# METU ELECTRICAL AND ELECTRONICS ENGINEERING

## EE463 Hardware Project

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## Introduction

In this project, the aim is to create an AC to DC converter that can run the DC machine at rated voltage and rotation speed for at least 2 minutes. The inductor current ripple frequency must be greater than 1kHz. The following topologies were considered:

**Single-Phase Full Bridge Rectifier + Buck Converter:** Simple topology. Uses fewer and readily available components. Requires large capacitor to smoothen the large ripple created by the rectifier stage.

**Three-Phase Full Bridge Rectifier + Buck Converter:** Comparatively lower voltage ripple while still having a relatively simple topology.

**Three-Phase Thyristor Rectifier:** Simpler topology, high power capability. High voltage thyristors are less affordable. The circuit requires more complex control to prevent issues and failure.

In the end, we decided to stick to three-phase full bridge rectifier + buck converter to have a smoother ripple. We utilized the topology in the "chopper" form, where the inductor and output capacitor are not present. We have chosen our switching frequency to be 5kHz.

## Design Decisions

a) Topology: Single-Phase Full Bridge Rectifier + Buck Converter (Figure 1)
   - Advantages:
     - Due to simplicity of the single phase rectifier it has small size and cheaper compare to 3 phase rectifier.
   - Disadvantages:
     - High voltage ripple.
     - Large harmonic currents at output.
     - A lower output voltage compared to 3 phase rectifier.

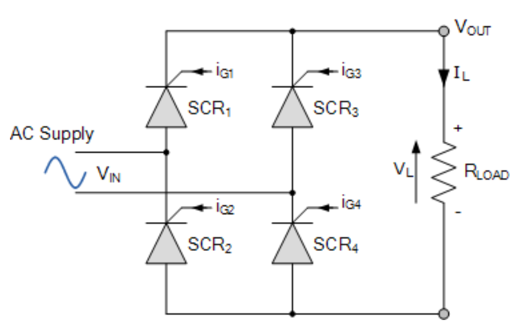


*Figure 1. Single phase rectifier circuit diagram.*

The output average voltage is expressed as $V_{av} = \frac{3\sqrt{2}V_s}{\pi}$. This topology introduces a high voltage ripple at output as expressed as $\Delta V_{out} = \sqrt{2}V_{ph}$.

b) Topology: Three-Phase Full Bridge Rectifier + Buck Converter (Figure 2)

- Advantages:
    - The main idea of choosing this topology is because of the simplicity of buck converter and ease of control with only one switch. As we have single input and single output it is sufficient to use a Buck converter.
    - One of the primary advantages of a three-phase rectifier is the significantly lower ripple factor compared to single-phase systems. The overlapping phases result in a much smoother DC output waveform even before filtering.
    - The fundamental frequency of the ripple in a three-phase bridge rectifier is six times the input line frequency. This higher frequency makes it much easier to filter out the noise using smaller and more cost-effective capacitors and inductors.

- Disadvantages:
    - Higher initial cost required.
    - Harmonic Distortion: Although the output ripple is low, three-phase rectifiers can introduce significant harmonic currents back into the AC power grid. Without proper harmonic filters, this can interfere with other sensitive equipment connected to the same power line.
    - Excessive heat.

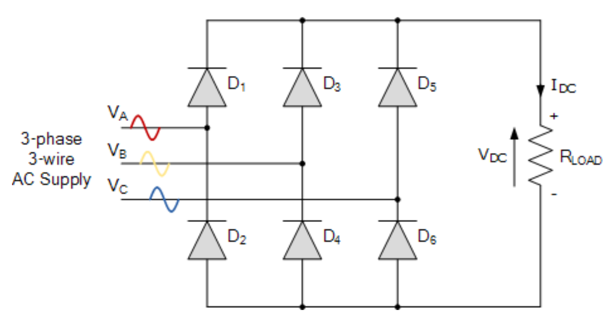


*Figure 2. 3-phase rectifier circuit diagram.*

Three phase rectifier output voltage $V_{av} = \frac{3\sqrt{6}V_s}{\pi}$ is expressed like this.

For our design, we used the buck converter Figure 3 is the diagram of buck converter.

