MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING

EE463 TERM PROJECT

DC MOTOR DRIVE

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Introduction

Electric motors are crucial components in various industrial and commercial applications due to their versatility, efficiency, and reliability. Specifically, DC motors are widely used in many applications where variable speed and torque control are required, such as in electric vehicles, robotics, and industrial automation. This project focuses on designing and modeling a controlled motor driver to drive a DC motor by powering with an AC source, which can be either single-phase or three-phase and driving with an adjustable DC output capable of achieving a maximum voltage of 180 V. The system integrates several components, including a power conversion stage to convert AC input into an adjustable DC output, a motor drive circuit to supply regulated power to the motor's armature, and a controller to maintain stable motor operation.

The project involves several key steps, starting with the selection of the drive topology, followed by computer simulations to validate the design. An important aspect of the project involves the accurate simulation of all non-idealities such as component resistances, parasitic inductances, and capacitances to ensure the robustness of the design. Additionally, a closed-loop speed controller will be implemented to provide precise control over the motor's operation.

By bridging theoretical knowledge and practical implementation, this project develops essential skills in power electronics and motor control. It addresses challenges such as efficiency optimization and controller design, offering valuable practices for applications in industrial settings and beyond.

Topology Selection

In designing the power electronics system for this project, various rectification and voltage regulation topologies were considered, each with its unique advantages and drawbacks. A single-phase diode rectifier, though simple and cost-effective, produces a pulsating DC output with significant voltage ripples. This necessitates the use of additional filtering components to ensure stable motor operation, which increases design complexity and size. On the other hand, three-phase diode rectifiers provide a much smoother DC output with reduced ripple, making them more suitable for high-power applications. The buck converter, a highly efficient DC-DC converter, offers precise control of the output voltage through pulse-width modulation (PWM) signals, making it a critical component for adjustable DC power supplies. Lastly, phase-controlled thyristor rectifiers, which allow precise control of the rectification process, are often preferred in applications requiring soft-start functionality, although their complexity and harmonic generation can pose challenges. After evaluating these options, the combination of a three-phase diode rectifier and a buck converter was selected as the primary topology for this project.

The chosen topology—a three-phase diode rectifier followed by a buck converter—provides significant advantages for the motor drive application. The three-phase diode rectifier ensures a smoother DC output with minimal ripple, which reduces the need for large external filtering components. This not only improves efficiency but also simplifies the overall design, making it more compact and reliable. Additionally, the three-phase rectifier can handle higher power levels, aligning well with the industrial-grade requirements of the DC motor used in this project.

The buck converter plays a critical role in regulating the rectified DC voltage to match the operational requirements of the motor. By using PWM control, the buck converter allows precise adjustment of the output voltage, ensuring efficient motor operation while maintaining high system efficiency. The output voltage can be regulated up to 180V, meeting the motor's specifications. Additionally, modifications were made to the standard buck converter design to better suit the application. Specifically, the MOSFET was repositioned to the low-side configuration, grounding its source terminal. This modification simplifies the gate drive requirements, as the gate can now be driven with a standard low-voltage signal, avoiding the need for a bootstrap driver circuit.

Further optimizations were introduced by leveraging the motor's inherent characteristics. The motor's armature inductance and interpole inductance, totaling 24.5mH, were utilized to filter the current, eliminating the need for an external inductor in the buck converter. This approach not only reduces component count and cost but also simplifies the circuit design. Similarly, the output capacitor of the buck converter was removed since the motor operates effectively with an average DC current, even if it contains some ripple.

In conclusion, the combination of a three-phase diode rectifier and a buck converter was chosen for its ability to provide smooth, adjustable, and efficient power delivery to the DC motor. The three-phase rectifier ensures a stable and reliable DC output, while the buck converter allows precise voltage control tailored to the motor's requirements. The modifications and optimizations in topology further enhance its efficiency, compactness, and reliability, making it the ideal solution for this high-power motor drive application.

Simulations

We created the simulation of our design with the selected topology. Each part of the design is simulated one by one and complete design is simulated. Results and expressions are provided.

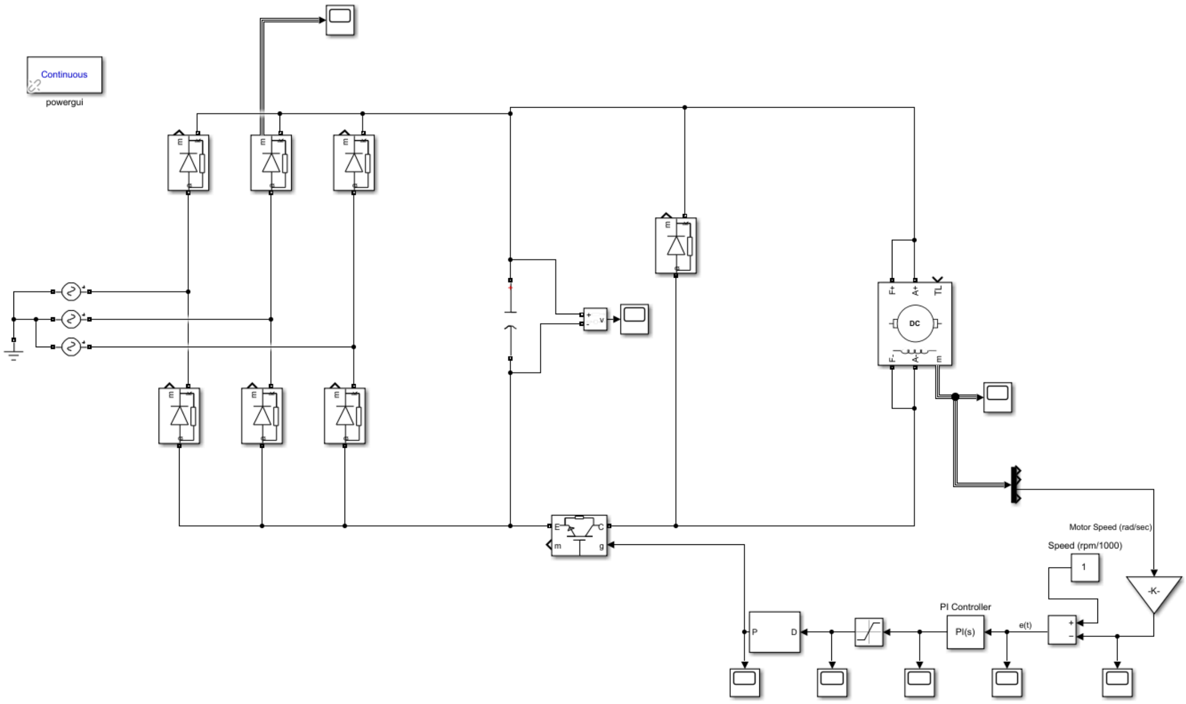

Figure 1: Complete simulation diagram

Our complete design simulation schematic is given in Figure-1, our design consists of 3 part which are rectifier, buck converter and closed loop speed control unit. In order to make more precise simulation firstly we simulated DC motor and found parameter of the motor that we will drive.

