EE 463 Static Power Conversion-1

Hardware Project Complete Simulation Report

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1. Introduction

The objective of this project is to design and implement a controlled rectifier in order to drive a DC motor. A controlled rectifier will be designed which can accept either single-phase or three-phase AC input from a grid and provide variable DC output through a variac. The specified maximum output voltage of the rectifier is 180 V; however, the voltage should be controllable according to the operating requirements of the motor. In the following pages, we provided information about the topologies we chose. Then, we designed the circuit based on the topology we chose and simulated it with appropriate parameters. According to the simulation results, we selected the most suitable and efficient component for the project.

2. Topology Selection

a) Single-Phase Diode Rectifier + DC-DC Buck Converter

As a result of our research, the first topology we chose consists of two parts. The first part is the circuit in Figure 1. This circuit rectifies the single-phase AC voltage and converts the low ripple into DC voltage. Then, we adjust the duty cycle of the buck converter circuit in Figure 2 to obtain an output voltage and current.

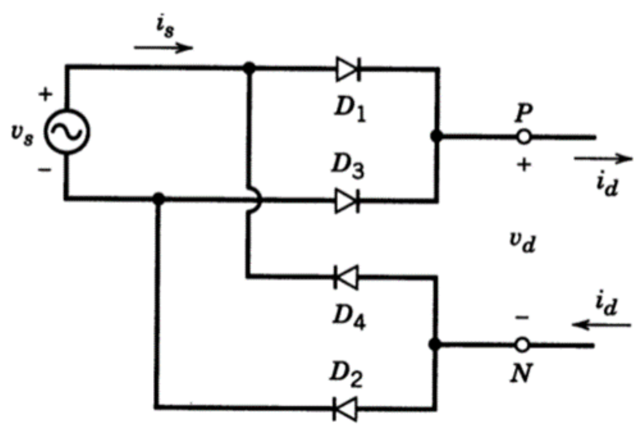

Figure 1: Single Phase Diode Rectifier

The working logic of the single-phase diode rectifier is based on the diodes passing current in one direction, when a positive voltage is given, current will pass through D1 and D4 and vice versa. The formula below contains the formula for the average voltage, ripple voltage and ripple frequency we can get when we use this circuit.

$$V_{avg} = \left(2\sqrt{2}\right)V_s/\pi$$

$$\Delta V_{out} = \sqrt{2}V_s$$

$$f_{ripple} = 2 \cdot f_s$$

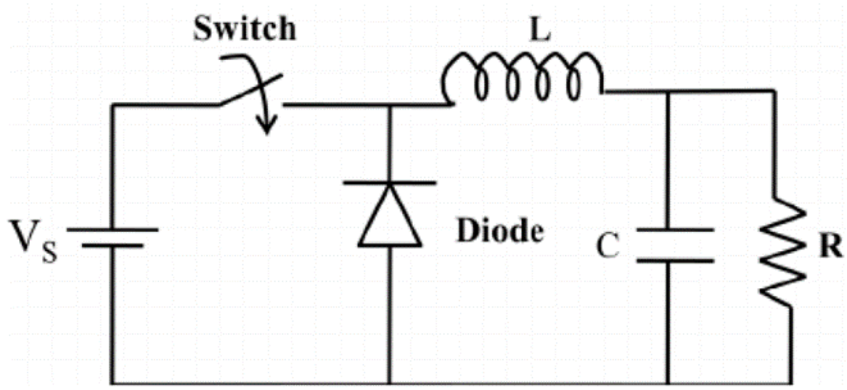

Figure 2: Buck Converter

A **buck converter** is a DC-DC power converter that steps down voltage from its input (source) to its output (load) based on the **duty cycle (D)** of the switching device, where . It employs a transistor, inductor, diode, and capacitor to regulate and smooth the output voltage.

If we combine and use these two circuits, the average voltage value we will obtain at the output can be found using the equation below.

$$V_{av} = \left(2\sqrt{2}\right)V_s D/\pi$$

Advantages:

- Simple design and widely used.
- Lower cost since it requires only a diode bridge and a buck converter.

Disadvantages:

- Limited power output compared to three-phase topologies.
- Output ripple depends on the filter design and input frequency.
- Efficiency may be lower due to high input ripple, requiring additional filtering.

b) Three-Phase Controlled Thyristor Rectifier

The second topology we tried for the project architecture is the Three-Phase Controlled Thyristor Rectifier. The important feature of this topology is that, unlike the first topology, we did not need to use any DC-DC buck converter to adjust the output voltage, but this topology had serious disadvantages compared to this advantage, we have listed these negative features below.

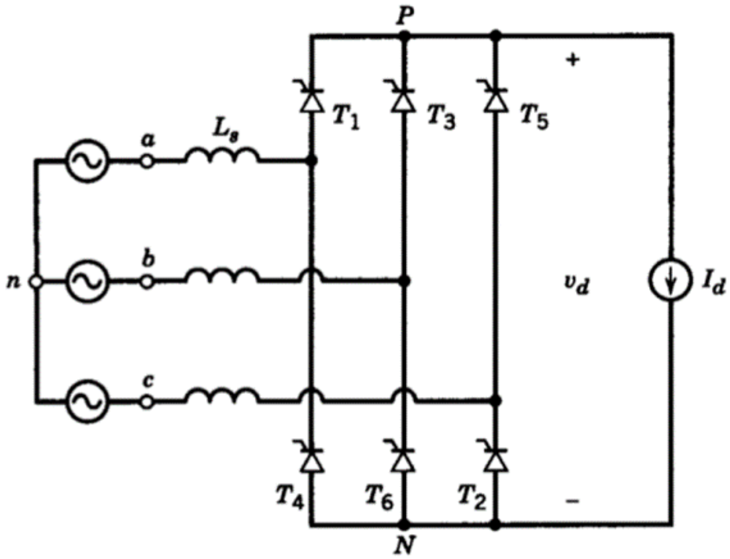

Figure 3: Three-Phase Controlled Thyristor Rectifier

A Three-Phase Controlled Thyristor Rectifier converts three-phase AC power to regulated DC power by controlling the firing angles of thyristors. By adjusting the conduction phase of the thyristors, it provides control over the output voltage and current. Average output voltage, ripple voltage and frequency can be calculated from the following formula.

$$V_{av} = (3\sqrt{2})V_{LL}cos\alpha/\pi$$

Advantages:

- Direct control of DC output voltage without the need for a DC-DC converter.
- Robust and efficient at high power levels.