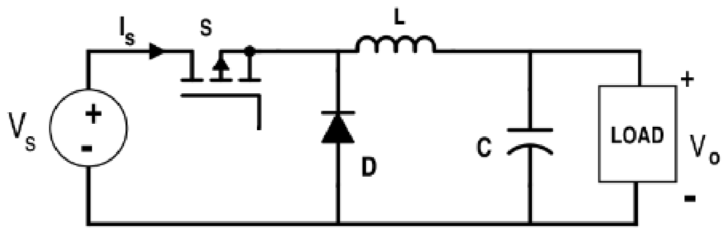


*Figure 3. Buck converter diagram.*

Reasoning of Selection:

The selection of the design has concluded with the 3 phase rectifier + Buck Converter. The design of buck converter does not have inductor or capacitor since the circuit is loaded with a motor, which is not a resistive load but is an inductive-resistive load. Therefore, we used the chopper form of buck converter. The output voltage of buck converter is expressed as $V_O = DV_{in}$. When we consider the total circuit diagram the input output relation is expressed as: $V_O = \frac{3\sqrt{6}}{\pi} \times DV_{in}$.

## Computer Simulations

In Figure 4, 3 phase rectifier + Buck converter (Chopper) is drawn in Simulink. The soft-start block is added. Soft start is increasing the voltage gradually to prevent high current passing over MOSFET and the motor as the demand is high initially on the motor load. The simulation has been held with different cases of scenarios: no load, with resistive load and motor load. The graphs are taken for the motor load.

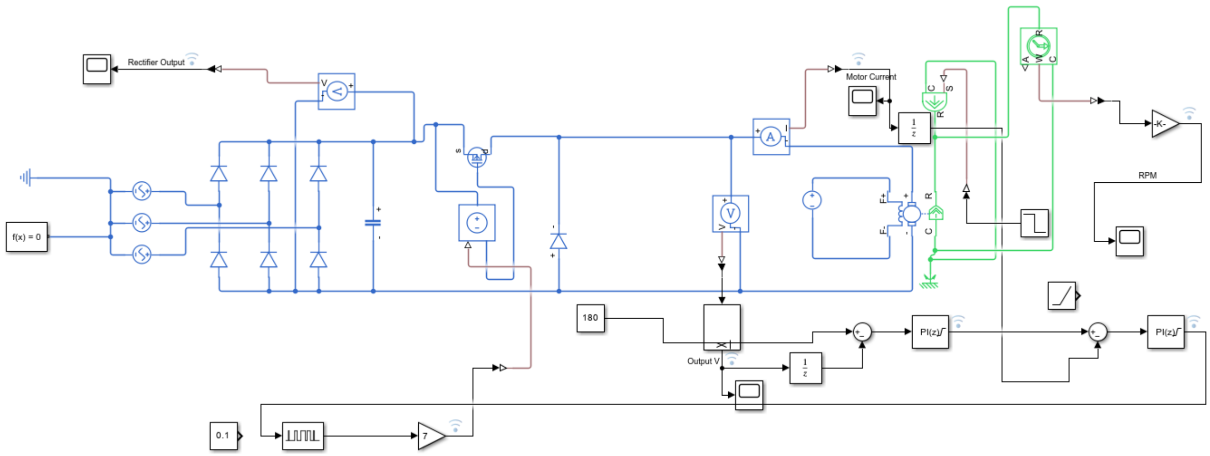


*Figure 4. Simulink drawing of the selected topology with the load.*

The output voltage graph is shown in Figure 5. It is as expected with the expression $V_{av} = \frac{3\sqrt{6}V_S}{\pi}$. On the graph we see around 347V with the ripple. The close look of the ripple can be seen in Figure 6.

