MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

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EE463 – STATIC POWER CONVERSION I

HARDWARE PROJECT

FINAL REPORT

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Muhammet Kamer Taha GENÇ 2234748

Mustafa Burak ÇORUK 2442812

Öykü KAYAN 2516391

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Introduction

This project focuses on designing a DC motor drive system using a controlled rectifier to convert AC grid input into an adjustable DC output. The report evaluates four topologies: single-phase diode rectifiers with buck converters, three-phase diode rectifiers with buck converters, single-phase thyristor rectifiers, and three-phase thyristor rectifiers. The performance of these topologies is assessed through simulations, and based on the results, the optimal topology is selected. Suitable components are identified, and the simulation-based analysis lays the groundwork for future hardware implementation, ensuring the design meets performance and stability requirements before the prototyping phase. Additionally, the thermal and control aspects of the system are analyzed, ensuring reliable operation under varying load conditions. The findings presented in this report serve as a foundation for further hardware implementation and practical testing.

Problem Definition

This project aims to design a controlled rectifier to power a DC motor by converting AC grid input (single-phase or three-phase) into adjustable DC output (up to 180 V).

Key Requirements:

- **Input**: Single-phase or three-phase AC (adjustable via variac)
- **Output**: Adjustable DC voltage, maximum 180 V
- **Topologies**: Options include:
  - Single-phase diode rectifier + buck converter
  - Three-phase diode rectifier + buck converter
  - Single-phase thyristor
  - Three-phase thyristor
- **Motor Specs**:
  - Armature: 0.8 Ω, 12.5 mH
  - Shunt: 210 Ω, 23 H
  - Interpoles: 0.27 Ω, 12 mH

Topology Options

In designing a controlled rectifier to drive a DC motor, various topologies can be considered to convert the AC grid input into an adjustable DC output. The primary objective is to ensure a stable and efficient DC voltage for reliable motor operation. For this purpose, four alternative topologies for this purpose are the single-phase diode rectifier with buck converter, the three-phase diode rectifier with buck converter, the single-phase thyristor rectifier, and the three-phase thyristor rectifier, each with its own set of advantages and limitations. These topologies are discussed in detail below. These topologies are discussed in detail below.

1) Single Phase Diode Rectifier with Buck Converter

In this configuration, the single-phase AC input is first rectified by the diode rectifier, converting the AC into DC, as shown in Figure 1. The output of the rectifier is then processed by the buck converter, shown in Figure 2, which steps down the DC voltage to the desired level.

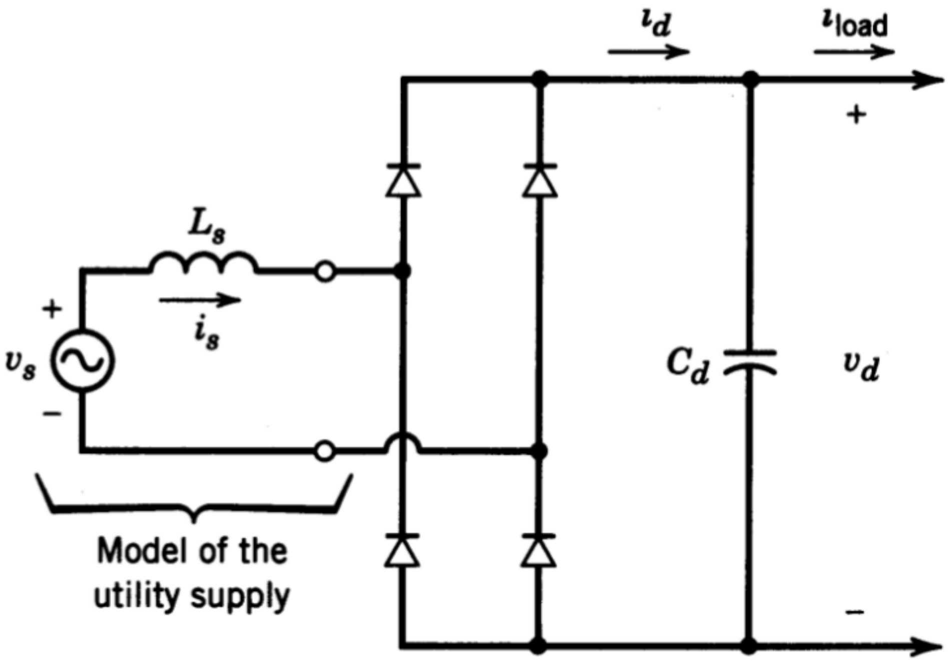

Figure 1: Single Phase Diode Rectifier Circuit

The first stage of the system involves converting the AC input into DC. This is done using a single-phase diode rectifier. In a single-phase full-wave rectifier, the diodes are arranged to rectify both the positive and negative halves of the AC waveform.

The output of the rectifier is a pulsating DC voltage. The average DC output voltage, which is the DC equivalent of the rectified signal, can be calculated using the following formula:

$$V_{out} = \frac{2\sqrt{2}}{\pi} \times V_{phase} \ (1)$$

However, the output voltage is still not pure DC, as it contains ripples corresponding to the AC input frequency. These ripples may affect the performance of the motor, which is why further smoothing, and regulation are needed in the next stage.

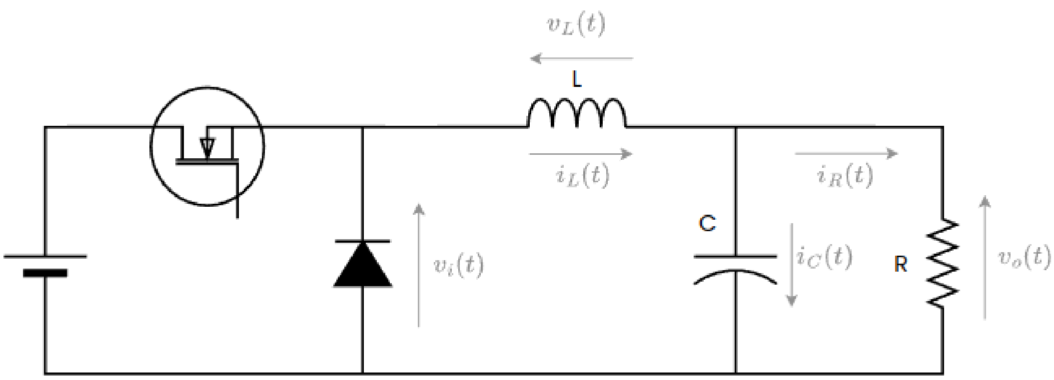

Figure 2: Buck Converter Circuit

A buck converter processes the resultant DC voltage after rectification to lower it to the required level. Buck converters are an example of DC-DC converter that reduces the DC voltage. In order to create a steady, lower DC voltage, it first converts the DC input into a high-frequency pulse using a switching device. Then, inductor and capacitor filter the pulse.

The duty cycle D of the buck converter, which is the ratio of the switch's on-time to the overall switching cycle period, determines the output voltage. The output voltage formula is as follows:

$$V_{out} = D \times V_{in} \ (2)$$

Overall formula for the system is:

$$V_{out} = D \times \frac{2\sqrt{2}}{\pi} \times V_{phase} \ (3)$$

Advantages

- The single-phase diode rectifier is a straightforward solution to convert AC to DC, requiring fewer components than three-phase alternatives.
- Due to fewer components, the single-phase configuration is generally cheaper to implement.
- This configuration provides a straightforward yet efficient solution for smaller motors and is ideal for low-power DC motor applications.
- With fewer diodes in the conduction path, single-phase systems experience lower voltage drops across the diodes compared to three-phase systems, leading to lower conduction losses at lower current levels.

Disadvantages

- There are ripples in the rectified DC output that could affect motor performance, necessitating extra filtering and regulation steps.
- Compared to three-phase rectifiers, single-phase rectifiers are less effective at higher power levels.

2) Three Phase Diode Rectifier with Buck Converter

This configuration involves two stages: the three-phase diode rectifier and the buck converter, working together to efficiently convert and regulate the voltage supplied to the DC motor.

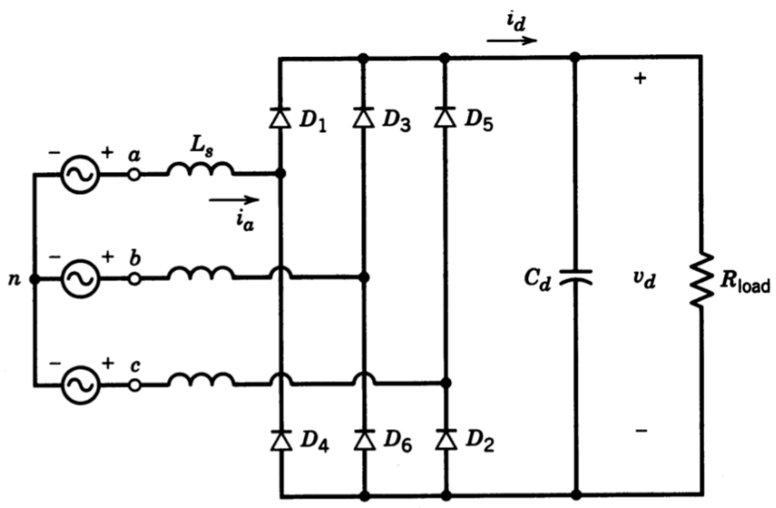

Figure 3: Three Phase Diode Rectifier Circuit

Each of the three sinusoidal AC waveforms in a three-phase system is 120 degrees out of phase with the others. The rectifier transforms the three-phase AC input into pulsating DC by allowing current to flow through the circuit in a single direction using six diodes placed in a bridge arrangement.

The output of the three-phase rectifier is pulsating DC, and the average DC voltage is given by:

$$V_{out} = \frac{3 \times \sqrt{2} \times V_{linetoline}}{\pi} \quad (4)$$

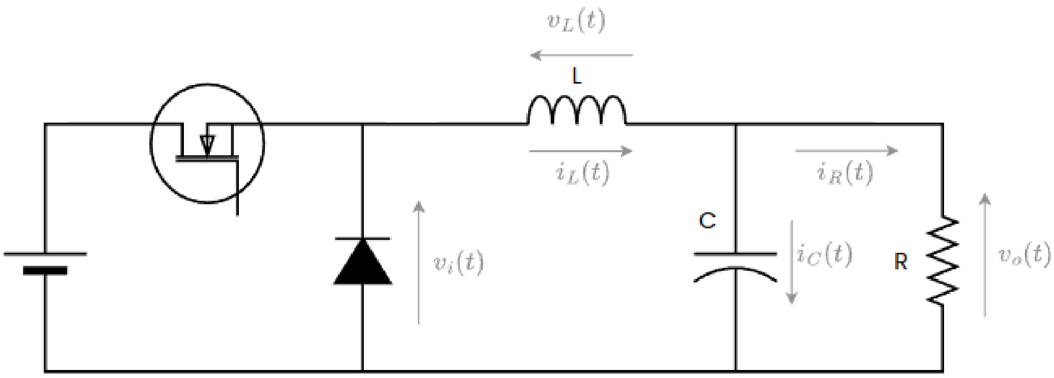

Figure 4: Buck Converter Circuit

Following the three-phase diode rectifier's correction of the DC voltage, the output still requires regulation and control. A buck converter, which lowers down the DC voltage to the required level, is used to do this. The formula for the output voltage is:

$$V_{out} = D \times V_{in} \quad (5)$$

Overall formula for the system is:

$$V_{out} = D \times \frac{3\sqrt{2}}{\pi} \times V_{linetoline} \quad (6)$$

Advantages

- The output voltage from a three-phase rectifier is higher compared to a single-phase rectifier for the same input AC voltage.
- The DC output of a three-phase rectifier is smoother than that of a single-phase rectifier because it generates less ripple. This is critical for efficient and reliable motor performance, especially at higher loads.
- By better utilizing the available AC input, the three-phase system improves efficiency and regulates the DC output. For DC motor applications, where steady power delivery is crucial, this is especially advantageous.
- Three-phase rectifiers are better for larger DC motors or applications needing larger amounts of energy production since they can manage higher power levels more effectively. Performance is enhanced and energy losses are decreased as a result.

Disadvantages

- Compared to the single-phase option, the three-phase diode rectifier system is more complicated. To handle the three-phase AC input, it needs more parts, including six diodes and more circuitry, which extends the design time and complicates the system.
- The system is more costly to implement due to the higher number of diodes and components.
- With more diodes in the conduction path, a three-phase full-bridge rectifier experiences greater total voltage drops across the diodes during operation.

3) Single Phase Thyristor

A single-phase thyristor rectifier is used to convert AC voltage to a controlled DC output voltage. By using thyristors instead of standard diodes, it allows for adjustment of the output voltage, making it suitable for applications that require variable DC voltage.

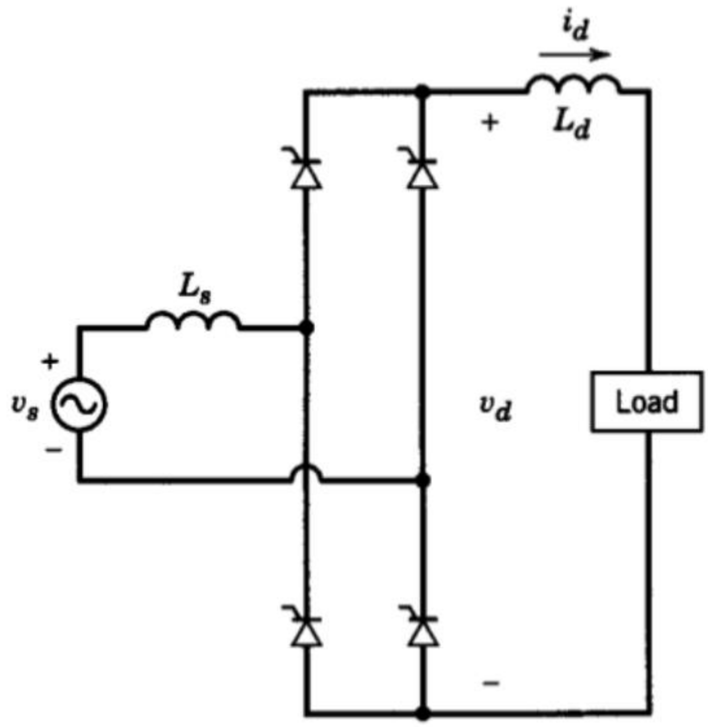

Figure 5: Single Phase Thyristor Circuit

A single-phase thyristor rectifier operates by converting AC into DC while allowing control over the output voltage using thyristors. During each half-cycle of the AC input, the thyristors remain off until they receive a gate pulse at a specific firing angle α. Once triggered, the thyristor conducts, allowing current to flow through the load. By adjusting the firing angle α, which ranges from 0° to 180°, the conduction period of the thyristors is altered. A smaller firing angle results in a higher output voltage, as the thyristor turns on earlier in the cycle, while a larger firing angle reduces the output voltage by delaying conduction. This control over the firing angle enables the rectifier to provide a variable DC output voltage.

