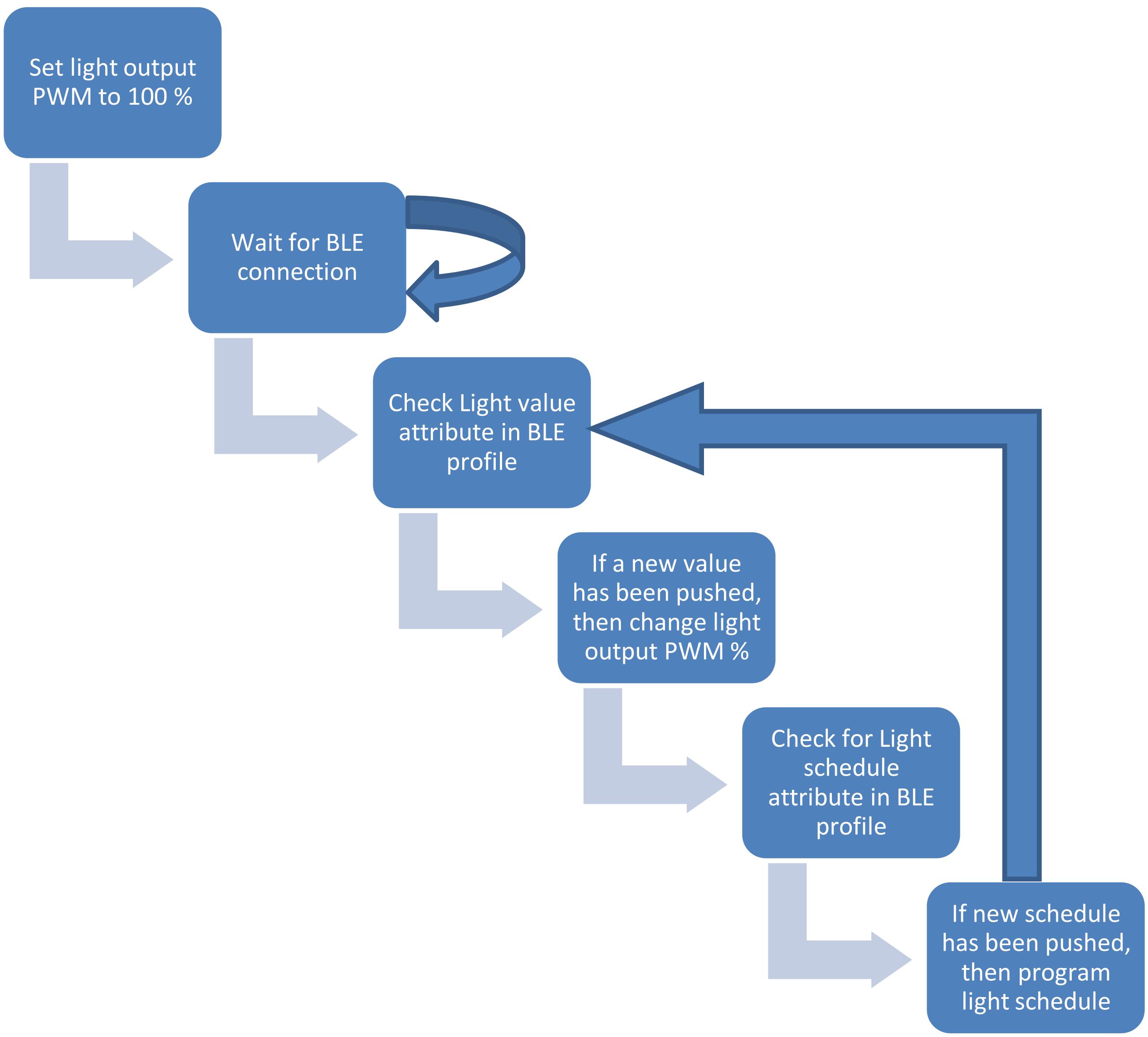

Figure 9: LED Bluetooth/Microcontroller Flowchart

Overall System Analysis

The overall design of the LED system is theoretically capable of meeting the initial specifications, but in practice failed to meet or exceed the standards I had designed for in a few categories.

The current limiting and linear dimming functionality did not work across the two board setup that I designed. Since the boards did not share grounds, the voltage reference supplied by the control board was not consistent and the output current of the power supply did not adjust properly with changes to input. My future board designs will probably forgo this feature until I can consistently control the light output with PWM dimming.

