MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE463 – STATIC POWER CONVERSION I

TERM PROJECT – COMPLETE SIMULATION REPORT

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1. INTRODUCTION

Renewable energy is defined as useful energy collected from renewable resources. Wind is one of the renewable resources. It is used to provide mechanical power to the wind turbines to generate electricity. Wind power is widely used in sustainable energy. However, there are some problems with using the electricity produced in wind turbines. These turbines, generally, behave like an electric generator with a continuously varying output voltage and output current. In this project, Kardeşler Elektronik A.Ş. introduces AC to the DC Converter project which regulates the output current. In the first part of this report, the topology of the converter has been discussed. The advantages and disadvantages of different topologies have been compared. Moreover, the reason for the topology selection has been given. In the second part, the circuit schematic and its simulation results with ideal cases have been provided. Moreover, the component selection including thermal analysis and PCB design stages have been shown. Finally, the cost analysis of the project has been provided for 1000 products. To conclude, our engineering skills in circuit design, simulations, and our project management skills have improved. Additionally, this project has given us an opportunity to implement the theoretical knowledge of us on EE463 lecture.

2. TOPOLOGY SELECTION

As mentioned in the 'Introduction' section, the generated voltage needs to be rectified to feed the given battery. To do this rectification, there are some topologies that can be used. Using a 3-phase thyristor rectifier and the diode rectifier with a buck converter are the most common ones. In this project, we preferred the diode rectifier with a buck converter topology because of some reasons. Firstly, controlled the thyristors considering their phase difference is not an easy job; however, the diode rectifier does not need any gate voltage and operates without any external intervention. On the other hand, we need to control the gate voltage of the MOSFET and hence the duty cycle of the buck converter to keep the output current the same. For this operation, again there is no one solution, using integrated circuits (IC) is one of the alternative solutions; however, the operating conditions are very important for these ICs. As shown in the 'Simulation Results' section, the input voltage varies, and this high voltage can damage the selected IC. That's why we preferred to control the gate signal of the MOSFET with an analog circuit design. Moreover, we wanted to observe the feedback operation step by step. If we used an integrated circuit, we would not be able to observe the entire circuit. Due to missing IC models in MATLAB and the modeling problem of input generator and battery in other simulation applications, we wouldn't be able to examine the performance of the design. Because of the pandemic conditions, we have also no chance to physically work on the designed circuit in the laboratory. Considering all these reasons, we decided to design an analog PI controller circuit. The last thing, we need to feed the gate of the MOSFET and hence we used one of the most common PWM generators called 555timer which can also be modeled in MATLAB Simulink. In short, we chose diode rectifiers with a buck converter topology and designed a closed-loop PI feedback controller without using any integrated circuit. In the following section, circuit blocks will be examined in detail and the simulation results will be shown.

3. CIRCUIT ANALYSIS & SIMULATION RESULTS

As mentioned before, our circuit design includes some parts and in this section, these blocks are examined in detail. In Figure 1, the block diagram of the circuit design is visualized.

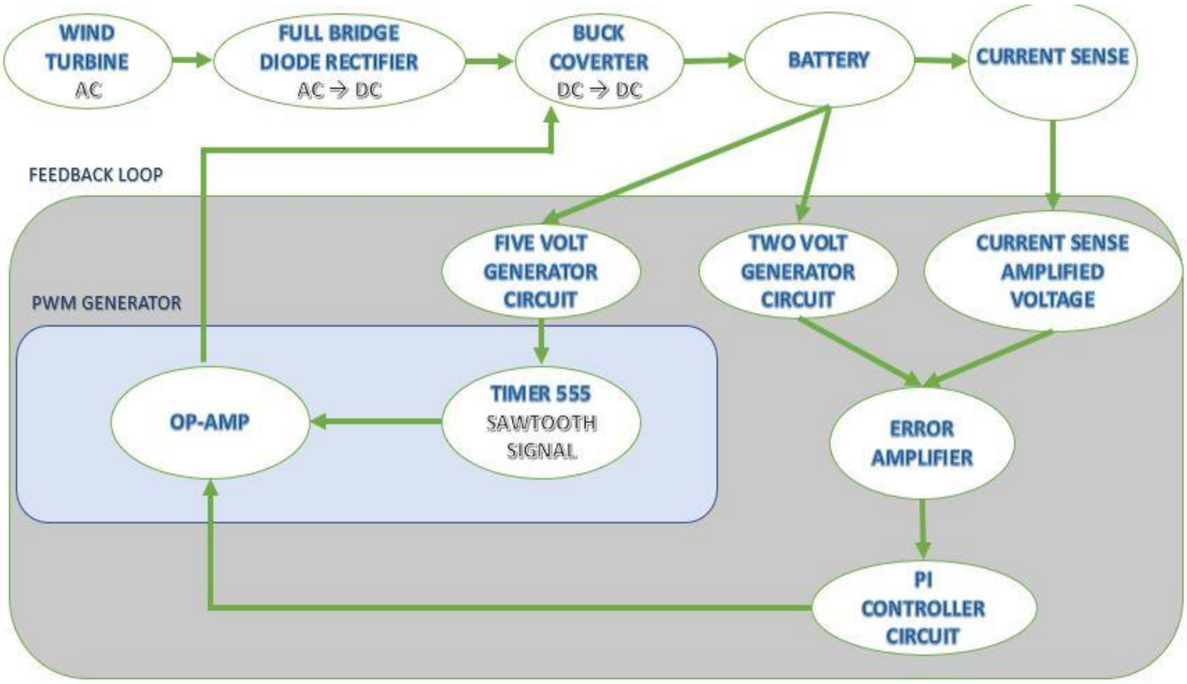


Figure 1 Block Diagram of the Circuit Design

3.1 Diode Rectifier and Buck Converter Block

As we learned in our lectures, a 3-phase diode rectifier is a good method to rectify the given AC signal; however, it is not enough to feed the battery without any external component since the output of the rectifier depends on the input voltage and it is affected by the changes in the input voltages. In the following Figure 2, the input voltage waveforms of the rectifier are illustrated.

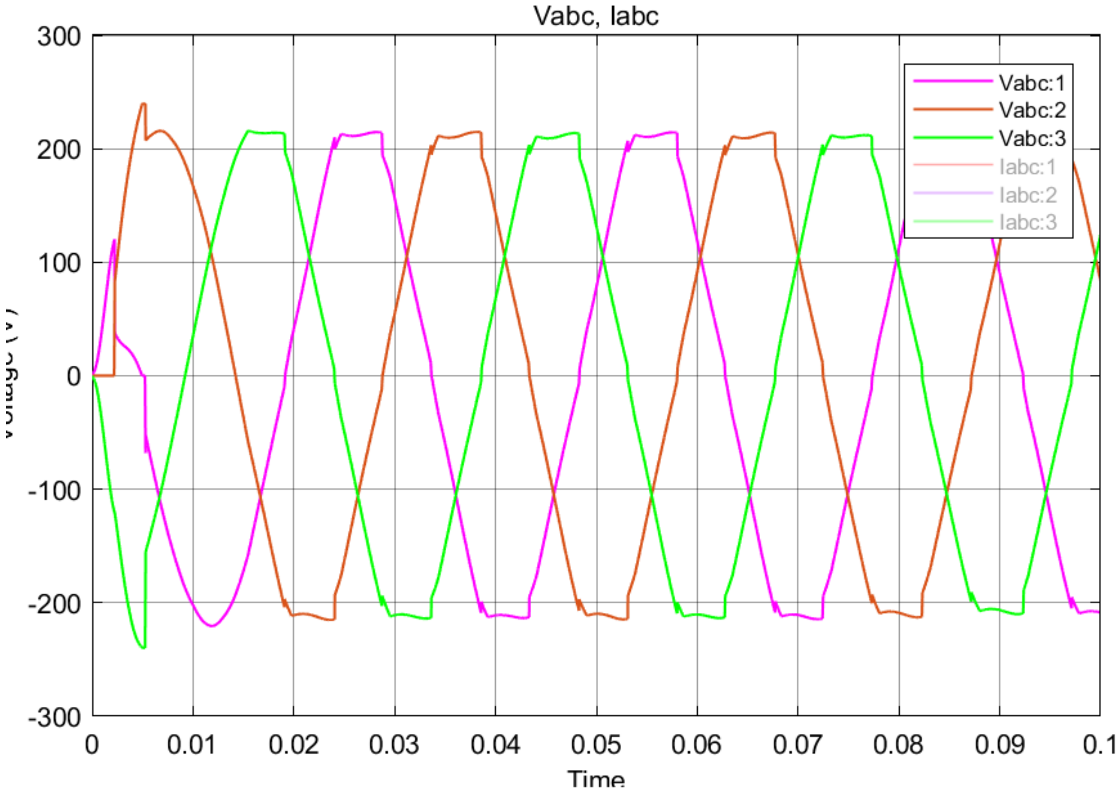


Figure 2 Input Voltage Waveforms of Diode Rectifier

The output voltage waveform is not a pure DC signal, in other words, the voltage ripple is very high on this waveform. Therefore, we used a shunt capacitor (100µF) to filter this signal. Then, we connected this output to the MOSFET of the buck converter. For the buck converter design 15mH inductor and 100µF capacitor are used. In the following Figure 3, this block of the design is shown, also in the next figure the input currents of the diodes are shown. These current values are important while selecting the proper diode.