The average DC voltage of single-phase thyristor is given by:

$$V_{out} = \frac{2 \times \sqrt{2} \times V_{phase} \times cos\alpha}{\pi} \quad (7)$$

Advantages

- The ability to adjust the firing angle provides control over the output voltage, which is ideal for applications needing variable DC voltage.
- Thyristors have low conduction losses, making the rectifier stage efficient.
- Compared to more complex multi-phase systems, a single-phase thyristor rectifier has a simpler design and fewer components, making it cost-effective.

Disadvantages

- Unlike diode-based rectifiers, thyristor rectifiers require an additional control circuit for triggering the thyristors at the correct firing angle.
- The output of the thyristor rectifier is pulsating DC, which can still affect sensitive loads, requiring additional filtering and smoothing to produce a more stable DC output.

4) Three Phase Thyristor

A three-phase thyristor rectifier is used to convert three-phase AC voltage into a controllable DC output. Like the single-phase thyristor rectifier, this system uses thyristors instead of diodes, allowing the output voltage to be controlled by adjusting the firing angles of the thyristors. The main advantage of using a three-phase system over a single-phase one is that it provides a higher DC output voltage and better efficiency.

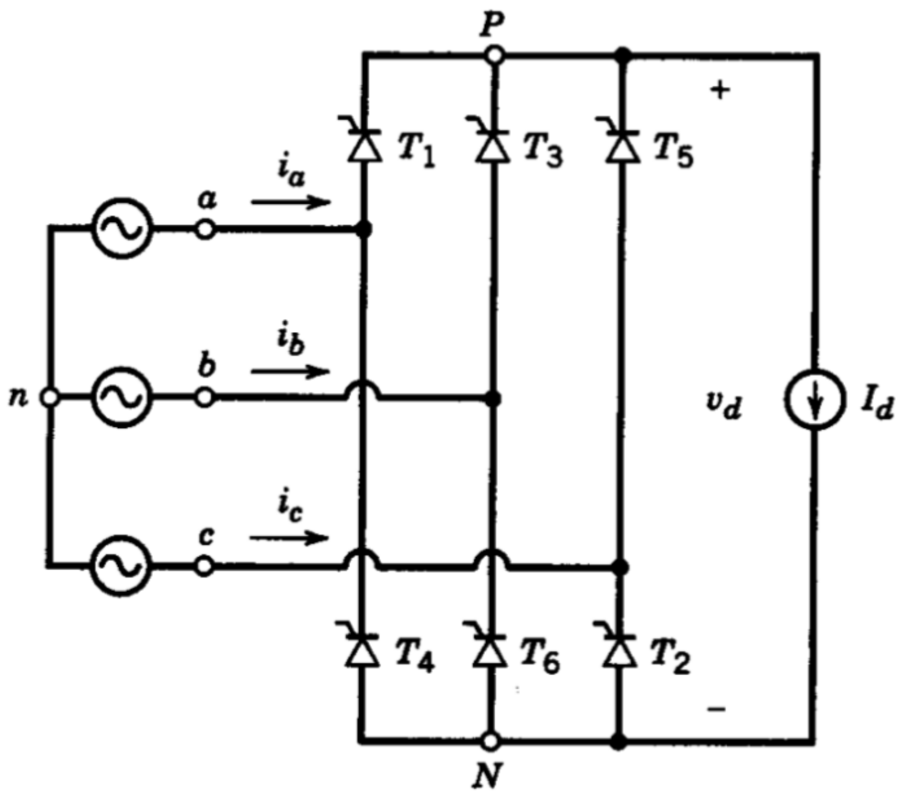

Figure 6: Three Phase Thyristor Circuit

In a three-phase thyristor rectifier, each of the six thyristors is triggered by a gate pulse at a specific firing angle, α, during the positive and negative half-cycles of the three-phase AC input. Each thyristor only conducts for a portion of the AC cycle, depending on when it is triggered, thereby controlling the duration and phase of the current flowing through the load. This allows for precise control of the average DC output voltage, like the single-phase system, but with a higher and more stable voltage due to the nature of the three-phase input.

The average DC voltage of three-phase thyristor is given by:

$$V_{out} = \frac{3 \times \sqrt{2} \times V_{linetoline} \times cos\alpha}{\pi} \quad (8)$$

Advantages

- The output DC voltage is significantly higher compared to single-phase rectifiers for the same input AC voltage, making it more suitable for high-power applications.
- Three-phase systems provide a smoother DC output compared to single-phase systems, as the voltage ripple is reduced.
- Three-phase systems provide more consistent power delivery and better utilization of the AC input.

Disadvantages

- The control system for a three-phase thyristor rectifier is more complex than for a single-phase system, as it requires precise timing of the gate pulses for each of the six thyristors. This increases design complexity and costs.
- Like all thyristor-based rectifiers, three-phase thyristor rectifiers generate harmonic distortions.
- Although smoother than single-phase systems, the output from a three-phase thyristor rectifier is still pulsating DC, which might not be suitable for applications requiring a very smooth and stable DC output. Additional filtering is often required.
- The use of more components and the need for a complex control system make three-phase thyristor rectifiers more expensive to implement than simpler rectifier circuits.

Topology Selection

After carefully evaluating the advantages and disadvantages of the four topologies—single-phase diode rectifier with buck converter, three-phase diode rectifier with buck converter, single-phase thyristor rectifier, and three-phase thyristor rectifier—the decision was made to select the three-phase diode rectifier with buck converter topology for the motor drive application.

Higher Output Voltage: The three-phase diode rectifier with buck converter offers a significantly higher DC output voltage compared to the single-phase systems, making it ideal for high-power motor applications. When combined with the buck converter, the system is capable of efficiently stepping down the voltage while maintaining stability.

Smoother DC Output: The integration of the three-phase diode rectifier with the buck converter results in a smoother DC output. A three-phase rectifier inherently produces less ripple in the DC output compared to single-phase systems. When this is paired with a buck converter, which further smooths the voltage, the result is an even more stable DC supply for the motor. This contrasts with thyristor rectifiers, which, despite offering adjustable voltage, still tend to introduce more ripple.

Increased Efficiency: For high-power motor applications, the three-phase diode rectifier with buck converter topology is more efficient than both single-phase systems and three-phase thyristor rectifiers. The three-phase rectifier ensures that the system operates with lower ripple and fewer losses, while the buck converter improves efficiency by stepping down the voltage only when necessary. Thyristor rectifiers, although they offer voltage control, are typically less efficient in high-power applications due to the increased switching and conduction losses inherent in thyristors.

Simplified Control and Design: The three-phase diode rectifier with buck converter combination simplifies the control system compared to a three-phase thyristor rectifier. While thyristor-based systems require complex control mechanisms to adjust the firing angle and timing of the gate pulses, the diode rectifier system with the buck converter requires less sophisticated control. The diode rectifier operates with a simpler and more reliable design, reducing both system complexity and cost.

Simulation Results

The parameter selection process for the simulations involves two key stages.

In the first stage, components for the three-phase diode rectifier are selected based on the guidelines provided in HW-1 of the EE463 course. Once these components are chosen, the system is simulated to ensure satisfactory performance. If the results meet the expected criteria, these components are retained for the subsequent stages of the design.

In the second stage, parameters for the buck converter are carefully selected to ensure the output voltage is reduced to a maximum of 180V, which depends on the duty cycle (D) and the efficiency of the components. The efficiency of the MOSFET, diode, inductor, and capacitor are key factors in determining the output voltage, and the following equation is used to maintain a 180V output:

$$V_d \times D \times efficiency = V_o \ (9)$$

The selection of inductance, capacitance, and resistance values plays a crucial role in the buck converter simulation. A resistance of 20 ohms is chosen, as it is a balanced value that is neither too low nor too high. This resistance value impacts the mode of operation, which can either be Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM). To ensure the converter operates in CCM, used formulas are:

$$L = \frac{V_{out} \times (1 - D)}{\Delta I_L \times f_s} \ (10)$$

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{out}} \ (11)$$

$$\Delta V_{out} = \Delta I_L \times \left(\frac{1}{8 \times f_s \times C} + R_{ESR} \right) \ (12)$$

During our research on switching frequency, we found that frequencies between 20-30 kHz are commonly used for semi-professional applications like ours. Based on this, we set the switching frequency at 25 kHz.

The first parameter that we can arrange is ripple of the inductance current because it depends on the duty cycle, output voltage, switching frequency and inductance. Given an average inductor current of 9.1 A (based on the duty cycle D=0.35 derived from the equation 9, where the efficiency was approximately 0.995), we targeted an inductor current ripple of 1-1.5 A. However, it should be noted that this value may change in a real application with actual components. Simulations using real component values will be presented in this report and the final report.

From equation 10:

$$L = \frac{180 \times (1 - 0.35)}{25000 \times 1.5} \cong 3 \ mH$$

With the inductance value set, we then calculated the capacitance to limit the voltage ripple. Our desired output voltage is 180 V, and we aimed for a voltage ripple of no more than 2.5%, which corresponds to:

$$\Delta V = 180 \times 2.5\% = 4.5\ V$$

Using the formula 11 for the output capacitor ripple:

$$C = \frac{1.5}{8 \times 25000 \times 4.5} \cong 1.7\ uF$$

To ensure better filtering and accommodate real-world variations, we increased the capacitance to 3 μF. This value also helps meet the corner frequency requirement. Corner frequency is the frequency at which the response of a system (such as a filter, amplifier, or control system) begins to decline or change.[1]

The formula for calculating the corner frequency is:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (13)$$

In our EE463 lectures, it was highlighted that the corner frequency should be set lower than the switching frequency to maintain safe operating conditions for the components. During the initial power flow, there may be ringing in the circuit, and special attention must be given to the corner frequency point. This is because if the gain of the filter increases unexpectedly due to ringing at the corner frequency, it could result in excessive voltage and current spikes, much higher than the expected values, potentially damaging the components.

For our buck converter, using L=3 mH and C=3 uF, the corner frequency is calculated as:

$$f_c = \frac{1}{(2 \times \pi \times \sqrt{3 \times 10^{-3} \times 3 \times 10^{-6}})} \cong 1677\ Hz$$

1) Three Phase Diode Rectifier Simulation

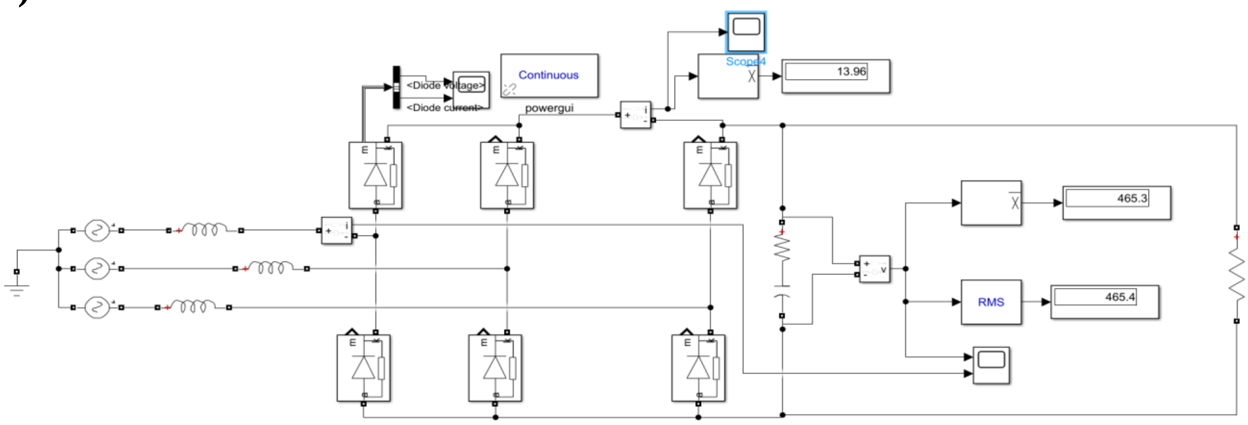

Figure 7: Three Phase Diode Rectifier Circuit

Figures 8, 9, and 10 illustrate the results obtained from the diode rectifier configuration based on the parameters specified in EE463 Homework 1.

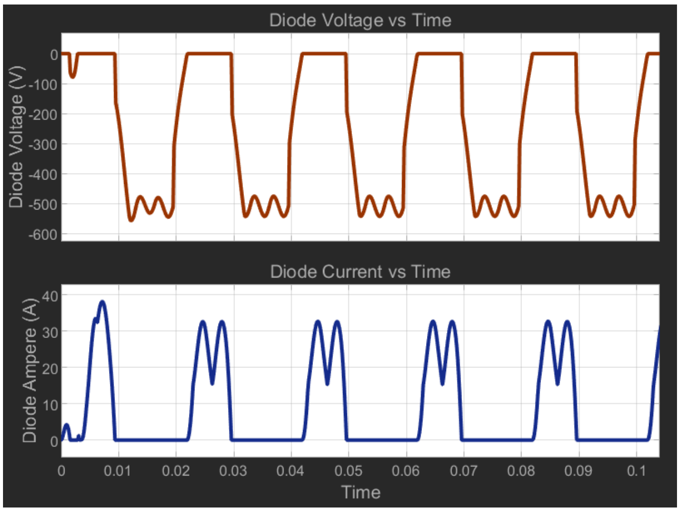

Figure 8: Diode Rectifier Diodes Voltage and Current vs. Time Waveform

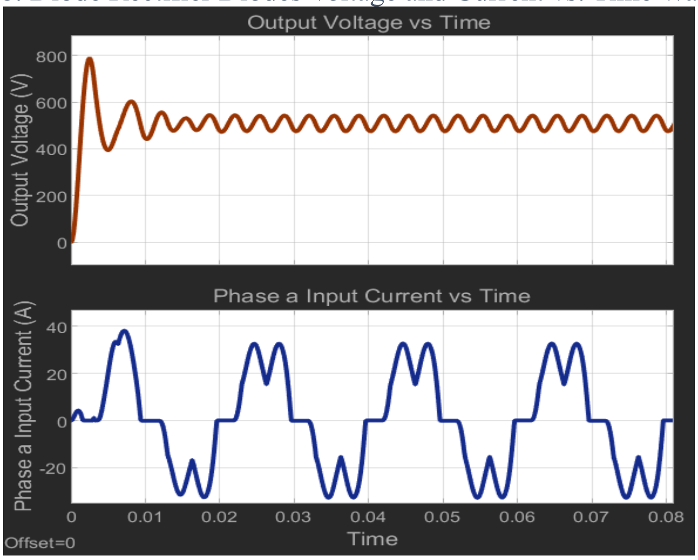

Figure 9: Output Voltage and Input Phase Current vs. Time Waveform

Figures 10 and 11 depict the performance of the combined diode rectifier and buck converter circuit, using component parameters from calculations.

