ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

EE463 POWER ELECTRONICS – I
TERM PROJECT FINAL REPORT

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INTRODUCTION

This is the final report for the term project of EE463 Static Power Conversion I. This project requires a solution for a problem. The problem is having a wind turbine for generating electricity but not having wind all the time so we need to store energy in a battery. The required solution here is an electrical device/circuit which can connect the output of the wind turbine to the battery for charging.

Wind turbines produce AC voltage and the battery works with DC voltage, so our aim here is to design an AC to DC type power converter circuit that will convert the three phase power from a wind turbine to 24V DC to charge a lead-acid battery.

There are some specific quantitative specifications needed for the system. For example, the battery should be charged with 2A DC current at 24V and the current ripple must be less than 20% of average current.

For our design we have analyzed different topologies and came to the conclusion that a Three-Phase Full Bridge Rectifier combined with a synchronous Buck Converter circuit is the most ideal topology for the design. We will then perform simulations on our design and select suitable components for the circuit. Using these components we will construct a PCB model using KiCad and then do a thermal analysis on the completed product.

DESIGN CHOICES

Topology Selection

There are two main topologies we can use for the AC to DC converter. These are the Three-Phase Thyristor Rectifier and the Three Phase Rectifier combined with a Buck Converter. Both of the two topologies have their own advantages and disadvantages compared to each other. The main advantage of a Three-Phase Thyristor Rectifier is that arranging the firing angle for desired output average voltage, 24 Volts in our case is very straightforward. The problem is that the output voltage’s frequency is much smaller compared to a buck converter and therefore is very hard to filter the harmonics and have a constant DC voltage with low ripple.

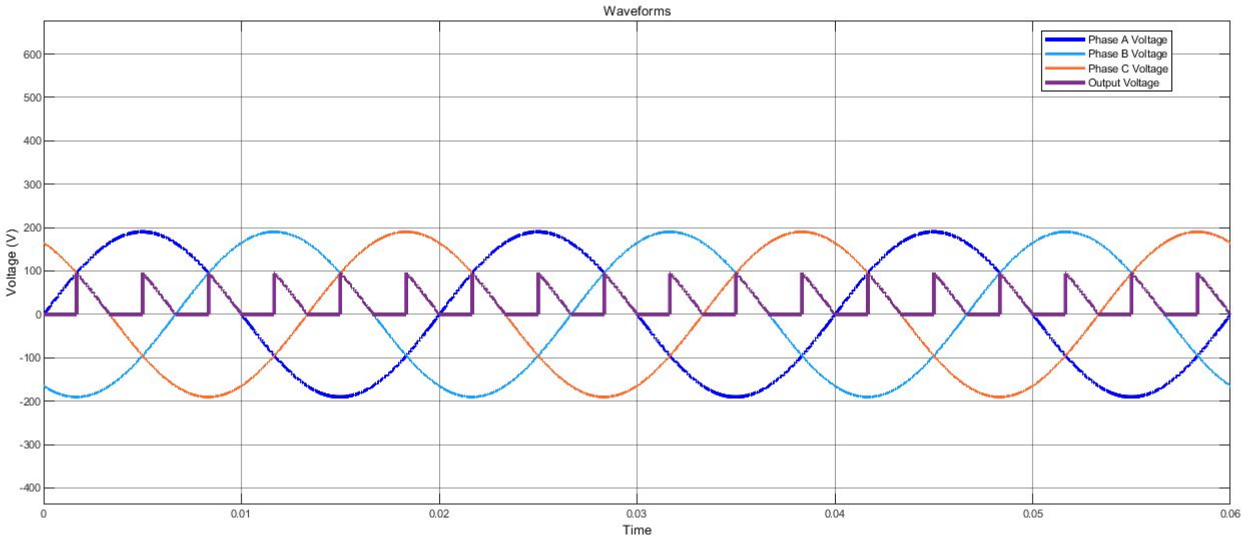

Figure 1: Thyristor Rectifier waveform for obtaining 24V DC from 135$V_{phase,rms}$AC

Three-phase Thyristor Rectifier's input and output waveforms are represented by Figure 1. The measured average voltage here is 24V with a peak to peak value of 95V. Fundamental frequency of voltage ripple is around six times of the input voltage frequency. Filtering out this frequency is very hard with an LC filter.

Diode Rectifier + Buck Converter topology also has some benefits and disadvantages when compared with the previous one. Main advantage of using this topology is obtaining a better DC waveform at the output of the diode rectifier then the thyristor rectifier with a firing angle. The disadvantage of this topology is that we will be converting voltages of around 250V down to 24V. This is not ideal as we will have a low duty cycle.

The two topologies both have their own advantages and disadvantages as stated. Using a transformer is not a great option when we consider the heating effect and increased production costs. As a team, we choose to use a diode rectifier and design synchronous buck converter. We chose a synchronous buck converter since our early simulations resulted in very high losses in the diode of the buck converter. To reduce the loss and increase the efficiency we changed our design. We also used a controller IC instead of designing our own controller to have better steady state performance and also to implement soft-starter and safety features. Final schematic of our design is given in Figure 2.