Disadvantages:

- Requires complex gate control for the SCRs to adjust the output voltage.
- Higher harmonic distortion on the AC side due to phase control.
- Not suitable for applications where a very smooth DC output is needed (output ripple is dependent on the AC frequency and firing angle).

c) Three-Phase Diode Rectifier + DC-DC Buck Converter

The last topology we considered is the 3-phase version of the first topology we mentioned. Similarly, the second part includes a DC-DC buck converter. In Figure 4 and Figure 2, we can see the first and second parts of the topology we chose, respectively.

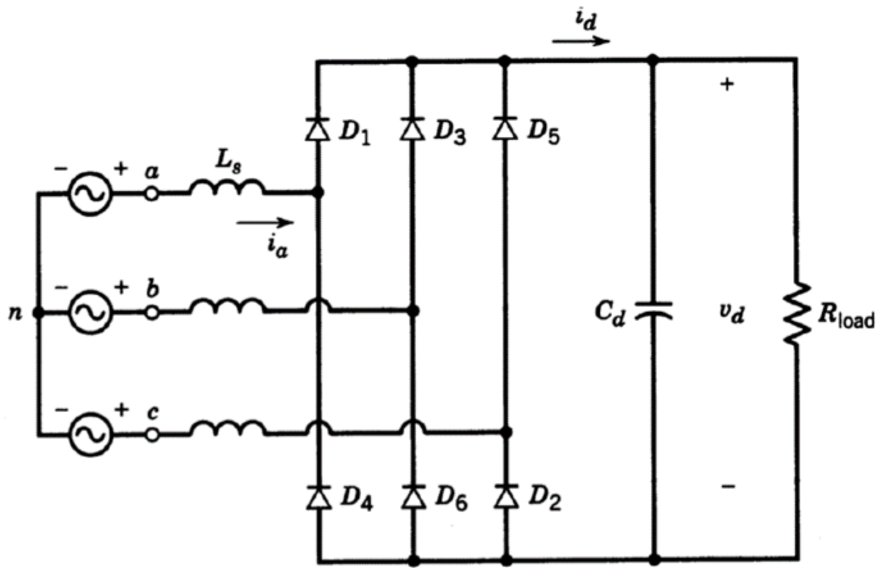

Figure 4: Three-Phase Diode Rectifier

A **Three-Phase Diode Rectifier** converts three-phase AC power into unregulated DC power using six diodes arranged in a bridge configuration. The diodes conduct alternately, depending on the phase voltages, to produce a pulsating DC output with lower ripple compared to single-phase rectifiers.

The average voltage of the 3-phase diode rectifier is calculated with the formula below.

$$V_{av} = \left(3\sqrt{2}\right)V_{LL}/\pi$$

$$\Delta V_{out} = \frac{\left(2-\sqrt{3}\right)\sqrt{2}V_{LL}}{2}$$

$$f_{ripple} = 6 \cdot f_s$$

In this topology, we chose the same circuit as the buck converter circuit in Topology 1 Figure 2, so our average output voltage will be the voltage we get from the rectifier multiplied by the duty cycle (D).

$$V_{av} = \left(3\sqrt{2}\right)V_{LL}D/\pi$$

Advantages:

- Higher power capability with three-phase input.
- Lower input ripple compared to single-phase, resulting in smoother DC output.
- Reduced filtering requirements due to lower ripple on the input DC bus.

However, in addition to these advantages, there are some disadvantages that may cause us problems: harmonic distortion, power factor, limited voltage control flexibility and due to buck converter side, efficiency.

The first topology we eliminated from these 3 topologies was the Three-Phase Controlled Thyristor Rectifier because it required a complex gate driver and we wanted a voltage that did not have much ripple on the DC output, doing these things we listed would reduce our efficiency and increase our cost. Then we made comparisons between single phase and three phase diode rectifiers. The first of these comparisons was the ripple comparison, three-phase rectifiers produce lower ripples in the DC output due to more frequent conduction intervals (6 pulses per cycle) compared to single-phase rectifiers (2 pulses per cycle). Also, three phase ripple voltage is smaller than single phase This makes the output of three-phase rectifiers smoother and less dependent on large filtering components. Other comparison we talked about is harmonics, A Single-Phase Diode Rectifier introduces lower-order harmonics (e.g., the 3rd, 5th, etc.) into the AC supply, which can distort the supply waveform and lead to higher levels of Total Harmonic Distortion (THD). In contrast, a Three-Phase Diode Rectifier generates higher-order harmonics (e.g., the 5th, 7th, etc.), which are less impactful on the system and easier to filter, resulting in lower overall THD. In summary, we decided to choose this topology since it provides a simple solution and is cheaper compared to other topologies. Moreover, it is straightforward to implement, provides adjustable DC output, and has relatively low ripple on the DC bus. In the following sections, the simulation of the topology we selected, its calculations and the selection of components to be used for the circuits are given.

3. Simulation Results

In this section, the selected topology shown in Figure 5 is modeled and simulated using MATLAB Simulink. The primary purpose of the simulation is to determine the maximum voltages and currents experienced by the components and identify any unwanted spikes or behaviors exhibited by the circuit. Based on these simulation results, appropriate component selections are made.