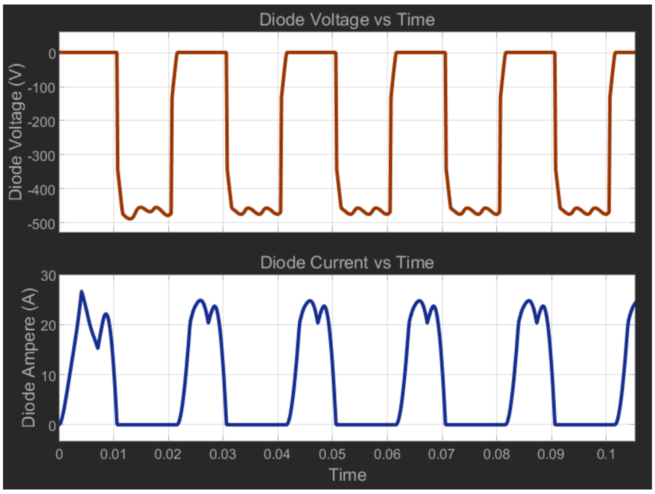

Figure 10:Diode Rectifier Diodes Voltage and Current vs. Time Waveform

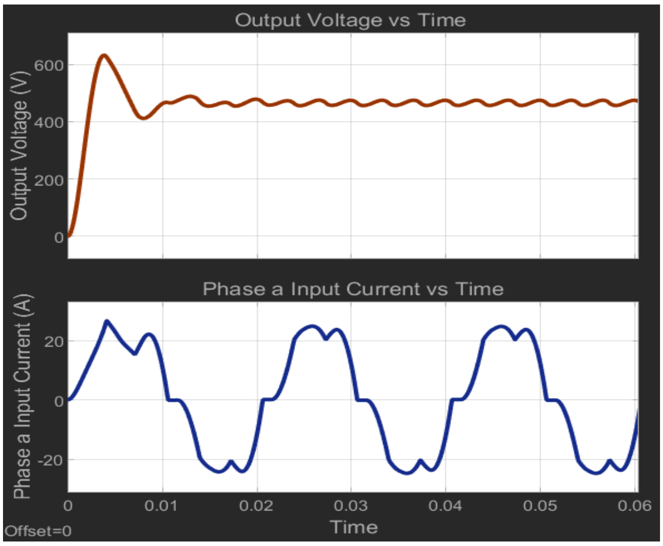

Figure 11: Output Voltage and Input Phase Current vs. Time Waveform

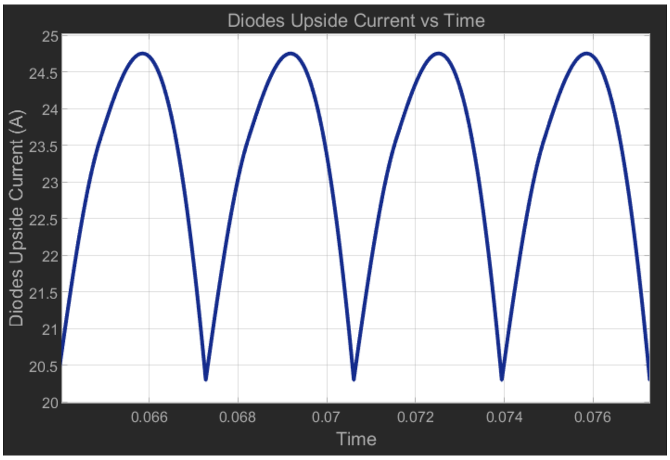

Figure 12: Diodes Upper-side Current vs Time Waveform From Closer Perspective

Figures 8 and 10 show us we should select diodes which have (around) 600 V repetitive peak reverse voltage. Figure 9 shows us this value is quite enough because it is %20 more than peak reverse voltage, it says peak value of the simulation results will be in safety margin when we select diode as 600V or more.

Figure 11 indicates that circuit gives enough good output voltage and voltage ripple to the buck converter, which is around 465V, and ripple is less than %4 from peak to peak. Input phase a current is going up to 25A and the current at the output of the three diode is like figure 12. 10mH source inductor and 100uF capacitor give us these simulation results.

These results are good enough for this project and results will be changed with buck converter integration, but as a result of integrated circuit simulations these changes will not be too much effective.

2) Buck Converter Simulation

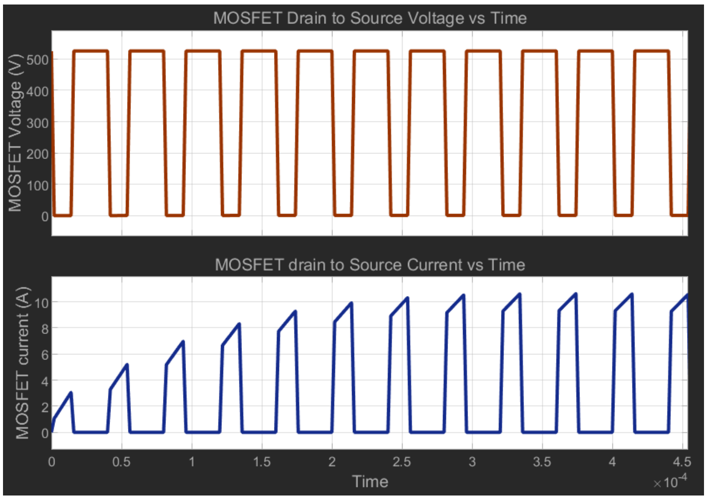

Figure 13: MOSFET Drain to Source Voltage and Current vs. Time of the Buck Converter

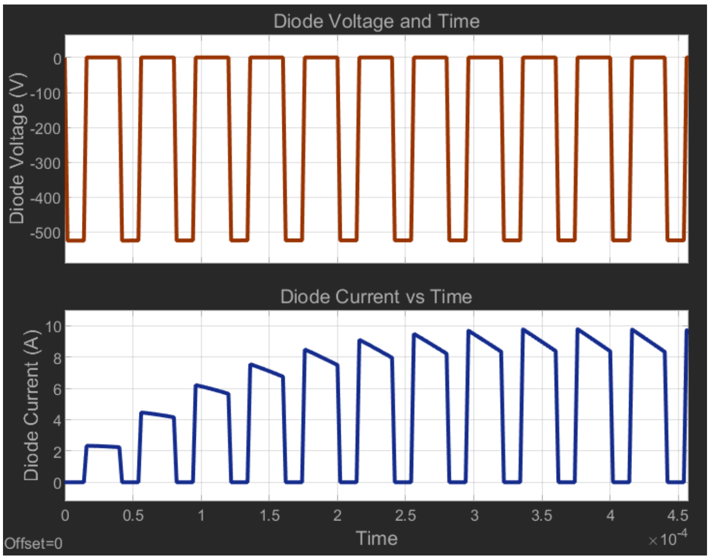

Figure 14: Diode Voltage and Current vs. Time of the Buck Converter

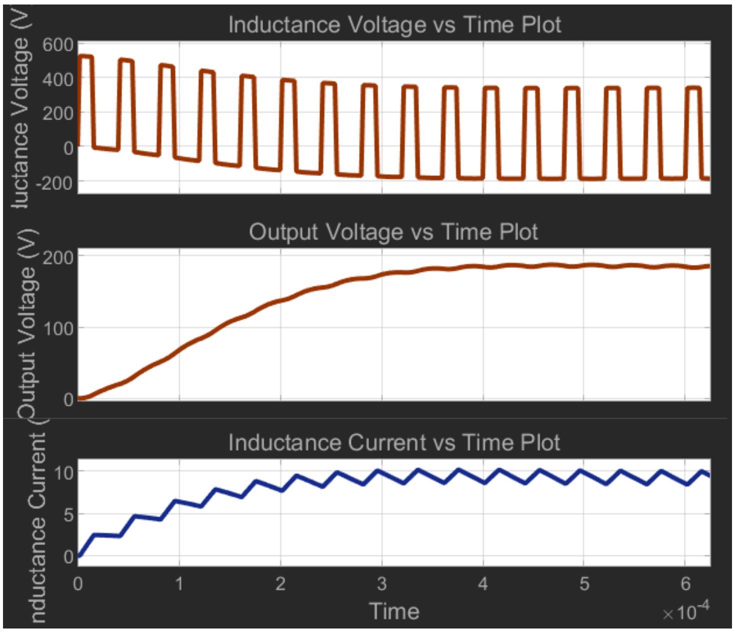

Figure 15: Inductance Voltage, Output Voltage and Inductance Current vs. Time of the Buck Converter

Figures 13-14-15 are the results for buck converter simulations. Still rectifier and buck converter are not connected each other, so these results are not final results for component selection, but they are good perspective decider and result for the system behavior. Figures 13 and 14 are very important for diode and MOSFET selection, we expect quite close results as a ratio (ratio between input and output current of the buck converter). Inductor behavior can be seen at figure 15. From figure 15 we see that the output voltage becomes higher and higher until the desired value. This behavior occurs because output capacitor and inductor are charging at the beginning of the process and as it can be seen from figure 17 after stability, output voltage ripple and inductor current ripple are quite small and smooth. As a result of duty cycle we see that the inductance voltage is going between 345V and -180V.

3) Three Phase Diode Rectifier and Buck Converter Simulation

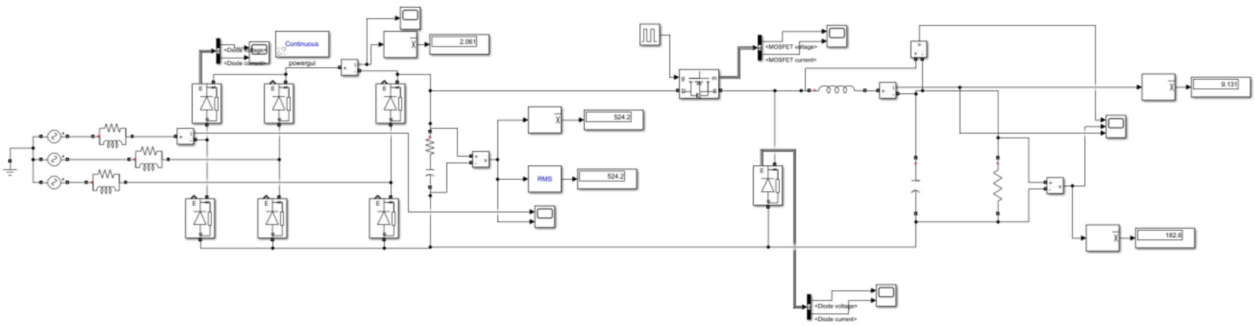

Figure 16: Connected Circuit of Three Phase Diode Rectifier and Buck Converter (Non-ideal Conditions)

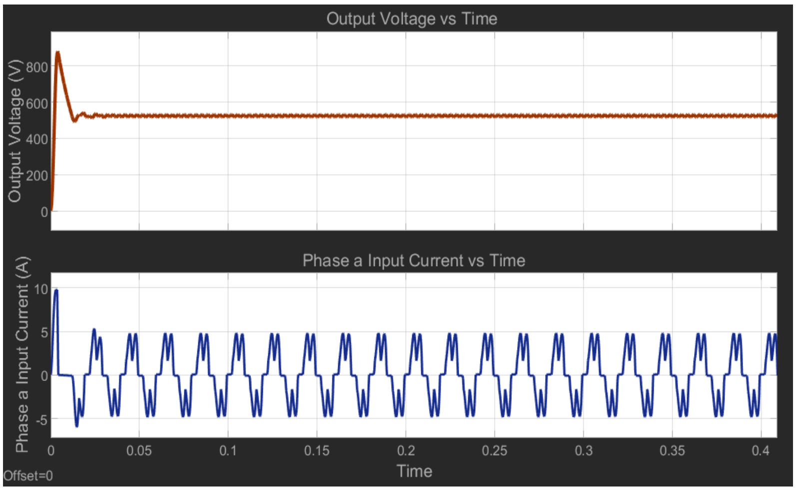

Figure 17: Phase a Input Current and Output Voltage vs. Time of Three Phase Diode Rectifier

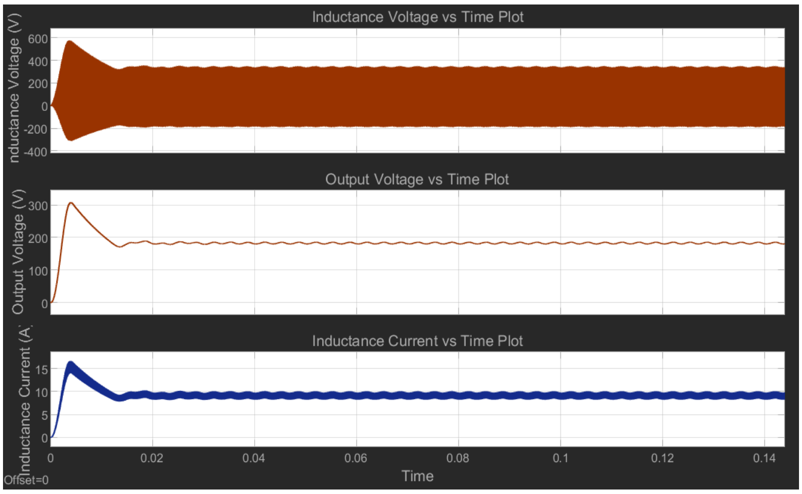

Figure 18: Inductance Voltage, Output Voltage and Inductance Current vs. Time of the Buck Converter