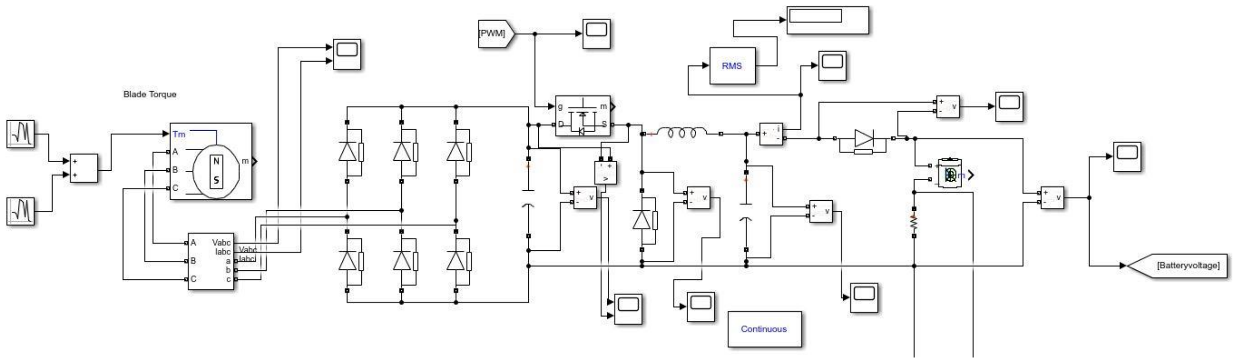


Figure 3 Diode Rectifier and Buck Converter Block

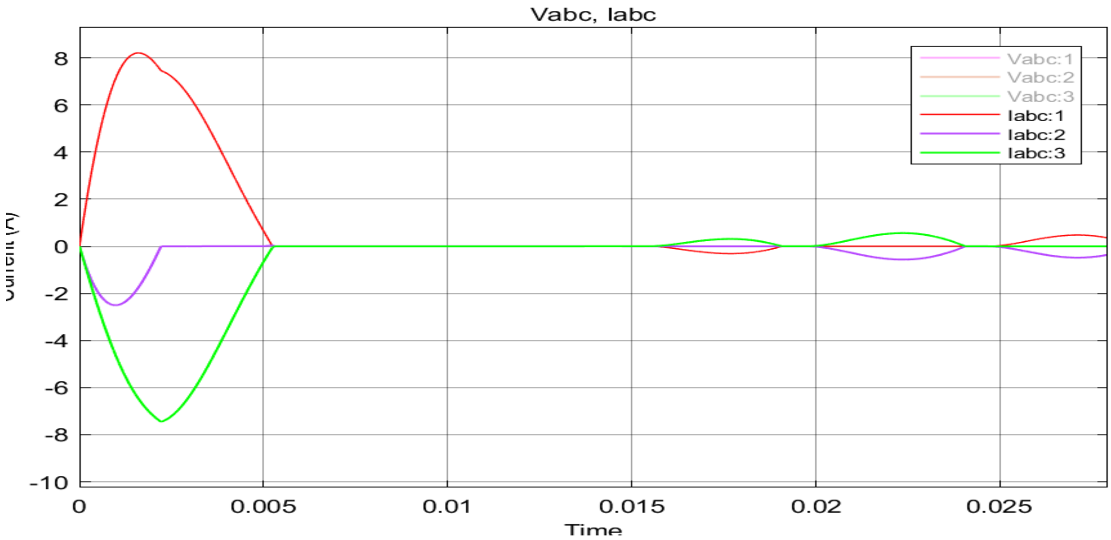


Figure 4 Input Current Waveforms of Diodes

3.2 Current Sense and Amplifier Block

In the project description, the input current value of the battery is given as a constant 2A and the ripple limit is 20% of the average current which is also specified in this description. Not to exceed this limit we connected a small resistor (250mΩ) to the negative leg of the battery. By checking the voltage on this resistor, we can understand the current flow through the resistor and hence the battery, and using this knowledge we can start our feedback loop; however, the resistance and current values are not high enough to decide the error. Therefore, we amplified this voltage value up to 3V and this block and this amplified voltage are shown in Figure 5 and Figure 6, respectively.

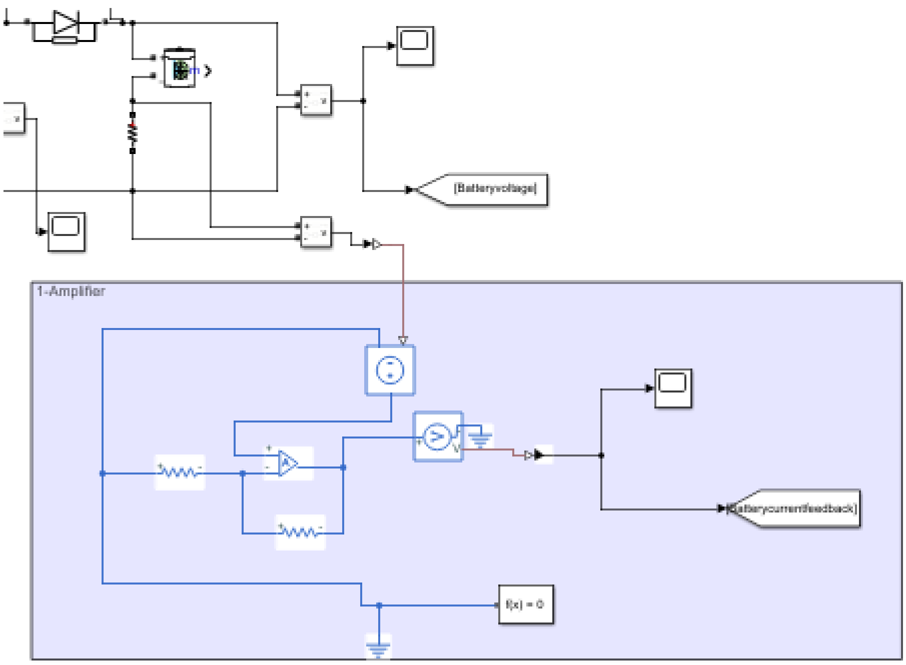


Figure 5 Current Sense and Amplifier Block

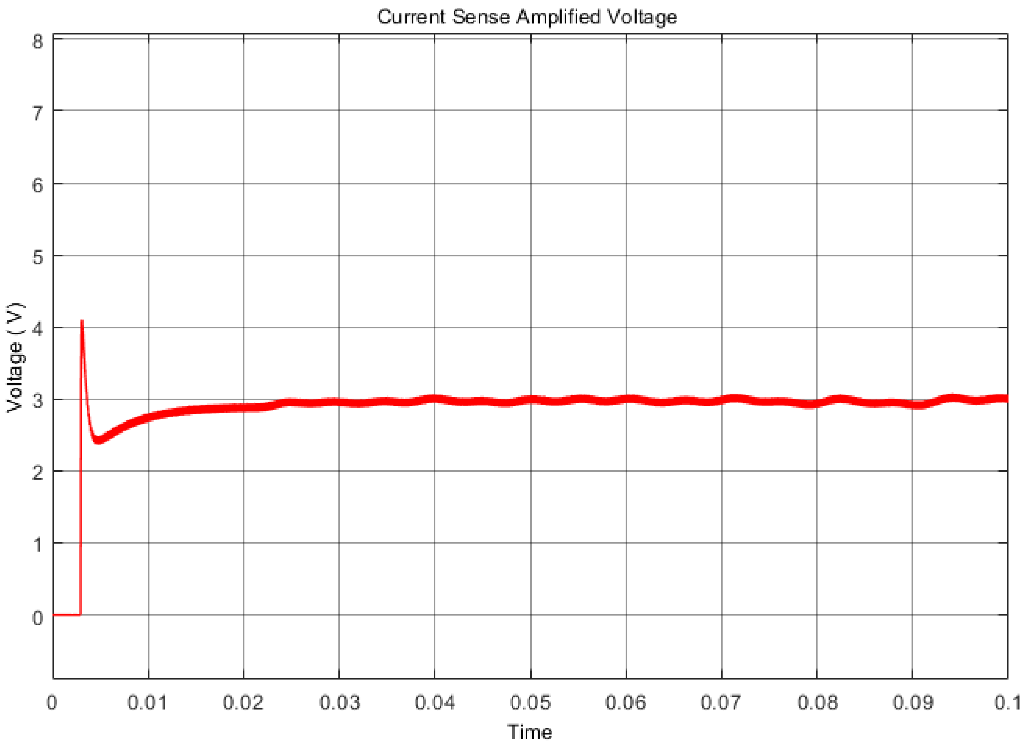


Figure 6 Waveform of Current Sense Amplified Voltage

3.3 DC Voltage Generator Block

In this design, we need to use DC voltages in some parts of the circuit such as feeding op-amps, the input of error amplifier, and input of 555timer component. Instead of using an external DC supply voltage, we use the battery input voltage. In the following Figure 7, the circuit schematic of this voltage generation block is shown. Note that, in this design, we need 2 and 5V values and their circuit schematic consist of two inverting amplifiers with different resistive values. In Figure 8 both 2V and 5V blocks' output values are shown.