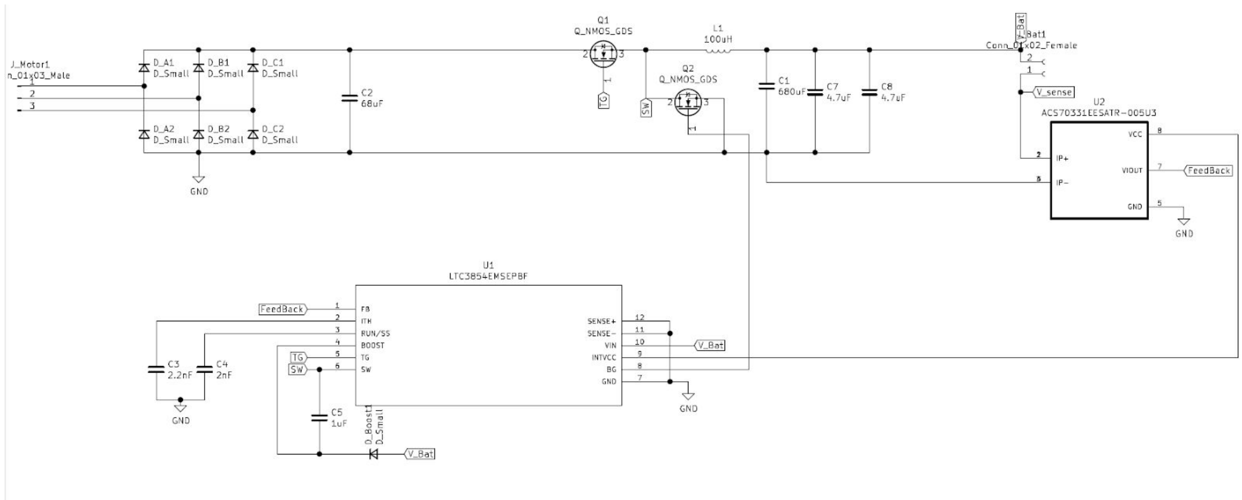

Figure 2: Schematic of the design

Component Selection

We had many different criteria (like price, availability, package etc.) for choosing the components. We tried to not overdesign any parts while keeping enough safety margins.

Rectifier diode selection: We chose 1N4007 due to its low price and availability. Its forward has 1000V blocking voltage and 1A forward current. 1000 V is high for this application but 1N4007 is much cheaper than 1N4004 due to its market size. Diode can withstand 30A of surge current which is enough for our 10A inrush current at the rectifier side. We did not use rectifier packages since they would increase the cost.

MOSFET selection: Our rectifier output voltage is around 250-350V depending on the wind and the required output current is 2A. We used these values to choose our MOSFETs. IPP60R099P7 has 600V drain-source breakdown voltage and it's maximum continuous current is 20A. We chose this MOSFET because it has low R_{ds} value of 99mΩ and low gate charge of 45nC which both of these parameters effects losses and thermal stress. MOSFETs with lower rated currents had higher resistances.

Controller selection: We chose LTC3854 since it could be simulated in LTspice and it's input voltage range was 4.5-38V which we can supply with the battery. LTC3854 can control synchronous buck converters with both voltage feedback and current feedback. It also has a built in linear regulator that outputs 5V which we use to supply our current sensor. Using a capacitor we can also adjust the soft-start time of our converter.

Filter selection: We chose an inductor with 100μH inductance and 110mΩ resistance. This inductor is enough to keep the converter in continuous conduction mode and also to keep the current ripple low. There are three capacitors at the output of the converter. Two of them are 4.7μF ceramic capacitors which are responsible to filter high frequency switching noises. They are chosen ceramic since they have lower ESR compared to electrolytic capacitors. Two of them connected in parallel to further reduce ESR and increase the filtration. Third capacitor is an electrolytic capacitor with 680 μF capacitance. This capacitor is used for storing energy.

Current sensor selection: ACS70331 is selected to measure the current for feedback. This IC measures currents up to 5A and gives an output voltage accordingly. The model that we chose has an output voltage of 400mV/A which corresponds to 800mV for 2A. Since our controller IC has 800mV internal reference voltage for feedback, we do not need any voltage division to control the output current.

High voltage capacitor selection: At the output of the rectifier we need a high voltage capacitor to reduce voltage ripples at the input of the buck converter. This capacitor needs to withstand high voltages like 350V. So we chose a 100 μF 450V electrolytic capacitor for this purpose.

SIMULATION RESULTS

For simulation we use both Simulink and LTspice. In Simulink we simulated a wind turbine, rectifier and battery. Using the result obtained from Simulink we modelled the rectifier and battery in LTspice in order to simulate our controller IC and MOSFET.

Simulink model consists of a permanent magnet synchronous generator, 3-phase diode full bridge rectifier, PI controlled synchronous buck converter and the battery. The reason why we used a PI controller with a PWM generator is that we did not aim to simulate our converter in Simulink. We just wanted to see the output of the generator and rectifier voltage to model them in LTspice. We tuned the PI controller so that output current waveform was close to our simulation in LTspice. It was an iterative operation going between two simulations to get an accurate simulation in LTspice.