To simplify calculations, a separately excited DC motor is used. To suppress armature reaction in the real setup, interpole windings are used. The armature controlled DC motor is modeled as a series combination of armature winding resistance, reactance, and interpole winding resistance and reactance.

Since we are not given motor constants and operation point does not known, to be able to calculate back emf and make simulations, rated values on the motor plate are used . Calculations are given below:

$$\mathrm{V_{rated}} = 220V \text{ , } I_{rated} = 23.4A$$

$$V_t = E_a + I_a * R_a$$

$$R_a = 0.8\,\Omega + 0.27\Omega = 1.07\Omega$$

$$220V = E_a + 23.4A * 1.07\Omega$$

$$E_a = 194.96V$$

This back emf value is used for the simulations later. Motor windings specifics are given below:

- Armature Winding: 0.8 Ω, 12.5 mH
- Shunt Winding: 210 Ω, 23 H
- Interpoles Winding: 0.27 Ω, 12 mH

Due to the requirements, at most 180V is desired at output of the buck converter. In case of any unpredictable situation due to non-idealities, buck converter is designed to supply 180V output at the %80 duty cycle. Therefore, rectifier output must be 225VDC and the line to neutral variac voltage must be 96.2VAC in the reality. For our simulations rectifier output is assumed to be 225VDC for rated values.

In reality:

$$\frac{180V}{0.8} = 225V$$

$$V_{LN_{rms}} = \frac{225\pi}{3\sqrt{6}} = 96.2V$$

For simulations:

$$\frac{220V}{0.8} = 275V$$

$$V_{LN_{rms}} = \frac{275\pi}{3\sqrt{6}} = 117.58V$$

In addition to this, MOSFET/IGBT, flyback diode and rectifier diodes are taken as ideal for observing a clear simulation result. It is designed that current ripple reaches at most 0.4A when motor is supplied with 180VDC in the practical case. To do this switching frequency is selected by using following formula:

$$f_s = V_0 * \frac{1 - D}{\Delta I_L * L}$$

$$f_s = 180 * \frac{(1 - 0.8)}{0.4 * 24.5mH} = 3570Hz$$

For convenience switching frequency is selected as 3.5kHz in the simulations. To sum up, simulation results were generated with an 80% duty cycle, a switching frequency of 3.5 kHz, and the rated parameters of the DC motor. Due to the motor's inherently inductive nature, voltage spikes are attenuated, eliminating the need for external inductance in the buck converter circuit. While determining the critical component values, error margins were considered to account for factors such as positive and negative temperature coefficients, material imperfections, and operational condition variances

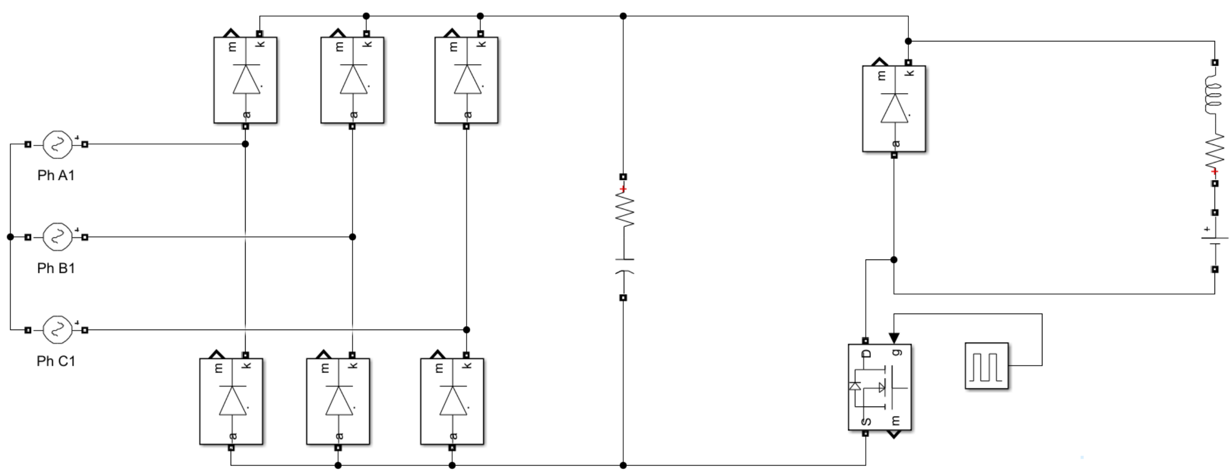

Figure 5 : Three Phase Diode Rectifier with Buck Converter Topology

The current waveform through the diode in the three-phase full-wave rectifier circuit is illustrated in Figure 6. The peak current is observed to reach approximately 27 A, as shown in the figure. Consequently, the selected diode must withstand at least 27 A, plus an error margin for safe operation.