The AC to DC conversion stage of both the power supply board and the control board tested at 120 V_{AC} functions as designed and maintains a stable 170 V_{DC} (+/- 1V) during operation.

The Bluetooth module does not work properly on my test board due to shorted pins from overly aggressive application of solder paste during assembly. This renders most of the control module dysfunctional since the Bluetooth module controls the PWM signal, the linear dimming signal, and the output to the two 12V fans. In my next design revision I am considering using a coin cell battery for powering the Bluetooth Low Energy module, the real time clock module, and the digital to analog converter. This will allow me to experiment with the board to make sure that I can program the outputs properly before adding in the extra complexity of an AC to DC converter.

The two 12V fan power supplies on the control board did not work during testing since they were connected to a MOSFET circuit to allow me to adjust the output duty cycle using the BLE module, which was dysfunctional due to the above mentioned assembly errors.

Future Considerations

In order to create a LED lighting system that is capable of meeting the desired specifications I created in the planning stage of this project I am going to redesign the both the power supply and control boards with a focus on simplifying their respective designs and following a more incremental design process.

LED Power Supply 2.0

The next revision of my LED power supply will have the following adjustments made to the design:

- Power MOFET Gate signal will not be routed through vias.
- The timing resistor will not be connected to the HV9861A through vias.
- The Linear Dimming/ Current limiting input will be removed until version 3.
- I will build both a high voltage version for powering the two 20W LEDs from my original design and a low voltage variant for testing the functionality of the power supply topology.
- Put an RC filter on the current sense input to the HV9861A power supply IC to clean up the signal.
- Validate the performance characteristics of the Power MOSFET using a test circuit before integrating it into the final design.

Control Board 2.0

The next revision of my control board will have the following adjustments:

- The Bluetooth Low Energy Microcontroller, the real time clock module and the DAC will be powered from a 3V coin cell battery instead of an AD – DC converter to simplify the design and reduce the possibility of error.
- I may also replace the BLE-113 chip with another Bluetooth module or microcontroller with better documentation and support or one the can run C code natively instead of using a proprietary scripting language.
- I may separate the BLE module and the microcontroller functionality so that I can run more complex programs.
- I may possibly add some non-volatile memory to the control board to store light output schedules.
- I may replace the BLE chip with a Wi-Fi module or MCU capable of running a full TCP/IP stack so that the LED systems can be integrated into larger or more complex environments.
- Or I may replace the BLE chip with a ZigBee wireless device in order to gain increased range and increase the number of devices running simultaneously (from 8 with BLE to 256 per channel with ZigBee).

12 V Fan Power Supply

The next revision of my 12V fan power supply will have the following adjustments:

- Remove the MOSFET for PWM fan speed control.
- Power the fans on independent AC – DC power supplies without any control inputs.

System Integration and Testing

Testing Results

In order to test the LED power supply I created a test load for the power supply that comprised of ten 6V Zener Diodes rated at 5 W each. I connected a digital multi meter in current measurement configuration between the positive output terminal of the power supply and the cathode of the first Zener diode in series. After power up the circuit I measured 169.8 V between ground and the positive terminal of the LED PSU output and 109.6 V between ground and the negative terminal of the LED PSU output for a voltage of 60.2 V across the test load. This voltage is consistent with expected value of the circuit.

However, there was less than 1 mA of current flowing through the test load throughout the testing process. Based on the characteristics of the buck topology power supply it is likely that the issue with the power supply stems from one of two main areas: poor voltage sampling across the current sense resistor due to noise, or improper triggering of the power MOSFET because I routed the Gate signal through vias during the PCB layout process.

The voltage I measured across the rest of the VDD output of the HV9861A was 9.69V with respect to ground which is 190 mV above its rated 9.5V output in the HV9861A datasheet. This may also indicate that there is a voltage drop of 190 mV between the ground pin on the HV9861 and the ground plane measurement point near the bridge rectifier that I used as a reference when taking voltage measurements. I was unable to get an accurate voltage measurement across the current sense resistor since the MOSFET triggering signal was noisy enough to cause improper functioning of the circuit.