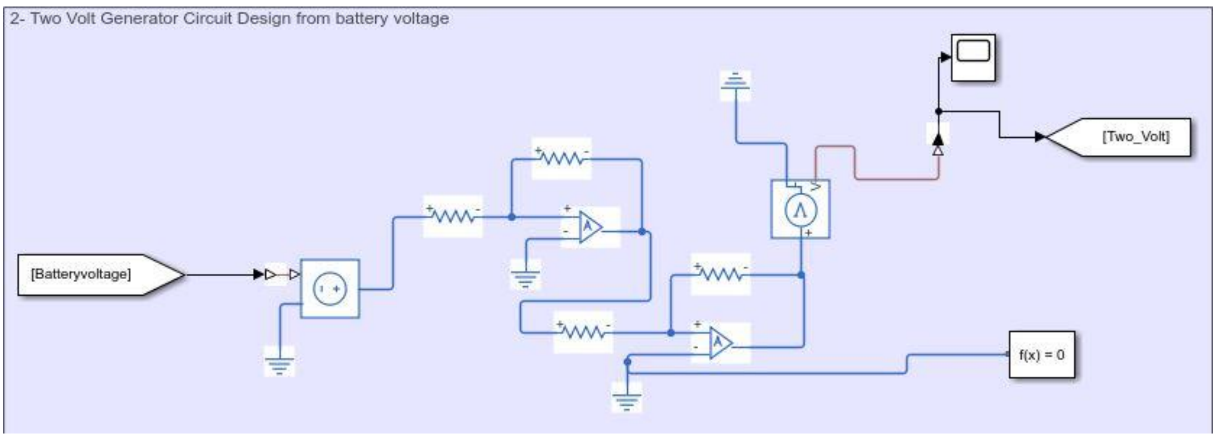
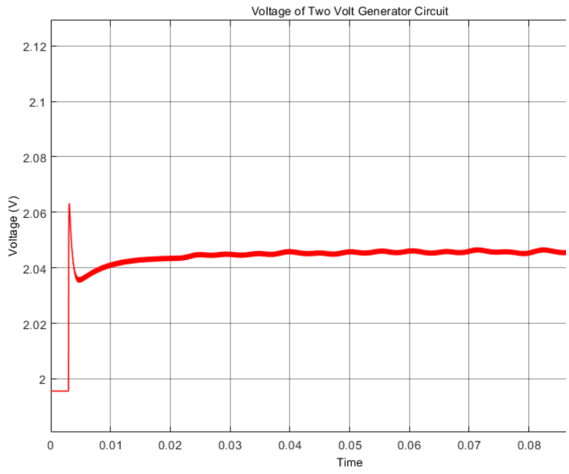


Figure 7 2 & 5V DC Generator Block



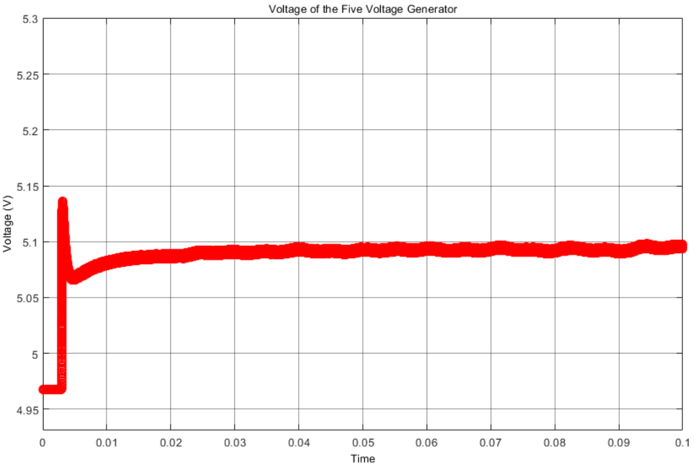


Figure 8 Output waveforms of 2- & 5-Volt Generation

3.4 Error Amplifier Block

In this part of the design, we found the error voltage using a differentiator circuit design. Using the 2 Volt DC and amplified current sense values, the difference between the (V+ & V-) input voltages of the op-amp is given as the output of this differentiator. Then, using this knowledge we can arrange the duty cycle of the buck converter. The positive error means that the current is lower than 2A and the duty cycle needs to be increased and if the negative error is observed, this time the current passing through the battery is higher than 2A and the duty cycle needs to be decreased in order to decrease the current value. The error amplifier block and the error signal can be shown in the following Figures 9 & 10, respectively.

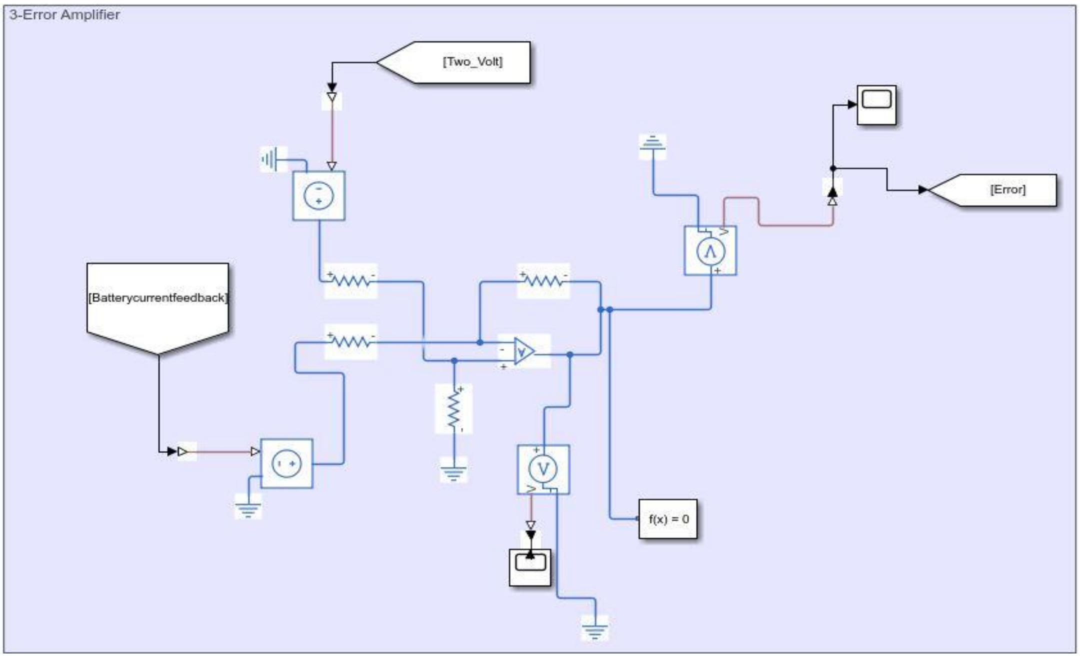


Figure 9 Error Amplifier Block

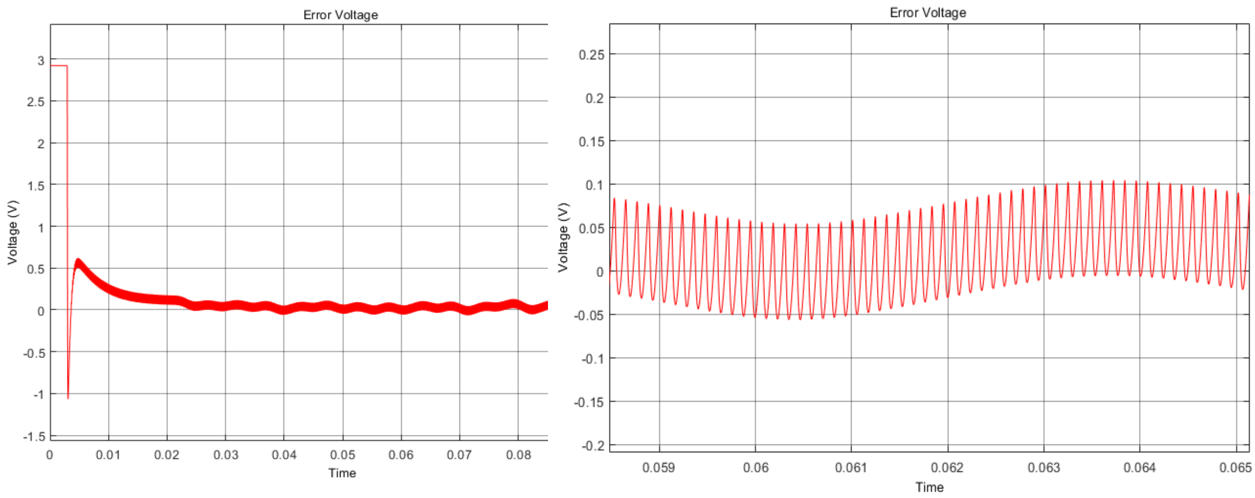


Figure 10 Error Voltage Waveform Before the Steady-State (Left Side) & Zoomed Version in the Steady-State (Right Side)

3.5 PI Controller Block

The aim of this block is to control the battery current using the error voltage which is explained in the previous section. As known, the transfer function of the PI Controller is $H(S) = K_p + \frac{K_i}{s}$, and to create this transfer function we used 3 sub-circuits that are proportional, integrator, and summer. If it is necessary to explain briefly, the proportional part amplifies the error voltage and the ratio of two resistors in this part is the important parameter. The integrator block takes the integral of error voltage and multiplication of resistor and capacitor values are the important parameter for this block. Finally, the summer block sums these two values. The following Figure 11 shows the PI Controller block and the output waveform of this block can be seen in Figure 12.