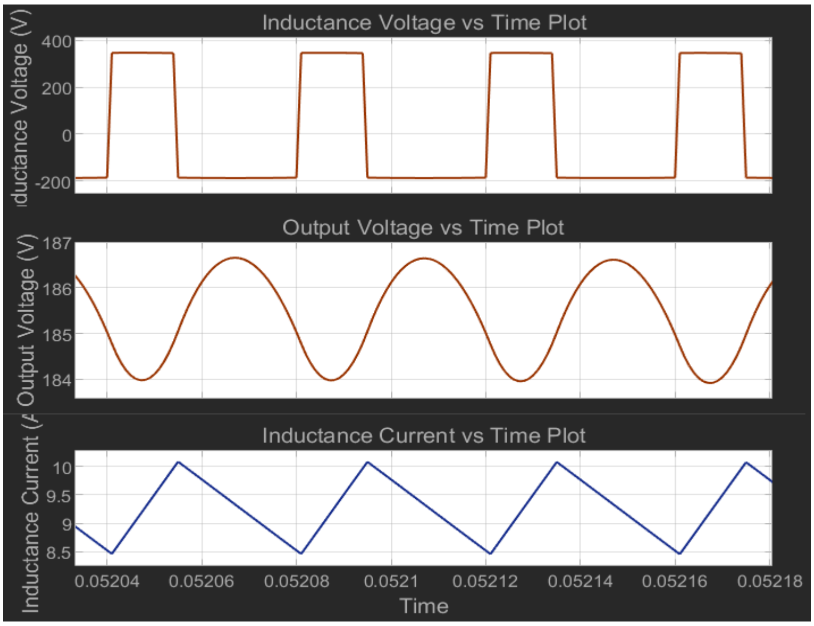

Figure 19: Closer Perspective for Inductance Voltage, Output Voltage and Inductance Current vs. Time of the Buck Converter After Power Flow Starts and Circuit Becomes Stable

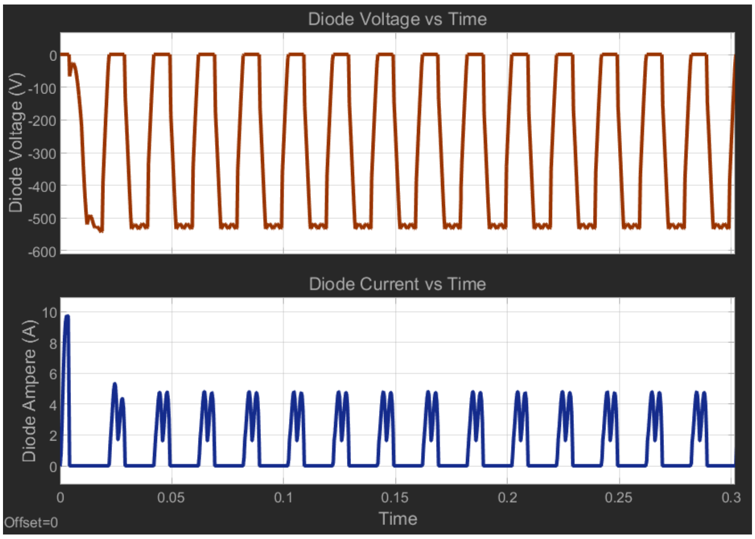

Figure 20: Diode Voltage and Diode Current vs. Time for the Three-phase Diode Rectifier

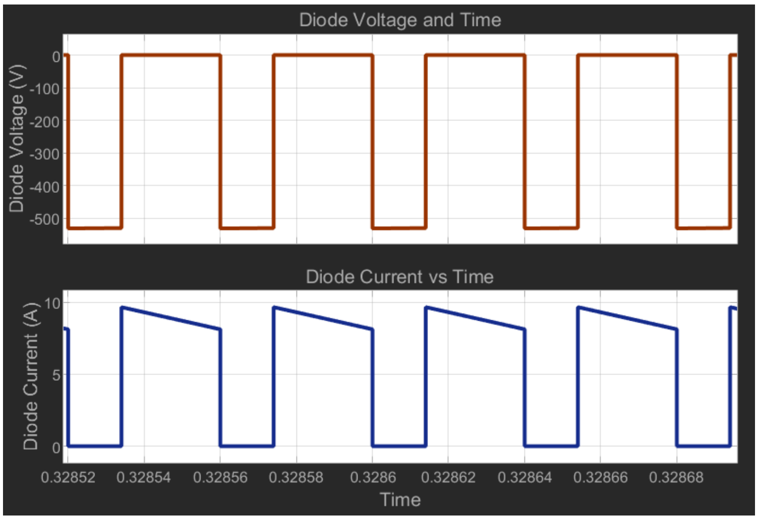

Figure 21: Buck Converter Diode Voltage and Current vs. Time After Circuit Becomes Stable

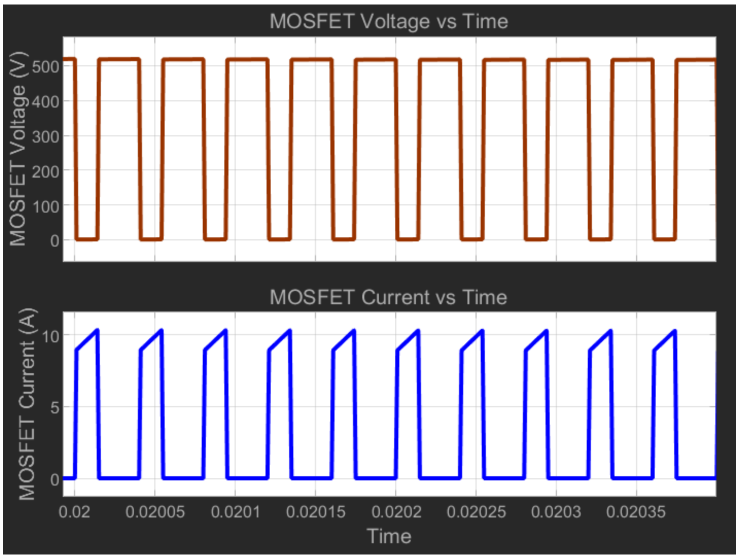

Figure 22: Buck Converter Switching MOSFET Voltage and Current vs. Time after circuit becomes stable.

These figures (figures from number 16 to number 22) are the schematic/results of the Simulink simulations of the integrated three phase diode rectifier and buck converter circuit while the duty cycle is 0.35.

We see that these results are similar (at least similar as a shape but not numerical) to the sub-blocks simulations which are given at first and second part of this section.

Figure 18 shows that there is good enough DC voltage at the output of the rectifier (so at the beginning of the buck converter) which has 524 V mean and rms voltage and 3% ripple. Phase current could be better, but, since there is an inductor at the buck converter this ripple of the current at the rectifier side is not a problem. At figure 17 there is too much ripple of the current which is going through output of the rectifier, but current result of the buck converter output current is enough good as it can be seen from figure 19. This current result fits our calculations and shows us we can use these parameter values for component selection. Output voltage ringing is less than 2% (almost 1%) is also enough for this project.

As a result of these simulations, we can say diode of the rectifier should have (at least) 600V reverse voltage capability as repetitive peak value and also should handle 20 A as a peak (at the beginning) and 4-5 A as a continuous value. Inductor of the buck converter will have 350 V and – 180 V voltage value while it has the current between 8.5-10 A. Selection of the diode of the buck converter is also very important and this diode should have at least 550*1.2 = 660V repetitive reverse voltage peak value while the current is up to 10 as continuous value. MOSFET selection is quite important for switching, duty cycle, output current and voltage ripple or value (mean and peak value both). Therefore figure 22 are very important and they should be examined carefully. Figure 22 shows that continuous current is 10 A peak and voltage value (which should be cut during the switch close times ((1-D) Ts)) is 524 V at least. Of course, these values can vary with duty cycle and variac opening ratio at the laboratory. For this duty cycle and circuit parameters, MOSFET sees 900 V voltage and 18 A current at the beginning of the switching process, until circuit becomes stable point. Under these information and results, circuit components will be selected at the "Component Selection" part of this report.

Component Selection

Diode Bridge Selection:

Our diode operates at a maximum voltage of 550V and 12A. To ensure additional safety, we set our design criteria to a maximum current of 35A and a maximum voltage of 1.2kV. During our search on the Digikey website, we identified diodes within a price range of $1.71 to $18.50. We initially focused on the two most economical options:

1. DIODE H.FAST SINGLE 80A 650V TO247-2 THT (single diode option)
2. DIODE BRIDGE 35A 1.2kV DB35-12 (bridge package option)

The second diode option (bridge option) offers a faster switching time, while the first diode features a lower forward voltage. Both diodes include power dissipation data in their catalogs. For our system peak current is 12A, and both 80A and 35A is okey. However, 80A offers too much safety margin which is unnecessary.

Since power loss of diode rectifier is too small, power dissipation level is not important, but still DB35-12 offers better power dissipation to us. However, power loss can be considered negligible and is not an advantage or disadvantage for component selection for diode. Based on this analysis, we selected the most cost-effective option, DIODE BRIDGE 35A 1.2kV DB35-12 . Instead of 10-12 dollars for 6 different (but identical) 80 A diodes, it is better to pay 2.98 dollar to one bridge (which is made by 6 diode) for 35A diode bridge rectifier.

MOSFET - SH32N65DM6AG

-2 N-channel 650 V, 89 mΩ, 32 A, half-bridge topology Power MOSFET

Features,

- Half-bridge power module
- 650 V blocking voltage
- Fast recovery body diode
- Very low switching energies
- Low package inductance
- Low thermal resistance
- Isolation rating of 3.4 kVrms/min [2]

As it is written "Simulation Results" part, we need MOSFET which can work under 550 V (according to input voltage change this value can be 250 V also but this is the highest case as it is indicated also in simulation results part). Also, current will be mostly 20-22 A in safety margin. As we can see from the features and also from the name of the MOSFET, this component can work under 650 V and 32 A which are fit our requirements. This component offer low package inductance and low gate charge which lets us to on and off it fast. Turn-on rise time is 10ns, turn-off fall time is 9ns which is okey for our circuit (25 kHz means 40000 ns). R_{DS}(on) is 89 mohms and it tells us the conduction loss will be very low. We can calculate it like that: R_{DS}(on)*ton*I*fs = 0.089*14.2us*18A*25kHz = 0.57 Watt for each second.

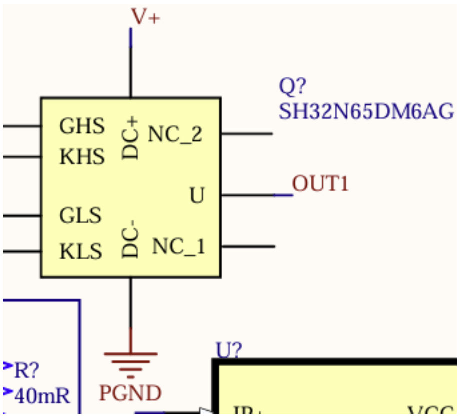

Figure 23. Half bridge MOSFETS SH32N65DM6AG circuit layout.

Current Sensor – ACS712ELCTR30AT
– Hall-Effect-Based Linear Current Sensor IC, 2.1 kVRMS

Features:
- Low-noise analog signal path
- 5 µs output rise time in response to step input current
- 80 kHz bandwidth ▪ Total output error 1.5% at TA = 25°C
- Small footprint, low-profile SOIC8 package
- 1.2 mΩ internal conductor resistance
- 2.1 kVRMS minimum isolation voltage from pins 1-4 to pins 5-8
- 5.0 V, single supply operation ▪ 66 to 185 mV/A output sensitivity
- Output voltage proportional to AC or DC currents [3]

For current sensing, ACS712ELCTR30AT hall effect current sensor is selected. Its bandwidth of 80 kHz and fast response time of 5 µs are sufficient to detect rapid changes in current, ensuring accuracy in real-time applications. Total output error is quite low (1.5% at 25 Celsius) which is desired value for high accuracy application. Additionally, the isolation voltage of 2.1kV RMS provides safe electrical isolation between the sensor and the circuit, a crucial feature for power electronics applications. Also, 5V singly supply operation is quite easy to implement. From figure 4.1 it can be seen 30A-T model of this current sensor can read current until -+30 A which is enough for our project (we need mostly 20 A which is mentioned at Simulation Results part). The sensor's high sensitivity (66 mV/A for 30A-T model) ensures precise and linear measurement of current. This component's robustness and precision make it an excellent fit for our design, ensuring reliable performance in demanding environments.[4]

Part Number	Packing*	T_A (°C)	Optimized Range, I_P (A)	Sensitivity, Sens (Typ) (mV/A)
ACS712ELCTR-05B-T	Tape and reel, 3000 pieces/reel	–40 to 85	±5	185
ACS712ELCTR-20A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±20	100
ACS712ELCTR-30A-T	Tape and reel, 3000 pieces/reel	–40 to 85	±30	66

Figure 24. Current sensor datasheet information for current sensing.

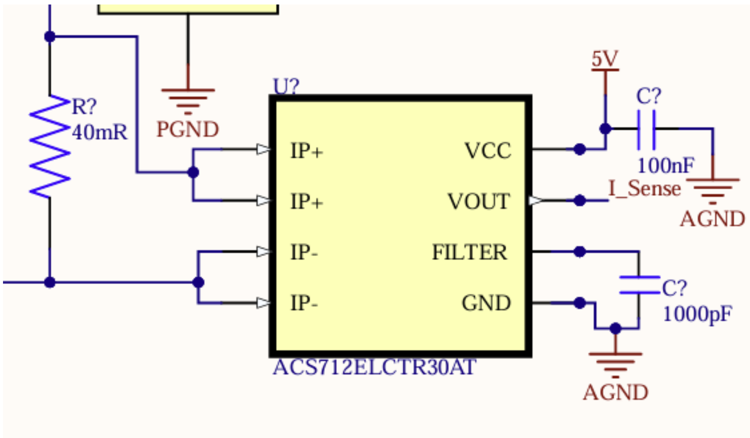

Figure 25.Hall effect current sensor ACS712ELCTR-30A-T circuit layout.