DC Motor Simulation

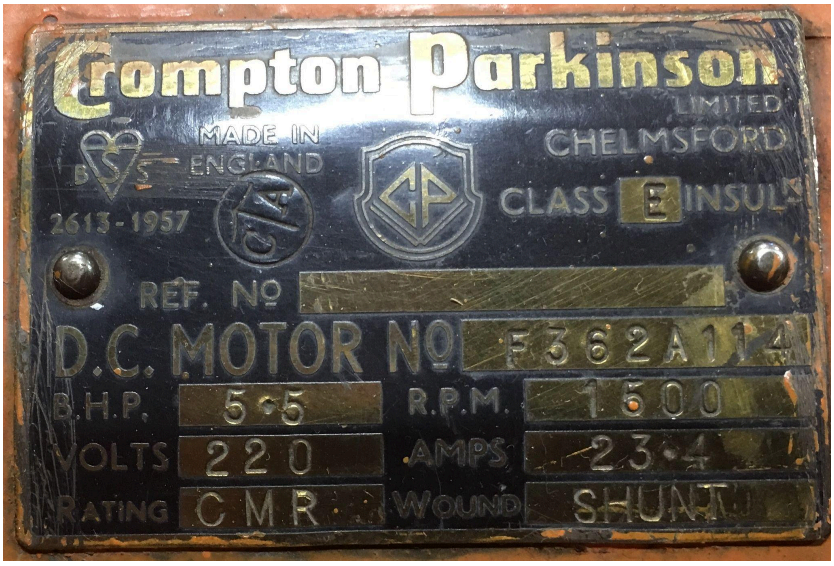

Figure 2: DC motor parameters

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

Rated values of the motor is given in Figure-2. As stated we connected field winding as shunt to armature winding and we applied 220 V DC to both armature and field winding.

We know armature current should be 23.4A when we give 220V DC input. Using this values we calculated the motor constant and rated torque value.

$$I_a = (V - E_a)/R_a$$

$$E_a = V - I_a * R_a = 201.28$$

$$E_a = K_a * K_f * I_f * w_{mech} = K * V/R_f * w_{mech} = K * 220/210 * 157$$

$$K = 1.224$$

$$T_{em} = K * I_f * I_a = 1.224 * 1.05 * 23.4 = 29.8 \text{ N*m}$$

To find our DC machine parameters we used expressions given in Mathworks website [1].

$$E_a = K_E * w_{mech}$$

$$L_{af} = 1.224$$

Using these calculated values we determined parameters of our model. The values that we determined satisfies the calculated values roughly, it could be because of we did not take into account interpoles winding parameters. Parameters of the motor are given in Figure-3 ,and speed, torque and current values are given in the graph in Figure-4.

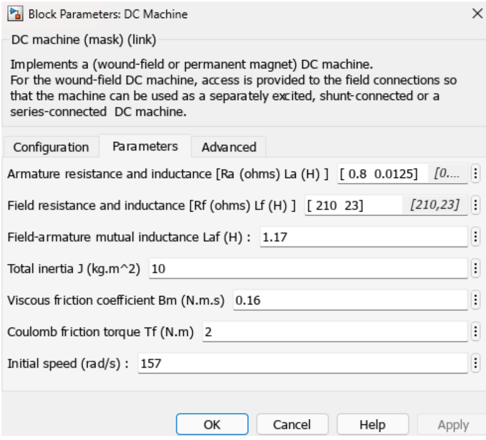

Figure 3: DC Motor parameters of the simulation model

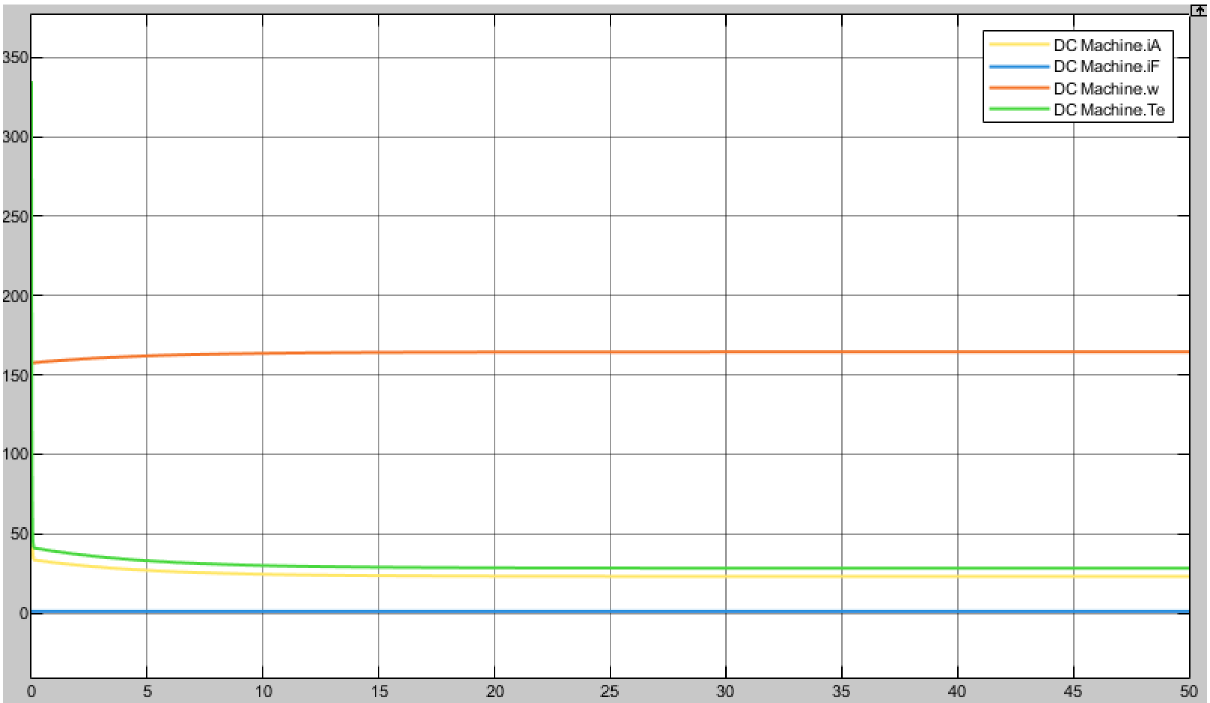

Figure 4: DC motor results with found parameter values

Rectifier Simulation

As we decided before while choosing topology, we have a three phase full bridge diode rectifier. We simulate circuit in ideal conditions first, then after selecting components detailed simulations will be given in later parts.

We selected duty cycle limit of the buck converter as 80% in order to not force components much. Since maximum output voltage of the motor must be less than 180 V. We calculated rectifier input AC voltage as:

