MIDDLE EAST TECHNICAL UNIVERSITY
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE463 Term Project: Wind Turbine Battery Charger

Simulation Report

Group SoC

Canberk Kaçan 2443240
Onat Şimşek 2375772
Selen Özge Özgür 2375566

ABSTRACT **3**
INTRODUCTION & SPECIFICATIONS **3**
TOPOLOGY SELECTION **4**
THREE PHASE THYRISTOR 4
Advantages 4
Disadvantages 4
THREE-PHASE DIODE RECTIFIER WITH BUCK CONVERTER 5
Advantages 5
Disadvantages 5
THREE PHASE THREE-LEVEL PWM RECTIFIER 6
Advantages 6
Disadvantages 6
DECISION 6
ANALYTICAL CALCULATIONS **8**
SIMULATION RESULTS **9**
Three Phase FBDR 10
Buck Converter 11
MOSFET 12
Inductor 12
Diode 12
Capacitor 13
Battery 13
Controller Selection 14
COMPONENT SELECTION **16**
Three Phase FBDR 16
Diode Rectifier 16
Capacitor 16
Buck Converter 17
MOSFET 17
Diode 17
Inductor 18
Capacitor 18
Battery Side 18
Current Sensing Resistor 18
Diode 19
REFERENCES **20**

ABSTRACT

In order to introduce the initial design of the Term Project for the EE463 Static Power Conversion course, our SoC group has compiled this simulation report. The primary objective of the term project is to create an AC-DC converter to charge the battery by using a small wind turbine generator. This report includes potential solution approaches, provides a detailed discussion of each, simulates in the Simulink environment to meet specified requirements, selects appropriate components based on crucial parameters, and outlines the PCB design necessary for product realization.

INTRODUCTION & SPECIFICATIONS

In this project, we are going to create a battery charging system utilizing power generated by a small wind turbine generator. The objective is to develop a design that effectively manages the input power from the wind turbine generator, ensuring a stable supply to both the load and the battery. This entails designing an AC to DC power converter circuit with the necessary control mechanisms. Since the wind speed is not constant, we need to design a system that gives the same output current while the input voltage is changing. Design specifications are given below:

- Input voltage: 15
- Vline-to-line to 25
- Vline-to-line Battery capacity: 100 Ah
- Battery nominal voltage: 12 V
- Output current: 10 A
- Output current ripple: %20 of the average current

TOPOLOGY SELECTION

In this section, we are going to discuss the advantages and disadvantages of two topologies, which are three-phase thyristor rectifier and three-phase diode rectifier+buck converter, to choose which topology we are going to use.

THREE-PHASE THYRISTOR

Three-phase thyristor rectifiers are composed of 6 thyristors and a controller. The three-phase full-wave thyristor rectifier topology is given in Figure 1.

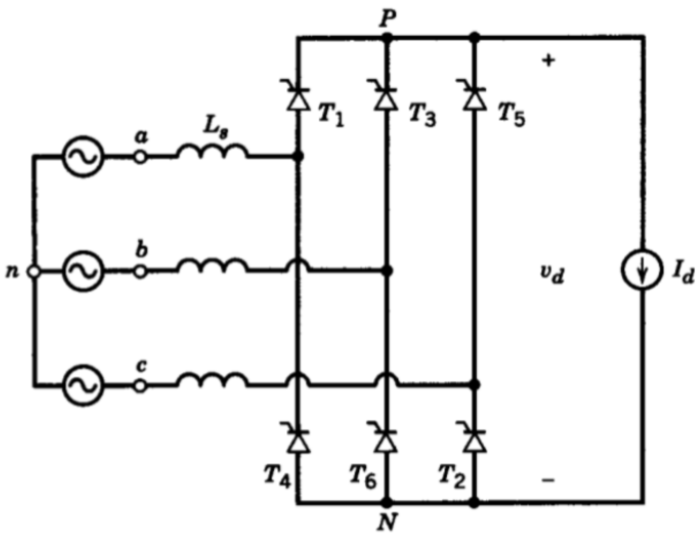


Figure 1: Three-phase full-wave thyristor rectifier topology

$$V_{d(\alpha)} = \frac{3\sqrt{2}}{\pi} V_{ll,rms} cos(\alpha) - \frac{3\omega LsId}{\pi}$$

Advantages:

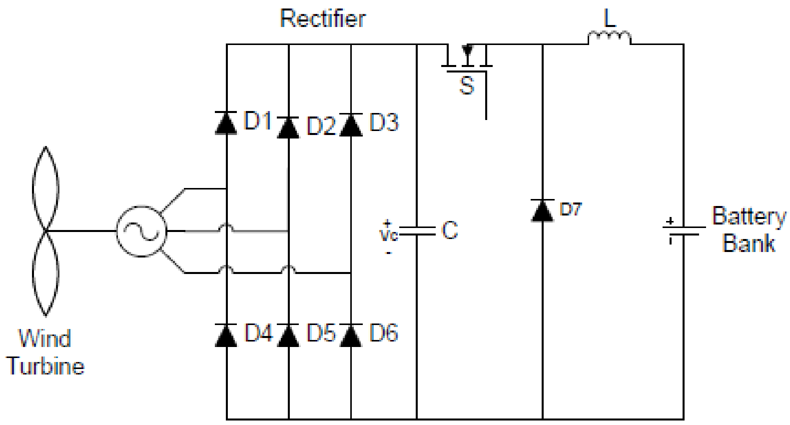
Thyristor rectifiers can handle high voltage and high current.
There is no need for extra topology; six thyristors are enough. By adjusting the fringing angle, we can set the average output voltage.
Since we do not need to use capacitors and inductors, the design would be smaller and more compact.