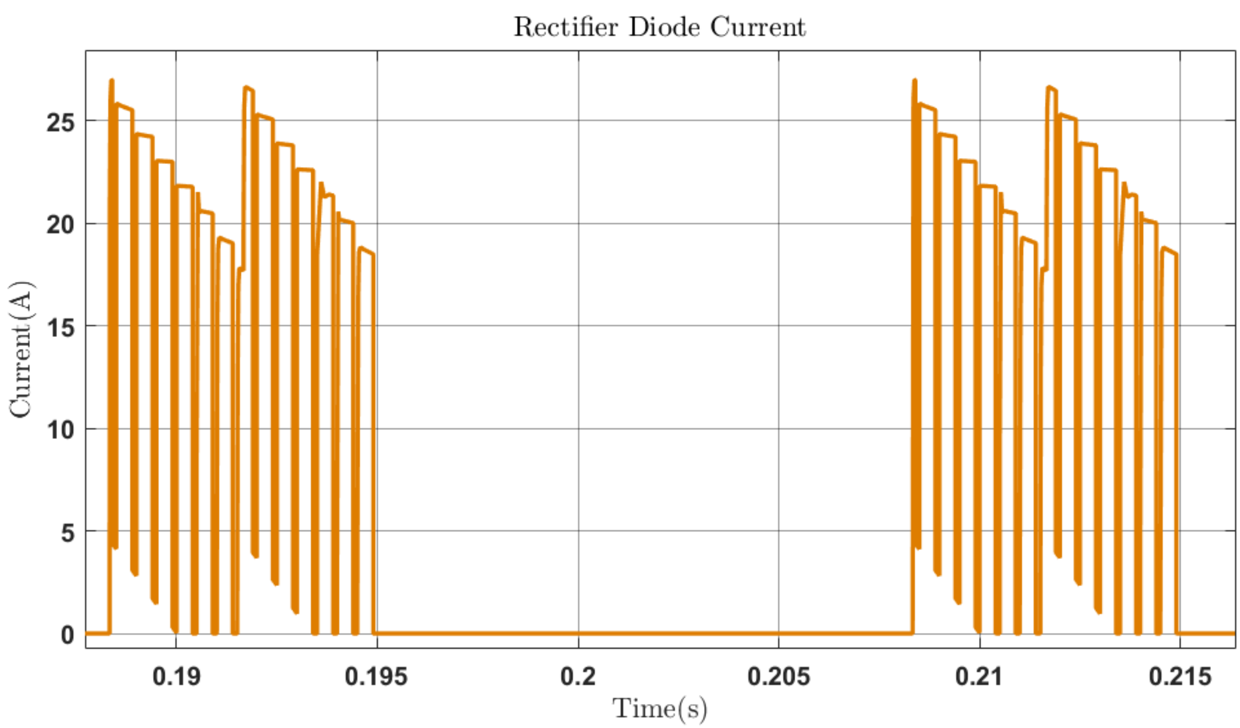

Figure 6 : Diode Current vs Time in Rectifier Circuit

The voltage across this diode is shown in Figure 7. The simulation indicates a peak reverse voltage of approximately 290 V. Therefore, the diode must be capable of blocking reverse voltages of at least 290 V, plus a reasonable error margin, to ensure reliable performance.

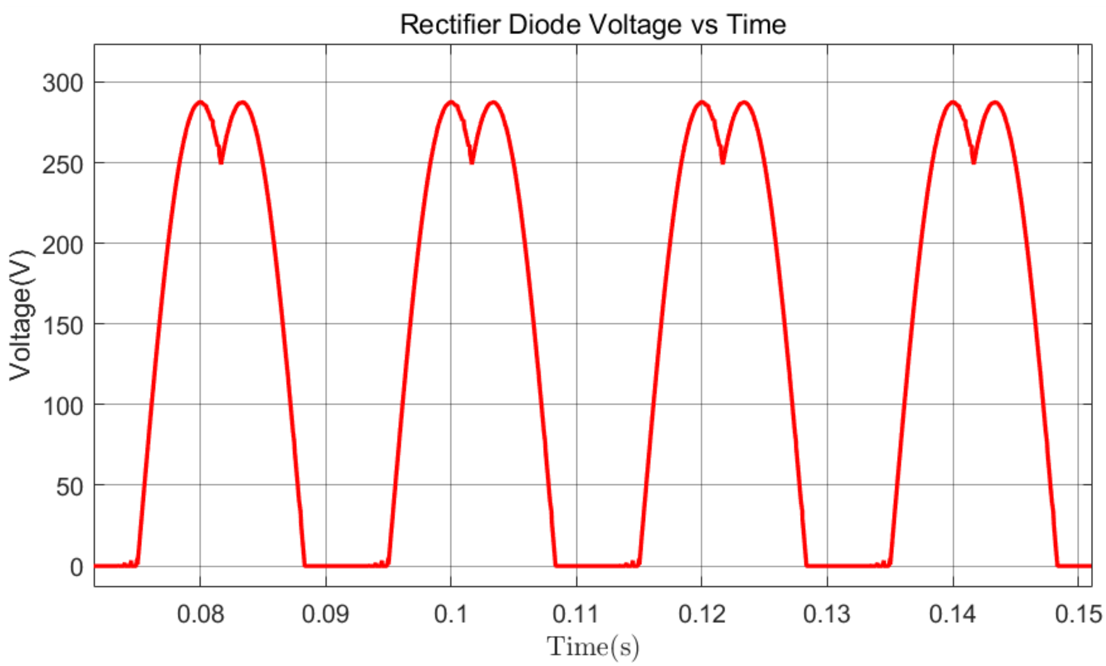

Figure 7 : Diode Voltage vs Time in Rectifier Circuit

The output voltage of the three-phase rectifier circuit is shown in Figure 8. The voltage waveform exhibits a ripple of approximately 6%, which is acceptable within the design parameters.