Raspberry pi - SC0915
RP2040 Based Microcontroller Board

SC0915 Raspberry pi is used for PWM generation and controlling. Since this card can work with 5V there is also another process inside of raspberry pi to be able to produce other voltage level from this voltage. We do not use this raspberry pi for complex purposes. There are 3.3V gate driver voltage level from raspberry pi (raspberry pi produces 3.3 V). There are four PWM outputs from this card, and it takes current senser output information as input (for controlling purpose), two fault analysis point as inputs, and two encoder inputs. This card has capability to be able to produce these PWMs if necessary inputs can be given to the card. Also, controlling is an aim of this project, and we can implement control thanks to this control card.[5]

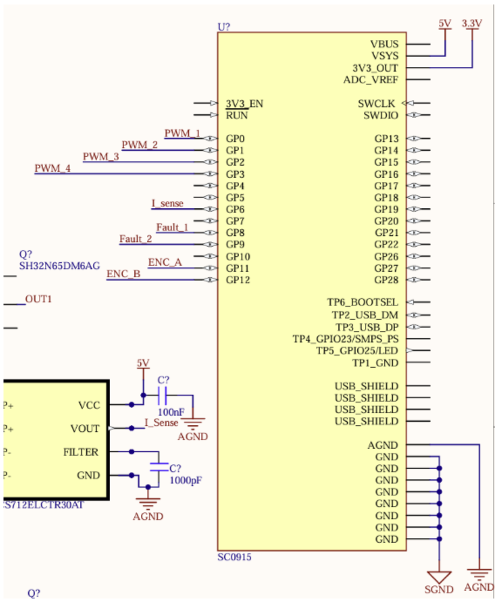

Figure 26. Raspberry pi SC0915 circuit layout.

Gate Drivers – L6491D
High Voltage High and Low-side 4 A Gate Driver

For SH32N65DM6AG half bridge, there should be gate driver. Features of this gate driver will be mentioned detailed in "Gate Driver Design" part.

L6491D gate driver features,
- High voltage rail up to 600 V
- dV/dt immunity ± 50 V/ns in full temperature range
- Driver current capability: 4 A source/sink
- Switching times 15 ns rise/fall with 1 nF load
- 3.3 V, 5 V TTL/CMOS inputs with hysteresis
- Comparator for fault protections
- Compact and simplified layout
- Bill of material reduction
- Effective fault protection

Since this gate driver has 600 V high voltage capability, 4A current capability, and quite small rise and fall time, we have chosen this gate driver for our MOSFETs (half bridge).
This gate driver model works with 15V Vcc power supply. [6]

Gate Driver Design

For full-bridge topology of this project there should be gate drivers for MOSFET driving. This gate drivers should drive the MOSFET via PWM signals which come from Raspberry pi. L6491D model of gate driver is selected for this purpose.

For low input and high input of gate driver there are PWM signals. For high inputs and low inputs of L6491D gate drivers, there are RC filters. Since PWM of the circuit has 25kHz frequency, and it is optimal to have cut off frequency higher than the operation frequency, 250 kHz filtering is selected (which is 10 times of frequency of PWMs. 10 time means 1 logarithmic scale, so it is enough good). From $f = \frac{1}{2*\pi*R*C}$ formula, resistor and capacitor were selected as 820 ohm and 820 pF. These filters are put at low inputs and high inputs of the L6491D gate drivers. In L6491D driver, there is an integrated comparator for fast protection against overcurrent, overtemperature, etc. For comparator pins, there is a filter for high frequency noises. To be able to eliminate high frequencies properly at the comparator positive pins, this time it is chosen 3 times safety instead of 10 times safer. So, filter is designed for 75 kHz, and resistance is 10 Kohm, capacitance is 220 pF were selected. For comparator negative pins, $V_{CP}^{-} = 0.9$ for noise margin. From voltage divider (it can be seen from PCB layout):

$$0.9 = \frac{RP2}{RP2+RP1} *3.3$$

$R_{P1} = 27$ Kohm, and $R_{P2} = 10$ Kohm.

Also, for voltage divider stabilization, capacitance is selected as 100nF.

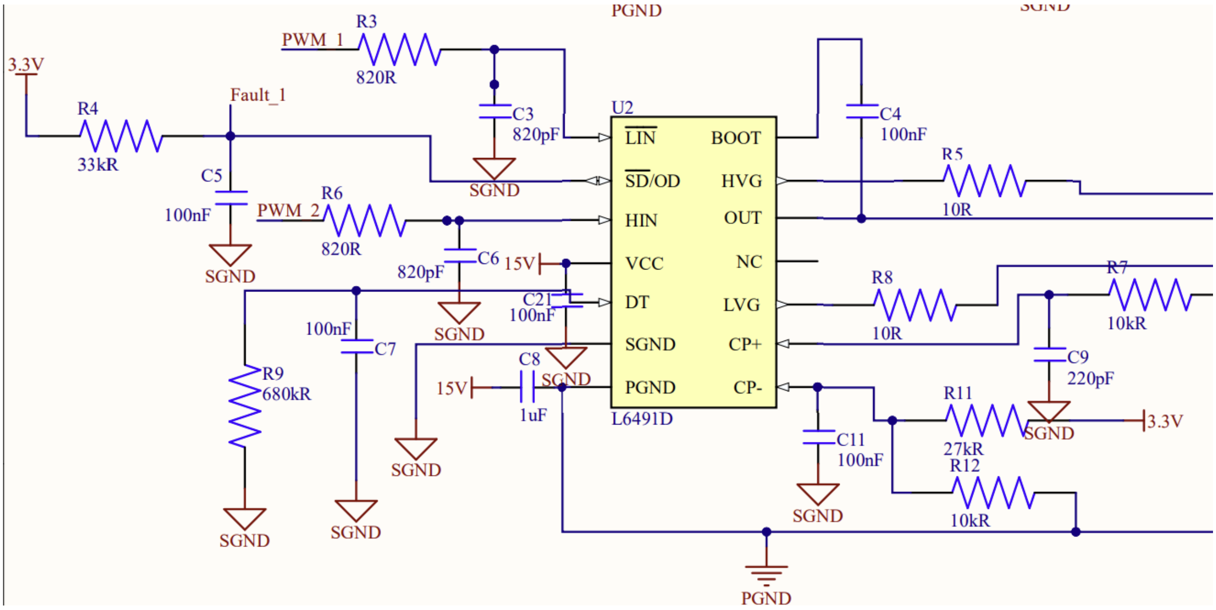

Figure 27. L6491D gate driver circuit layout.

Thermal Analysis

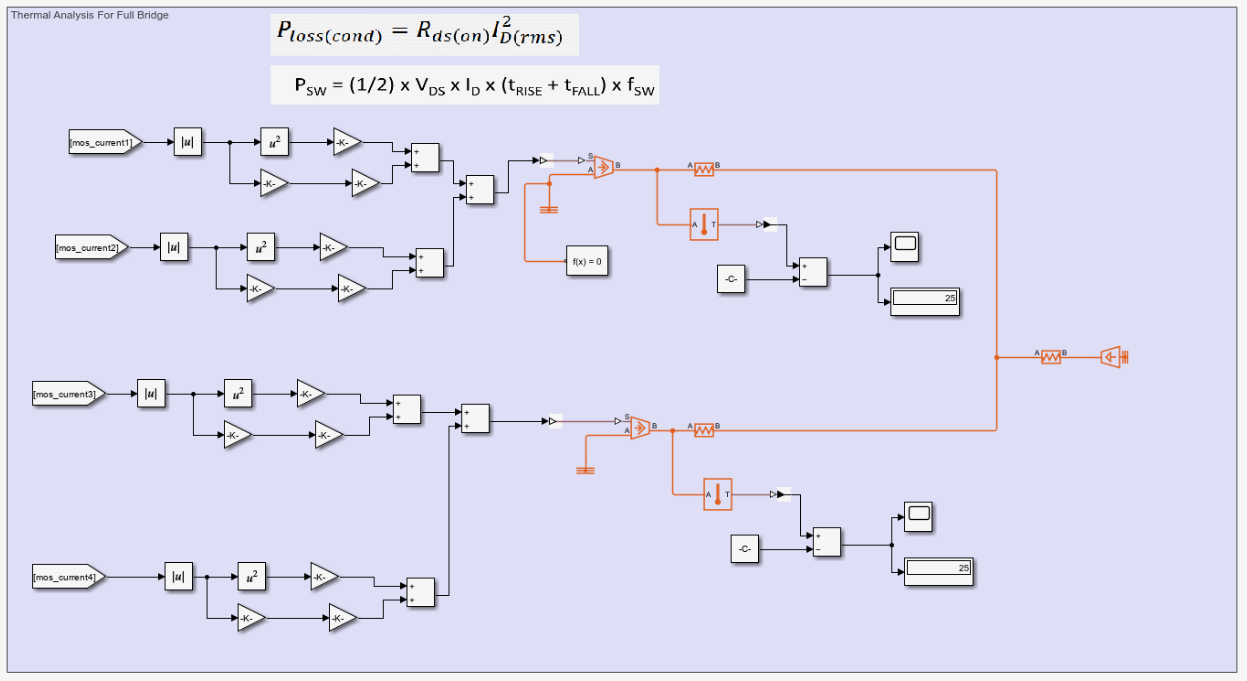

Figure 28. Thermal Analysis for Full Bridge Buck Converter

For the thermal analysis of the MOSFETs, two types of losses are calculated: switching losses and conduction losses. Conduction losses arise from the MOSFET's on-resistance, while switching losses are determined by factors such as voltage, current, on-time, off-time, and switching frequency.

For the component SH32N65DM6AG, each module contains two MOSFETs, and their losses are summed accordingly. On the PCB, two SH32N65DM6AG components share a single heat sink, and this configuration is mirrored in the simulation.

The thermal pad Non-Silicone Heat Transfer Compound Plus has a thermal conductivity of 2.5 W/m·K. With a thickness of 1 mm, its thermal resistance is calculated to be 0.0025 W/K. The junction-to-case thermal resistance of the MOSFET is 0.6 W/K, while the heat sink, utilizing forced convection, has a thermal resistance of 0.47 W/K.

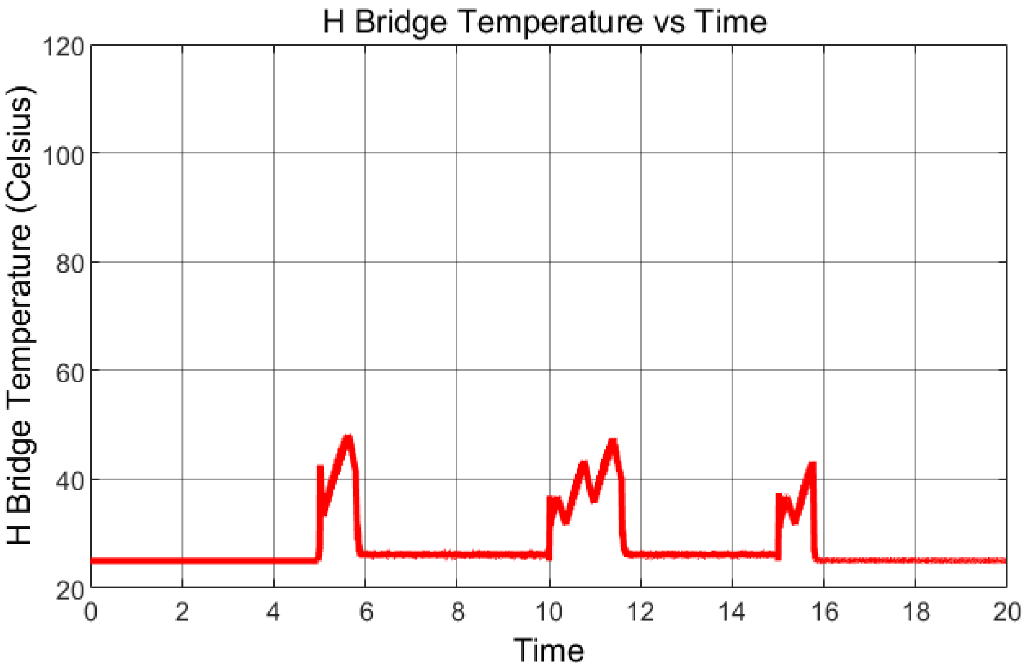

Figure 29. Temperature of SH32N65DM6AG

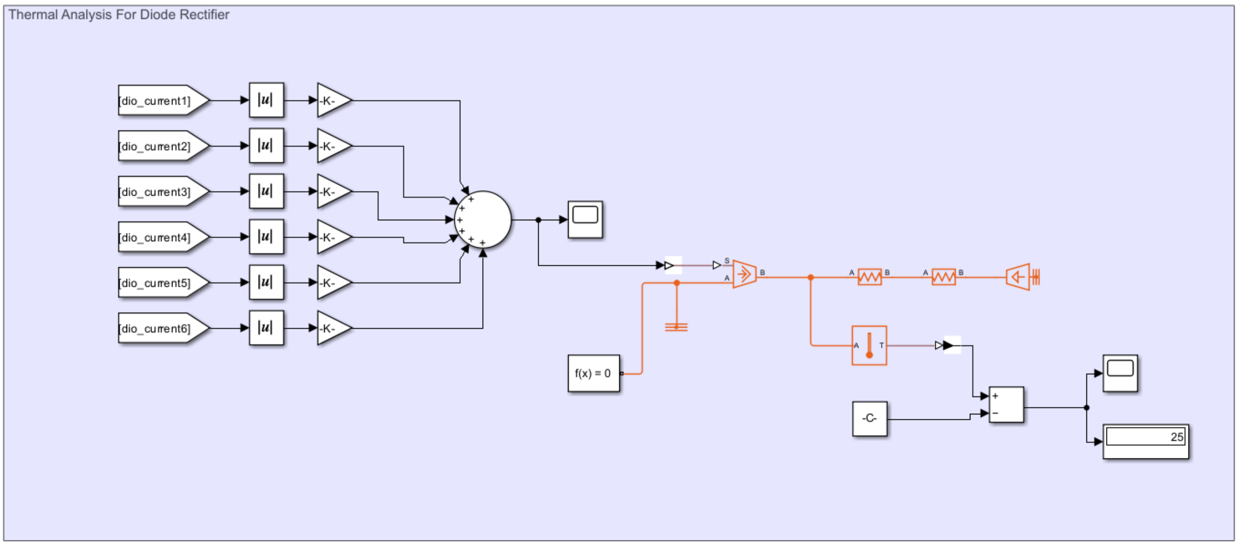

Figure 30. Thermal Analysis for Diode Rectifier

For the diode rectifier, turn-on and turn-off times are not specified in the datasheet. Since the operation occurs at 50 Hz, switching losses are considered negligible. Conduction losses are calculated by multiplying the diode current with its forward voltage.