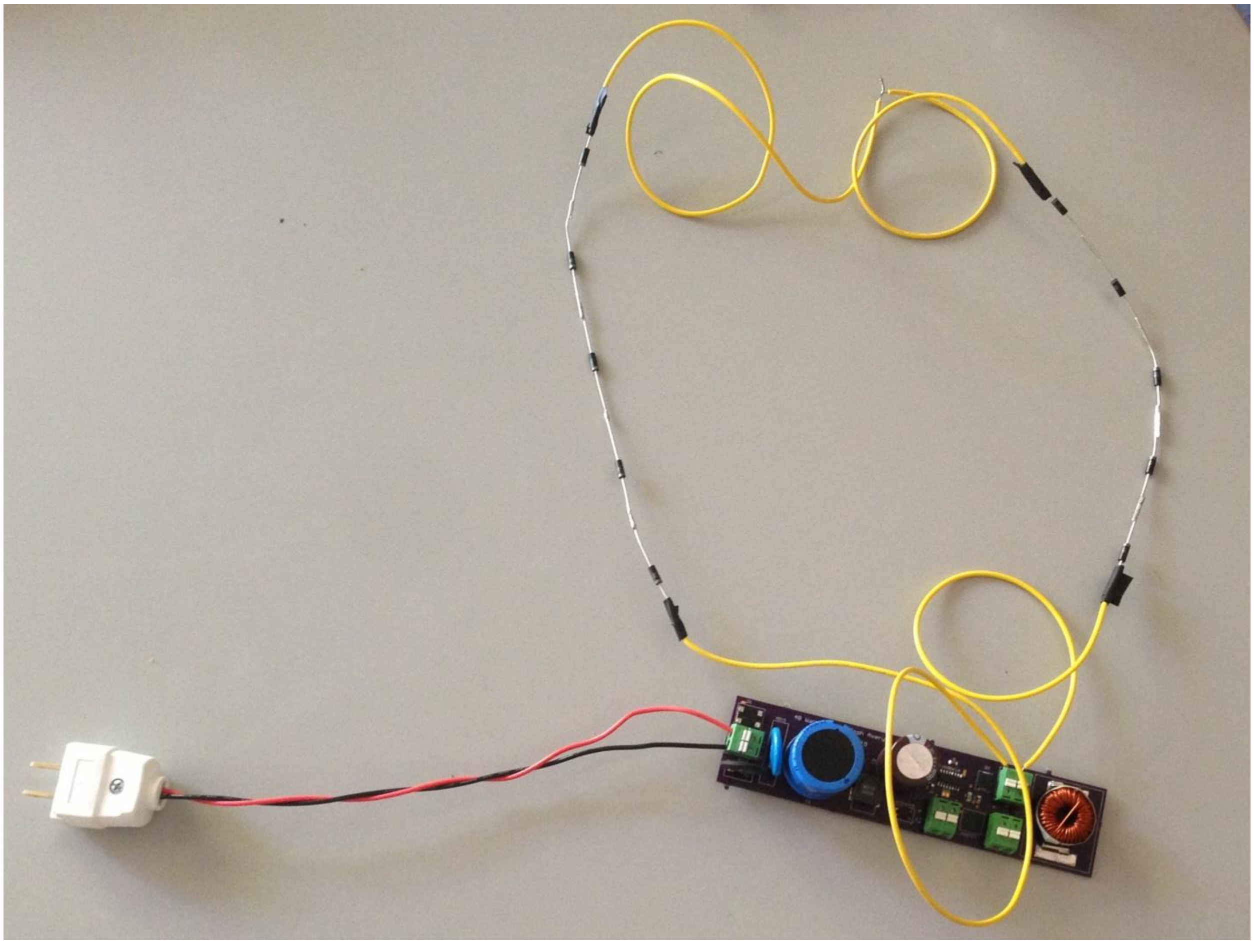

Figure 10: Power Supply Test Rig

Bluetooth Programming Interface

In order to program the Bluegiga BLE-113 Bluetooth module the module must be properly powered and a Texas Instruments CC Debugger programming module must be connected to the JTAG header on the control board. Since the BLE module was improperly assembled it was incapable of being programmed but in future designs, it will be programmed using the JTAG header.

FMEA Analysis

When designing a system to be run off of AC mains power there are numerous design considerations that must be made in order to mitigate the chance of catastrophic system failure. In my design I looked at three main causes of system failure:

Input over voltage:

The HV9861A buck topology power supply is capable of regulating output current at input voltage from 15 – 450 V which allows it to run across the full range of AC mains voltages across the globe. However in an over voltage situation the input voltage may exceed this rating and permanently damage the LEDs and/or the power supply. In order to prevent an over voltage condition from damaging the circuit I included a metal oxide varistor that clamps the input voltage at 620V to offer protection from input over voltage scenarios such as a lightning strike.