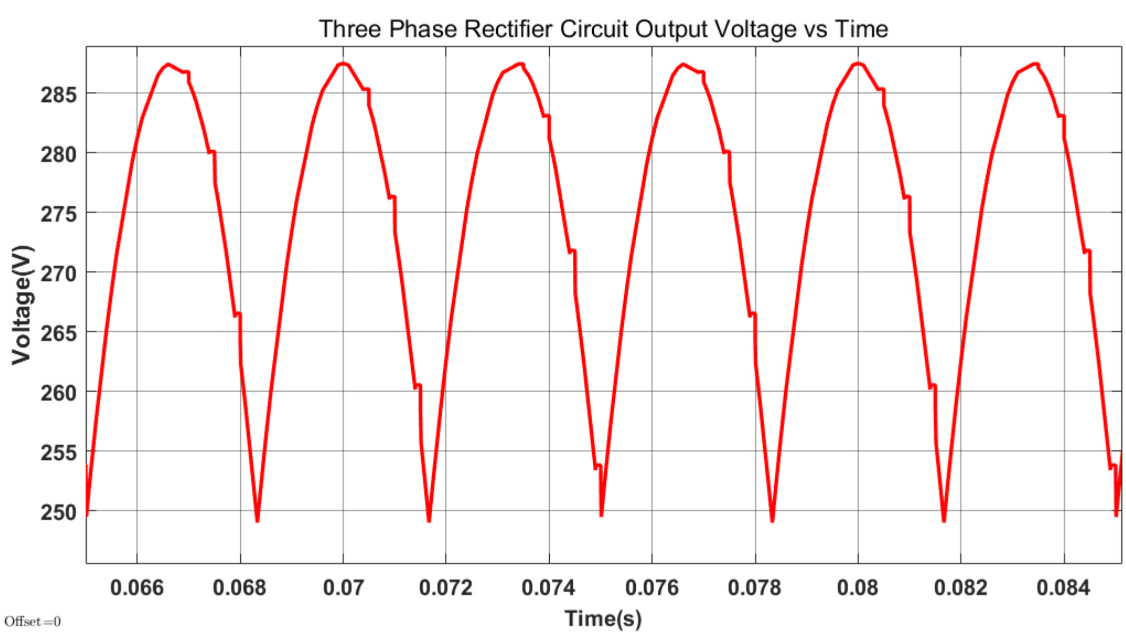

Figure 8 : Rectifier Circuit Output Voltage vs Time

The current passing through the flyback diode in the buck converter circuit is illustrated in Figure 9. Based on the results, this diode must handle a current of at least 23 A, with an added error margin to ensure operational safety.

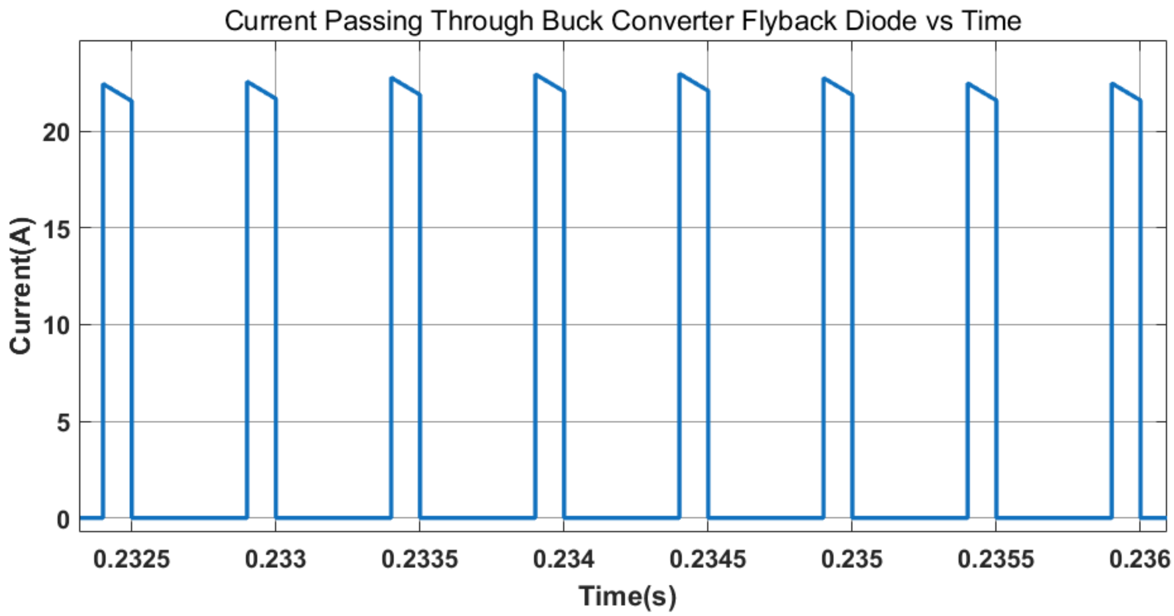

Figure 9 : Current Passing Through Buck Converter Flyback Diode vs Time

The voltage waveform across the flyback diode is shown in Figure 10. The simulation indicates that the diode must block reverse voltages up to 285 V, plus a reasonable error margin, and safely operate under forward bias at the same voltage level.