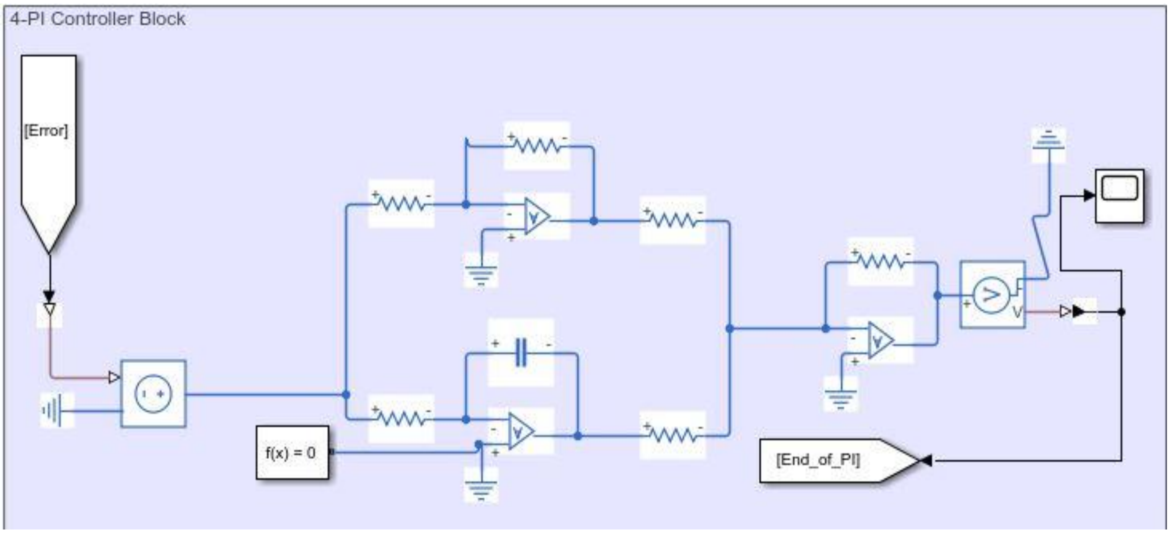


Figure 11 PI Controller Block

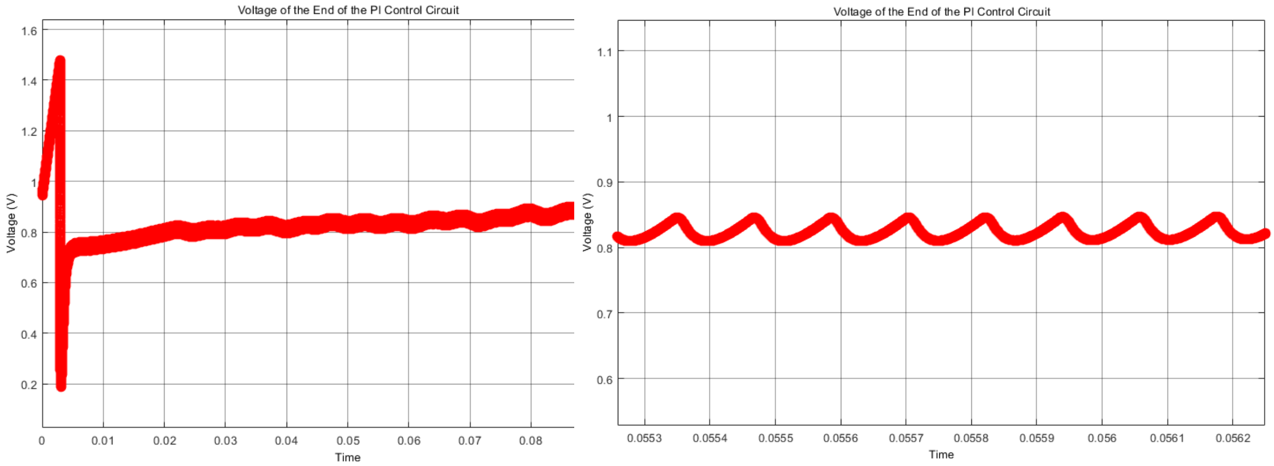


Figure 12 Output Voltage Waveform of the PI Controller Block (Zoomed Version is Shown in the Right Side)

3.6 PWM Generator Block

The last step of the feedback loop is generating the pulse voltage considering the output voltage of the PI Controller block. In this part, we used a common component called 555Timer and this creates the sawtooth signal. In order to activate this 555Timer device, we feed it with 5V which is mentioned in the previous sections of the report. Then using an op-amp, we can compare the output of the PI Controller, and this generated sawtooth voltage. After this comparison operation, the output is a form of a square wave, in other words, pulsating voltage waveform with changing duty cycle depending on the battery current. Both op-amp and Timer555 components create the PWM Generator block which is shown in the following Figure 13. Moreover, the output of this PWM generator can be seen in Figure 14. Note that, this voltage is directly connected with the gate of the MOSFET of the buck converter.

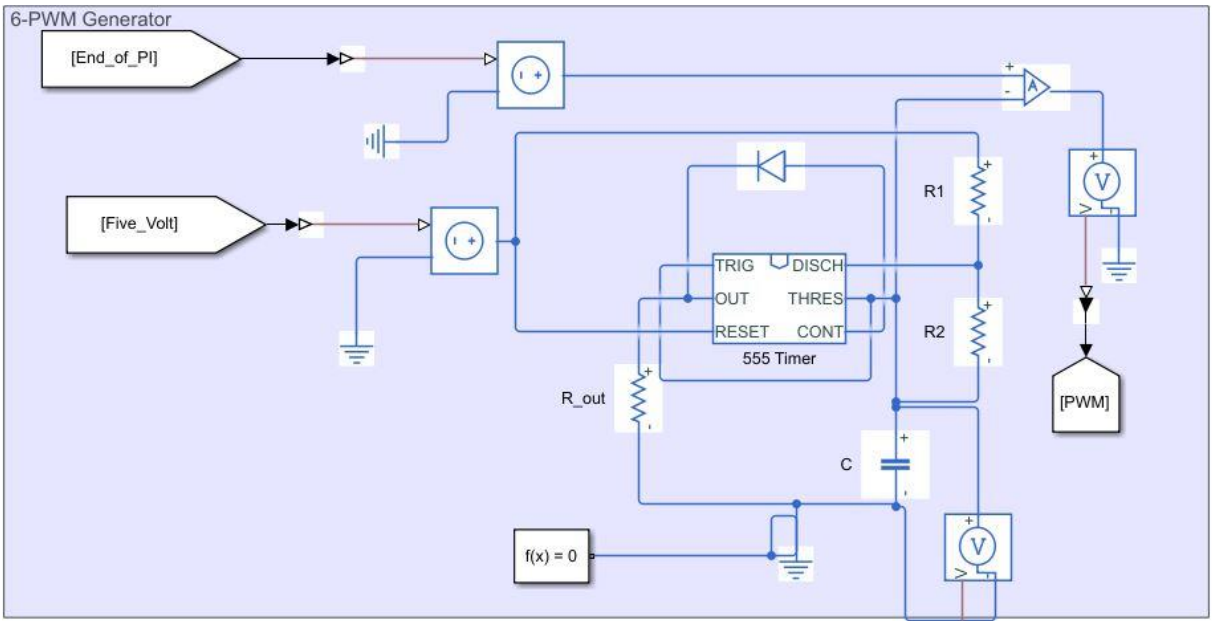


Figure 13 PWM Generator Block

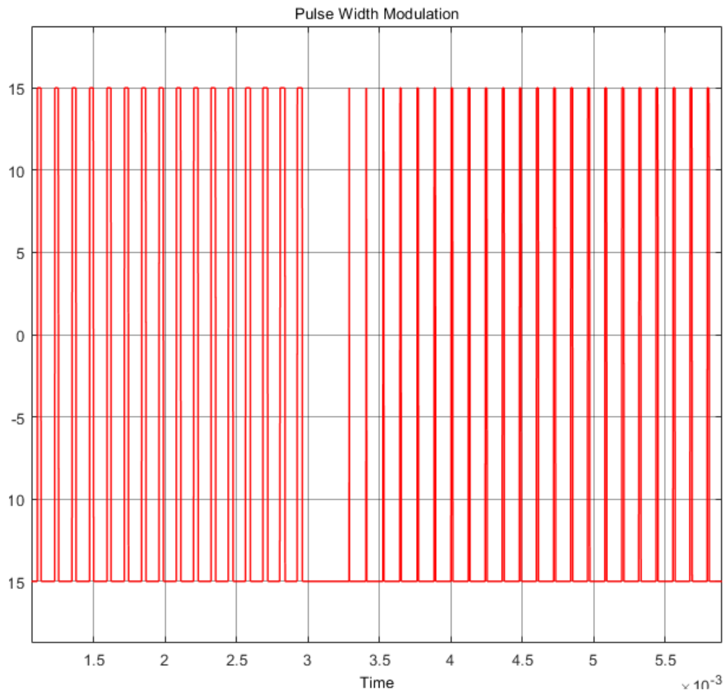


Figure 14 Input of the MOSFET's Gate

According to our simulation results in the previous report, at the end of this feedback loop, we were able to get an average of 2.013 A current through the battery. The ripple on this current was about 5% of the average current. In other words, it changed between 1.96 and 2.06A. In addition, when the circuit first started to work, the current suddenly increased to 5 A for a very short time. Thereupon, we reduced this peak current to around 2.75 A by arranging the necessary ratio by changing the resistor and capacitor value in the PI controller circuit. After making these changes, at the end of this feedback loop, we can achieve an average of 2A current through the battery. The peak to peak ripple on this current is about 5% of the average current. In other words, it changes between 1.95 and 2.05A in the following Figure 15, this battery current can be seen.