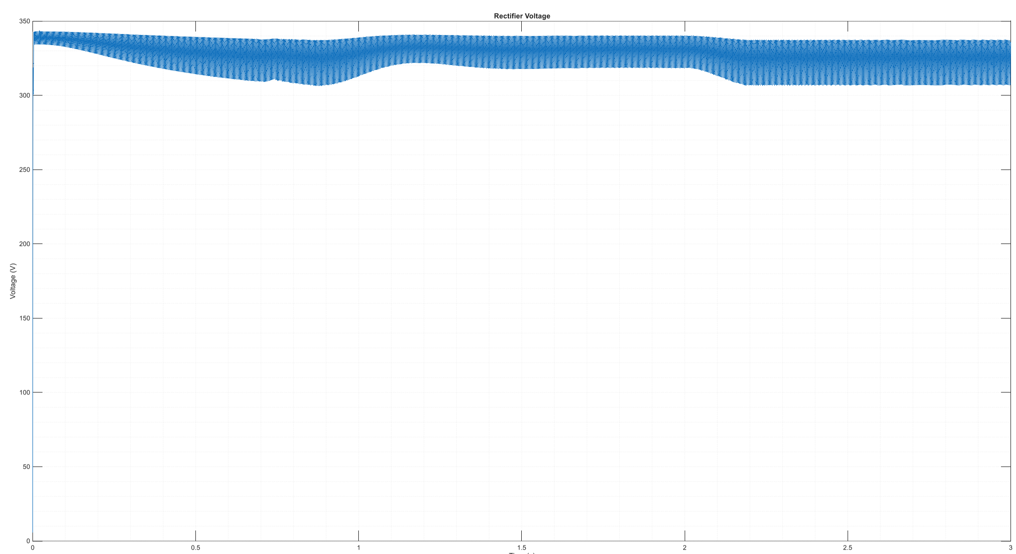


*Figure 5: Rectifier voltage.*

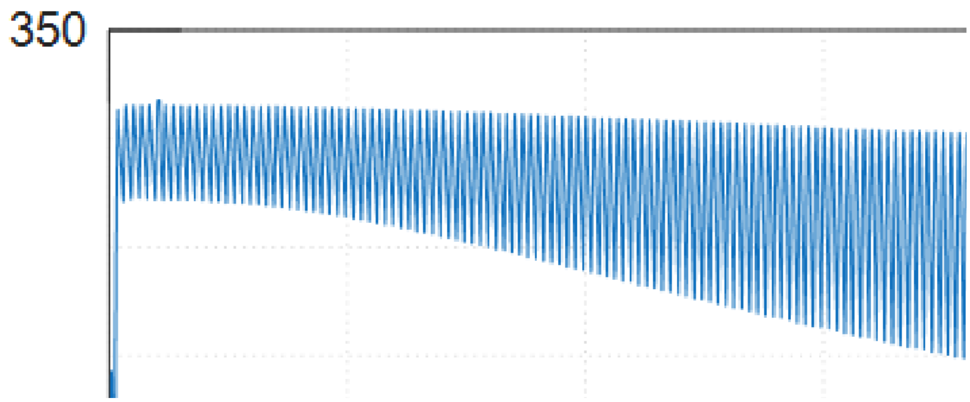


*Figure 6. Ripple of the rectifier output*

The output voltage of the Motor Driver can be seen in Figure 7. In the graph, the output wave form is fluctuating between 340V and 0V Due to our selected topology which is the chopper. Therefore, the average is calculated according to that waveform and the duty cycle.

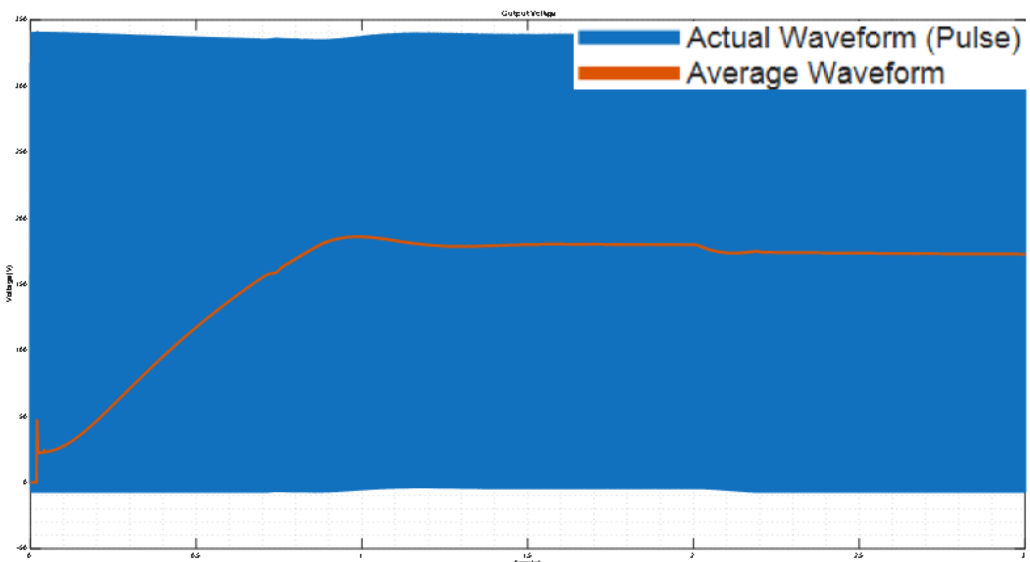


*Figure 7: Output voltage of the circuit.*

In Figure 8, the output current can be seen. In the graph, there is a drop in current and then it rises back up. This behavior is because of the negative torque applied at that instance. This torque simulates the motor load.