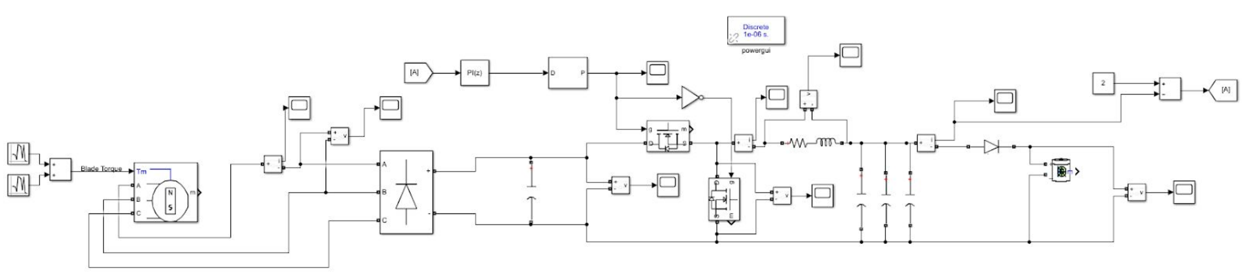

Figure 3: Simulink model

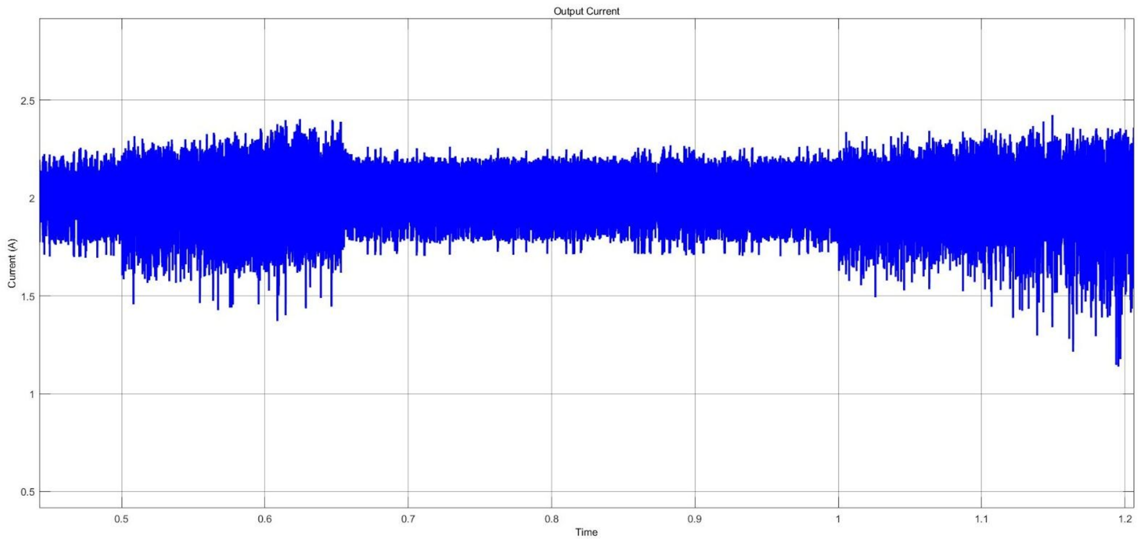

Figure 4: Output current from Simulink

As we can see in Figure 4, output current is around 2A. However we did not try to get good output current since we are only interested in the rectifier voltage with output current around 2A. Since we could not implement the controller IC in Simulink it would be a pointless attempt to get exact 2A using PI controller and changing the circuit parameters.

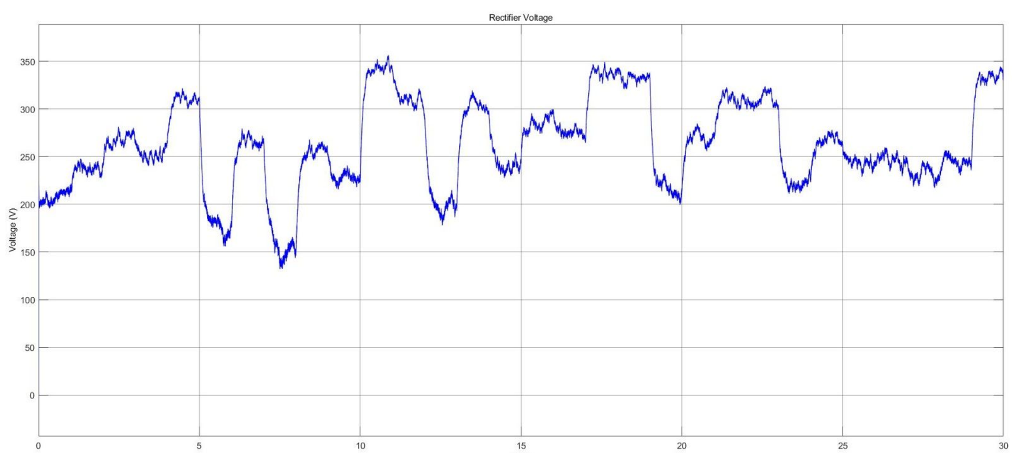

Figure 5: Rectifier voltage from Simulink

As it can be seen in Figure 5, we concluded that rectifier voltage swings between 150V and 350V with changing wind speed (torque).