Disadvantages:

Thyristors are expensive components, and we need to use other components for control purposes, which increases the cost.
We need to control six different thyristors by adjusting their firing angle, which is possible, but it is a complex procedure and will take too much time.

THREE-PHASE DIODE RECTIFIER WITH BUCK CONVERTER

The three-phase diode rectifier+buck converter topology consists of 6 diodes and a buck converter. The topology is given in Figure 2.



$$V_{avg} = \frac{3\sqrt{2}}{\pi} V_{LL} D$$

Figure 2: Three-phase diode rectifier+buck converter

Advantages:

Although we use more components when we compare to the first topology, the cost would not increase much when we compare with the first topology because the cost of the thyristor is much when we compare diodes, capacitors, inductors, etc.
Controlling is easy when we compare it to the first topology.

Disadvantages:

Using an extra capacitor, inductor, MOSFET and diode increases the size of the design.
It may need a greater heat sink due to power MOSFET.

THREE-PHASE THREE-LEVEL PWM RECTIFIER

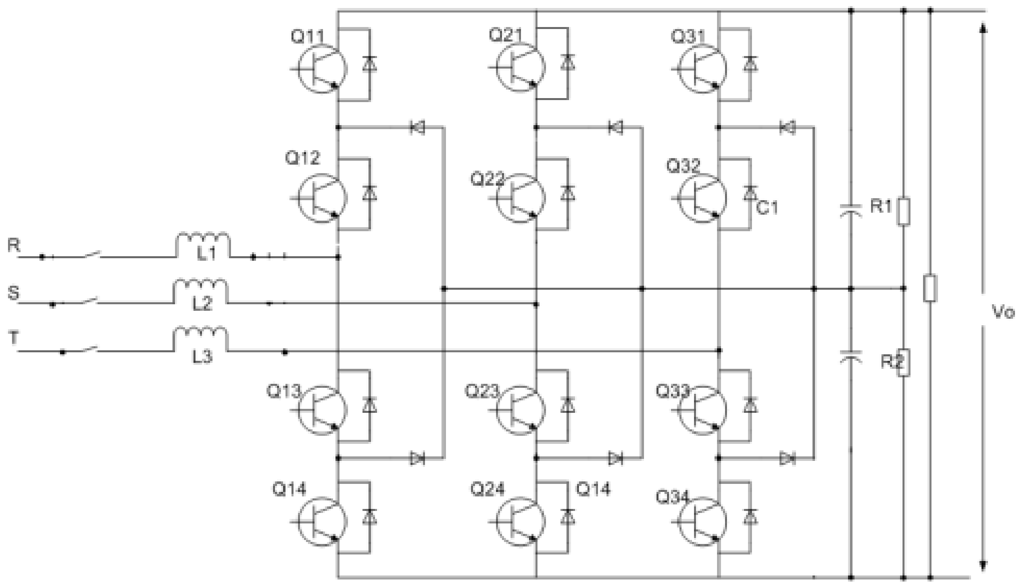


Figure 3: Three-phase three-level PWM rectifier topology

Advantages:

Controllable output power.
Controllable power factor, high power factor with low THD.
High efficiency.

Disadvantages:

Cost can be increased due to the number of components.
Control of the converter is challenging.
The large number of switching elements can cause electromagnetic interference and parasitic effects.

DECISION

As the group SoC, we are going to use three-phase diode rectifiers and buck converter topology. The reasons for this choice:

Controlling is easy when we compare it to the first topology.
Thyristor's advantage is that it is able to work in high current and high voltage applications, but the voltages and currents that we are going to work with are low.
We have limited time, and in the following weeks, our busy periods will start. Easy implementation is a crucial factor in choosing this topology.

Moreover, since we decided to implement three-phase diode rectifiers and buck converter topology, and since a buck converter is a type of SMPS (switch mode power supply), we also need to determine the switching frequency f_s, which was determined by trial and error method in the simulation, and by using application report in [1]. Switching frequency affects the switching losses, which occur when the device turns on and off.

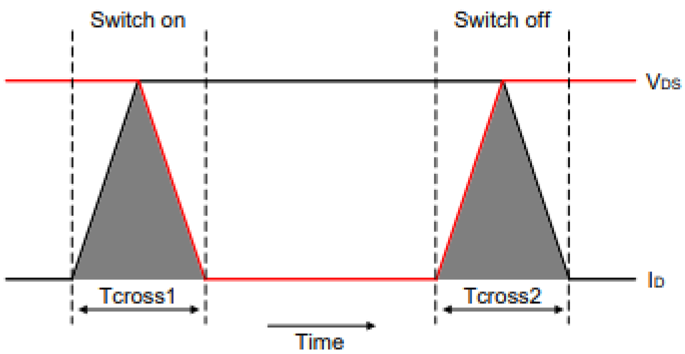


Figure 4: The voltage and current waveform when switching an inductive load

By using Figure 4, the switching losses, which is the area enclosed in the above figure, can be calculated in the following way:

$$E = \int_{0}^{t_{cross}} V(t)I(t)dt = V_{DSmax} I_D t_{cross}$$

where
V_{DSmax} is the voltage across the switch (when it is OFF)
I_{Dmax} is the current through it (when it is ON)
t_{cross} is the crossover time during turn-on and turn-off, respectively.