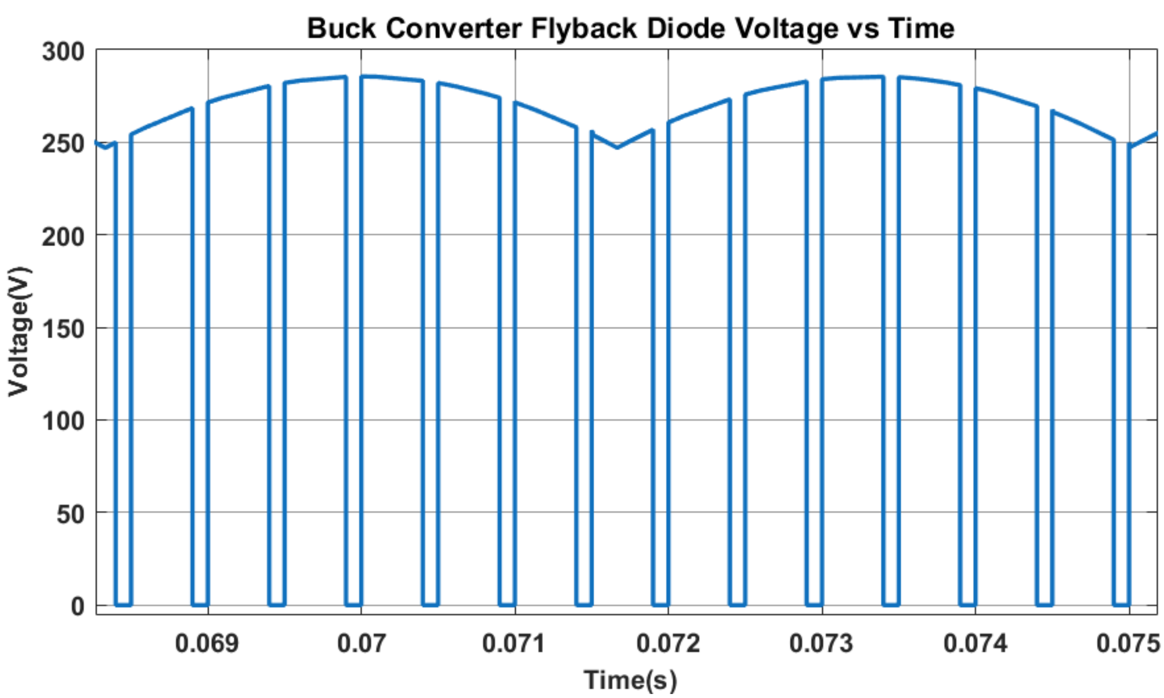

Figure 10 : Voltage Across Buck Converter Flyback Diode vs Time

The current passing through the MOSFET or IGBT used for switching in the buck converter is shown in Figure 11. The selected switching component must handle a current of at least 23 A, plus an error margin, at the specified switching frequency.

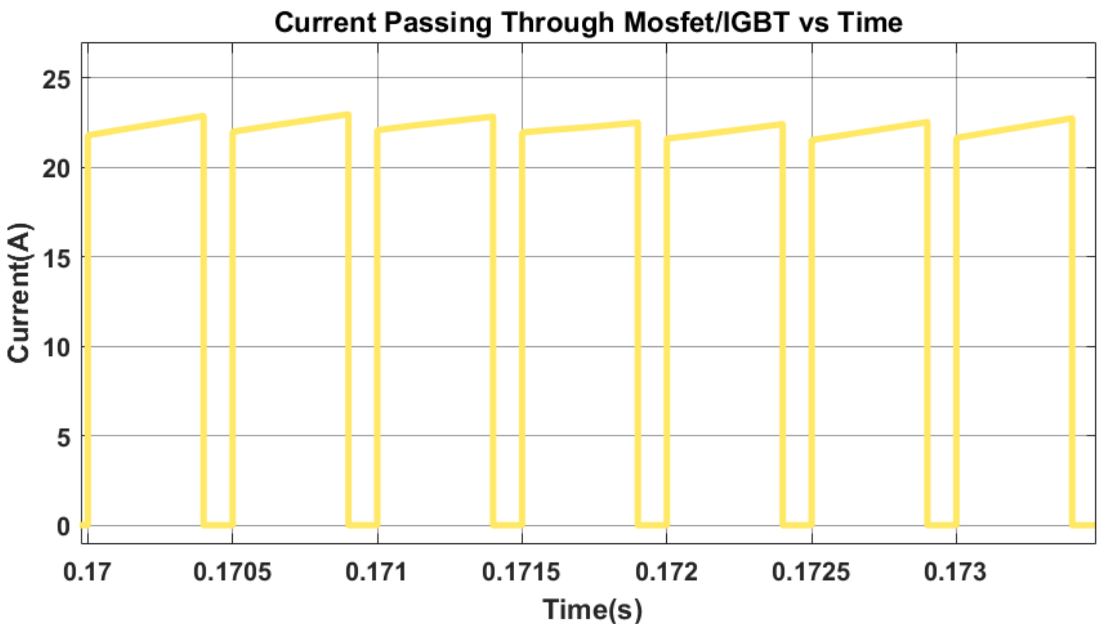

Figure 11 : Current Passing Through Mosfet/IGBT vs Time

The voltage measured across the MOSFET or IGBT terminals during switching is shown in Figure 12. The simulation results indicate that the device must block reverse voltages around 290 V, plus an error margin, while supporting safe operation at these voltage levels and the specified switching frequency.

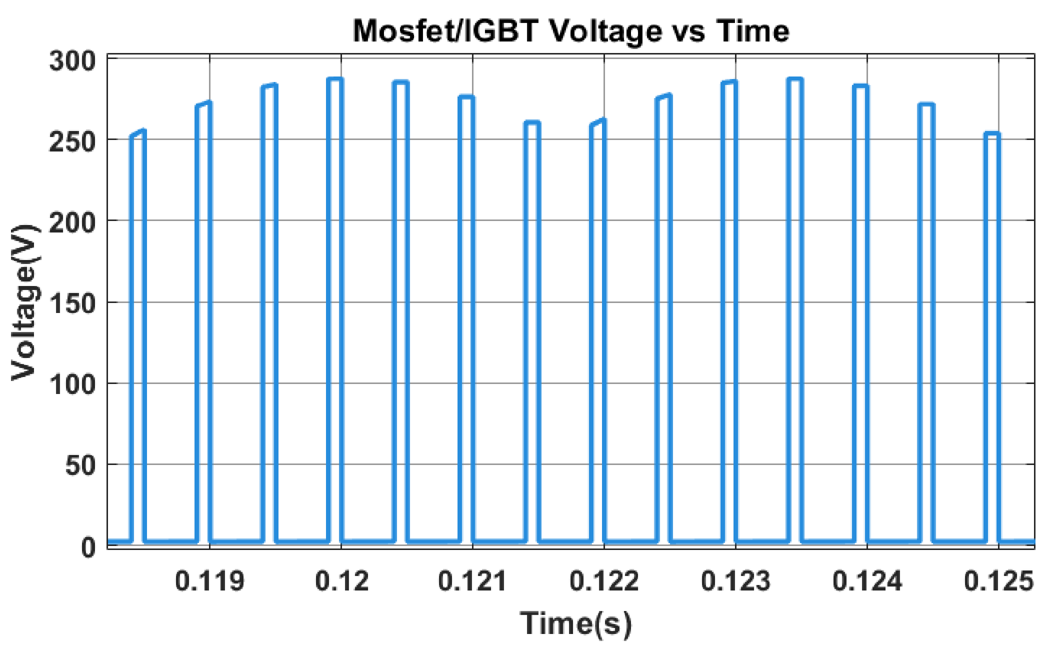

Figure 12 : Voltage Across MOSFET/IGBT vs Time

4. Component Selection

Component selection is one of the most critical part for this project. There are thousands of different types of models for each different component, and we are required to select optimum one for our application. In this section, the reasons for selection of each component and advantages-disadvantages of them are provided.