Inrush current:

In order to protect the AC – DC converter stage of the power supply I added a negative temperature coefficient (NTC) thermistor to the input stage of the circuit to limit the amount of current that can flow through the circuit when it is first plugged in. The NTC thermistor's resistance drops as it is heated by an influx of current over time protecting the input filter capacitors from being charged to quickly and being damaged.

Overheating:

In order to protect the power supply from overheating I choose a power supply IC that had built in over temperature protection. The HV9861A shuts down at 140^{o} C and does not turn back on until the temperature of the circuit has dropped below 20^{o} C. The control board also has temperature measurement capabilities due to the integration of a temperature measurement system on the BLE-113. The system should be able to operate in a variety of environments due to the inclusion of two 80 mm fans to cool the LEDs and power supply.

Bill of Materials and Cost Breakdown

40 W Power Supply

Number of boards: 3

Cost per board: $49.78

Component Name	Quantity	Cost	Total Cost
2 pin header	3	$1.79	$5.37
Bridge rectifier	1	$1.29	$1.27
NTC thermistor	1	$3.50	$3.50
Metal oxide varistor	1	$0.72	$0.72
180 µF capacitor	1	$5.99	$5.99
47 µF capacitor	1	$3.46	$3.46
330 µH inductor	1	$1.99	$1.99
HV9861A power IC	1	$1.08	$1.08
Fast Diode	1	$0.96	$0.96
Power MOSFET	1	$5.17	$5.17
560 µH inductor	1	$2.22	$2.22
50 kΩ timing resistor	1	$0.52	$0.52
LTV-357T opto-isolator	1	$0.18	$0.18
390 mΩ current sense resistor	1	$0.36	$0.36
2.2 µF capacitor	1	$0.06	$0.06
3 kΩ resistor	1	$0.08	$0.08
10 kΩ resistor	1	$0.08	$0.08
Power supply PCB	3	$50.30	$50.30

Control and Cooling Board

Number of boards: 1

Cost per board: $98.21

Name	Count	Cost	Total Cost
2 pin header	1	$1.79	$1.79
Bridge rectifier	1	$1.29	$1.27
NTC thermistor	1	$3.50	$3.50
Metal oxide varistor	1	$0.72	$0.72
4.7 µF capacitor	1	$4.12	$4.12
47 µF capacitor	1	$3.46	$3.46
UCC2880D power IC	3	$1.89	$5.67
2.2 mH inductor	3	$0.42	$1.26
51 kΩ resistor	3	$0.10	$0.30
Fast Diode	6	$0.96	$5.76
0.1 µF capacitor	4	$0.06	$0.24
560 kΩ resistor	2	$0.10	$0.20
120 kΩ resistor	1	$0.10	$0.10
402 kΩ resistor	3	$0.10	$0.30
1 µF capacitor	3	$0.10	$0.30
47 µF capacitor	3	$1.25	$3.75
BLE-113-A-M256K	1	$12.70	$12.70
0.47 µF capacitor	3	$0.70	$2.10
JTAG header	1	$0.80	$0.80
Real time clock	1	$9.26	$9.26
Digital to analog converter	1	$2.06	$2.06
CR2032 battery holder	1	$0.82	$0.82
10 µF capacitor	1	$0.10	$0.10
10 pin header	1	$9.15	$9.15
10 kΩ resistor	10	$0.03	$0.30
3-pin fan header	2	$0.20	$0.20
Fan control MOSFET	2	$0.25	$0.50
TVS Diode	2	$0.40	$0.80
Control and cooling PCB	3	$80.05	$80.05

LED lights

LED Cost: $214.96

Name	Count	Cost	Total Cost
Gallery White 20W LED	2	$49.02	$98.04
Studio White 20W LED	2	$45.98	$91.96
LED lens and assembly	4	$6.24	$24.96

References

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[1]. T. Zaun. (2005, January 12). *Japanese Company to Pay Ex-Employee $8.1 Million for Invention* [Online]. Available: http://www.nytimes.com/2005/01/12/business/worldbusiness/japanese-company-to-pay-exemployee-81-million-for-invention.html

[2]. BBC News. (2006, September 8). *Top prize for 'light' inventor* [Online]. Available: http://news.bbc.co.uk/2/hi/technology/5328446.stm

[3]. B.T. Chan. (2001, February 4). *Phosphor Film Conversion for White LEDs* [Online]. Available: http://www.digikey.com/en/articles/techzone/2011/feb/phosphor-film-conversion-for-white-leds

[4]. B. MacEvoy. (2009, March 19). *Color Temperature* [Online]. Available: http://www.handprint.com/HP/WCL/color12.html

Appendices

LED Enclosure Design

In my original design I planned on having 4 Gallery White and 4 Studio White LEDs in each LED system. Figure 11 shows a design of the bottom panel where each of the lenses would rest flush with the panel.