The DB35-12 component includes all six diodes, so the losses for each diode are summed. The junction-to-case thermal resistance is 1.8 W/K, and the heat sink, operating with forced convection, has a thermal resistance of 0.56 W/K.

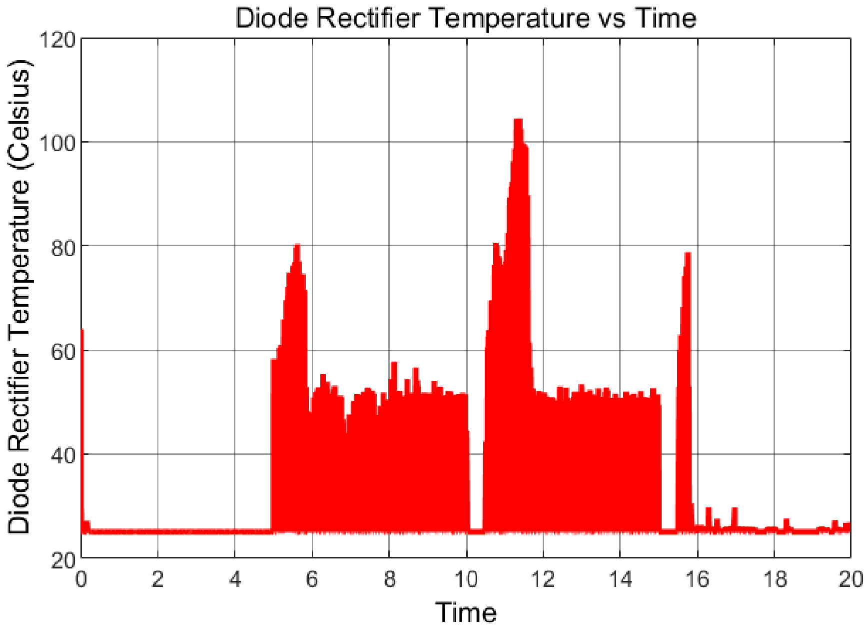

Figure 31. Temperature of DB35-12

Test Simulations

1) Controller Simulation

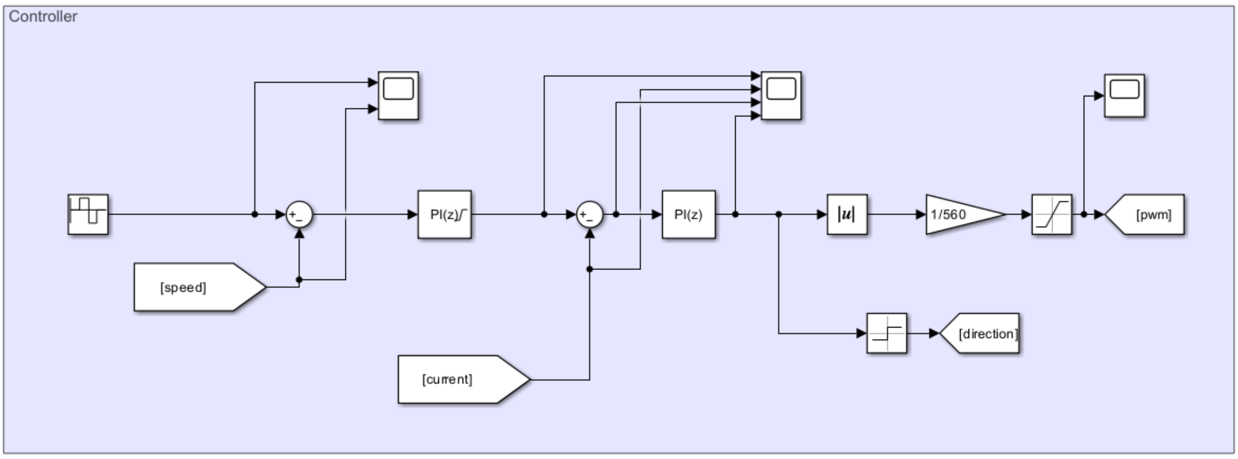

Figure 32. Controller Diagram

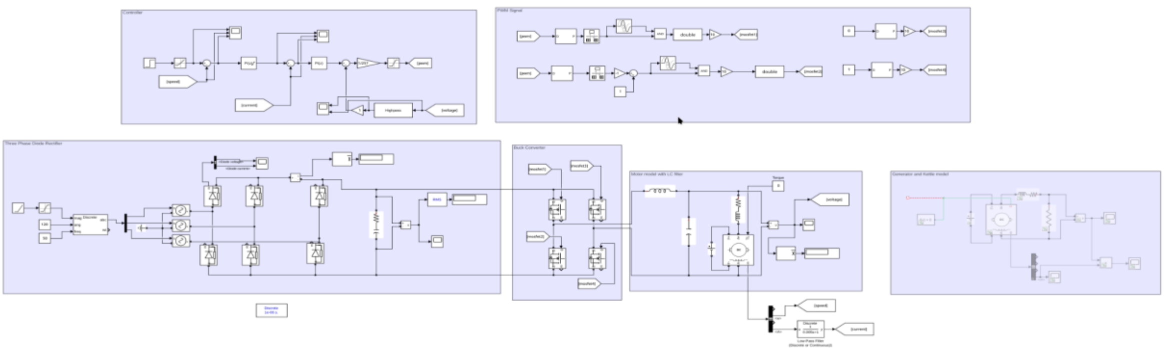

Figure 33: Simulation Model for Control

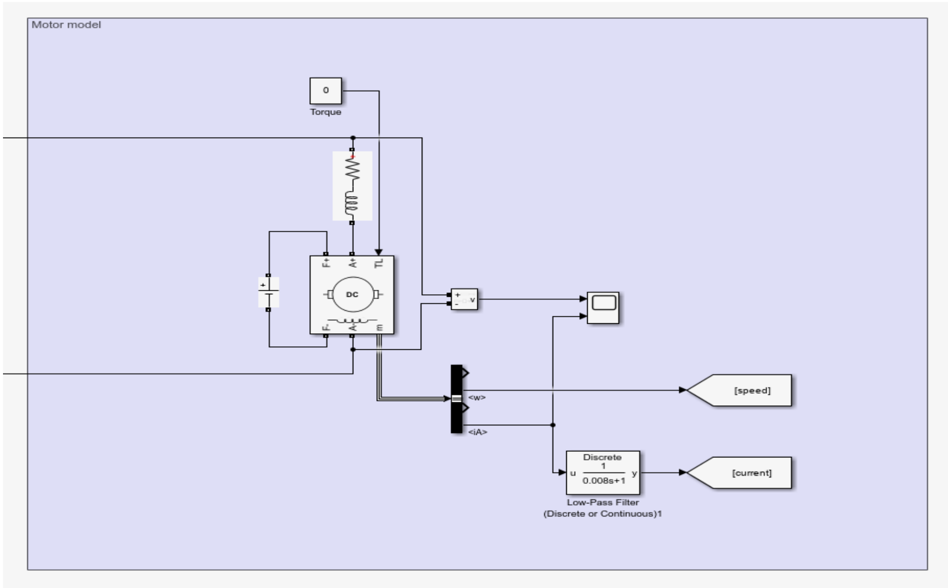

Figure 34. Motor Model

To achieve four-quadrant speed control, two PI controllers are employed: one for speed control and the other for current control. The speed control PI controller calculates the current reference, which is then saturated to ensure it does not exceed 20 A. The parameters are designed such that the output of the current control PI controller represents the desired motor voltage. By analyzing the sign of this output, the system determines whether to operate in forward or backward mode. Subsequently, the absolute value of the reference voltage is divided by the DC input voltage—supplied by the diode rectifier—to calculate the desired duty cycle. Finally, the duty cycle is verified to ensure the motor voltage does not exceed 180 V.

Once the duty cycle is determined by the controller, PWM waves are generated. To enable four-quadrant motor operation, four MOSFETs are utilized. Based on the direction calculated by the controller, the appropriate half-bridge is supplied with the duty cycle, while the other half-bridge is configured to establish a low-side connection between the motor and the power supply. For a duty cycle of 0.1 the following 4 PWM signals are generated:

- MOSFET 1: PWM with 0.1 duty cycle
- MOSFET 2: PWM with 0.9 duty cycle
- MOSFET 3: PWM with 0 duty cycle
- MOSFET 4: PWM with 1 duty cycle

Between MOSFET 1 and 2, MOSFET 3 and 4 a dead time of 1 microsecond is selected. Moreover, the switching frequency is selected as 25 kHz.

Three phase diode rectifier is utilized for rectifying AC input to DC. At the output of the rectifier 200 μF capacitor is utilized and it is connected to full bridge buck converter and the parallel resistors in the high side are for running simulation without errors (1e11 ohm resistance is selected to not affect the system).

To regulate input voltage to a desired output voltage, a buck converter is employed. For four-quadrant operation, an H-bridge configuration of the buck converter is utilized. Shunt resistors are incorporated for the gate drivers, while high-side parallel resistors are included to ensure error-free simulations.

These resistors are assigned an extremely high resistance value (1×10^{11} ohms) to minimize their impact on the system.

1.1) No load simulations (Perfect Conditions)

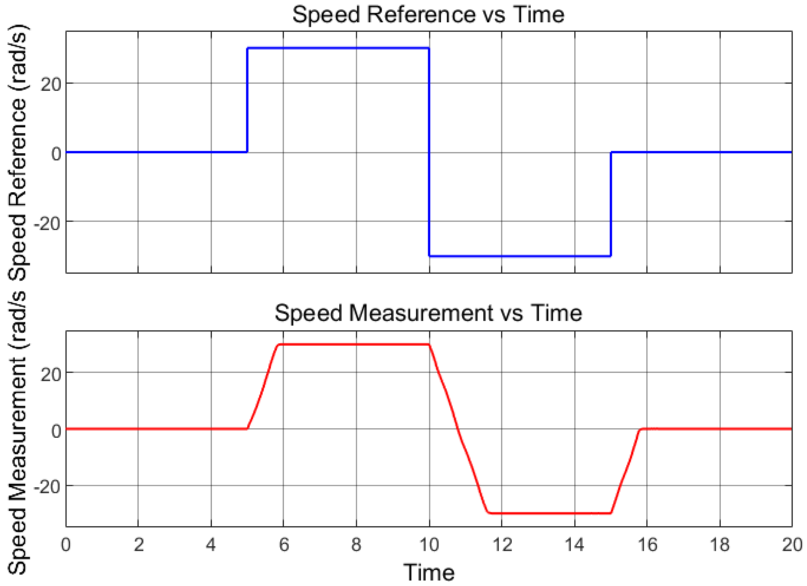

Figure 35. Speed Reference and Measured Speed

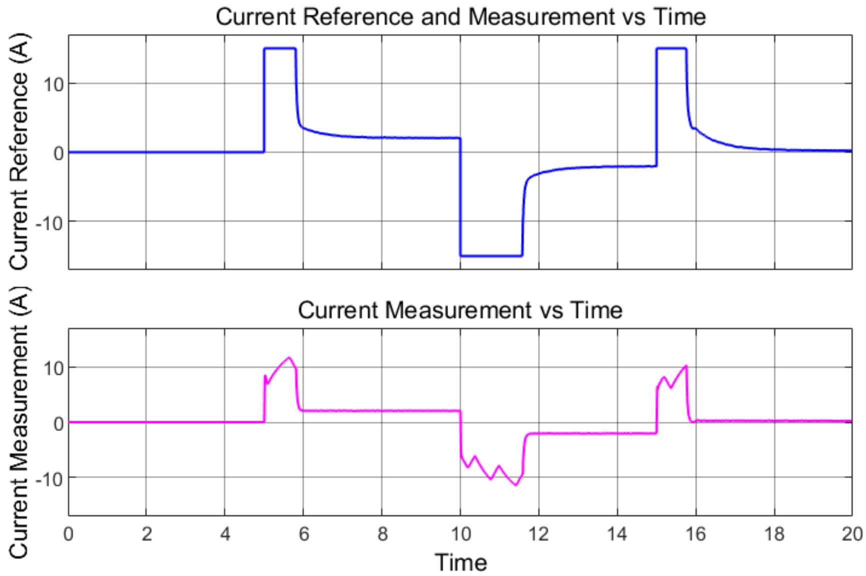

Figure 36. Motor Current Reference and Measured Motor Current

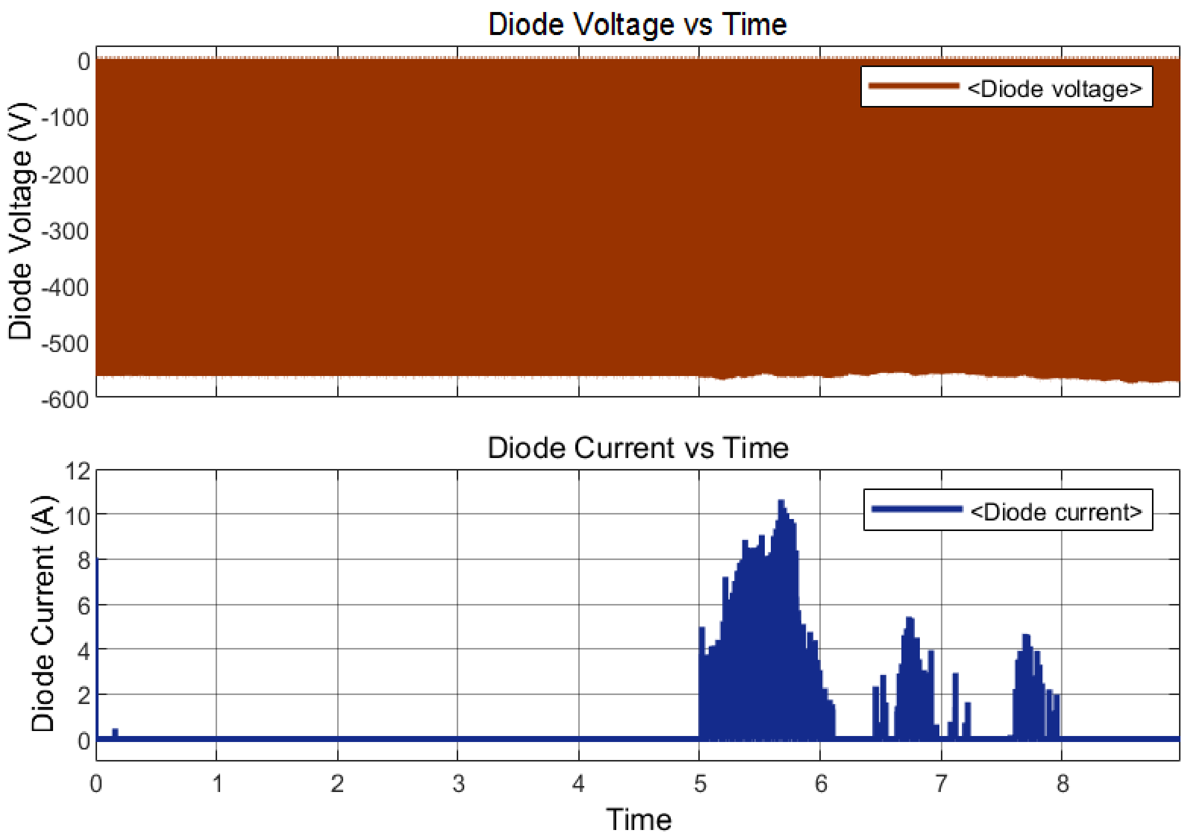

Figure 37. Diode voltage and diode current vs time plot of three phase diode rectifier.