$$V_{rec,out} = V_{motor}/D = 225\, V_{rms}$$

$$V_s = V_{rec,out} * \frac{\pi}{3\sqrt{6}} = 96V_{rms}$$

$$V_{s,peak} = 96 * \sqrt{2} = 135V$$

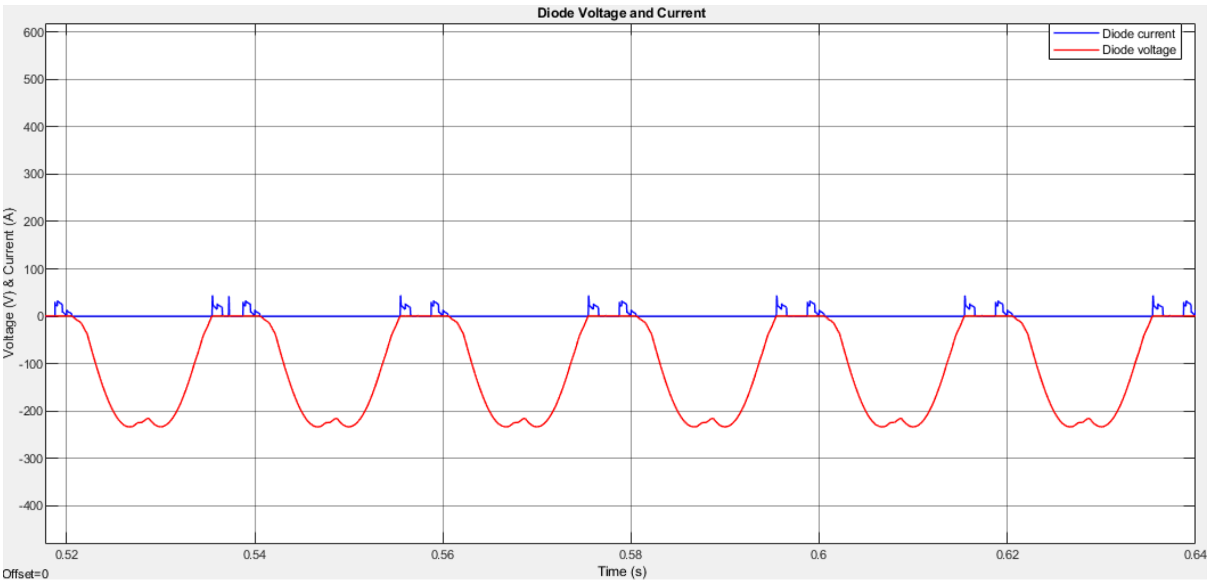

Figure 5: Diode Voltage and Current Waveforms

Diode voltage and current are given in Figure-5. System is simulated when the motor is rotating at nearly 90 rad/sec. Reverse breakdown voltage of the diodes must be higher than 250V, and current is passing up to 35 A when diode is ON.

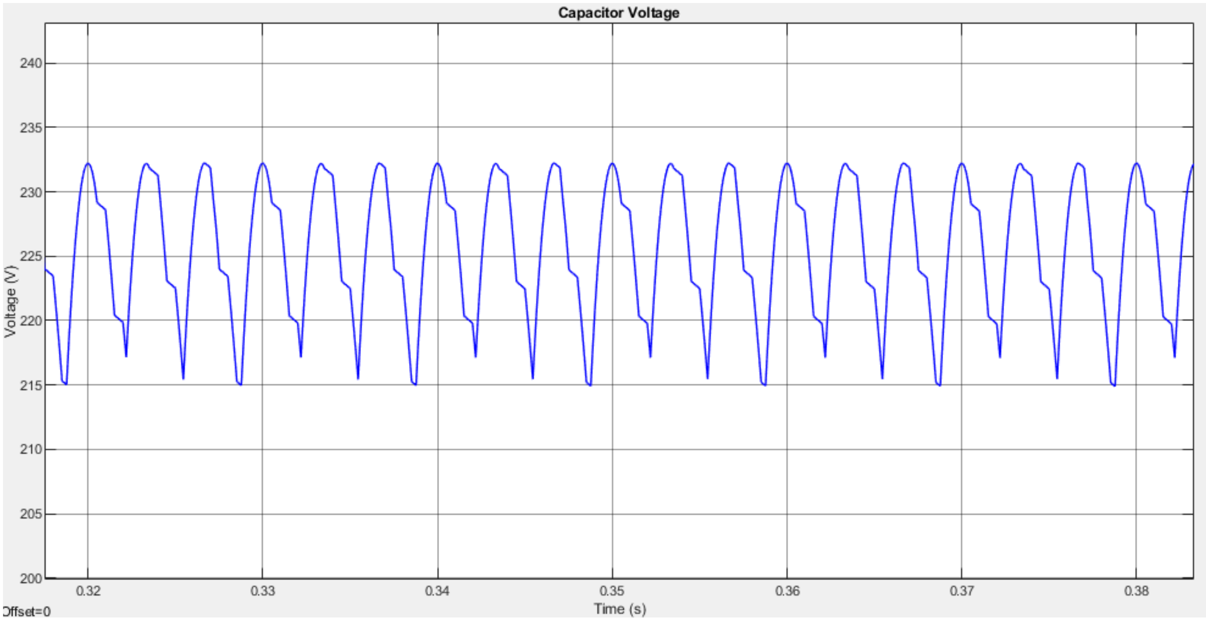

Figure 6: Capacitor Votlage Waveform

Voltage of the capacitor at the output of the rectifier is given in Figure-6. To decrease ripple voltage we determined to use 880 μF capacitor.

Buck Converter

Since DC motor has a momentum and storing energy like an inductor, we do not need to use an LC filter for buck converter. Only a diode and IGBT is enough for driving the motor.

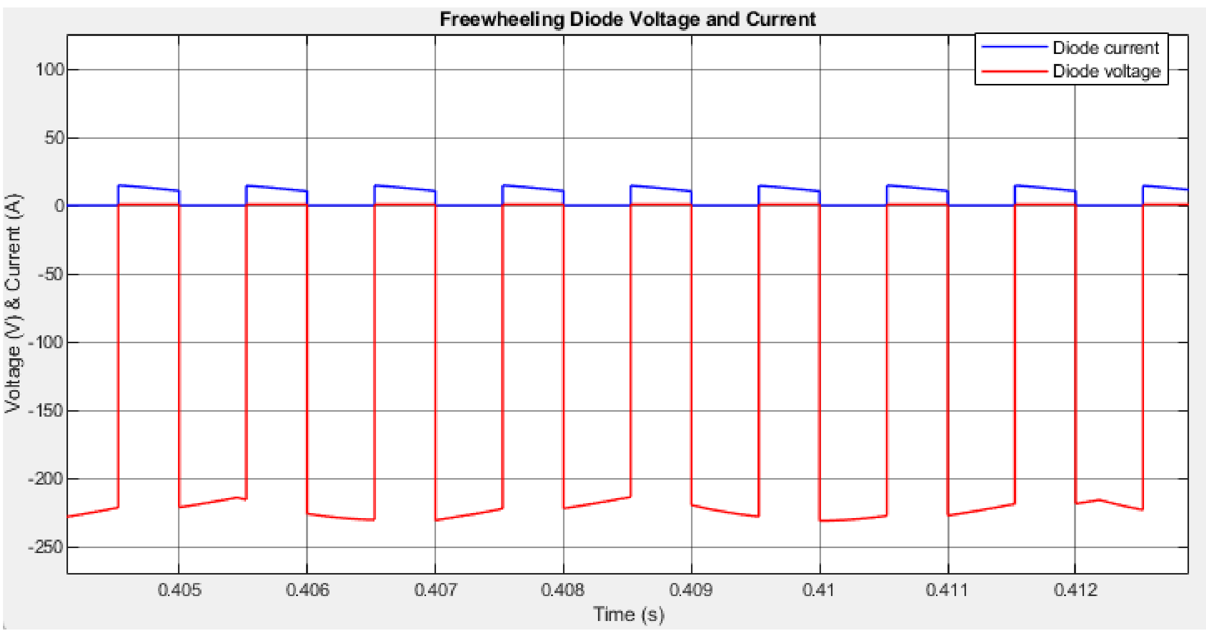

Figure 7: Diode Voltage and Current Waveforms

Voltage and current waveforms of the diode are given in Figure-7.