Since E corresponds to energy in the above equation, the power lost due to switching can be computed by the following equation:

$$P = V_{DSmax} I_D t_{cross} f_s$$

It can be concluded that as the switching frequency increases, the power losses increase. This is an expected case since the switching occurs as the switching frequency in one second.
On the other hand, as the switching frequency increases, the sizes of the filtering components, which are the inductor and the capacitor, also decrease. This can be validated by considering the characteristics of both the inductor and the capacitor. Since both of them are energy-storing elements, as the switching frequency increases, the time they need to supply and store energy decreases, which is the main reason for their sizes.
Furthermore, as the switching frequency increases, both the voltage and the current ripple at the output decreases since the time for the capacitor to discharge and the time for the inductor to supply current to the circuit decreases.
Although the above discussions are valid, according to [1], when we tried to increase the switching frequency in the simulation linearly from 20kHz to 100kHz, we realized that the size of the filtering elements did not decrease too much. Hence, in order to limit the switching losses in the system, we decided to have a switching frequency of 50kHz.

ANALYTICAL CALCULATIONS

Instead of jumping through the simulation part directly, we have made some calculations to find the critical values of the components. Using [2], [3] and Assoc. Prof. Keysan's notes allowed us to do some calculations. You can see the used equations below.

$$V_0 = DV_{in}$$

$$I_{Lmin} = V_o\left[\frac{1}{R} - \frac{1-D}{2Lf}\right]$$

$$I_{Lmax} = V_o\left[\frac{1}{R} + \frac{1-D}{2Lf}\right]$$

$$\Delta I_L = \frac{D(V_{in(max)} - V_{out})}{Lf}$$

$$I_{MOSFET(max)} = \frac{\Delta I_L}{2} + I_{out(max)}$$

$$I_{diode} = (1 - D)\, I_{out(max)}$$

$$L_{min} = \frac{(1-D_{max})R_{max}}{2f} \; or \; Vo\frac{1-D}{\Delta I_L f}$$

$$C_{in} = \frac{D(1-D\ )I_{out(max)}}{f\Delta V_{in}}$$

$$C_{out} = \frac{\Delta I_L}{8f\Delta V_{out}}$$

$$\Delta V_{out} = \text{ESR}*\Delta I_L$$

Then, by plugging the numbers into their respective equations, we calculated the critical values for the components.

$$V_o = 14V$$

$$V_{in} = 33V$$

$$D = 0.424$$

$$f = 50kHz$$

$$I_{out} = 10A$$

$$\Delta I_L = 2\text{A}$$

$$L_{min} = 14\frac{1-0.424}{2*50e3} = 80.64\mu H$$

$$C_{in} = \frac{0.424*(1-0.424\ )*11}{50e3*6} = 8.95\mu F$$

$$C_{out} = \frac{2}{8*50e3*6} = 0.83\mu F$$

$$I_{MOSFET} = \frac{2}{2} + 11 = 12A$$

$$I_{diode} = 11 * (1 - 0.424) = 6.336A$$

From these values, we started our simulations.

SIMULATION RESULTS

Simulation of the three-phase full wave rectifier and buck converter topology with PI control loop is performed in the MATLAB Simulink environment. The design topology is given in Figure 5.

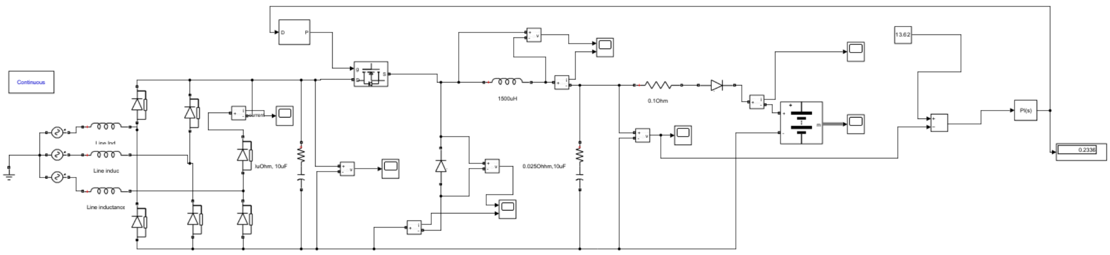


Figure 5: Design topology

First, a simulation was conducted based on the results obtained from analytical calculations, and some values were adjusted to enhance the output waveforms. Table x shows the used parameters in the simulation.

Component	Value
Source Inductance	200 μH
Three-phase FBDR capacitor	10 μF
Buck Converter Inductor	1500 μH
Buck Converter Capacitor	10 μF

Table 1= Used parameters in the simulation

Load-side resistor (0.1 Ω) is placed to model the internal resistance of the battery.

Three Phase FBDR

The current passing through diodes of the three-phase FBDR with 25 V_{l-l} input voltage is given in Figure 1. 25 V_{l-l} is the maximum input voltage for our design, so the maximum current passing through the diodes will be 12.5 A.