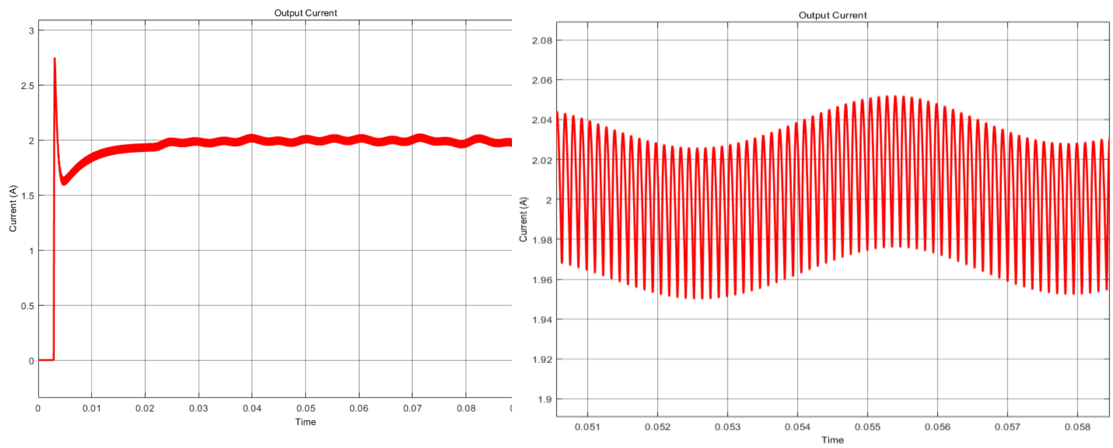


Figure 15 Waveform of the Output Current (Zoomed Version is Shown in the Right Side)

4. PERFORMANCE ANALYSIS OF THE DESIGN

In this section, the performance of the circuit design has been observed under different input voltage values by changing the input torque parameters. As it is known, the input voltage is AC and this AC voltage is obtained from the wind turbine. The input voltage can vary with the torque generated by the wind on the turbines. In this part, the performance of the design has been observed under different torque values and hence different input voltage values. At the end of this different condition experiment, it has been determined the performance of the whole system.

In Figure 16, the input torque value has been increased as much as possible. As can be seen from the figure below, the input voltage has converged to 800 V.

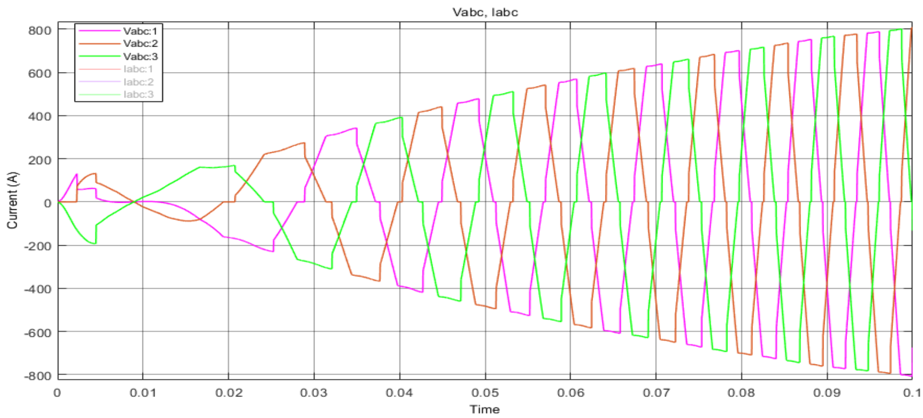


Figure 16 High Input Voltage Case

In Figure 17, the current flowing through the battery is shown. As can be seen from the figure below, when the input voltage is 800 V, the circuit also provides a current of around 2A to the battery. For this high input voltage condition, the performance of the design is slower; however, after some time it provides the necessary 2A to the battery.

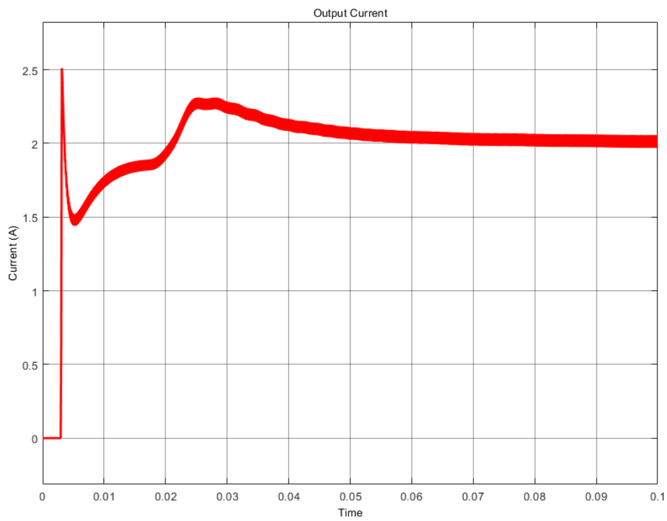


Figure 17 Performance Analysis of the Design for High Input Voltage Case

In Figure 18, the input torque has been decreased, then the input voltage has converged to 190V.

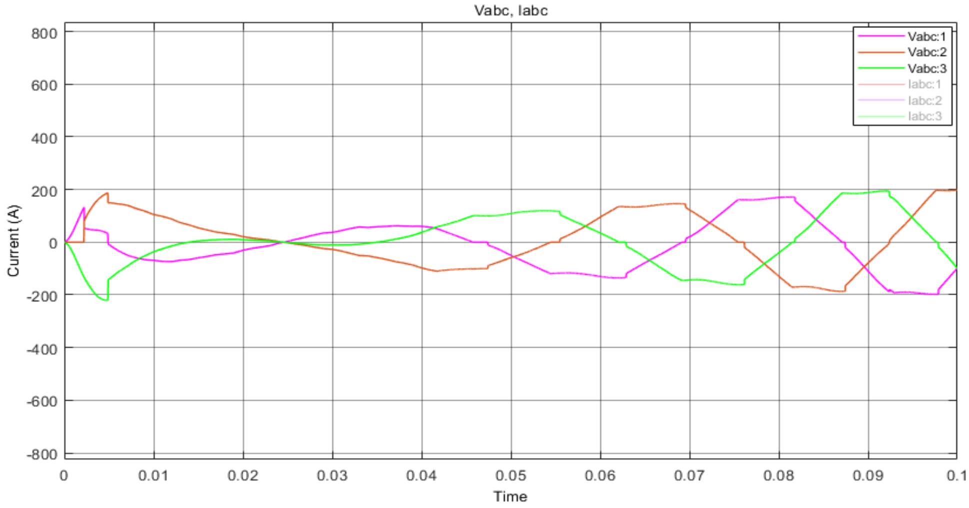


Figure 18 Low Input Voltage Case

In Figure 19, the current flowing through the battery is shown. As can be seen from the figure below, when the input voltage is 190V, the circuit design also provides a current of around 2A to the battery.

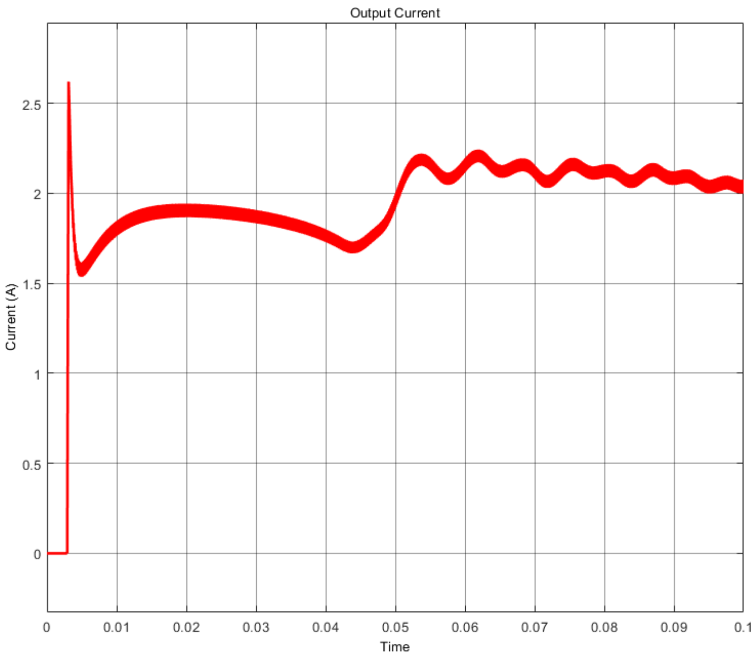


Figure 19 Performance Analysis of the Design for Low Input Voltage Case

As can be seen from the graphics above, our circuit that we designed provides an average of 2A to the battery even though the input torque has been changed. In other words, 2A passes through the battery. As a result, it can be said that the circuit we have designed can operate safely between 190-800 V input voltage range.

5. COMPONENT SELECTION

There are many issues to be considered while selecting parameters. The parameters we choose may vary depending on the area we will use. In addition, since the parameter values of the component, we will select will vary, these parameters should also be considered. Each component has its parameters that we can consider the most important. When choosing components for our system, we have made the selection by evaluating the component types suitable for the area we will use based on parameters. We decided the parameter values according to the simulation results we got from the circuit we designed, and the cost analysis for the design is shown in Table 2.

5.1 MOSFET Selection

While choosing the MOSFET, we selected by considering the maximum and rated values of voltage and current of our system. At first, we did not consider the warming phenomenon when choosing MOSFET. The MOSFET we chose did not have any function for self-cooling. In other words, we couldn't install any heatsink to dissipate the heat on the MOSFET. Later, to eliminate this problem, we chose one of the TO-220 packaged MOSFETs. In this way, we will be able to dissipate the heat on the MOSFET by attaching the heatsink. In addition, while choosing the MOSFET, we paid attention to the small R_{ds} value, since if this resistance value is not small, the loss on this MOSFET will be very high. In other words, the operating temperature will be very high, and to decrease this temperature value, a better heatsink should be used which may increase the cost and size of the design. In addition to these, what we expect from the selected MOSFET is that it meets the following values. However, these values may increase depending on the change of input torque. That's why we kept the voltage range of our MOSFET more than the following values for safety. Considering these values, we chose N-Type MOSFET.

Table 1 shows the maximum and rated values of voltage and current of our system.