a) Rectifier Diodes

For the rectifier side, one possible approach is using six separate power diodes since we chose three phase bridge rectifier topologies. However, this design would require more space and since there will be six different components to be implemented on the board, it would be more likely to make mistake while cabling and soldering. Instead, we decided to use single-module component which involves whole three-phase bridge rectifier. Hence, they are providing three phase rectification with single component, the main advantages of them are simplicity and compactness. However, these characteristics make them relatively hard to cool and it can be interpreted as disadvantage when we compare it to using sperate diode components. To overcome this issue, we planned to use heatsinks mounted to rectifier module so that we can use the components with higher performance.

Unlike the other components, finding this type of single module rectifier component was a bit hard in the local electronic markets. Thus, we had limited number of options in terms of our maximum and rated voltage and current values. As can be seen from Fig. 7, maximum voltage value across the diodes at rectifier side is around 288V. Also, the diode current values can reach up to 27 A values especially during the transient period. By considering these numbers, we decided to use GUO40-12NO1 for our rectifier component. The important rating of these component is given below.

Parameters	Maximum Ratings
Bridge Output Current (I_{DAV})	40 A (@ T_J=175 °C)
Reverse Blocking Voltage (V_R)	1200 V (@ T_J=25 °C)
Forward Voltage Drop (V_F)	1.23 V (@T_J=25 °C)

Table 1: GUO40-12NO1 Ratings Table

As can be seen from table above, this device can carry 40 A even at very high junction temperature value. Even though we don't expect to reach these current values, it is logical to put around +10 A error margin to protect circuit from possible spikes. Similarly, voltage rating of this device is much higher than what we have, and this high voltage rating has the effect of high forward voltage drop as given above. However, this voltage drop is insignificant while considering our output voltage range. In addition, one important advantage of this component is that its mounting type is Through Hole (THT) which means we will be able to mount this component board easier when it is compared with other options which most of them has screw types of mounting legs.

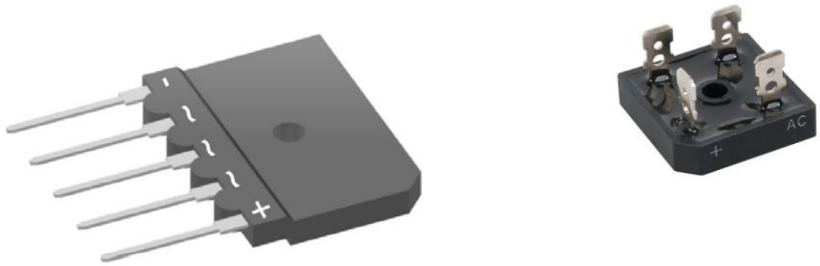

Figure 13: Through Hole Mounting (GUO40-12NO1) and Screw Type Mounting (GBPC3510-E4/5)

b) Rectifier Capacitor

Rectifiers are responsible for conversion from AC to DC, however, their output waveforms are not pure DC signals. Therefore, it is required to put large DC-link capacitor to minimize the voltage ripples. Theoretically, larger capacitance will provide less ripples and more like DC signals but in practical cases having too large capacitors will not be charged with given currents and the voltage at output will never reach steady state. Therefore, it is important to select capacitance value large enough but within the acceptable range. In our simulations, we obtained that 100 uF capacitance value is suitable in terms of both ripples and transient performance. Also, by examining the previous projects and other applications through internet, we saw that this value of capacitance is very common in these voltage ranges.

Figure 14: 400V 47uF electrolytic capacitors

Simulations showed that maximum expected voltage value at the output of rectifier is around 300 V. Thus, we decided to use 400 V capacitors to have reliable output filtering. For this purpose, we searched for electrolytic capacitor because these types are known for providing high capacitance values in a compact form factor and so highly used in power supply applications. Also, as a design choice, we decided to use two 47 uF capacitors instead of one 100 uF capacitor. One reason for this choice is to have low resistance caused by capacitor characteristics at the output side. This characteristic is known as ESR (equivalent series resistance) and it can be diminished by connecting capacitors in parallel.

Furthermore, having two capacitors is more reliable approach than using one since if one capacitor is burned during the tests the other one can continue to filter and protect rest of the circuit from high transient currents or ripples. As a result, it is planned to order these capacitors from a local market *özdisan.com*.

c) Buck Converter Switch

Buck converter is a type of switching converter family which are based on storing the input energy periodically and then releasing that energy to the output at a different voltage. Thus, a proper switching is a critical part of the implementation of a buck converter. For this purpose, we had two types of alternatives for the switch components: MOSFETs and IGBTs. MOSFETs are one of the most common switch semiconductor devices used in power electronics area. Their field-controlled characteristics and high switching speed makes them optimum choices for high frequency applications. However, they have limitations in terms of voltage ratings. On the other hand, IGBTs have a higher voltage handling capability and provide lower conduction losses at higher voltages compared to MOSFETs and still they can work under high frequencies. In this manner, we decided to use IGBTs in our project and start with examining the model IXGH24N60C4D1 we have in our lab storage.