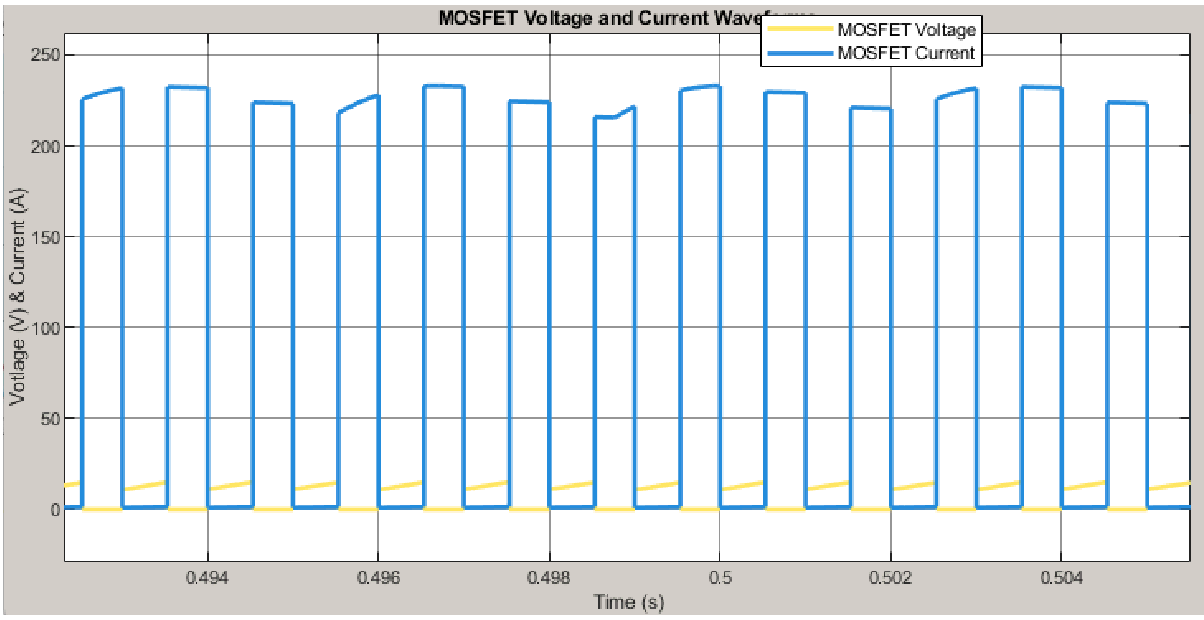

Figure 8: MOSFET Voltage and current Waveforms

Voltage and current waveforms of the MOSFET are given in figure-x. As we expected current and voltage magnitudes are close to diode. When switch is OFF current is passing through diode and decreases. When switch is ON current is passing through switch and increases.

Speed Controller

A Proportional-Integral (PI) Controller is a widely used feedback control mechanism in various engineering applications. It combines two components: the proportional term, which reacts to the current error (e(t)), and the integral term, which accounts for the accumulation of past errors. The proportional term ensures a rapid response to changes, while the integral term eliminates steady-state errors, allowing the system to achieve a desired output over time. This balance between responsiveness and accuracy makes the PI controller an effective solution for maintaining stability and precision in control systems.

In this system, the PI controller is used to regulate the speed of a DC motor. Both the motor's actual speed (Actual Speed) and the desired speed (Desired Speed) are initially converted from radians per second (rad/s) to revolutions per minute (rpm) by multiplying the values by 9.54929689. To simplify computations and reduce the range of numerical values, both the actual and desired speed values are scaled by dividing them by 100.

The scaled desired speed is compared with the scaled actual speed in a subtraction block to calculate the error (e(t)). This error signal is then fed into the PI controller, which has been configured with proportional and integral gains of Kp=3 and Ki=0.5 respectively. The

PI controller processes this error signal to generate a control signal that adjusts the motor speed to match the desired speed.

To prevent the control signal from exceeding the operational limits of the PWM generator, the PI controller output is passed through a saturation block. The saturated control signal is then used as input for the PWM generator, which creates a pulse-width modulation (PWM) signal. This PWM signal is sent to the gate driver, which modulates the MOSFET to regulate the voltage applied to the motor.

This closed-loop system continuously adjusts the motor speed to counteract external disturbances or load changes, ensuring that the motor operates at the desired speed. The inclusion of a PI controller allows for precise speed regulation while minimizing overshoot and steady-state error, resulting in a stable and efficient motor operation