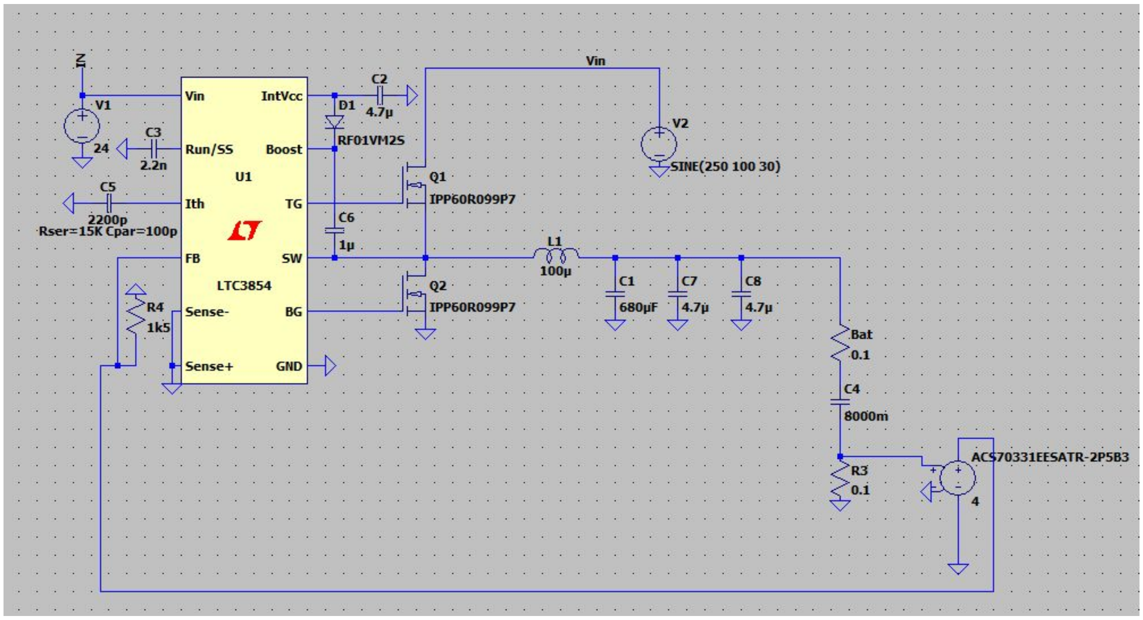

Figure 6: LTspice simulation of the circuit

Simulation of our converter is made in LTspice so that we can simulate LTC3854 controller IC. However, using LTspice prevented us from simulating the wind turbine, battery and current sensor. Therefore, we modelled the battery as a large capacitor with an initial voltage of 24V. We also modelled the current sensor with a voltage controlled voltage source with a current sense resistor. Output voltage of the rectifier is modelled as a sinusoidal voltage with 200V DC component, 100V amplitude and 30Hz frequency. These values are obtained from Simulink simulations with a similar converter.

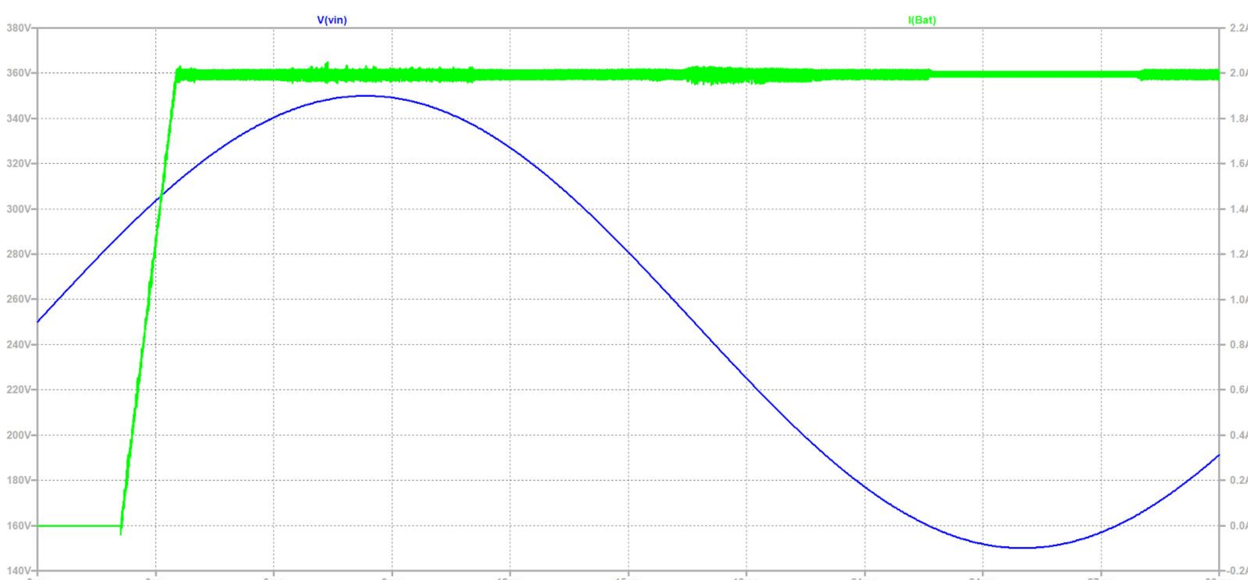

Figure 7: Output current and input voltage

As seen in Figure 7, the current output is about 2A and has a current ripple much less than 20% of the average current. Our converter design handles varying input voltage which is mandatory due to changing wind speeds which will change the output voltage of the generator. Also it is worth noting that we do not observe any inrush current due to the soft-start feature of our controller IC.

PCB DESIGN

For the PCB design we used KiCad. KiCad is a free to use software for electronic design. It lets us turn the schematics of our circuit into PCB designs. It also possesses features such as letting us create a bill of materials and taking 3D views of the PCB and its components.

We chose some parameters for our PCB design. We used FR4 as our PCB material with 1.6mm thickness. Thicker copper means less loss and less heating, we used 1 oz of copper thickness. We set the minimum track spacing as 0.2mm.