Table 1 Maximum and Rated Values of Voltage and Current of our system

	Rated Value	**Max Value**
Voltage (V)	210	240
Current (A)	2	2.5

5.2 Diode Selection

While choosing the suitable diode, we determined the maximum voltage values of the diode I would choose by calculating the voltage of the diode in the circuit. We have diodes in 3 different places. The diodes we chose were selected to be used in the rectifier circuit, buck converter circuit, and before the battery. There are diodes specially designed for rectifier circuits. We made our choice by looking at the voltage rating. We calculated the voltage values of the diodes in the other two places with the help of Simulink and made the selection in that way. The diodes we selected are Schottky diodes.

Figure 20 shows the voltage waveforms of diodes at the buck converter and before the battery respectively. The diode before the battery is used as a safety diode.

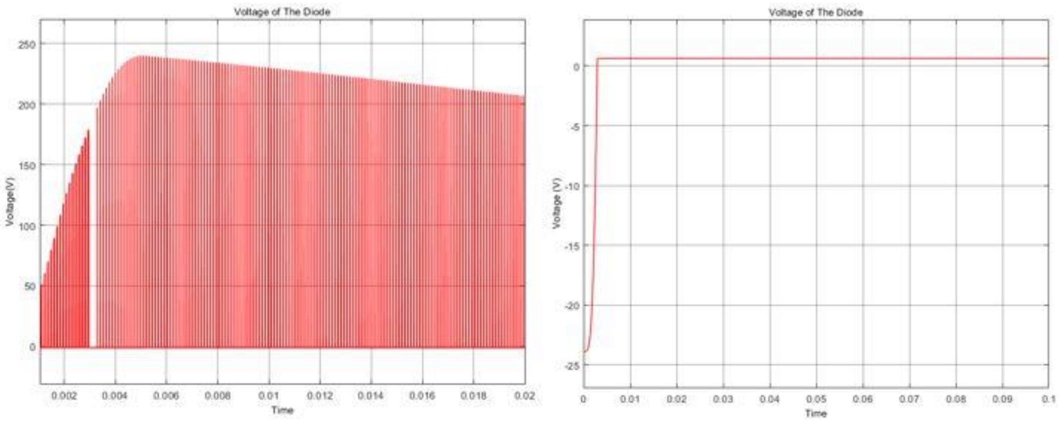


Figure 20 Voltage Waveforms of Diodes at the Buck Converter and Before the Battery Respectively

5.3 Capacitor Selection

While choosing capacitors, we calculated the voltage between capacitor terminals in the same way. Also, one of the other things to consider when choosing a capacitor is the size of the capacitor and its ripple factor. In addition to these, it is the endurance to current and voltage on the capacitor. Considering these, we made a capacitor selection. The capacitors we have selected are cheaper than others, the ripple factor is better. Also, their endurance performance is good enough and they have low ESR.

Figure 21 shows the voltage waveforms of the capacitors in our circuit. These capacitors were used at the output for filtering, a buck converter circuit, and TIMER 555 circuit for generating sawtooth signal respectively.

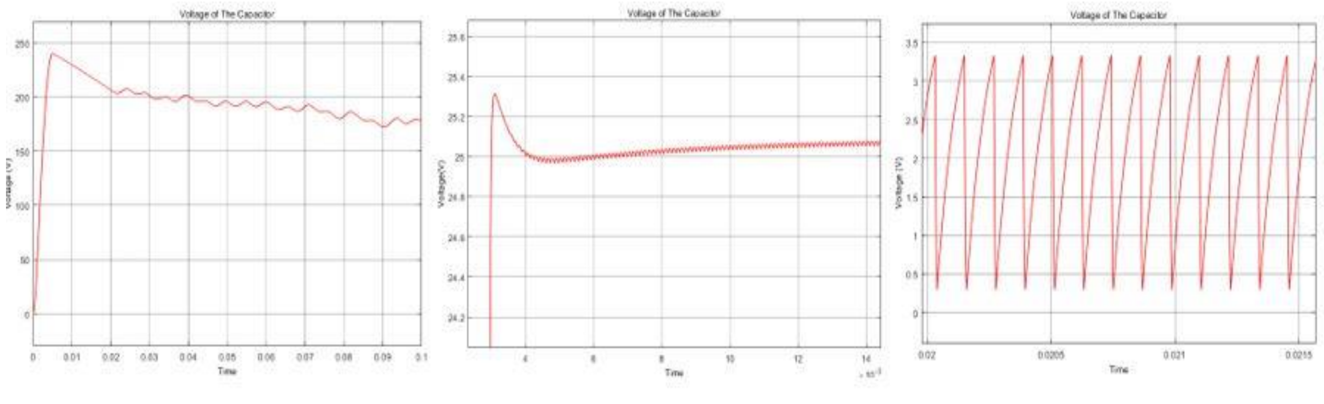


Figure 21 Waveforms of the Capacitors at Output, Buck Converter Circuit, and TIMER 555 Respectively

5.4 Inductor Selection

While choosing the inductor, we made a selection considering the current flowing through it and the voltage value of the system. We also tried to choose a low-cost inductor.

Figure 22 shows the current through the inductor. As can be seen from the graph, at first it takes a close order of 5A, but then it flows stably around 2A.

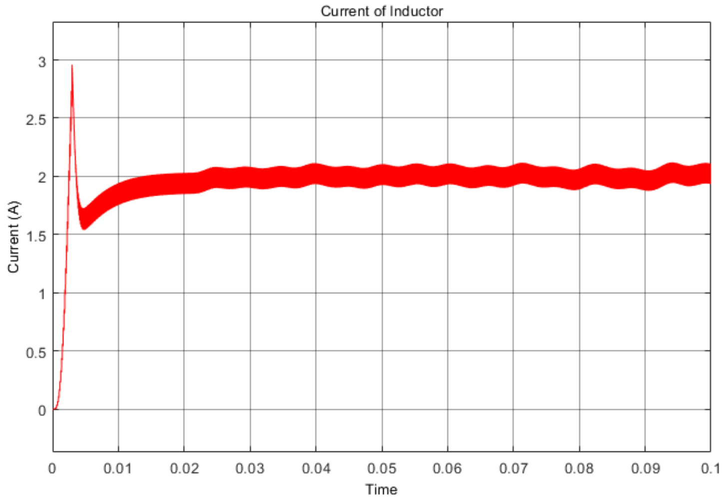


Figure 22 Current Waveform of the Inductor at the Buck Converter Circuit

5.5 Resistor Selection

One of the things we paid attention to when choosing a resistor was the material. Since the number of resistors in our circuit is high, we chose resistors made of a material with a low weight.

5.6 Op-Amp Selection

There are op-amps in 2 different regions in our circuit. One is in the main circuit; the others are in the feedback loop. While choosing op-amps in these places, we took into account the voltage values there. Our voltage value in the main circuit is too much compared to other places. For this reason, we have chosen an op-amp that has a higher endurance compared to the op-amps in the feedback loop.

5.7 Heatsink Selection

Due to resistance, R_{ds} on the MOSFET, and switching losses, the temperature of the component increases. This situation affects the performance of the circuit, even it may cause the MOSFET to burn. Clearly, this kind of problem results in a non-working circuit design. That's why temperature analysis must be made and a suitable heatsink should be selected. In the following subsection, this thermal analysis has been explained in detail.

Thermal Analysis

As mentioned before, there are two types of losses that cause a temperature increase. The first one is conductor loss and the reason for this loss is the resistance, R_{ds} on the MOSFET. This power loss can be calculated as follows.

$$P_{cond} = R_{ds} * I_{out}^2 * D$$

In the above equation, D represents the duty cycle and it can be found with the common formula for buck converters as can be seen as follows.

$$D = \frac{V_{out}}{V_{in}}$$

In this project these values are not constant; however, we can use their approximate values, and the duty cycle can be calculated.

$$D = \frac{24}{210} = 0.115$$

The drain-source resistance is given in the datasheet of the selected MOSFET as 2.2Ω. Finally, the desired output current is 2A. The reason why the current must be multiplied with the duty cycle is that when the switch is off position there is no current flow passing through the MOSFET and hence there is no conduction power loss. In short, the conduction power loss can be calculated as follows.

$$P_{cond} = 2.2 * 2^2 * 0.115 = 1.012\ W$$

The second power loss type is switching loss. Clearly, the reason for this power loss is switching operation and it directly proportional to the switching frequency, the sum of rise and fall time. The switching power loss can be calculated as follows.

$$P_{sw} = \frac{1}{2} * V_{in} * I_{out} * f_{sw} * \left(t_{rise} + t_{fall}\right)$$

$$P_{sw} = 0.5 * 210 * 2 * 8.34 * 10^3 * 646.4 * 10^{-9} = 1.132\ W$$

Then the total power loss can be calculated as follows.

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 1.012 + 1.132 = 2.144\ W$$

This power loss causes the temperature to increase. Assuming the ambient temperature is 25ºC, the junction temperature without a heatsink can be calculated as follows.

$$T_{junction} = T_{ambient} + P_{total} * R_{thJA}$$

In the above equation, R_{thJA} represents the resistance between junction to ambient, and this value is also given in the datasheet of the MOSFET. All the thermal parameters of MOSFET can be seen in the following Figure 23.

THERMAL RESISTANCE RATINGS				
PARAMETER	SYMBOL	TYP.	MAX.	UNIT
Maximum Junction-to-Ambient	R_{thJA}	-	62	°C/W
Case-to-Sink, Flat, Greased Surface	R_{thCS}	0.50	-	
Maximum Junction-to-Case (Drain)	R_{thJC}	-	1.7	

Figure 23 Thermal Parameters of the Selected MOSFET

$$T_{junction} = 25 + 2.144 * 62 = 157.93^{0}C$$

Clearly, the operating temperature is very high and most probably the MOSFET cannot withstand this temperature value. Therefore, using a heatsink to decrease the operating temperature could be a good solution for this problem. The following equation shows the calculation of minimum thermal resistance of the heatsink, R_{HA} for below 75ºC operating temperature.

$$R_{HA} < \frac{T_{junction} - T_{ambient}}{P_{total}} - R_{thCS} - R_{thJC}$$

$$R_{HA} < \frac{75 - 25}{2.144} - 0.5 - 1.7$$

$$R_{HA} < 21.12 \ {}^{0}C/W$$

While selecting a proper heatsink, there are some important things that should be considered. These important points have been listed as follows.