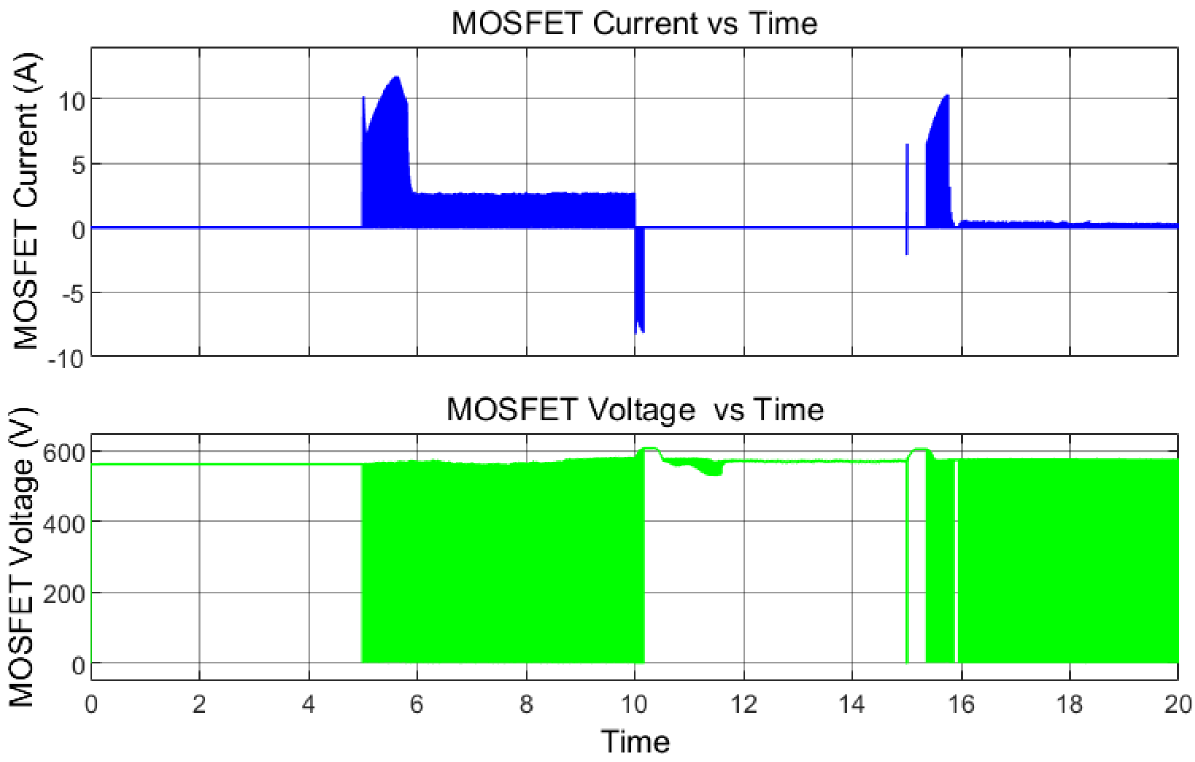

Figure 38. MOSFET Voltage, MOSFET Current

In the simulations, the motor is assumed to operate under no-load conditions. Current measurements are smoothed using a low-pass filter with a time constant of 0.008, ensuring more stable readings. The interpole winding impedance is modeled as an RL load connected in series with the motor. Additionally, the field windings are excited with a 220V supply.

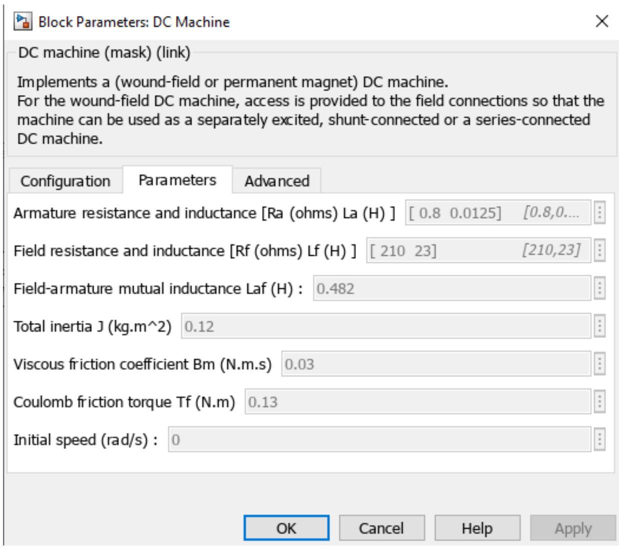

Figure 39. Motor Parameters

Armature and field resistances and inductances were given however field-armature mutual inductance, total inertia and friction constants are assumed as given in figure 2.10.