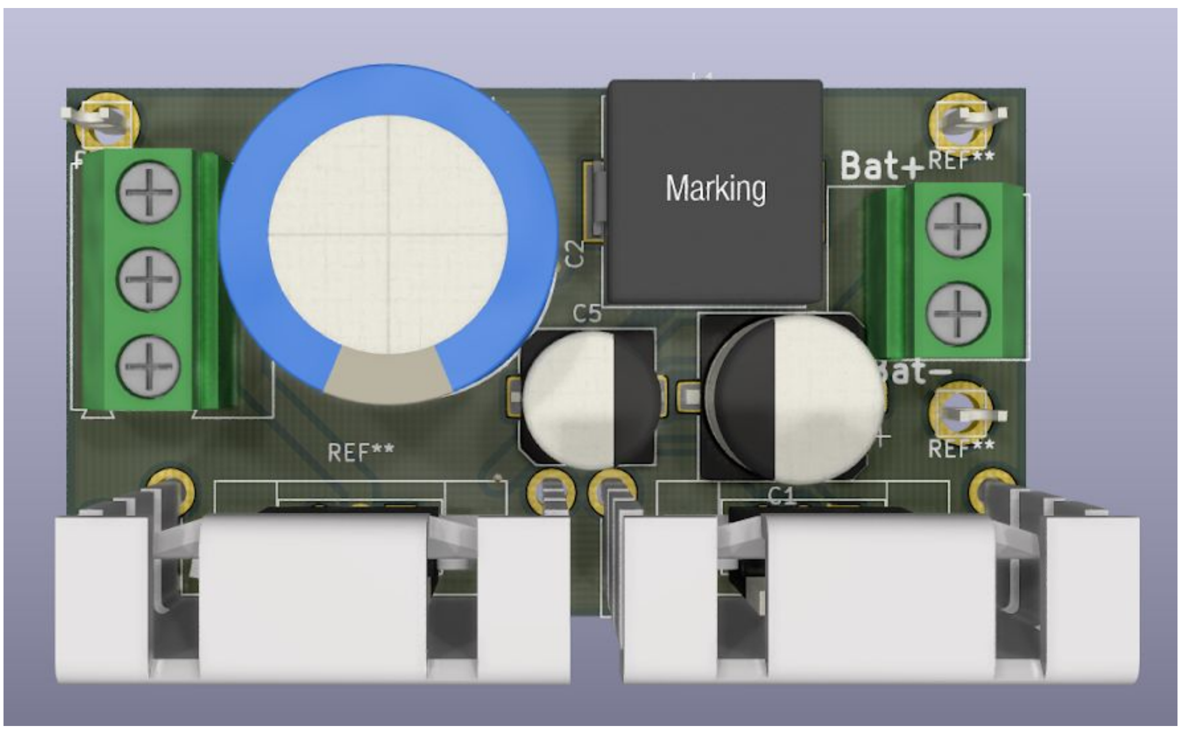

Figure 8: Top view of the PCB

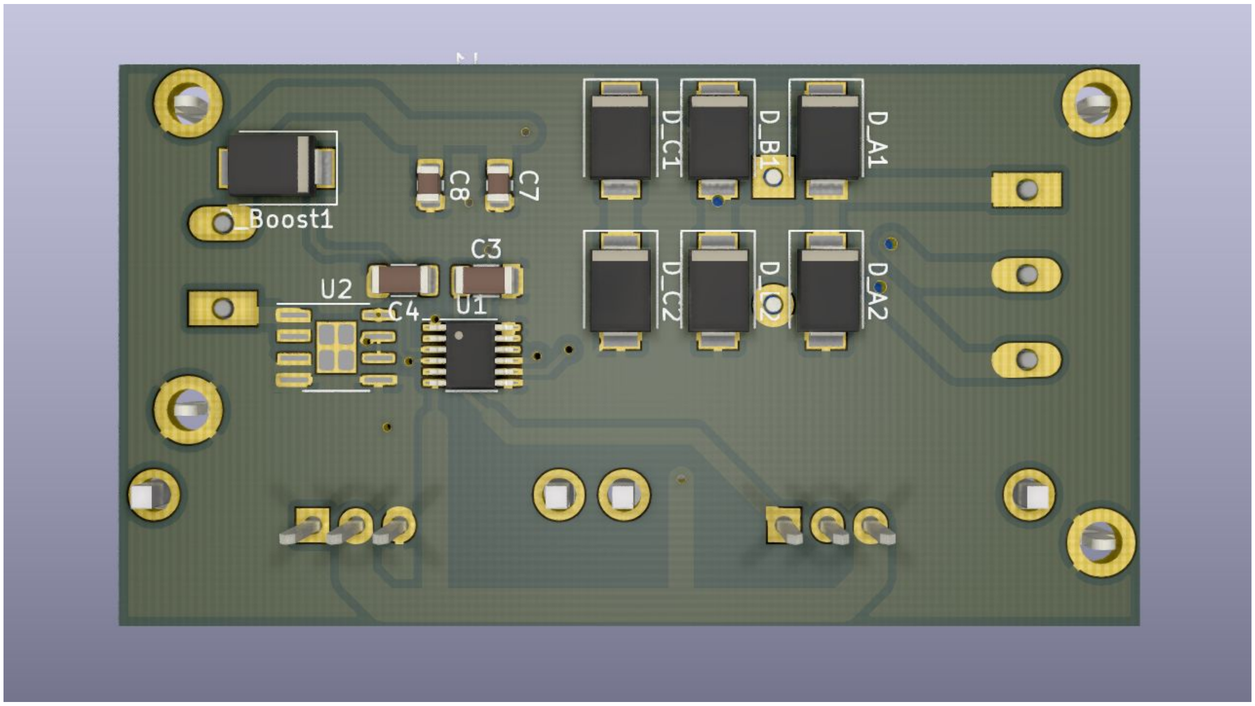

Figure 9: Bottom view of the PCB

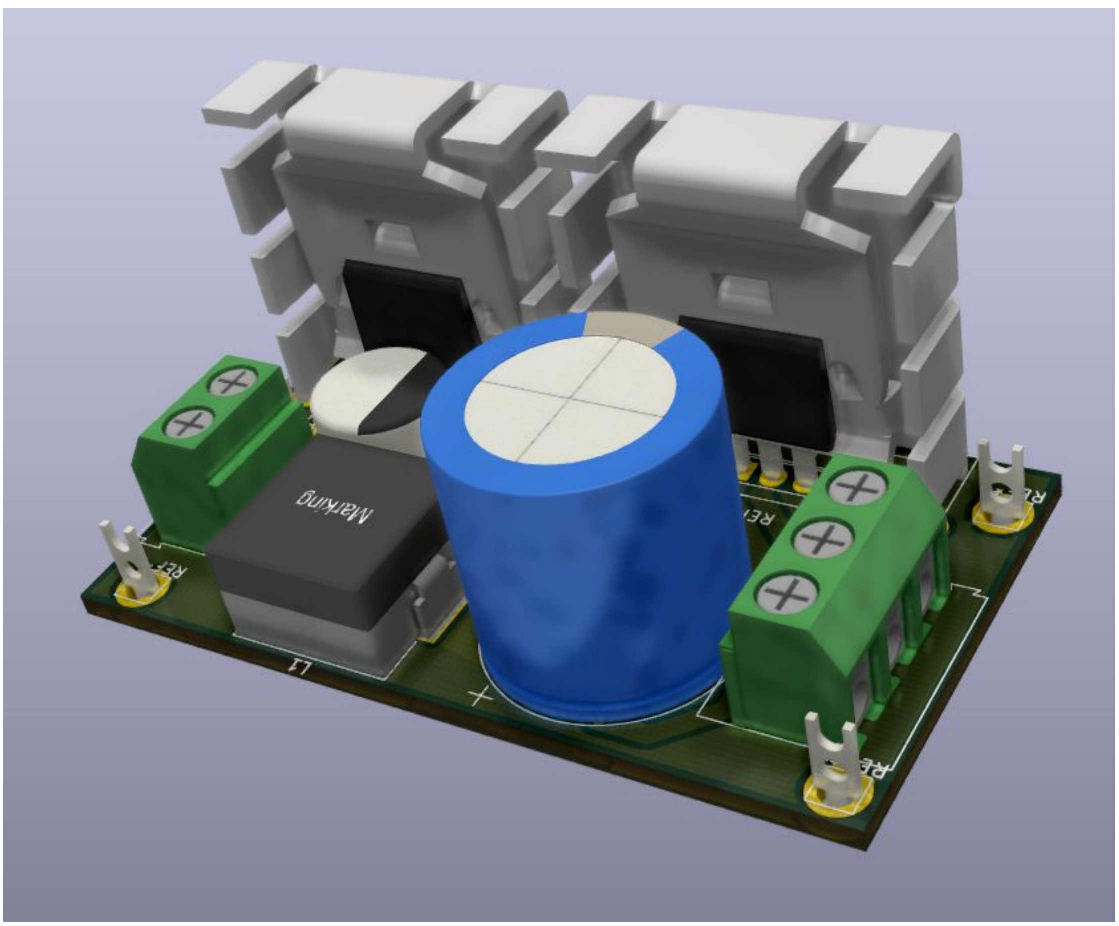

Figure 10: General view of the PCB

THERMAL ANALYSIS

High side MOSFET:

$$P_{conduction} = I_o^2 * D * R_{ds} = 4 * 0.1 * 0.099 = 39.6\ mW$$

$$P_{switching} = \frac{1}{2} V_{in} * I_o * (t_r + t_r) * f = \frac{1}{2} * 250 * 2 * (15 + 5) * 10^{-9} * 400 * 10^3 = 2\ W$$

$$P_{gate} = V_{gs} * f * Q_{g-H} = 5 * 400 * 10^3 * 45 * 10^{-9} = 0.09W$$

Low side MOSFET

$$P_{conduction} = I_L^2 * (1 - D) * R_{ds} = 4 * 0.9 * 0.099 = 0.356\ W$$

$$P_{switching} = \frac{1}{2} V_{f,body} * I_o * (t_r + t_r) * f = \frac{1}{2} * 0.9 * 2 * (15 + 5) * 10^{-9} * 400 * 10^3 = 7.2\ mW$$

$$P_{gate} = V_{gs} * f * Q_{g-L} = 5 * 400 * 10^3 * 45 * 10^{-9} = 0.09\ W$$

Inductor:

$$P = I_L^2 * R_L = 4 * 0.11 = 0.44\ W$$

Bootstrap diode:

$$P = V_f * I = 0.8 * 3.1 * 10^{-3} = 2.48\ mW$$

Rectifier:

$$P = 2 * V_f * I_{rectifier} = 2 * 1 * 0.33 = 0.66\ W$$

Current sensor:

$$P = V_{cc} * I_{cc} = 5 * 6 * 10^{-3} = 30\ mW$$

Controller IC:

$$P = V_{cc} * I_{cc} = 24 * 3 * 10^{-3} = 72\ mW$$

Total:

$$P_{loss} = 3.8\ W$$

$$eff = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{48}{51.8} = 92\%$$

We have made a thermal analysis for our system in order to calculate its power loss and efficiency. Another advantage of this analysis is deciding if a heatsink is needed and choosing the heatsinks capacity according to this analysis.

Our system contains several types of devices and several types of losses. For example, the inductor has conducting losses due to its ESR and MOSFET devices have conducting losses and also switching losses due to charging/discharging of its regions. Diodes also have conduction losses which increase with increased forward voltage. We have considered diodes with lower forward voltage but the price was increasing so we found an optimal point for our application. Actually, most of the loss is caused by high side MOSFET since it is switching under high voltage so switching causes more charges to be carried.