- *The thermal resistance of the heat sink*: As calculated above the thermal resistance value affects the operating temperature which directly affects the performance of the temperature. Therefore, a smaller thermal resistance value means better performance.
- *Size of the heatsink:* In the PCB design, heatsink is one of the biggest components. To minimize the design, a high size heatsink should not be selected.
- *Suitable with TO-220 pack:* The heatsink also should be suitable with the selected MOSFET in the buck converter. As mentioned before, the pack of the MOSFET is TO220. Therefore, suitability is also important to integrate the heatsink into the design.

Considering the above points, the selected heatsink model is ML8G which is manufactured by AAVID THERMALLOY. The dimensions of this heatsink are 12.3x29x35mm (LxWxH). It is suitable with the TO-220 package and has 13 ºC/W thermal resistance. After selecting the heatsink, the operating temperature can be calculated as follows.

$$T_{junction} = P_{total} * \left(R_{HA} + R_{thCS} + R_{thJC}\right) + T_{ambient}$$

$$T_{junction} = 2.144 * (13 + 0.5 + 1.7) + 25$$

$$T_{junction} = 57.588 \ {}^{0}C$$

As a result, as can be seen in the above calculation, the operating temperature has been decreased from 157.93ºC to 57.58ºC by using the selected heatsink.

6. PCB Design

While designing a PCB, some EMI (Electro-Magnetic Interfere) issues have been considered. These considered points are explained in the following subsection.

Electro Magnetic Interfere (EMI)

What is EMI?

According to Maxwell equations, changes in the electrical field causes a change in the

magnetic field the opposite of it is also correct. This effect can be called EMI and designing a PCB has a big role to make some decisions. Some tricks are listed below.

- *Trace Spacing Layout:* Traces are the conducting paths on which the current flows. If those traces are very close to each other, there should be some capacitive effect between them. To prevent this capacitive effect on the design performance, most of the time the distance between traces on PCB has been left 3 times of the trace width.
- *Using Sharp Bends:* Using 90º turns on the traces increases the capacitive effect and change of characteristic impedance of traces. Therefore, most of the time, sharp bends have been used in the PCB design stage. In the following Figure 24, some possible bends usage from the worst choice to the best.

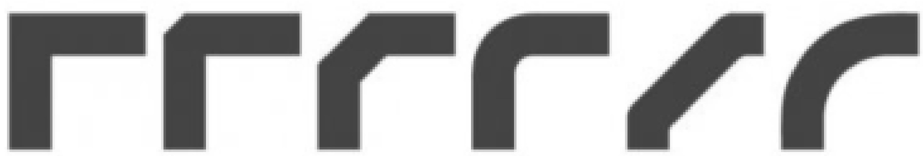


Figure 24 Corner examples of traces from the worst case to the best one

- *Grounding:* In all circuit designs, the ground point is used as a reference bus. While designing a PCB using more than one ground line may cause some voltage difference between those ground points. This situation results in using different references in the same circuit design and hence the performance of the circuit may be affected by this difference.

The above tricks can be increased, and these issues are not insignificant. In industry, an electronic device should be taken CE certificate to be released. To make this certificate, some EMC (Electro Magnetic Compatibility) standards must be provided. These standards have been specified based on the EMI performance of the designs. Therefore, in the designing steps, using these kinds of tricks may increase the EMC performance of the product.

Considering the above tricks, the PCB for this project has been designed, and in the following Figure 25, Figure 26 & Figure 27 shows 2D and 3D views from different perspectives of the PCB design.

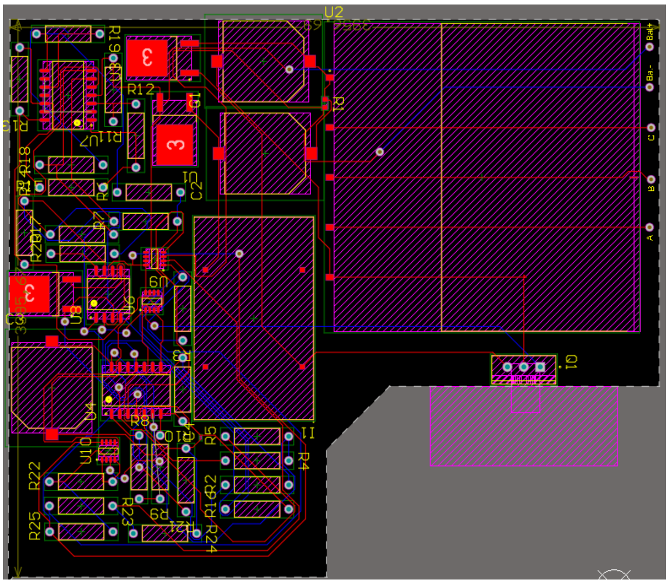


Figure 25 2D view of PCB Design

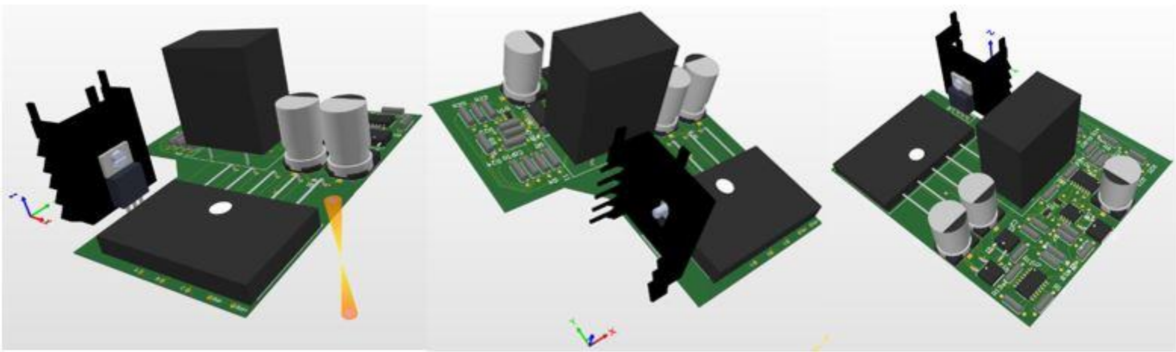


Figure 26 3D view of PCB Design from Different Perspectives

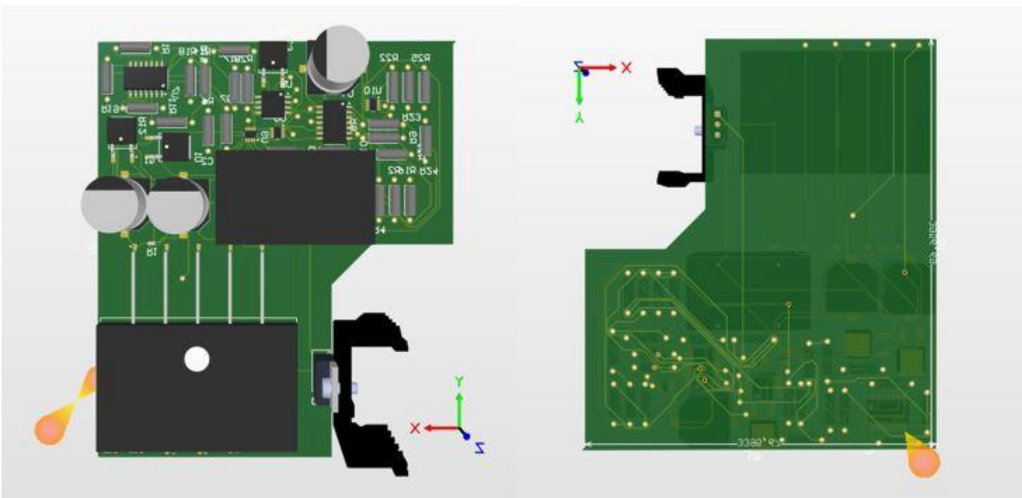


Figure 27 3D view of PCB Design from Top and Bottom views

Figure 28 shows the box that has been designed to cover the PCB design. The dimensions of the box are 45 × 90 × 105 mm. We adjusted the dimensions in this way to fit inside the PCB. Also, since the circuit will be in a closed box, it may have a heating problem. To prevent this, we drilled holes in the surfaces in the corner of the heatsink. Thus, the heatsink will be able to contact with air comfortably. In this way, we will solve the heating problem.