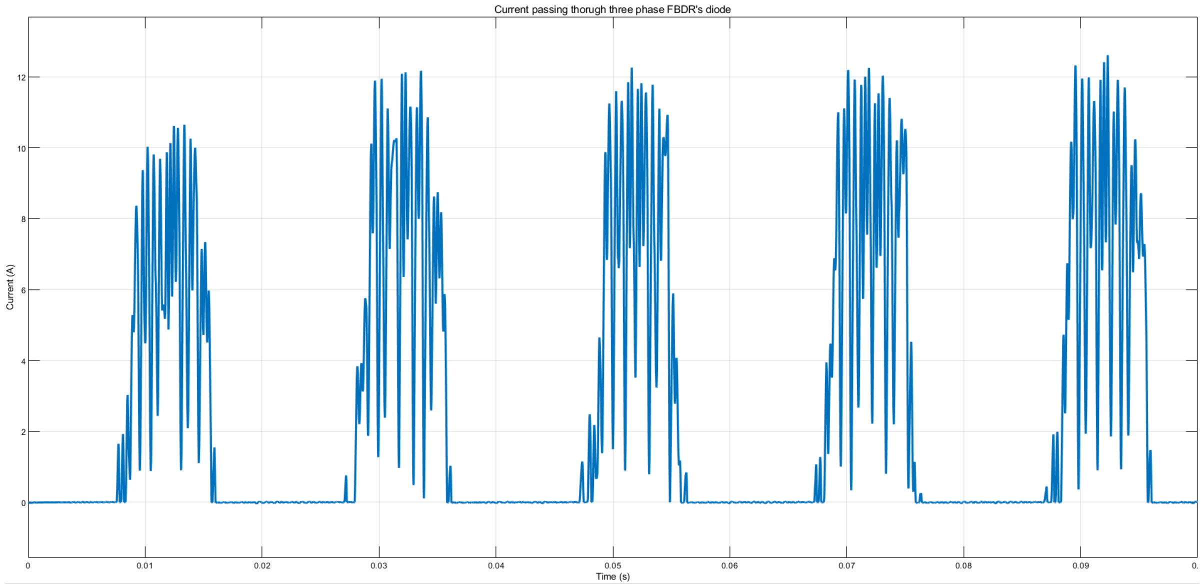


Figure 6: Current passing through diodes of the three-phase FBDR with 25 V_{l-l} input voltage.

Figure 7 shows the output voltage of the three-phase FBDR. Output voltage does not exceed 60V for 25 V_{l-l} input voltage. This means that the maximum voltage output for three-phase FBDR is smaller than 60V.

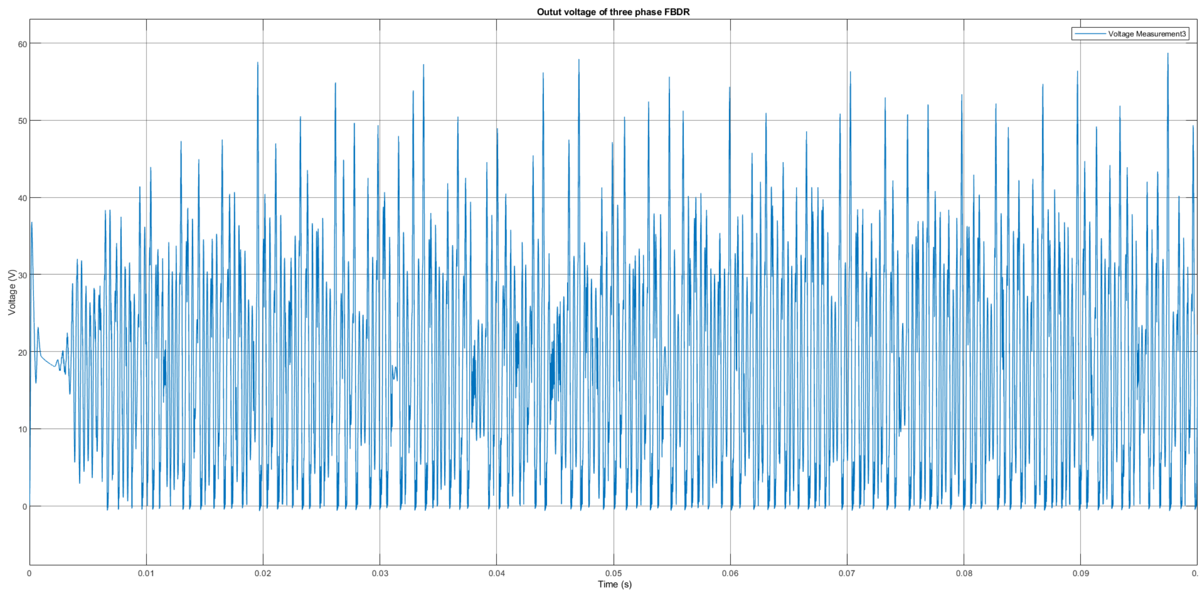


Figure 7: Output voltage of the three-phase FBDR with 25V_{l-l} input voltage.

Buck Converter

The aim of the buck converter is to decrease the voltage level and supply constant current to the battery. Voltage and current measurements of the buck converter components with given 25 V_{l-l} input are given below.

MOSFET

Figure 8 shows the voltage and current waveforms of the buck converter MOSFET. As we can see from Figure 8, the output current oscillates between 0-10 A.

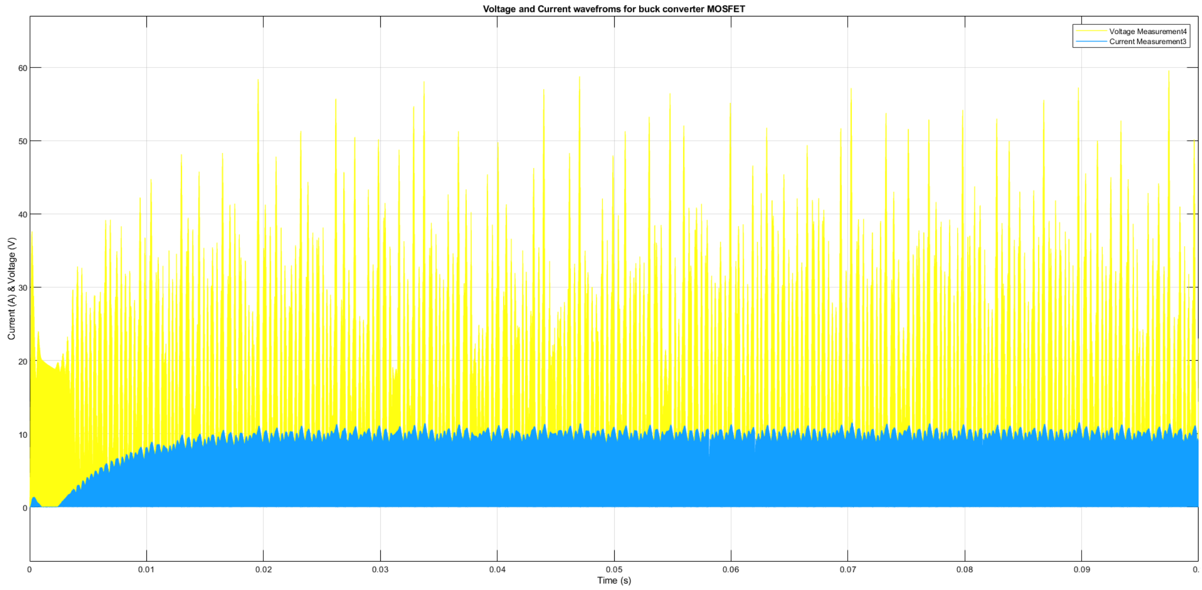


Figure 8: Voltage and current waveforms of the buck converter MOSFET.