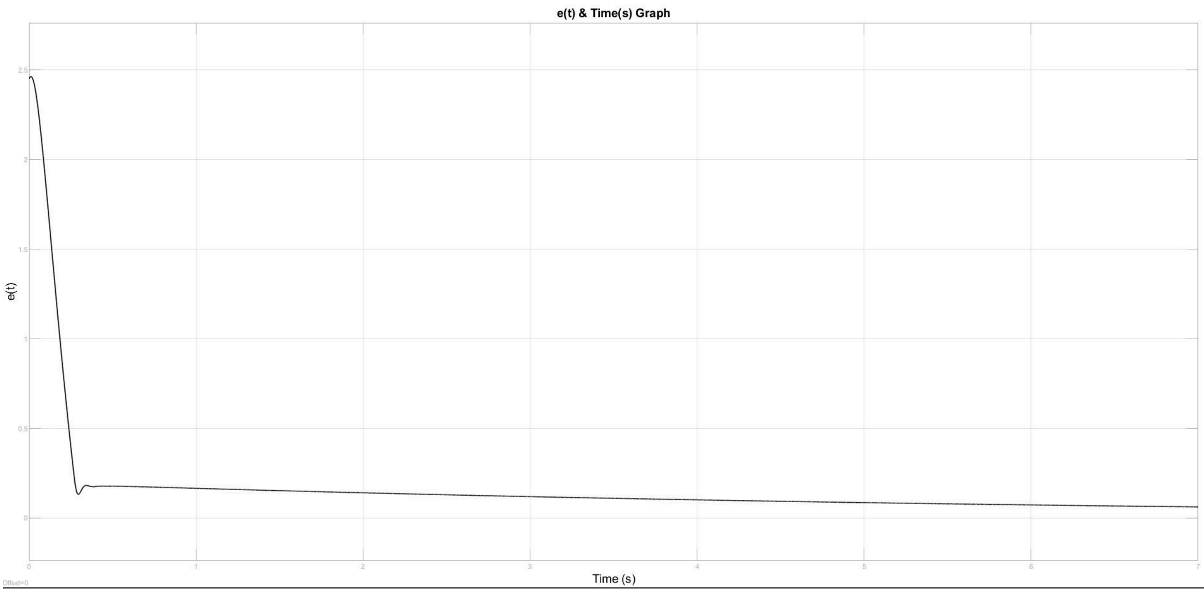

Figure 9: e(t) & Time(s) Graph

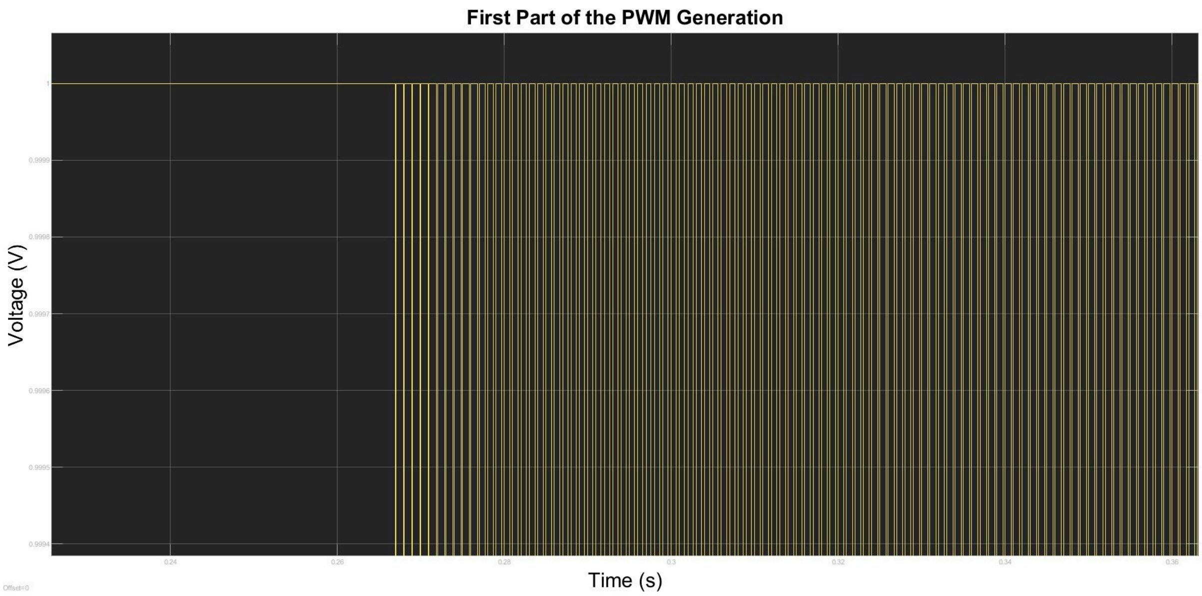

Figure 10: First Part of the PWM Generation

To control the motor speed, the PWM duty cycle starts high to provide sufficient voltage for rapid acceleration. As the motor speed increases, the error signal (e(t)) decreases, and the PI controller reduces the duty cycle to prevent overshooting. Once the desired speed is reached, e(t) converges to zero, and the duty cycle stabilizes to maintain the speed efficiently. This approach ensures smooth acceleration, precise speed regulation, and stable operation.

DC Motor Simulation

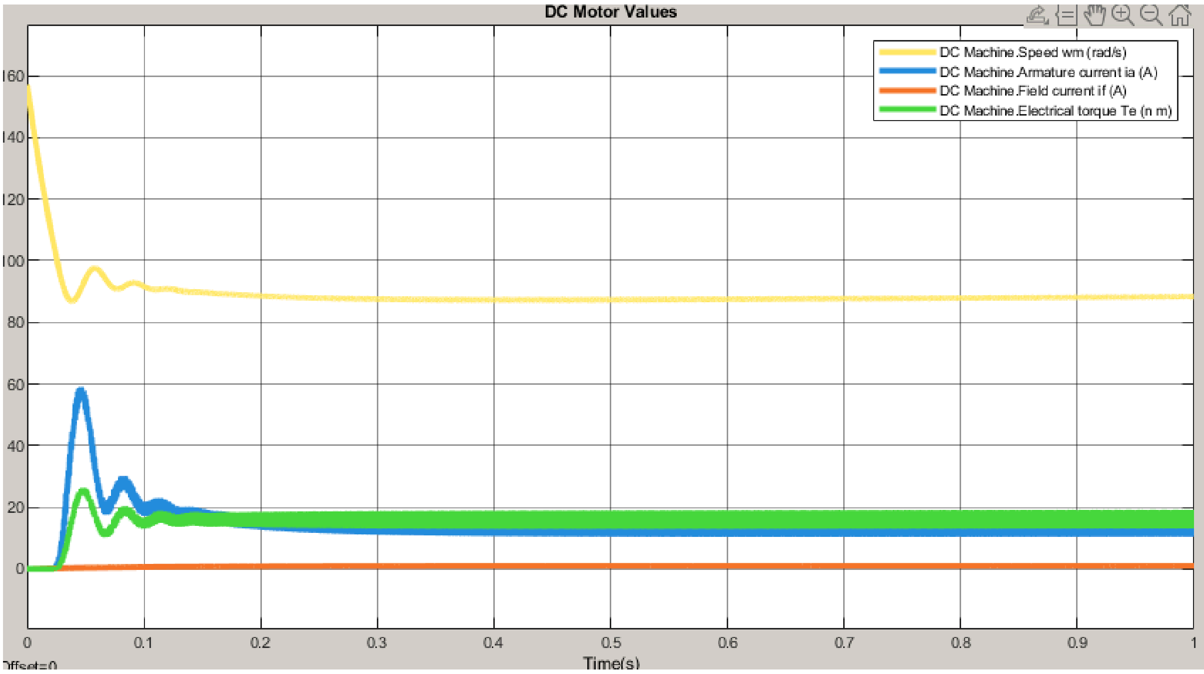

Figure 11: DC Motor current, torque and speed graphs

Simulations are made at 90 rad/sec motor speed. Motor current, torque and speed graphs are given in Figure-11

Component Selection

Rectifier

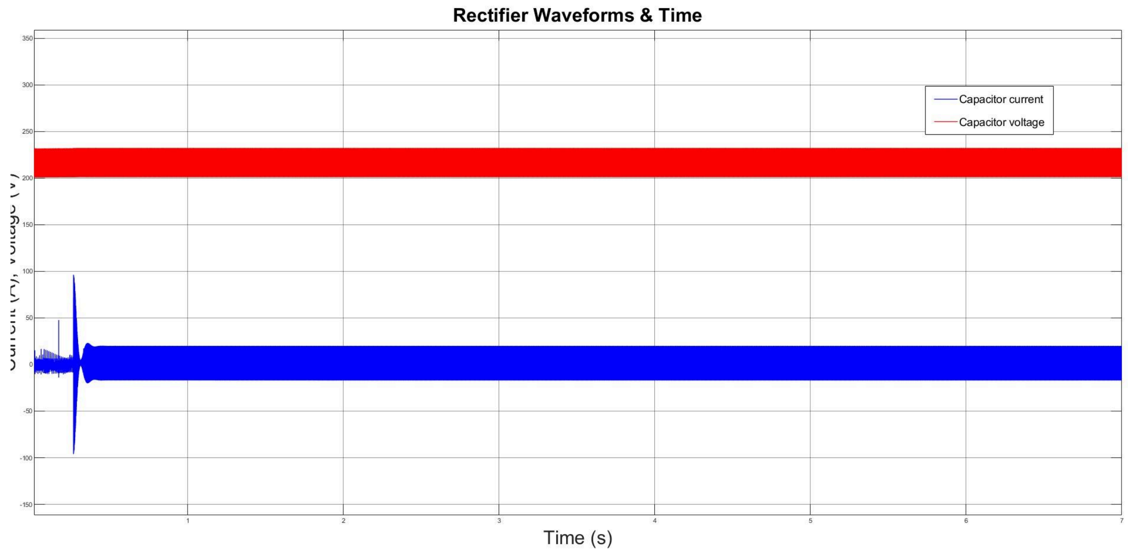

Figure 12: Rectifier Waveform & Time

The VS-36MT Series Three-Phase Bridge Rectifier was chosen for its ability to handle high-power demands efficiently. Supporting up to 35A continuous DC current and a peak reverse voltage of 1600V, it ensures reliability in demanding conditions. The rectifier features a low forward voltage drop of 1.19V at 40A, minimizing power losses, and can handle surge currents up to 500A (60 Hz)**,** making it robust against transients. Its encapsulated D-63 package ensures electrical insulation and efficient heat dissipation.