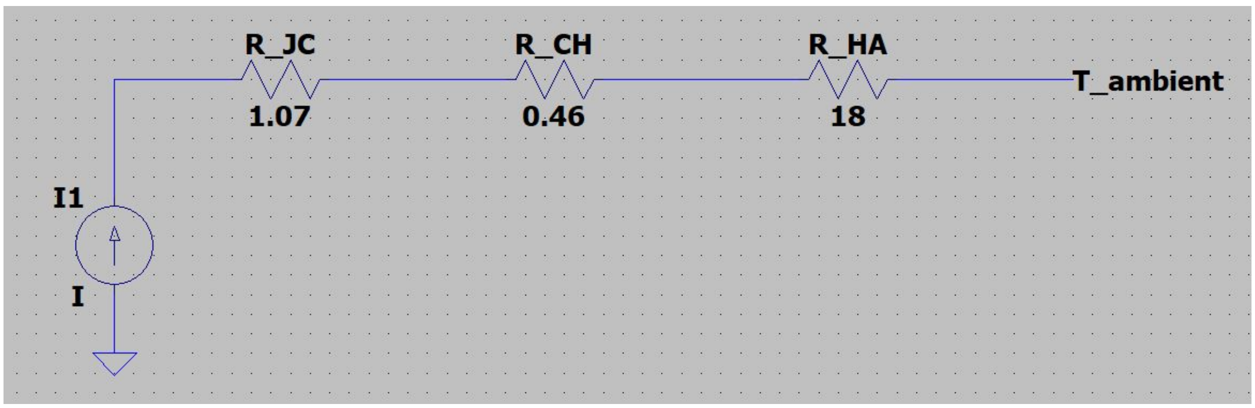

Figure 11: Thermal Circuit for the High MOSFET, Thermal Pad and Heat Sink

$$T_{junc} = 25° + P_{loss} * R_{total} = 25° + 2.1296 * 19.53 = 66.59°$$

Finite element analysis is done by using SolidWorks thermal simulation; the result is shown in Figure 12. To do the simulation following assumptions has been made, the ambient temperature is 25° C, the contact resistance between mosfets and heatsink is sum of junction to case thermal resistance of MOSFET and the thermal resistance of thermal interface material which is about 1.5K/W and the air convection coefficient is taken as 2 K/m^2W. As seen in Figure 12 maximum temperature of the heatsink is about 324K(51°C) which is less than the lumped thermal circuit analysis probably due to the convection differences.

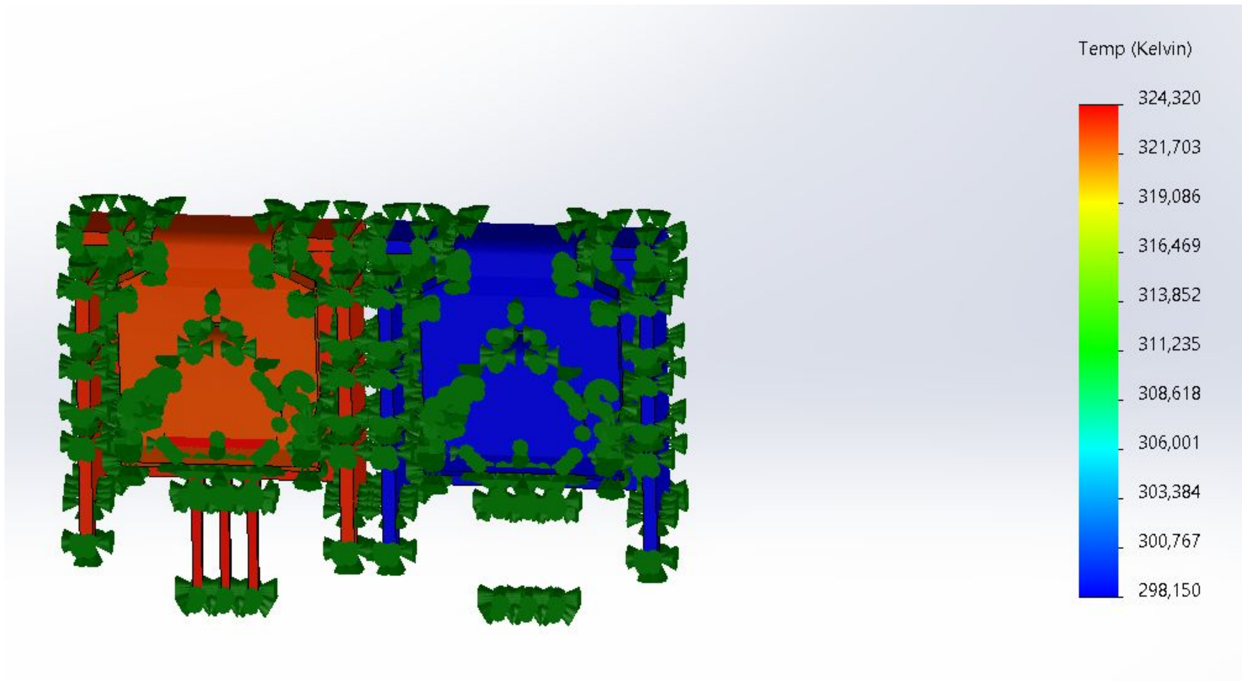

Figure 12: Thermal Analysis using SolidWorks thermal simulation

CASE DESIGN

For the case design we decided to use Siemens NX and constructed the case we see in the Figures 13 and 14. Total size of the case is 65.5x40x39mm and the thickness of the material is 2mm. We designed our own case since it can be easily modified according to thermal or size requirements and its prototype production can be done using a 3D printer.

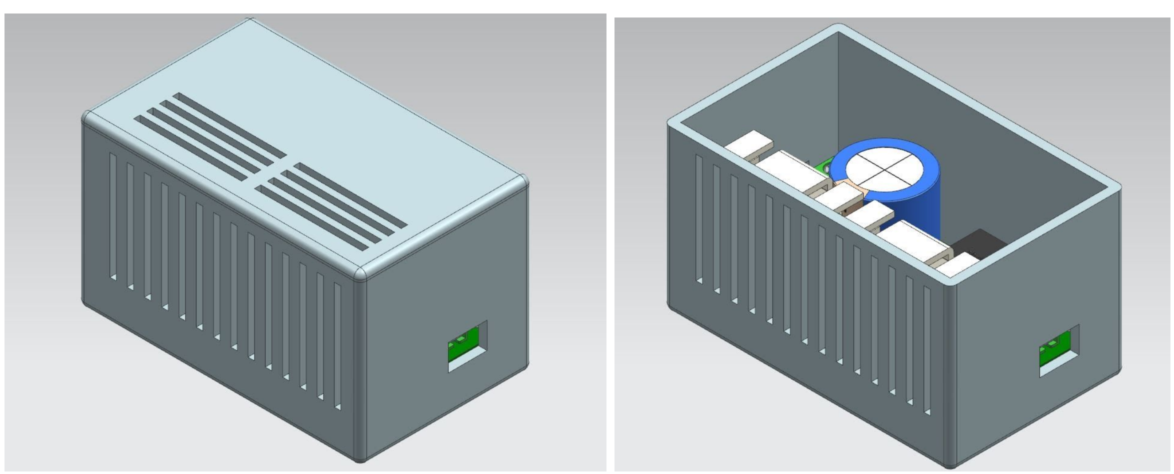

Figure 13: Case Design

From Figure 13 we can see the vents that we added to the design so that the components that give off heat (which are mainly the MOSFETs) can dissipate their heat much easier due to convection. Since our components do not dissipate that much heat, we opted to go with a fanless, passive design for the case. This makes the case much more compact.