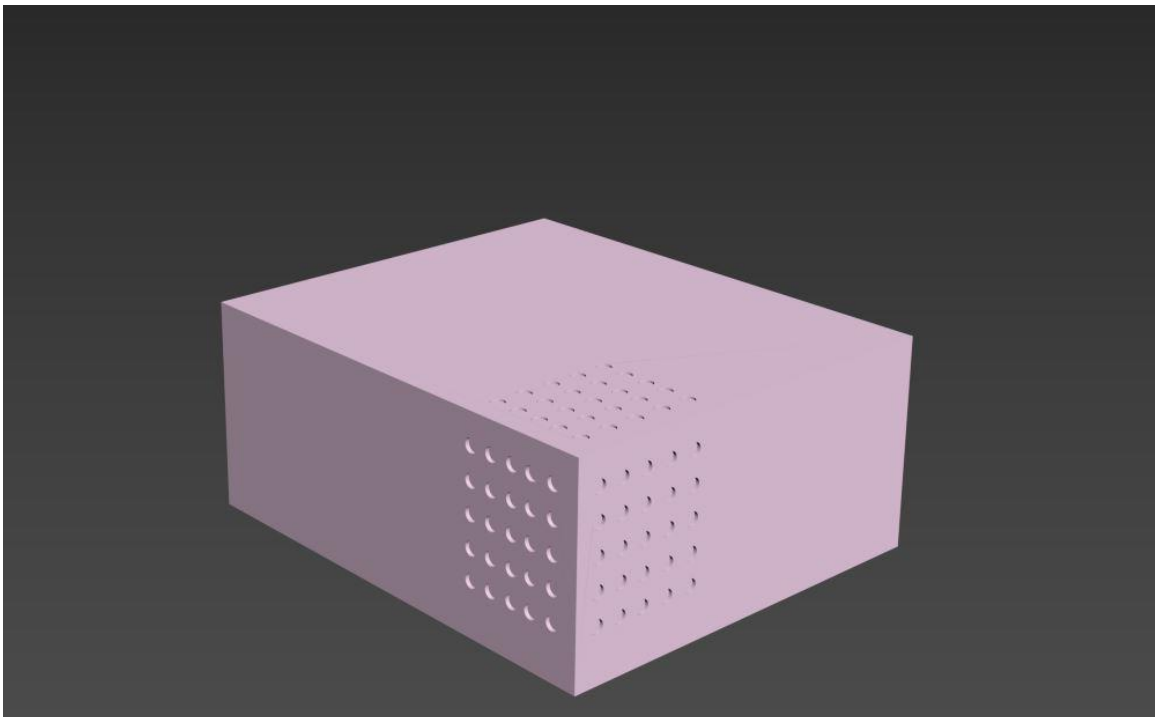


Figure 28 The View of the PCB Box

7. COST ANALYSIS

Table 2 Cost Analysis of the Design

Component	Rated Value	Place in the Circuit	Type of the Component	Manufacturer	Serial Number	Unit Price ($)	Total Price ($)
Resistors (Ω)	0.25	Current Sense	Chip Resistor - Surface Moun	Venkel	LCR0603-R250FT	0.03062	30.62
	1k	2 Volt Generator	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4C102J	0.011	11
	5.1k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
			CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
	12k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R123J	0.011	11
	560	5 Volt Generator	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R561J	0.01738	17.38
	2.7k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R272J	0.01738	17.38
	5.1k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
			CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
	240	Amplifier	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R241J	0.01738	17.38
	1.2k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R122J	0.011	11
	1.2k	Error Amplifier	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R122J	0.011	11
	3.3k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R332J	0.011	11
	5.1k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
			CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R512J	0.00848	8.48
	680	PI Controller	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R681J	0.00848	8.48
	820		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R821J	0.01738	17.38
			CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R821J	0.01738	17.38
	2.2k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R222J	0.01738	17.38
	8.6k		CARBON FILM RESISTOR	Stackpole Electronics Inc	RNF18FTD8K60	0.0085	8.5
	5.6k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R562J	0.011	11
	1.2k	Timer	CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CFS1/4CT52R122J	0.00848	8.48
	3.3k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/4CT52R332J	0.011	11
	100k		CARBON FILM RESISTOR	KOA Speer Electronics, Inc.	CF1/2CT52R104J	0.01738	17.38
Capacitors (F)	100µF	Buck Converter	Aluminum Electrolytic	Illinois Capacitor	107RZM05	0.15351	153.51
	100µF	Filter	Aluminum Electrolytic	United Chemi-Con	EKXJ221ELL101MK25	0.71258	712.58
	5µF	PI Controller	Aluminum Electrolytic	Vishay Sprague	TE1404	1.5636	1563.6
	1nF	Timer	Ceramic	Yageo	CC0100KRX5R4BB102	0.01475	14.75
Inductor (H)	15mH	Buck Converter	Fixed RING CORE CHOKE	EPCOS/TDK	871-B82724J8302N040	2.9524	2952.4
MOSFET	240V (max), 210V(Rated); 5A (max), 2A (Rated)	Buck Converter	N-MOSFET	Vishay Siliconix	IRFBC30APBF	1.386	1386
Diodes	Not Applicabl	Rectifier (6)	Bridge Rectifier	Micro Commercial Components	833-3GBJ3516-BP	16.8432	16843.2
		Buck Converter	Schottky Diode	Wolfspeed / Cree	941-C6D04065E	0.89177	891.77
		Before the battery	Schottky Diode	Vishay General Semiconducto	78-V8PAM10S-M3/H	0.15246	152.46
		Timer	IC OSC SINGLE TIMER	Texas Instruments	296-1857-5-ND	0.3584	358.4
LM324 (x2)	Not Applicabl	2 Volt Generator (2 OP-APM) 5 Volt Generator (2 OP-APM) PI Controller (3 OP-AMP) Error Amplifier (1 OP-AMP)	QUADRUPLE OP-AMP	Texas Instruments	595-LM324KADR	0.363	363
OP-AMP	Not Applicabl	Timer	Operational-Amplifier	NJR	513-NJU7067M-TE2	0.09075	90.75
OP-AMP	Not Applicabl	Current Sense	Operational-Amplifier	Texas Instruments	595-OPA2990IDDFR	0.69454	694.54
PCB	Not Applicabl	Not Applicable	Not Applicable	PCBWay	Not Applicable	1.022	1022
TOTAL COST =						27.50458	27504.58

The above Table 2 shows the cost analysis to manufacture 1000 times from the circuit design. It can be seen that per circuit cost is $27.50. Note that the details of PCB cost analysis are shown in the Appendix part.

8. CONCLUSION

In this project, we aimed to regulate the output current of a wind turbine to charge a battery with constant voltage and constant current. In this report, the project and its processes are explained. First of all, topology selection is explained. After that, the circuit is analyzed, and its simulation results are provided with the components that are selected for the project. To choose a suitable component, necessary analysis such as thermal analysis is shown. Furthermore, the PCB design steps are also shown. Finally, the cost analysis is provided for the component selection.

Starting with this early stage of the project, we have improved our engineering skills on circuit design and simulation and management skills with the cost analysis of the project. In conclusion, by implementing this project, we have improved our skills to use the theoretical knowledge from the EE463 course.

Appendix

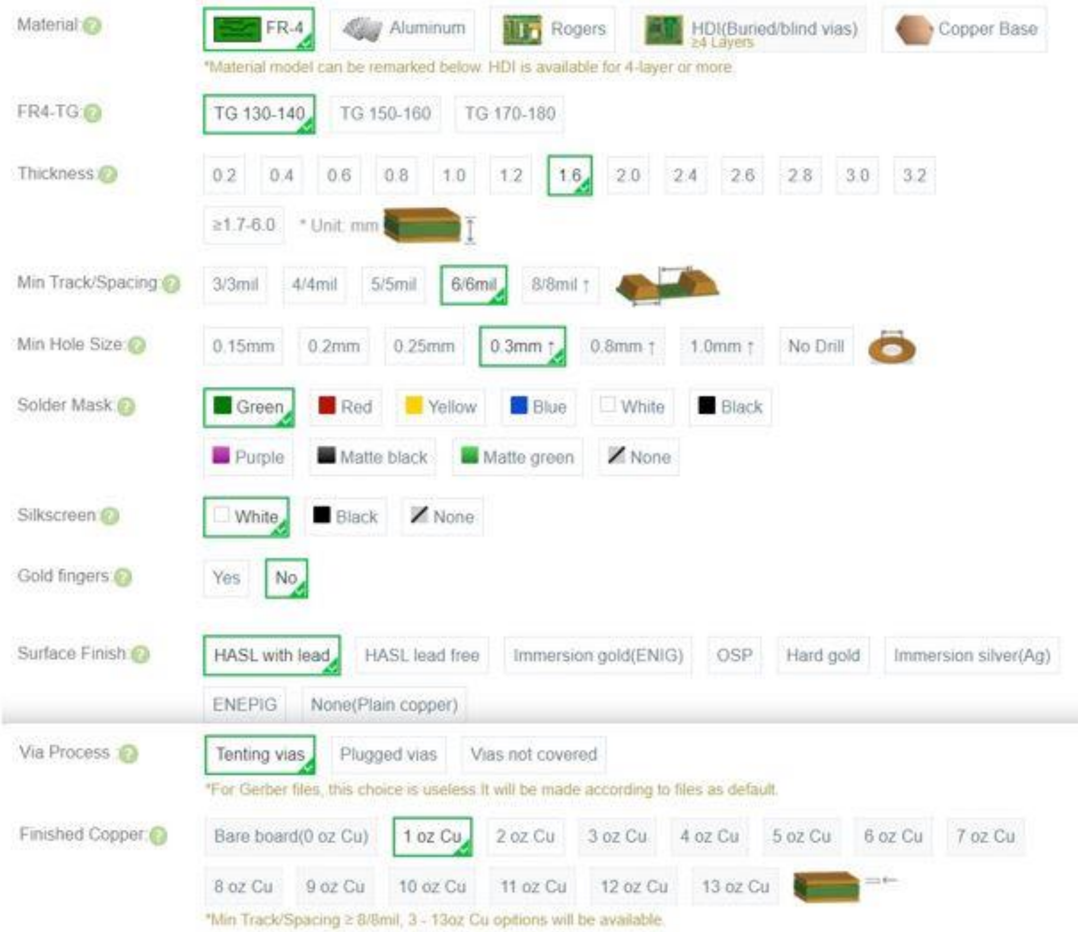


Figure 29 Specifications of the PCB Design

Figure 30 Cost Analysis to manufacture 1000 PCB