Simulation results validate the rectifier's performance, with the capacitor voltage (red waveform) stabilizing around 220V and the capacitor current (blue waveform) leveling near 20A. This stability highlights its capability to produce smooth DC output with minimal ripple, reducing the need for additional filtering. These features make it a reliable and efficient choice for this project

IGBT

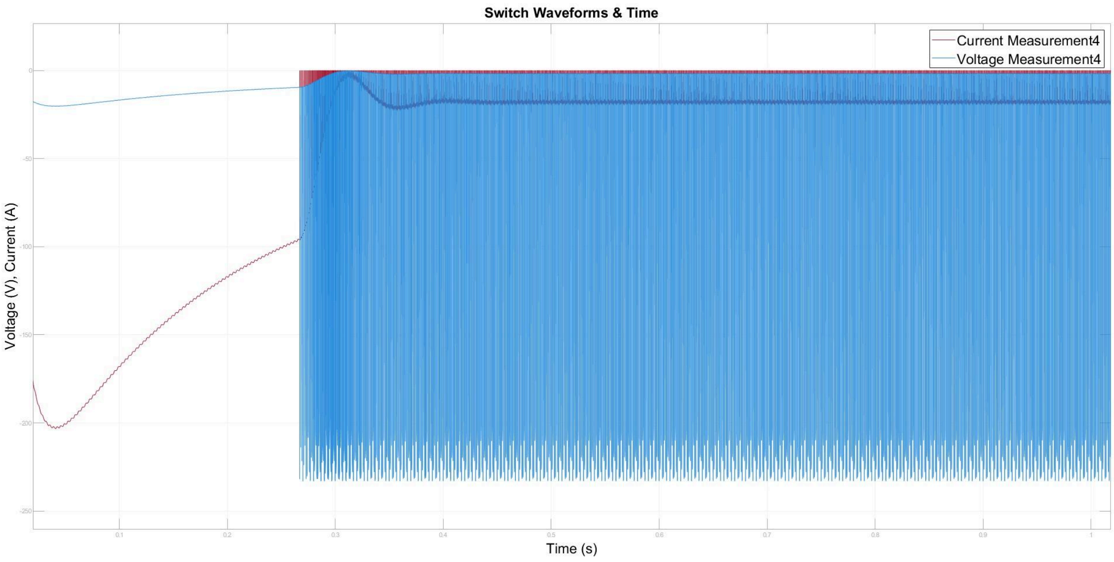

Figure 13: Switch Waveforms & Time

The IRGI4085PbF insulated-gate bipolar transistor (IGBT) was chosen for this project due to its robust performance and compatibility with high-power applications. This IGBT is rated for a collector-to-emitter voltage (Vce) of 330V and supports a continuous collector current (I_C) of 28A at 25°C, with a repetitive peak current capability of 210A. Its low on-state voltage (VCE(on)) of 1.21V ensures reduced conduction losses, enhancing system efficiency.

The simulation results validate the component's performance, showing the ability to handle high-speed switching with stable voltage and current waveforms. The voltage waveform stabilizes around 200V, while the current reaches approximately 20A, demonstrating the IGBT's suitability for efficient motor control under dynamic operating conditions. Its thermal stability (T_J up to 150°C) and low thermal resistance (R_θJC=3.29°C/W) further make it an ideal choice for reliable and efficient operation in this application.

Freewheeling Diode

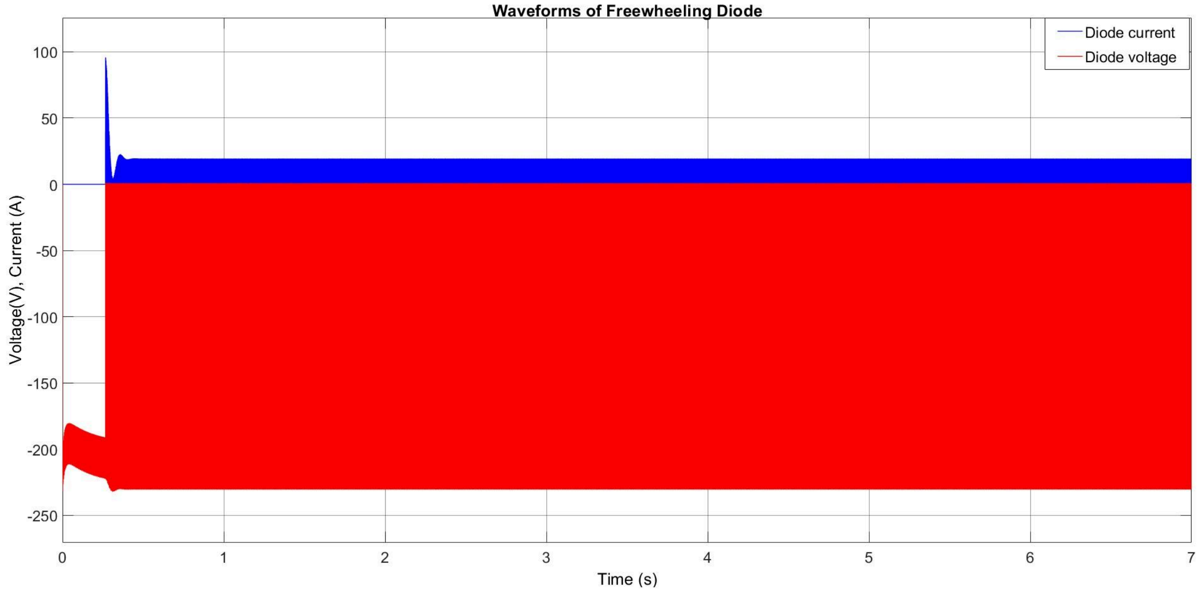

Figure 14: Waveforms of Freewheeling Diode & Time

The DSEI30-06A freewheeling diode was selected for its exceptional performance in high-frequency switching and power dissipation management. It features a 600V maximum repetitive reverse blocking voltage (V_{RRM}) and an average forward current (I_F) of 30A, making it suitable for high-power applications. Its fast recovery time of 35ns and soft reverse recovery behavior reduce EMI/RFI, improving system stability and efficiency. Additionally, its low forward voltage drop (V_F) of approximately 1.52V minimizes power losses during conduction.

Simulation results confirm its performance, with the diode voltage stabilizing around -220V (red waveform) and the current fluctuating near 25A (blue waveform). The stable operation under dynamic conditions demonstrates its ability to handle freewheeling current effectively, preventing voltage spikes and protecting the circuit components. These features make the DSEI30-06A diode an ideal choice for ensuring reliability and efficiency in the system.