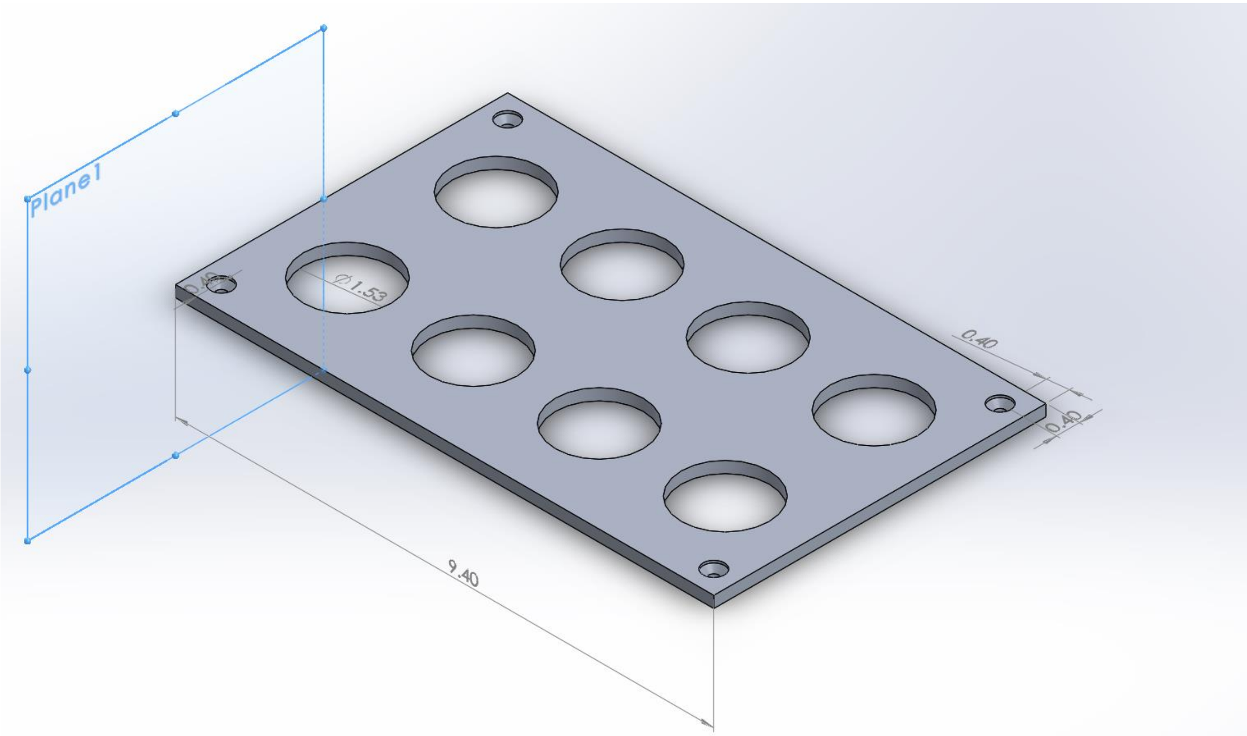

Figure 11: LED Enclosure Bottom Panel Design

Buck PSU LT-Spice Simulation

This simulation in Figure 12 shows the output behavior of a buck topology power supply running off of a rectified 100 V_{AC} Input with the same components values as my 40 W power supply (besides the HV9861A which did not have simulation files). The test circuit in Figure 13 is powered for 100 ms before the cool down time is analyzed.