1.2) Loaded simulations

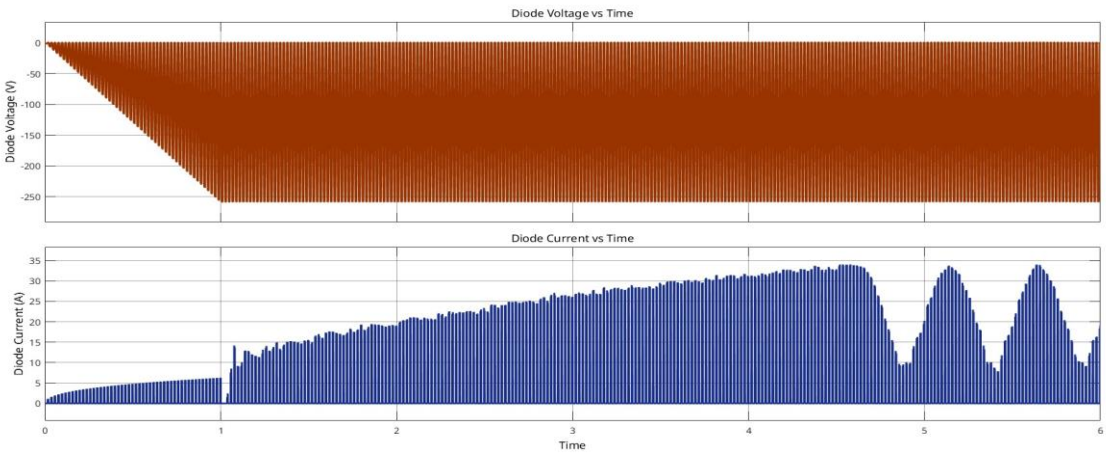

Figure 40. Voltage and Current on the Diode

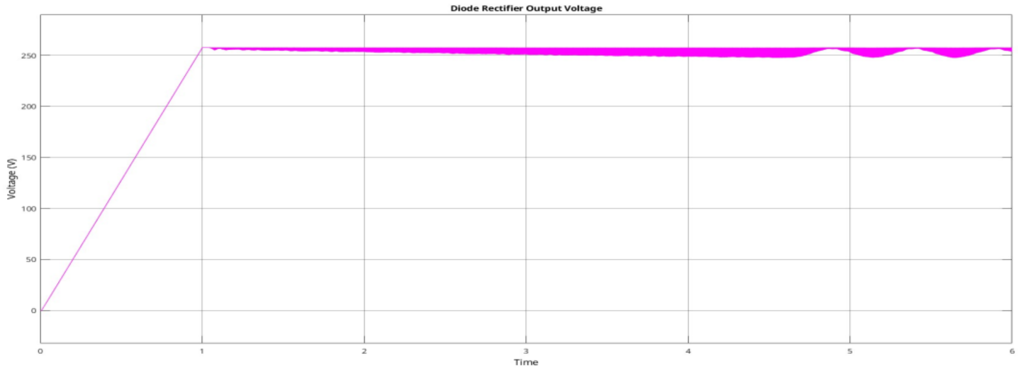

Figure 41: Rectifier Output Voltage

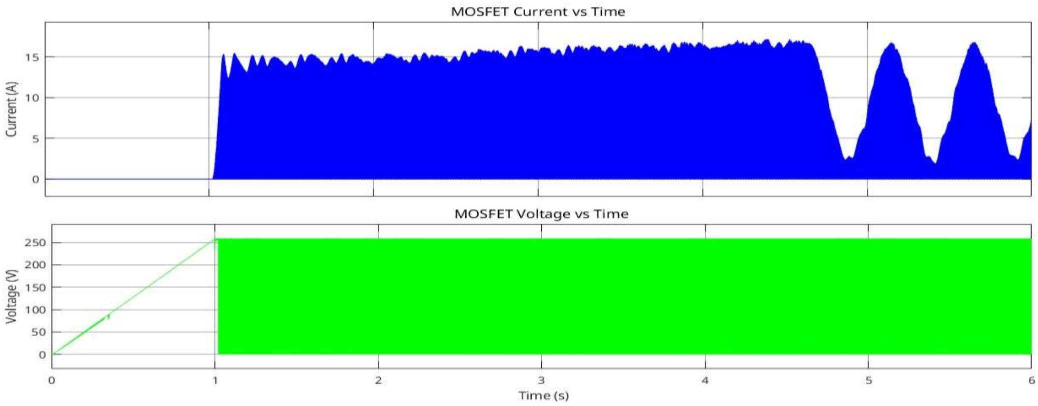

Figure 42. Voltage and Current on the MOSFET

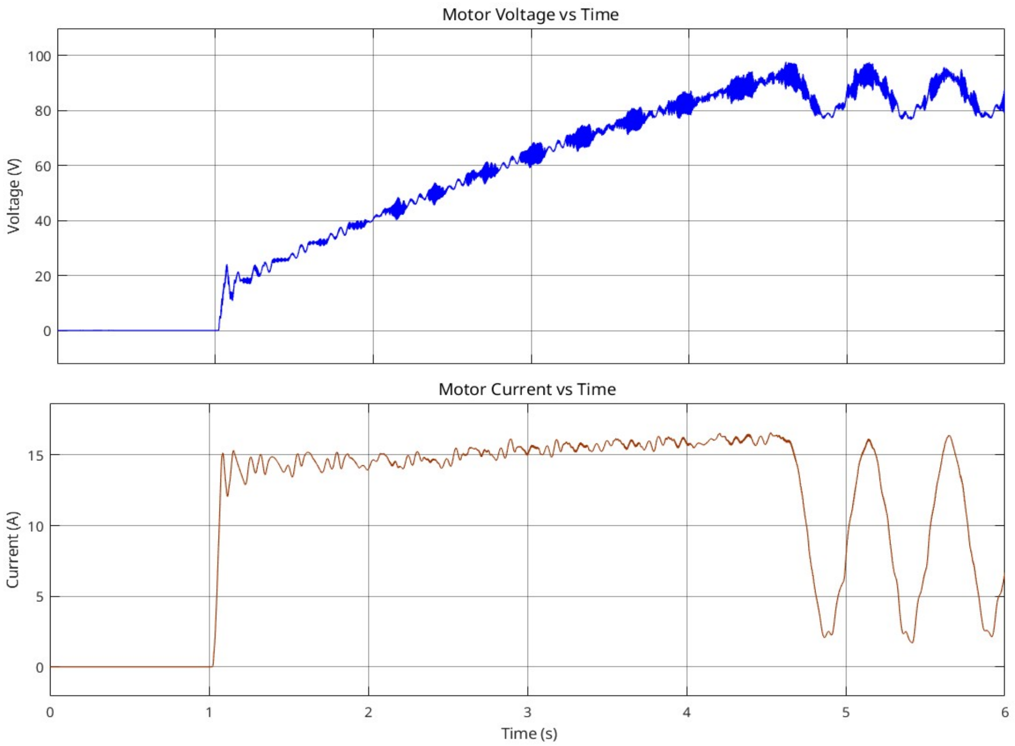

Figure 43. Voltage and Current on the Motor

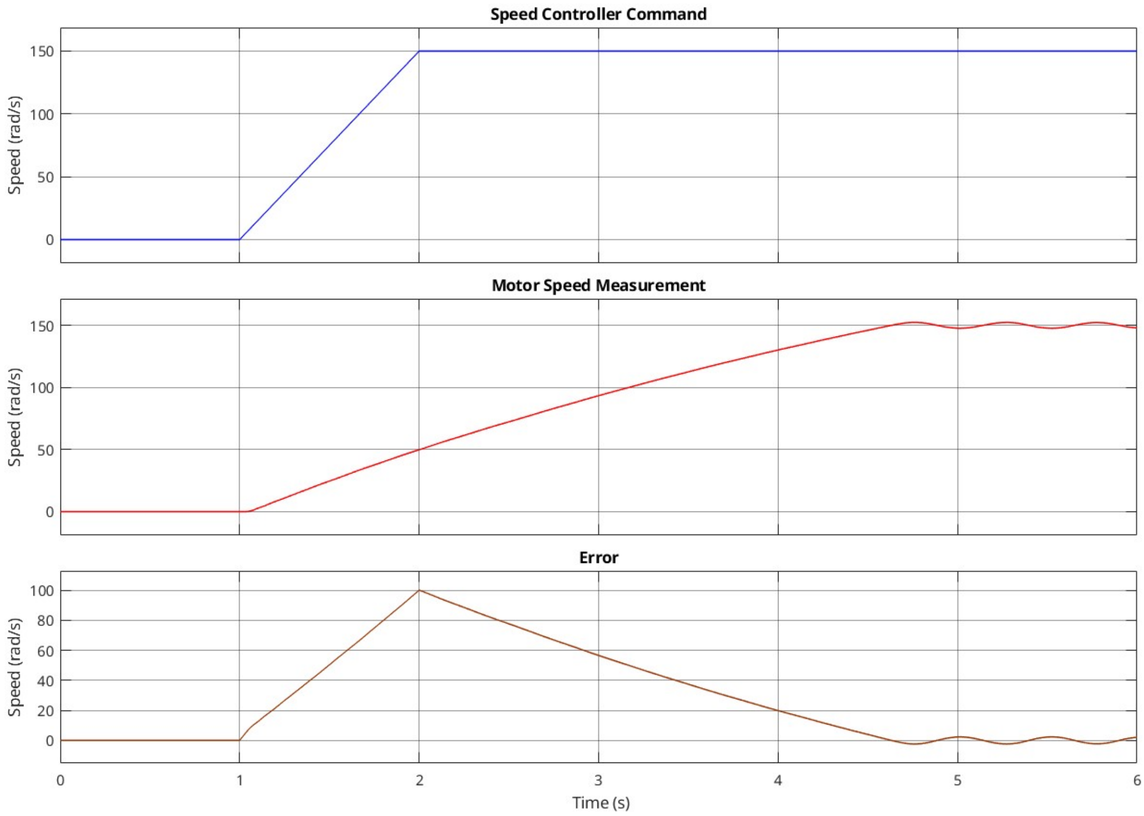

Figure 44. Speed Controller Command, Measurement, and Error

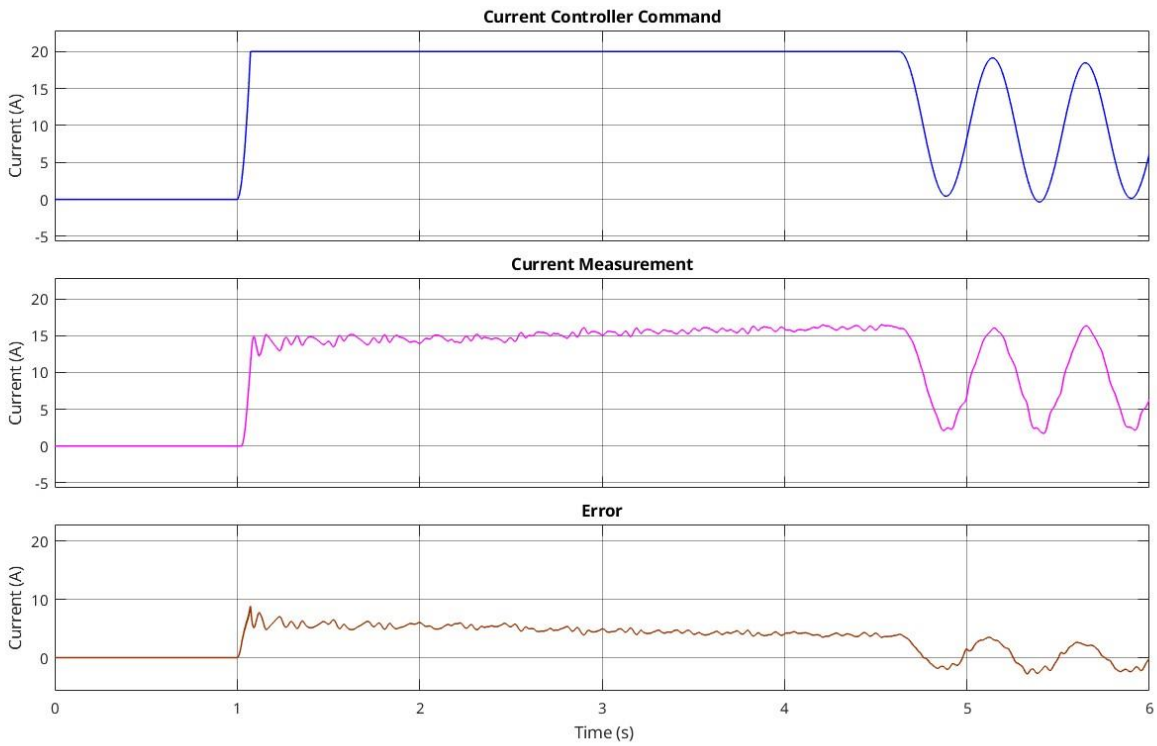

Figure 45. Current Controller Command, Measurement, and Error

The speed control model is constructed for 150 rad/s speed control (desired speed of the motor) which is calculated as 157 rad/s (rated) according to the configuration and parameters of the motor. Speed controller command and the speed result can be seen at figure 44. According to figures 40-41-42 our motor driver starts to work but at the second 1 (1 second after we give the electricity to the driver) it starts to excite motor. At figure 40 it is clear that we charge the capacitors until the end of the 1st second, and figure 41 (rectifier output voltage graph) Figure 42 (MOSFET Voltage) shows us this capacitor charging process. We can understand that until our system comes to the excitation point there is no current flow through motor (from figure 43) and no speed at the rotor of the motor (figure 44).

This information tells us that we need diodes for the three-phase rectifier which can stop 250 V reverse voltage and let 35 A current at least. Of course we should think about the safety margin which can be thought of as 20-25%. Therefore, we should select diodes of the rectifier as 300-320 V voltage and 42-45 A simulation result values in safety margin. From figure 45, we can think about MOSFET parameters. The voltage value of the MOSFET should be 255*1.2 or 255*1.25 V voltage in safety margin which implies 305-325 V, and 17*1.2 or 17*1.25 A current in safety margin which implies 20-22 A.

For security there is current control for the motor which can be seen from figure 45. We set the limit as 20A to be able to prevent any problem on the motor since it will be 20A*180V = 3.6kW power on the motor (which can be thought as 9 times desired value, also almost 2 times of the tea bonus desired value). However, the buck converter output voltage should not be thought of as motor input voltage (current also), figure 43 shows us the current and voltage value of the motor and we can say there is 1.2-1.5 kW power on the motor (80V*15A or 100V*15A).

Since this voltage level requires high current from the grid, higher input voltage can be presented as input to decrease required current for required power (400W for motor and 1.6kW for tea bonus if project would continue as physical project instead of simulation).

Conclusion

This project successfully identifies and implements an optimal topology for a DC motor drive system. The combination of a three-phase diode rectifier and a buck converter was selected based on its superior performance in terms of output voltage stability, efficiency, and reduced ripple. Simulations validated the effectiveness of this configuration, highlighting its suitability for high-power motor applications. Key components, including MOSFETs, diodes, and gate drivers, were carefully chosen to meet design requirements and safety margins. The thermal analysis and control simulations further ensured system reliability and efficiency under varying operational conditions. This project not only demonstrates the viability of the proposed design but also provides a robust framework for transitioning to hardware prototyping and real-world testing, paving the way for practical implementation in industrial applications. Besides these, thermal simulation, loaded and unloaded motor simulations are presented in this report. Also, PCB design is made for this DC motor driver circuit. 3D model of the PCB design is successfully presented in this report.

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Appendix

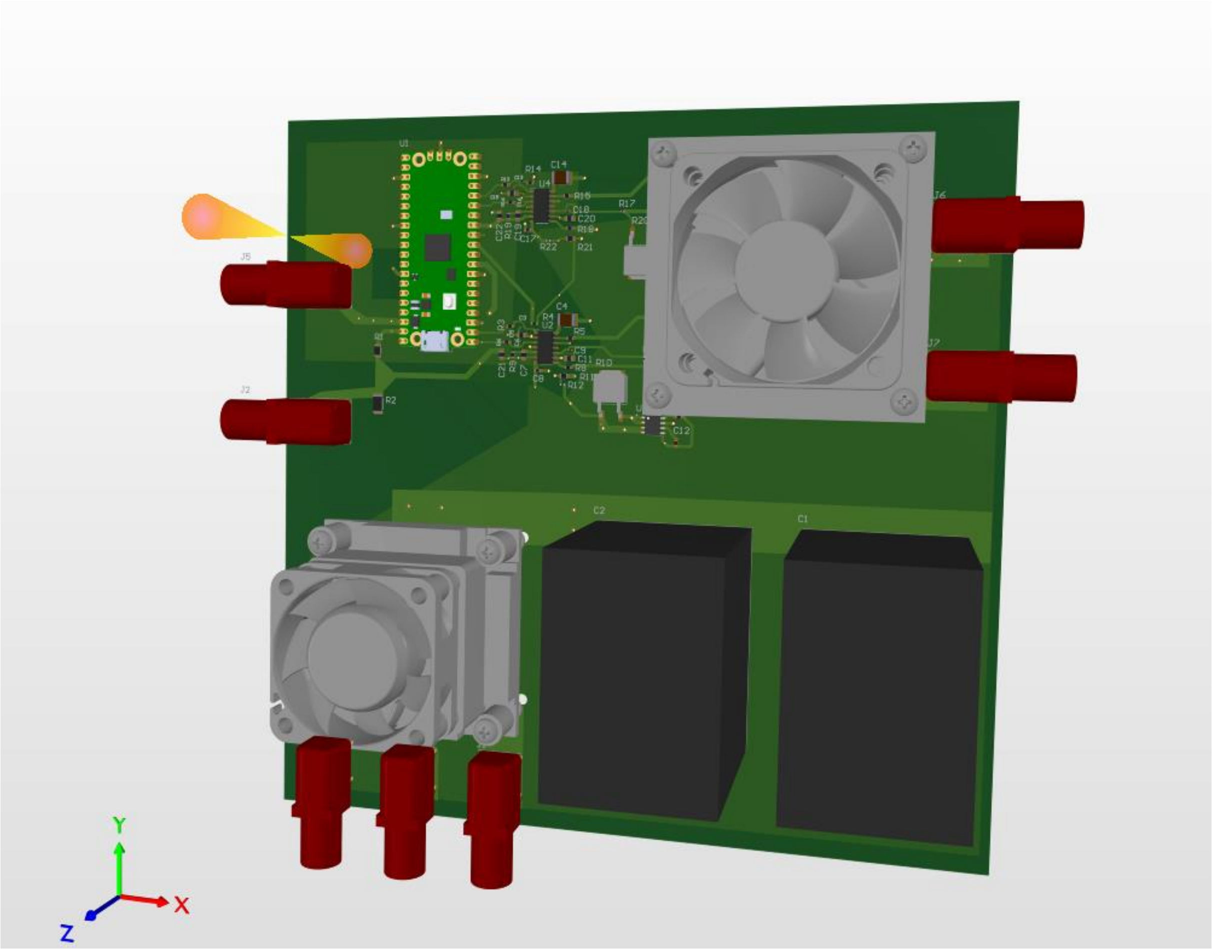

Figure 46. 3D View of PCB

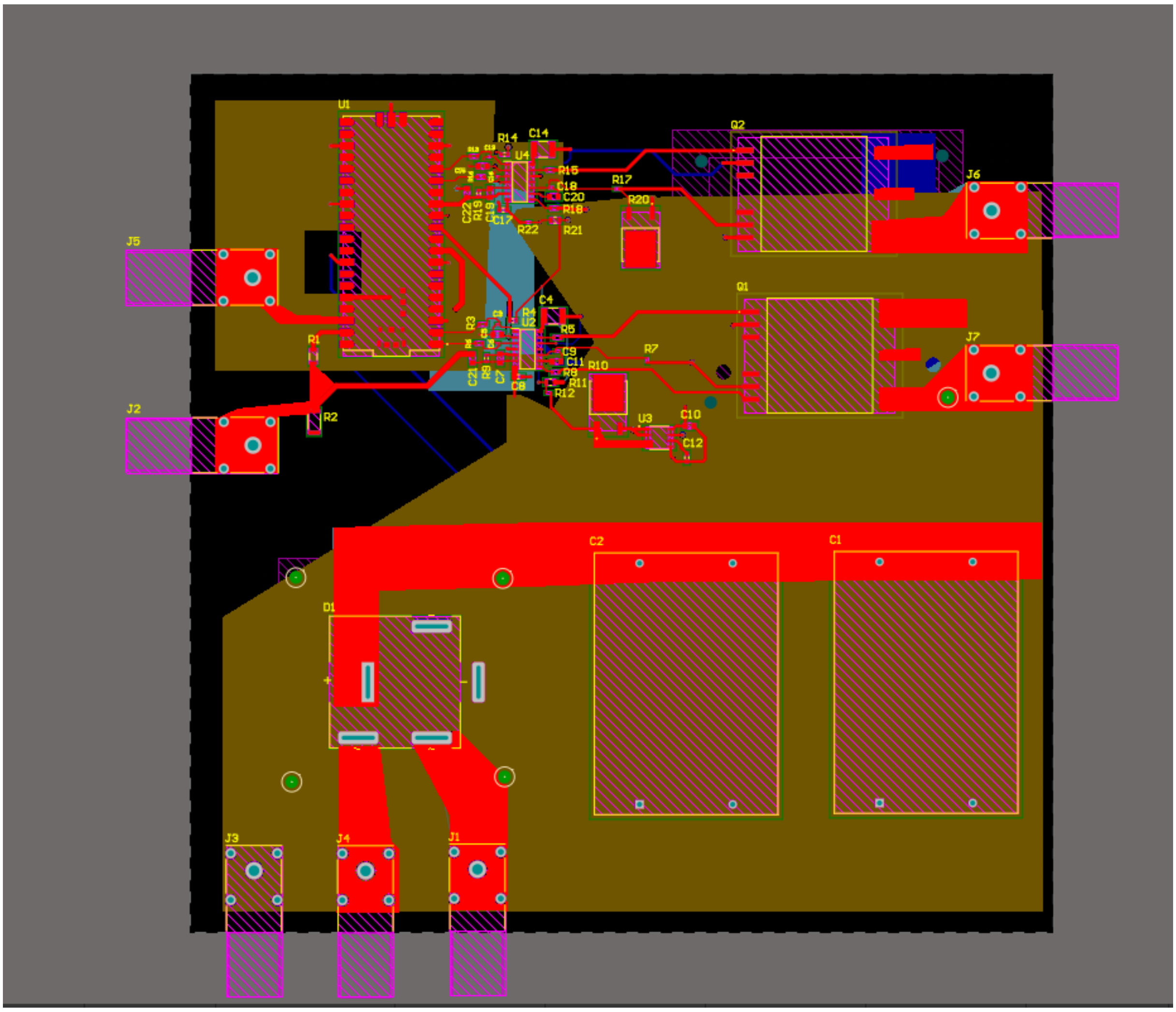

Figure 47. Layout of the PCB