Inductor

Voltage and current waveforms for the inductor are given in Figure 9. Current oscillates between 8.75-10 A. Maximum voltage over the inductor is 45 V.

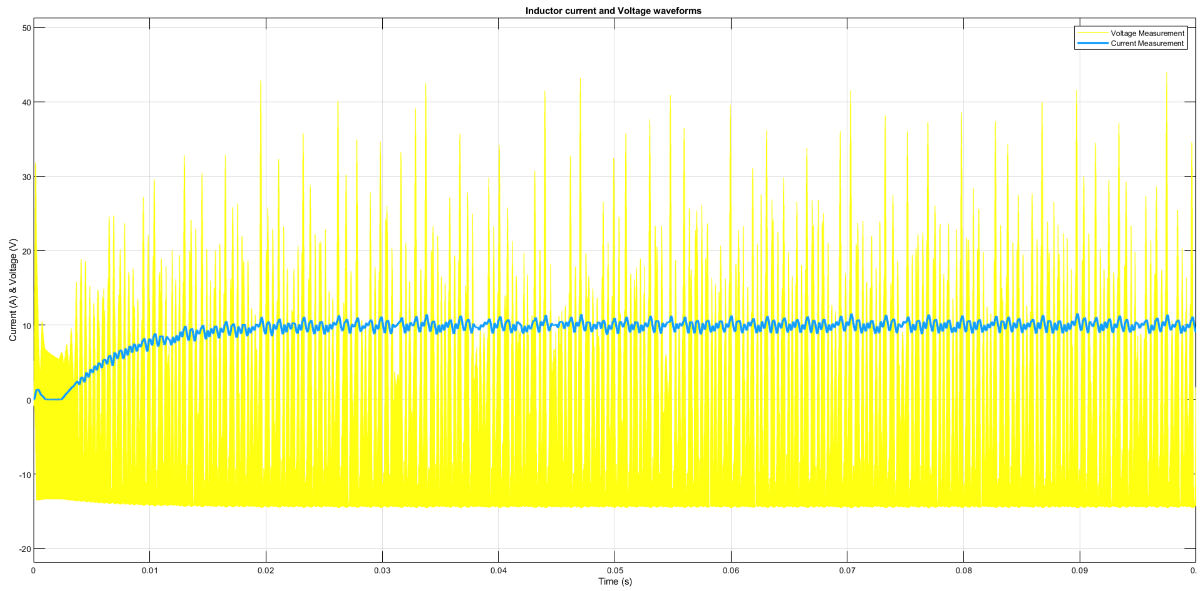


Figure 9: Voltage and current waveforms for the inductor.

Diode

The current and voltage waveforms of the diode are similar to MOSFET characteristics. The maximum voltage on the diode is 58V, and the maximum current passing through the diode is 11.5 A, as can be seen in Figure 10.

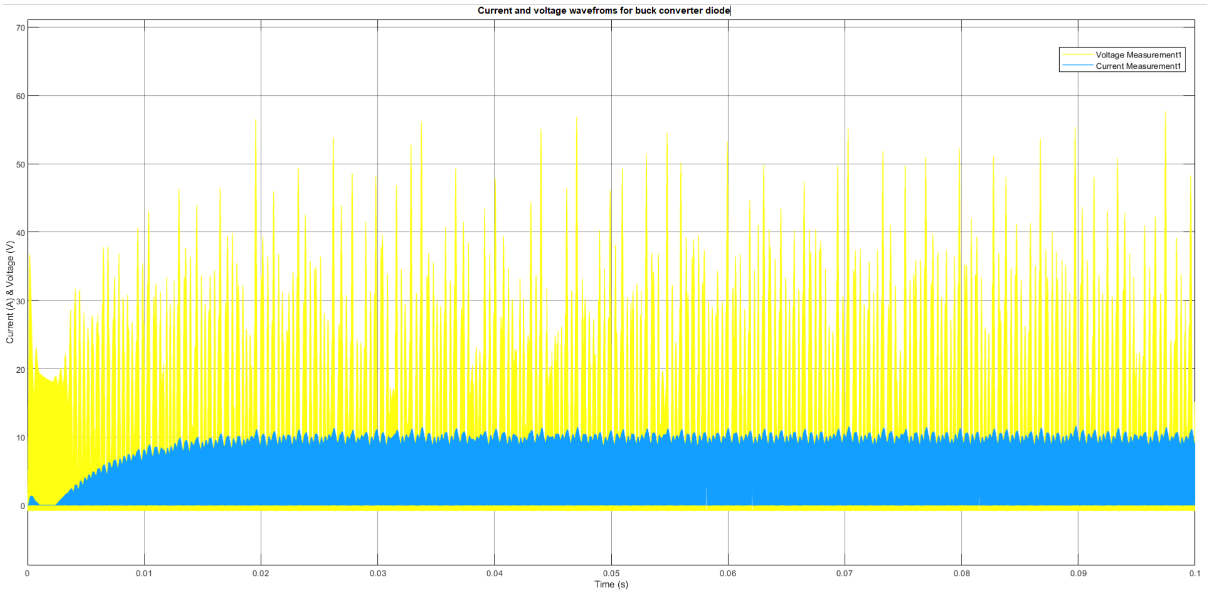


Figure 10: Voltage and current waveforms for buck converter diode

Capacitor

The capacitor voltage of the buck converter is actually the output of the buck converter. One of the aims of this project is to design an AC-DC converter with a ripple voltage that is as small as possible. As we can see from Figure 11, the ripple voltage is very small, 0.5 V.