PCB Design

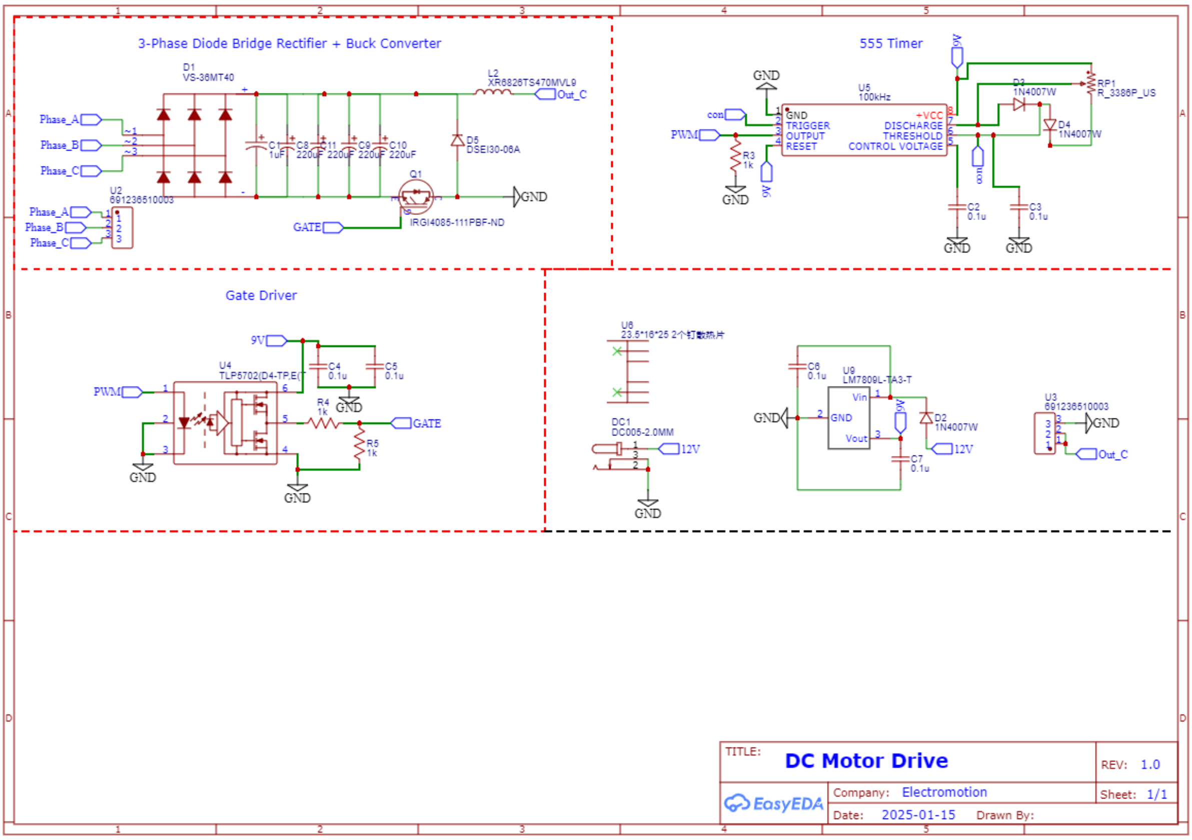

Figure 15: Circuit Schematic of the PCB

Circuit schematic seen in Figure 15 is drawn with EasyEDA. In addition to the rectifier + buck converter topology, we implemented a gate driver with a 555-timer circuitry followed by an optocoupler in order to drive our IGBT switch on the buck converter. Also some other components are added for purposes such as heat dissipation, inlets and outlets for input and output, and low voltage regulation.

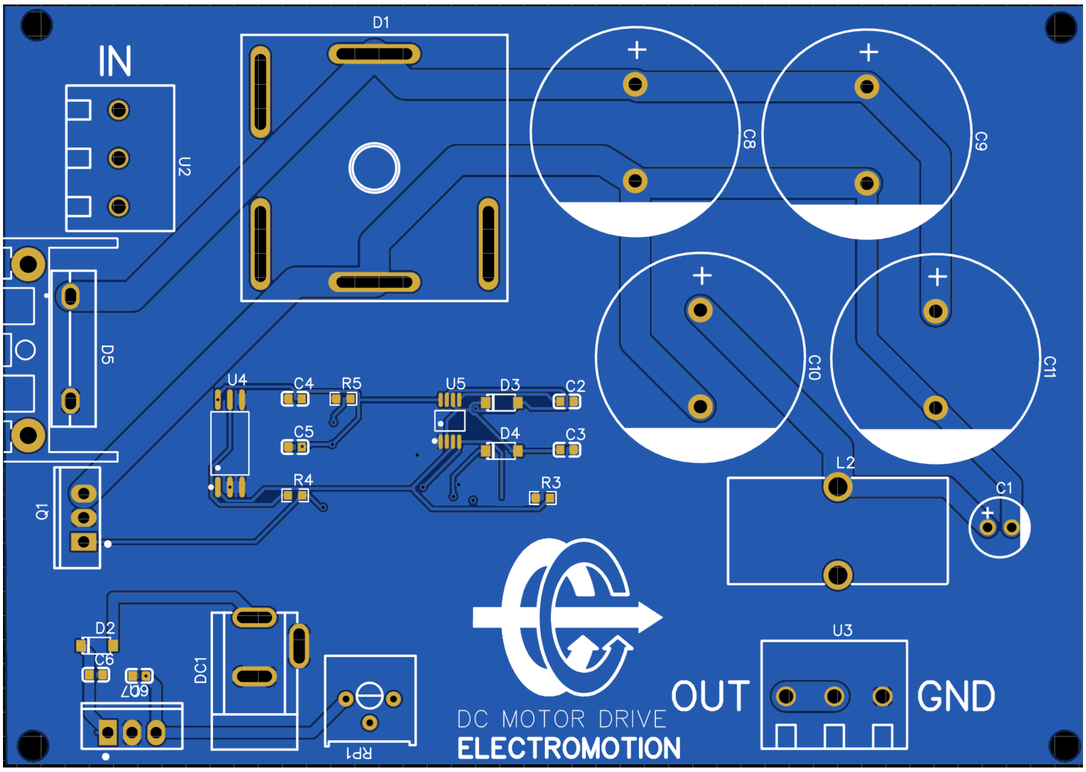

Figure 16: 2-D Design of PCB Layout (top side)

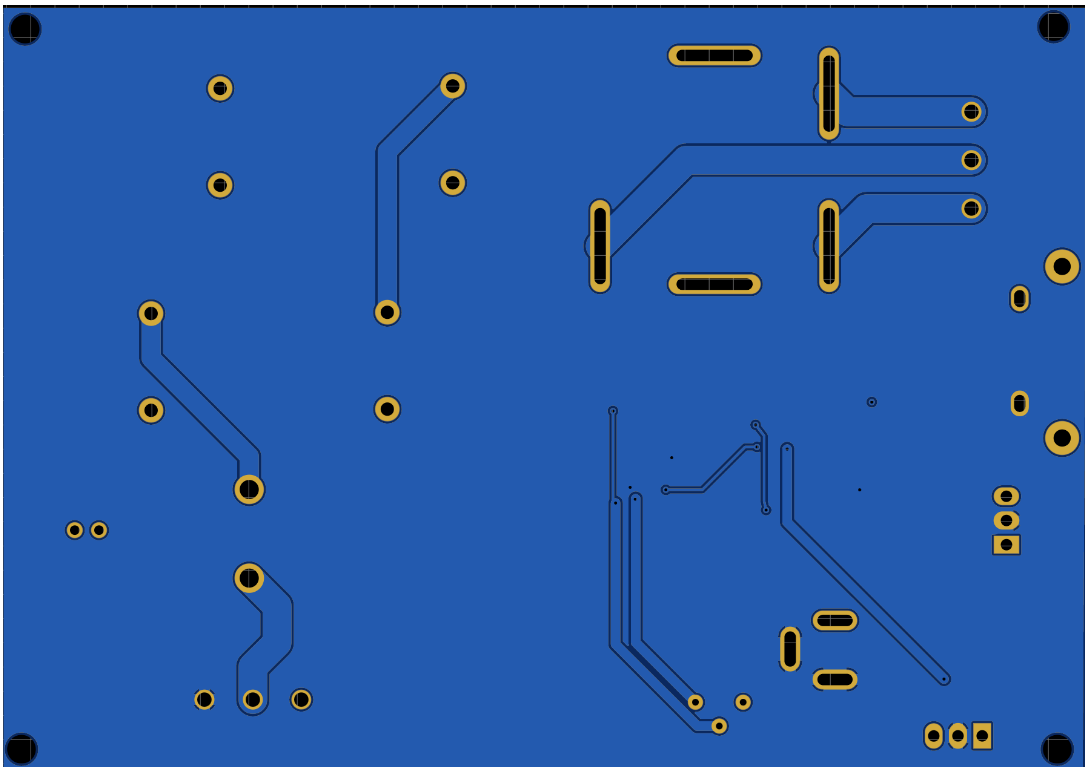

Figure 17: 2-D Design of PCB Layout (back side)