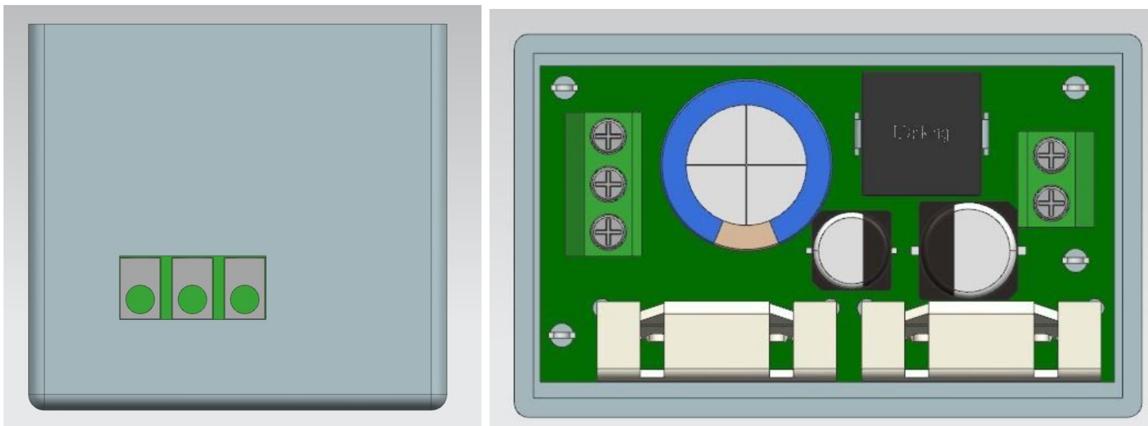

Figure 14: Case side and top view.

From Figure 14, we see the openings for the power cables. Also, the lid can be removed to have access to the insides. We can use this opening to screw in the power input and output cables.

COST ANALYSIS

Cost of the design is tracked using DigiKey's BOM manager. Each component is added as we are manufacturing 1000 systems. Total cost of the components for each system is $13.65. Price of the PCB is determined by JLCPCB's online ordering tool. Price for 1000 PCB is $131.6 which corresponds to ~$0.14. This brings the total cost of the system to around $13.80. Bill of materials is given below.

Table 1: Bill of materials

Component	Manufacturer Part Number	Manufacturer	Digi-Key Part Number	Quantity	Unit Price	Extended Price
Controller IC	LTC3854EMSE#PBF	Analog Devices Inc.	LTC3854EMSE#PBF-ND	1000	2,0881	$2,088.10
MOSFET	IPP60R099P7XKSA1	Infineon Technologies	IPP60R099P7XKSA1-ND	2000	1,78553	$3,571.06
Inductor	AMDLA1306Q-101MT	Abracon LLC	535-AMDLA1306Q-101MTTR-ND	1000	1,31376	$1,313.76
Capacitor	UVK2V101MHD	Nichicon	493-12432-ND	1000	1,07648	$1,076.48
Current sensor	ACS70331EESATR-2P5U3	Allegro MicroSystems	620-1890-1-ND	1000	0,8325	$832.50
Heatsink	FK 224 SA 220-1	FISCHER ELEKTRONIK	-	1000	0,8	$800.00
Thermal pad	5590H-TO220	3M (TC)	3M12137-ND	2000	0,56086	$1,121.72
Capacitor	UCV1V681MNL1GS	Nichicon	493-14357-2-ND	1000	0,52196	$521.96
Screw terminal	TB005-762-03BE	CUI Devices	102-6190-ND	1000	0,4032	$403.20
Bootstrap diode	RFN2L4STE25	Rohm Semiconductor	846-RFN2L4STE25CT-ND	1000	0,30226	$302.26
Capacitor	UUB2G010MNL1GS	Nichicon	493-9967-2-ND	1000	0,29266	$292.66
Screw terminal	TB001-500-02BE	CUI Devices	102-6134-ND	1000	0,1512	$151.20
Capacitor	12065A202JAT2A	AVX Corporation	478-6053-1-ND	1000	0,1114	$111.40
Capacitor	C3216X7R2J222K115AA	TDK Corporation	445-2289-1-ND	1000	0,07854	$78.54
Capacitor	CL21A475KBQNNNE	Samsung Electro-Mechanics	1276-1248-2-ND	2000	0,05667	$113.34
Rectifier diode	1N4007FLTR	SMC Diode Solutions	1655-1N4007FLTR-ND	6000	0,01217	$73.04

CONCLUSION

During this project, we have worked mainly on power conversion and regulation. This work includes, AC/DC conversion, step-down voltage regulation, thermal analysis, PCB design, part selection and cost analysis.

Firstly, we made a topology decision for our circuit. Then, we chose an appropriate integrated circuit and made a circuit design by using it. After, we made some arrangements in circuit elements in order to decrease the inrush current, decrease the output voltage ripple and other undesired characteristics. Then, we chose parts for our design from the market by considering price and compatibility. We conducted a thermal analysis with the components we had selected. At last, we have designed a PCB with all of the parts we had chosen.

There are several outcomes of this project for us. We learned to make a complete design for a system, which is not only making calculations and simulations with arbitrary component values but also researching the market, comparing prices against features and making optimal selections. We also prepared a thermal analysis and PCB design of our system which one should do for manufacturing a system.