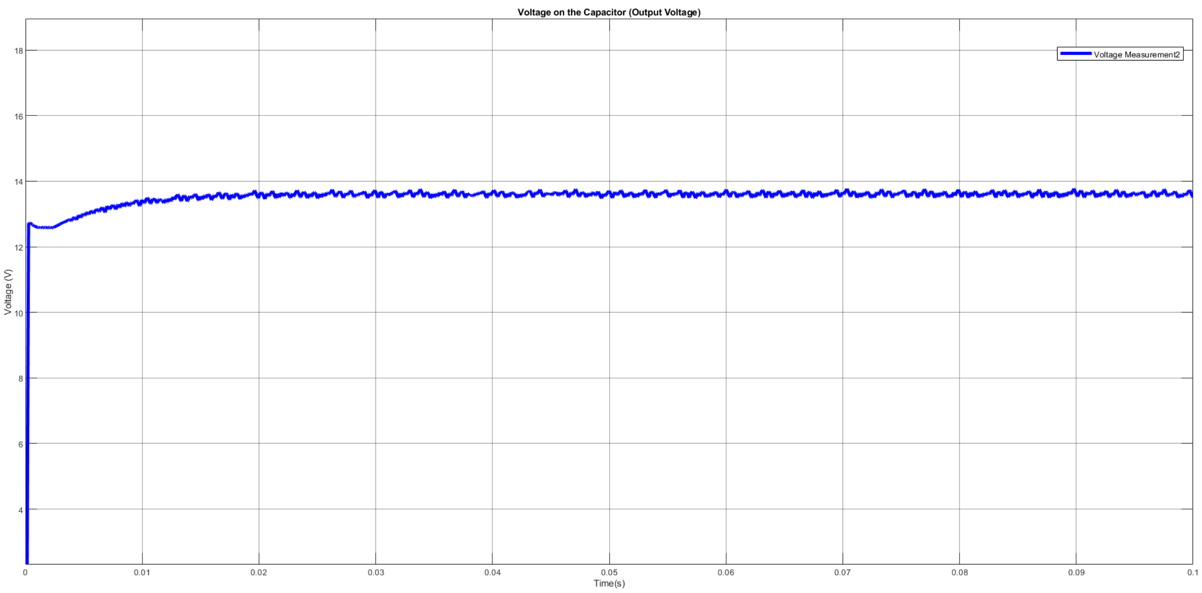


Figure 11: Voltage waveform for buck converter capacitor

Battery

The main aim of this project is to charge the battery with a constant 10 A current. As mentioned in the specification section, the current ripple must be at a %20 of the average current. In our design, as can be seen from Figure 12, current oscişates between 8.75- 11.5 A.

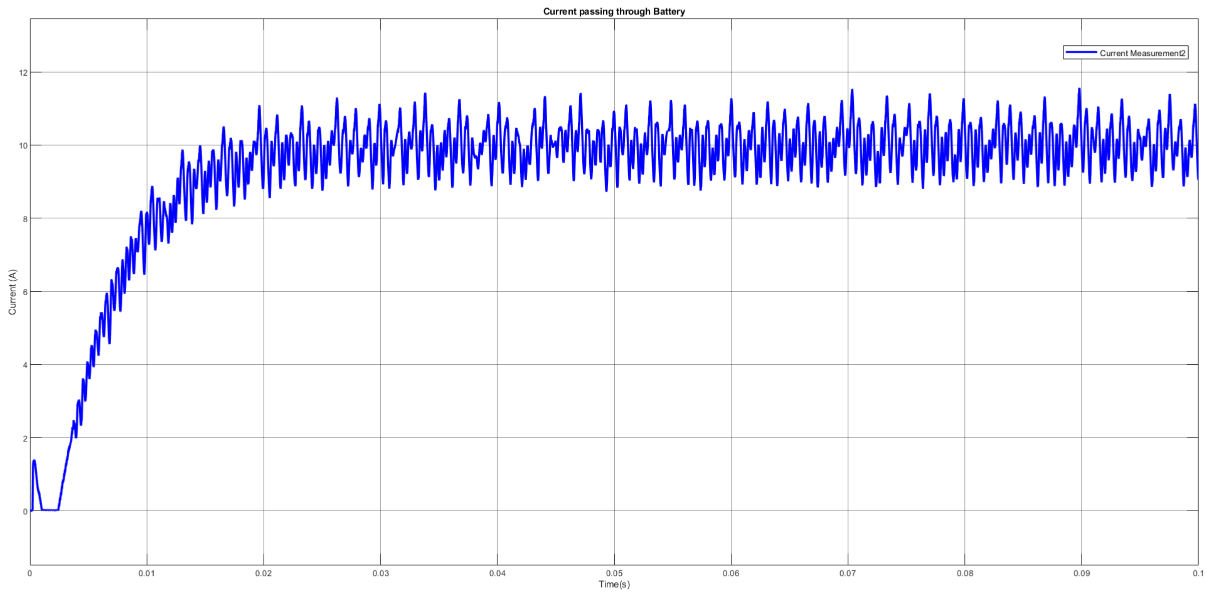


Figure 12: Current passing through the battery.