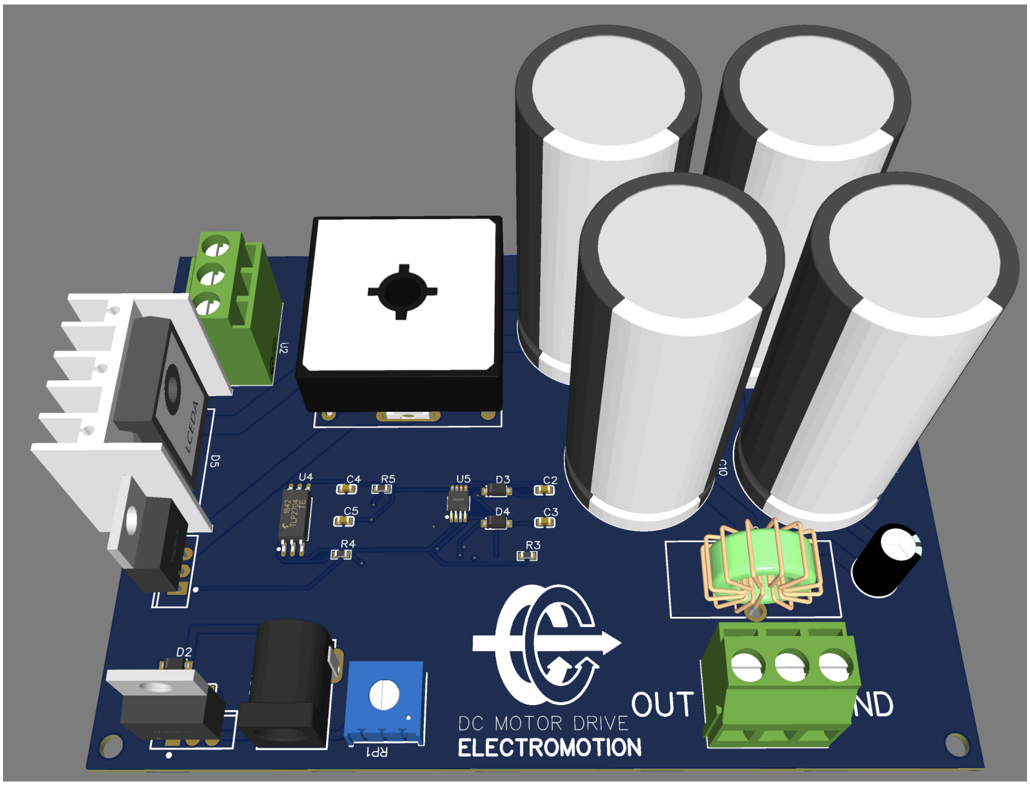

Figure 18: 3-D Design of PCB Layout

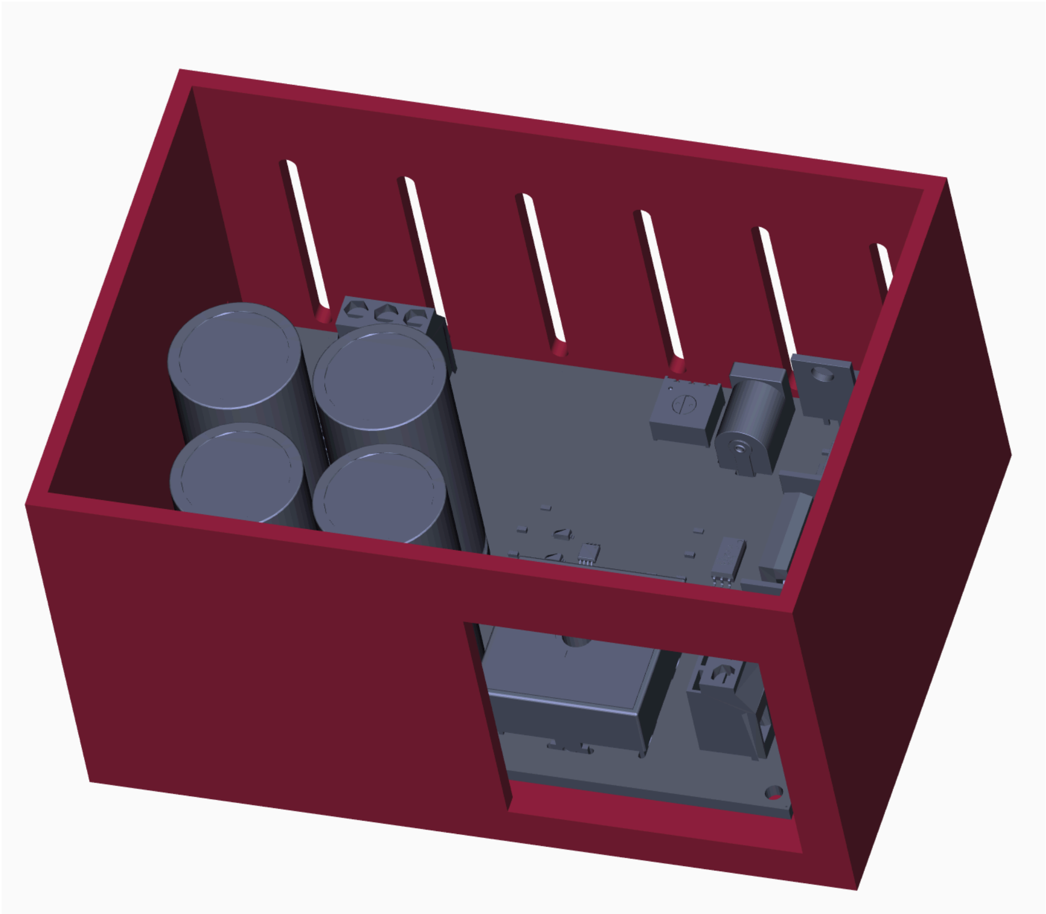

Figure 19: 3-D Design of Coverbox for PCB

In the PCB design, as can be seen from Figure 16 and Figure 17, we used thicker copper traces for paths that carry high current, while paths that carry signals use thinner traces. Both layers of the PCB have a ground plane. Some of the paths are copied to the other layer and linked using special holes called vias. The signal and power sections are kept separate. Connectors that are mounted on the panel are attached to the PCB using screw terminals. These screw terminals are fixed onto the PCB, and 3 mm thick traces are used for these connections.

As can be seen from Figure 18 and Figure 19, we designed the 3-D model of the PCB layout and the coverbox for it. We tried to reach high power densities in the drive circuit by keeping the overall volume small. In coverbox design, necessary air inlets are considered and holes are created on it. Also, since our PCB will need additional cooling options, we spaced out an area crafted for a 50x50 fan.

Conclusion

This report explains the design and development of a DC motor drive system using a controlled rectifier to change AC power into a steady DC output. Throughout the project, we carefully chose the circuit design, selected the right components, and ran detailed simulations to check how the system works under different conditions.

The project helped us apply what we learned in class about rectifiers and buck converters to a real-life situation. We got a better understanding of power electronics by working on simulations and designing the PCB. We also learned about circuit noise, heat management, and the proper arrangement of components for efficient operation. Maybe as the most valuable asset, we gained an ability and habit of searching through datasheets when we are planning to use some components.

Even though we did not build a real hardware version, this project gave us a great learning experience. We saw how important it is to run good simulations to predict how the circuit would work in real life. The PCB design part helped us learn about practical aspects such as selecting the right component sizes and planning the layout for better performance.

In the end, this project improved our technical knowledge and problem-solving skills, which will be useful in future projects. We would like to thank Assoc. Prof. Ozan Keysan and our course assistant Ogün Altun for their support, helpful feedback, and guidance throughout the project.