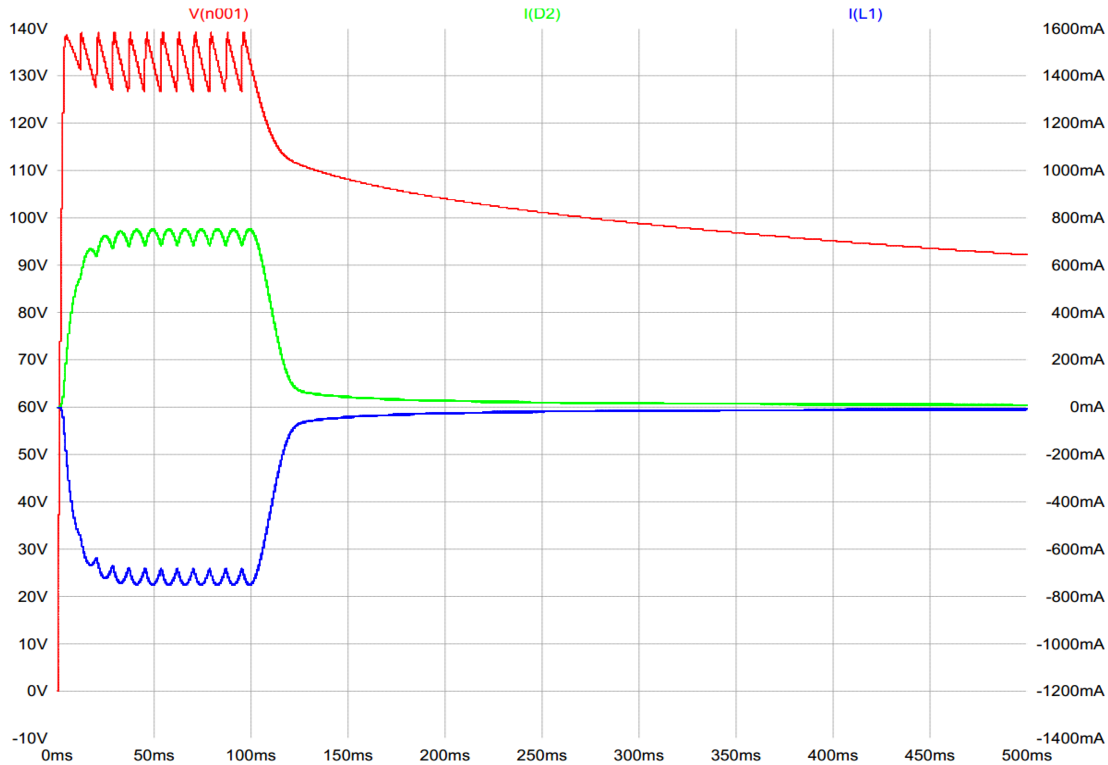

Figure 12: Simulation Output

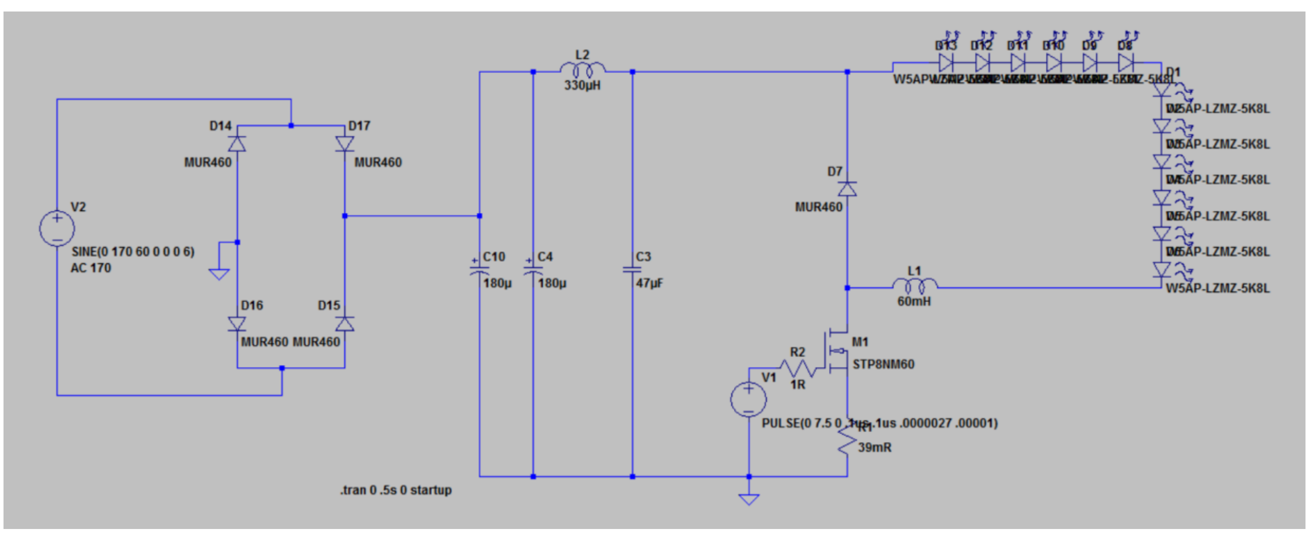

Figure 13: Buck Topology Test Circuit