Controller Selection

After simulating the circuit and determining the components, the need for a controller arose to compensate for the voltage changes on the FBDR side. Even though there exists a smoothing capacitor at the output of the FBDR, or the input of the buck converter, our circuit should operate between the input voltage range of $15V_{l\text{-}l}$ and $25V_{l\text{-}l}$, and the output voltage needs to be constant for all of the input voltage values. Thus, we designed a controller for our circuit in accordance with our component parameters.

First, we obtained the block diagram of the system and then the transfer function of the buck converter, as the output capacitor voltage is the output of the system, and the duty cycle is the input to the system [4].

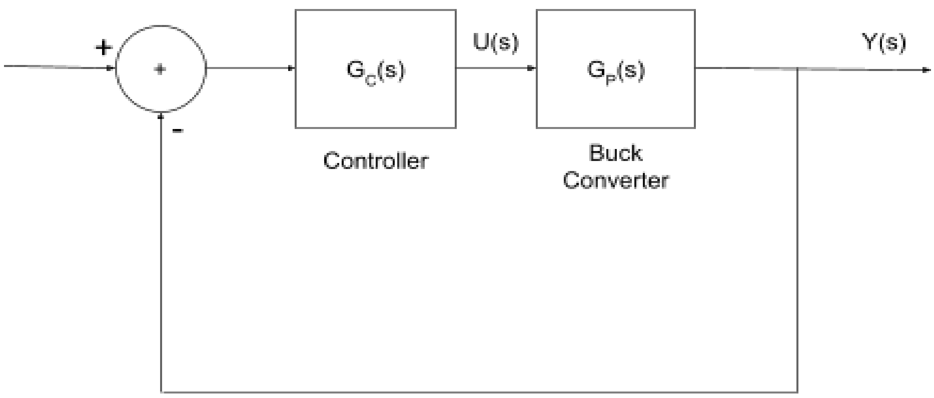


Figure 13: Block diagram of the buck converter and the controller

$$G_P(s) = \frac{Y(s)}{U(s)} = \frac{\frac{V_{in}}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}}$$

where V_{in} is the output of the FBDR.

Then, the bode plot of the buck converter is obtained using the built-in "*bode*" function in MATLAB, according to the above transfer function, which is also obtained in the MATLAB environment using the built-in "*tf*" function, and the calculated component values. The input voltage value is approximated to be 30V as the controller is designed. Furthermore, after obtaining the transfer function of the buck converter, the controller is designed using the built-in "*pidtune*" function. A PI controller is designed and its parameters are obtained according to the transfer function of our buck converter design. One can find the MATLAB algorithm developed for the controller design below:

```
R_out = 0.1;
C_out = 10^-5;
L = 1500*10^-6;
V_in = 30;
buck_converter = tf([V_in/(L*C_out)], [1 1/(R_out*C_out) 1/(C_out*L)]);
bode(buck_converter)
grid minor;
controller = pidtune(buck_converter,'PI');
```

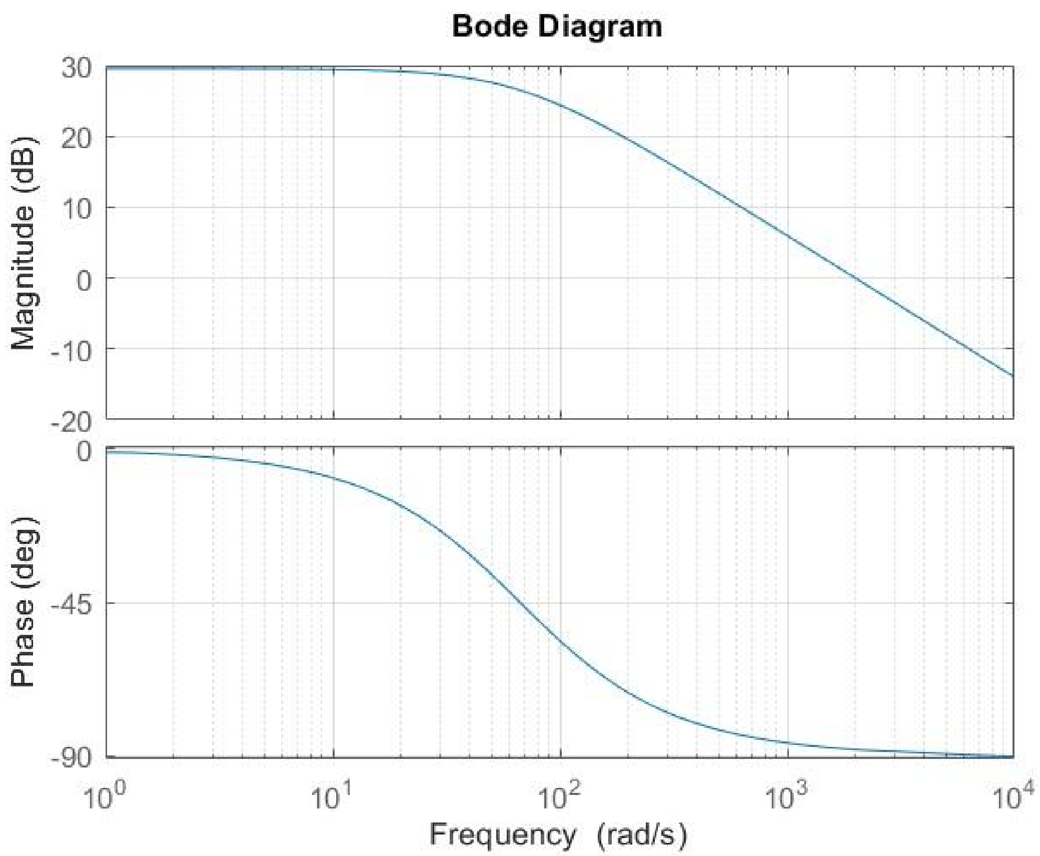


Figure 14: Bode plot of the buck converter obtained using the above MATLAB code

The controller parameters obtained are as follows:

Kp = 0.068125711694835
Ki = 6.811891811116887

After obtaining the controller parameters according to the transfer function, the design of the topology in Figure 5 is obtained.