Maximum Ratings	**IXGH24N60C4D1**	**IXGH30N60C2**
Collector-Emitter Voltage (V_{CEmax})	600 V (@ T_J=150 °C)	600 V (@ T_J=150 °C)
Collector Current (I_{Cmax})	24 A (@ T_J=110 °C)	30 A (@ T_J=110 °C)
Gate Charge (Q_g)	64 nC (@ I_c=24A)	70 nC (@ I_c=30A)
Turn-On Delay Time (t_{Don})	21 ns (@ T_J=125 °C)	13 ns (@ T_J=125 °C)
Turn-Off Delay Time (t_{Doff})	143 ns (@ T_J=125 °C)	120 ns (@ T_J=125 °C)

Table 2: IXGH24N60C4D1 vs. IXGH30N60C2

This IGBT model IXGH30N60C2 has the 600V voltage rating, which is more than enough for our project as can be seen from Fig. 12, the maximum voltage we see on the terminals of switching device is around 285V. Its dynamic characteristics are also suitable in this project while considering our switching frequency range. However, its rated current value is close to our simulation result which has maximum at 23A. Even though our simulations are applied for the worst-case scenario and we don't expect to these current values, it is safe to be consistent with the result and put an safety margin. According to our research for the possible alternatives, we found another IGBT which has the model number as IXGH30N60C2. This device is from the same manufacturer of IXGH24N60C4D1, but from the higher-class component family and with better performance. First, its maximum current rating is around 30A which is a good value for our application. Although it has higher current capacity, its switching and dynamic performance is comparable with its alternative as can be seen from its gate charge and rise-fall time values in Table 2. Thus, instead of IXGH30N60C2, we chose IXGH30N60C2 for its higher current capabilities and slightly better switching performance.

d) Buck Converter Freewheeling Diode

Freewheeling diode is a critical component for the buck converter side of the project. This diode plays a crucial role in ensuring the proper operation of the converter by providing a path for the current when the switch is turned off. According to our simulations for the rated conditions, the diode must block reverse voltages up to 285 V. Also, maximum current is in around the range of 20 A. By considering these values, we decided to use the DSEI30-06A power diode. One big advantage of this diode is its short recovery time. Hence, it is suitable for high frequency switching applications and it can be used in our switching frequency range (1-3 kHz) safely. With the current capacity of 37A and 600 V breakdown voltage this component seems like a good choice for our project.

Parameters	Maximum Ratings
Forward Current (I_F)	37 A (@ T_J=85 °C)
Reverse Blocking Voltage (V_R)	600 V (@ T_J=125 °C)
Reverse Recovery Time (t_{rr})	35 ns (@ I_F = 30 A)

Table 3: DSEI30-06A Parameters

e) PWM Generator

For creating the PWM signal and controlling the switch at the buck converter side, we decided to use LM555 Timer IC. Given the availability of this component in the lab storage, it was worth exploring its potential applications. It can be configured in various modes, including astable mode for generating continuous square waves, which is ideal for PWM generation. In astable mode, the LM555 timer operates as an oscillator, continuously switching between its high and low states. The frequency and duty cycle of this square wave are determined by two external resistors (RA, RB) and a capacitor (C). By adjusting these components, we can control the PWM characteristics by using the formulas given in datasheet. To adjust the duty cycle properly, it is decided to use a potentiometer for R_B and by slowly increasing this resistance we will be able to achieve soft starting for the DC motor. A circuit that we will implement is given in datasheet and can be seen in below.

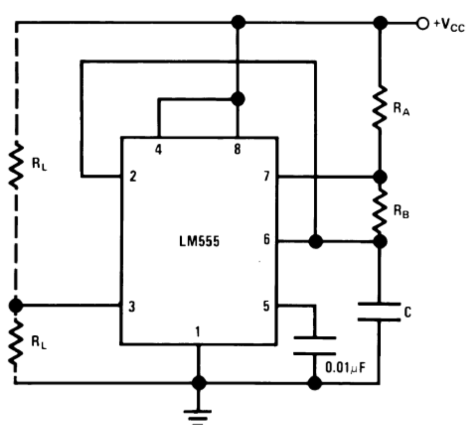

Figure 15: Astable operation of LM555 Time

f) Auxiliary Components

The components mentioned until this point were the main components for this project. Apart from them, it is worth to also talking about some other necessary items. From the gate driver side, one resistor, one potentiometer and one small capacitor will be used for the LM555 IC. A small gate resistor will be connected to series and 10kohm pull down resistor will be connected to parallel to IGBT gate. Also, an optocoupler device will be implemented between the driver and IGBT. For the optocoupler it is decided use the model of TLP250 due to high-speed switching capability. The banana types of connectors will be used for both input and output side of the circuit. Heatsinks will be mounted to rectifier module, IGBT and to freewheeling diode to have efficient cooling performance

5. Conclusion and Remarks

In this hardware implementation project, we aim to design a circuit that converts AC voltage to DC using a three-phase bridge rectifier, followed by a buck converter to step down and regulate the DC voltage for driving a DC motor. The three-phase rectifier topology was chosen for its higher average output voltage and low ripple characteristics, providing a more stable DC source. The buck converter will use a low-side switching configuration, with the N-type switch reference connected at the emitter side for better control. For simplicity, a single rectifier module will be used, though it will require effective heat dissipation through heatsinks due to the power dissipation in the rectifier. Large DC link capacitors will be placed at the rectifier output to filter out ripples effectively. Since the motor is an inductive load, no additional LC filter will be necessary at the output of the buck converter, as the motor will naturally smooth the current. For the switching device, an IGBT will be used instead of a MOSFET, due to its superior voltage rating capabilities. The switching frequency and duty cycle will be controlled using a timer IC, with a potentiometer connected to adjust the duty cycle. The entire system has been simulated in Simulink under rated conditions and the component models are selected accordingly. In the next phase, we will order the necessary components and implement the circuit on a copper board.