COMPONENT SELECTION

After the simulation results, we have an idea about what the voltage and current limitations of the components would be. We decided to use the following components after an extensive search.

Three-Phase FBDR

Diode Rectifier

We are going to use two half-wave bridge rectifiers and connect them properly to get three-phase FBDR. Specifications of the half-wave diode rectifier are given below.

Component Name	35A 1000V Diode Rectifier
RMS Voltage	1000V
I_{Favg}	35A
Operating Temperature Min	-55℃
Operating Temperature Max	150℃
Component link	35A 1000V Köprü Diyot Uygun Fiyatıyla Satın Al - Direnc.net®
Price	27.09 TL

Capacitor

Component Name	10µF 100V Capacitor
RMS Voltage	100V
Component link	10uF 100V Kondansatör 5x11mm Uygun Fiyatıyla Satın Al - Direnc.net®
Price	0.83 TL

Buck Converter

MOSFET

Component Name	IRF540NSPbF
R_{DSon}	44 mΩ
V_{DSS}	100V
I_D	33A
$V_{GS(th)}$	2.0- 4.0 V
Operating Temperature	-55℃ to +175℃
Component link	IRF540NSPBF Infineon Technologies | Mouser Turkey
Price	1.29 $

Other possible MOSFETs:

IRFZ24 N Kanal Power Mosfet --> 55V 17A 0.07ohm 14.08₺
IRFZ44 N Kanal Power Mosfet --> 60V 48A 0.023ohm 12.32₺
50N06 N Kanal Mosfet --> 60V 50A 0.022ohm 16.90₺

Diode

Component Name	MBR20100 SCHOTTKY
RMS Voltage	45V
I_{Favg}	20A
I_R at 25 ℃	1 mA
I_R at 125 ℃	6 mA
V_F	0.74- 0.88 V
Operating Temperature	-55 to +150 ℃
Component link	MBRF20100CT - MBR20100CT - MBR20100CTF - MBR20100FCT

	MBR20100 20A. 100V. Schottky Barrier Rectifier MBR SERISI | Çakır Elektronik (cakirelektronik.com)
Price	13.08 TL

Inductor

Component Name	TH Power Inductors – AGP4233-474ME (470 µH)
Operating Temperature	-40 ℃ to +120 ℃
Component link	AGP4233 Series TH Shielded High Current Power Inductors | High current flat wire | Coilcraft
Price	13.75 $

Capacitor

Component Name	10µF 25V Tantalum Capacitor
RMS Voltage	25V
Component link	10uF 25V Tantal Kondansatör Uygun Fiyatıyla Satın Al - Direnc.net®
Price	6.50 TL

Battery Side

Current Sensing Resistor

We are going to use a current-sensing resistor for the control loop.

Component Name	VISHAY WSL3637R0100FEA
Resistance	0.01 Ω
Temperature Coefficient	± 50ppm/ ℃
Operating Temperature Min	-65℃
Operating Temperature Max	170℃
Power Rating	3W

Resistance Tolerance	± 1%
Component link	WSL3637R0100FEA - Vishay - SMD Current Sense Resistor, 0.01 ohm, WSL3637 Series (farnell.com)
Price	0.863 $

Other possible component links :

- https://tr.farnell.com/vishay/wslp12065l000fea/current-sense-res-0r005-1-1-w/dp/2420761
- https://tr.farnell.com/vishay/wsl3637r0100fea/current-sense-res-0r01-1-3-w-3637/dp/2395994

Diode

Component Name	DSS 16-0045A
RMS Voltage	45V
I_{Frms}	35 A
I_{Favg}	16A
I_R at 25 ℃	0.5 mA
I_R at 125 ℃	5 mA
V_F	0.57- 0.69 V
Operating Temperature Min	-55℃
Operating Temperature Max	170℃
Component link	DSS16-0045A | IXYS - POWER SEMICONDUCTORS (ozdisan.com)
Price	0.95 $

REFERENCES

[1] Xie, H., & Guo, E. (2019). How the switching frequency affects the performance of a buck converter. Texas Instruments Incorporated: Dallas, TX, USA. [Online]. Available: https://www.ti.com/lit/an/slvaed3/slvaed3.pdf?ts=1701550171169

[2] Taufik. Practical Design of Buck Converter [PowerPoint slides]. Available: https://www.researchgate.net/profile/Taufik-Taufik/publication/321903540_Practical_Design_of_Buck_Converter_By_Taufik/links/5a3a9ff3aca272563a7f775a/Practical-Design-of-Buck-Converter-By-Taufik.pdf

[3] B. Hauke, "Basic Calculation of a Buck Converter's Power Stage," Texas Instruments, Dallas, Texas, USA, 2015. Accessed: Dec. 3, 2023. [Online]. Available: https://www.ti.com/lit/an/slva477b/slva477b.pdf

[4] Soriano-Sánchez, A. G., Rodríguez-Licea, M. A., Pérez-Pinal, F. J., & Vázquez-López, J. A. (2020). Fractional-order approximation and synthesis of a PID controller for a buck converter. Energies, 13(3), 629. [Online]. Available: https://www.researchgate.net/publication/339018028_Fractional-Order_Approximation_and_Synthesis_of_a_PID_Controller_for_a_Buck_Converter