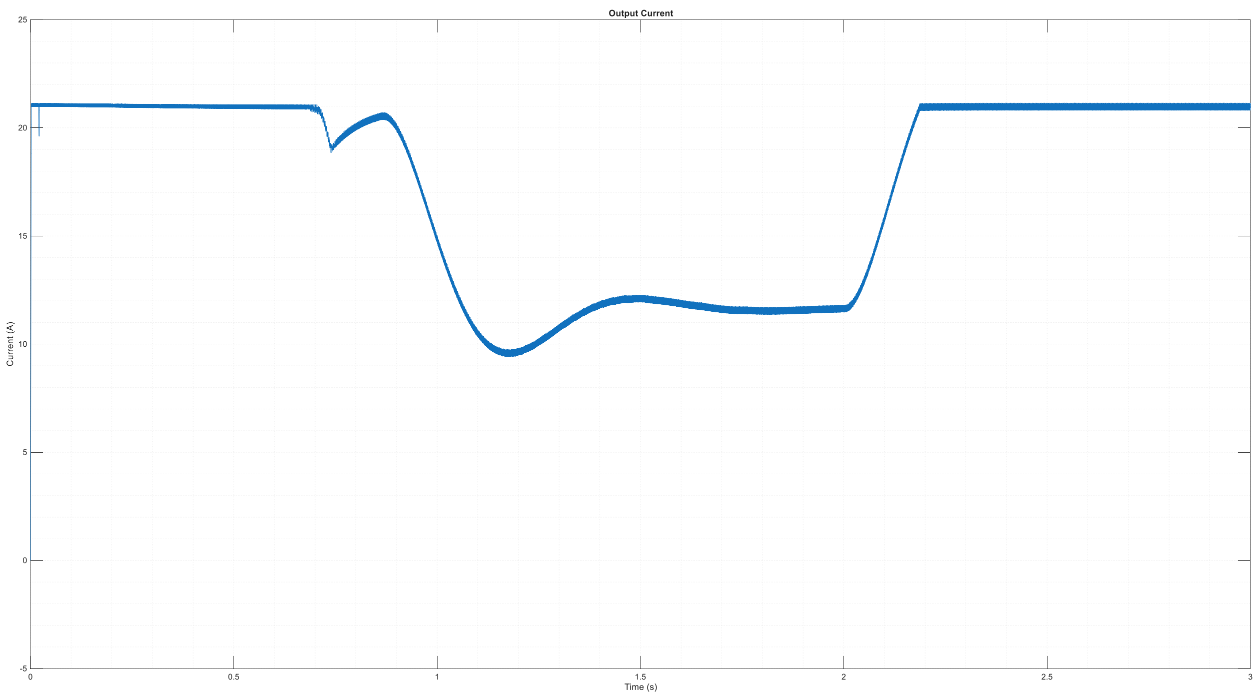


*Figure 8. Output current of the converter.*

The simulation tells us that, we can set the output voltage to 180V and with a duty cycle period of around 0.5-0.7 depending on the input.

**Soft Start Performance**

The output voltage simulation shows a highly controlled startup phase. Instead of an immediate jump to the target voltage, the average DC level follows a linear ramp. This confirms that the soft start logic is working correctly, which is vital for protecting the circuit from high in-rush currents that occur when the filter capacitors are initially empty and the motor is at a standstill. The high density of the underlying pulse waveform indicates that a high-frequency switching strategy is used to modulate the output, which helps in maintaining a smooth average voltage. Also, charging the capacitor before connecting the motor as load can help reduce the current drawn from the rectifier.

### Rectifier Output and Ripple Behavior

The results regarding the rectifier output illustrate the typical characteristics of a three-phase system. The ripple waveform shows a periodic oscillation centered around 350V. In a three-phase configuration, the ripple is naturally smaller and occurs at a higher frequency compared to single-phase systems, which makes it easier to filter. The steady-state rectifier voltage remains stable over time, as seen in the broader view, which indicates that the DC bus is well-supported by the input stage and can handle the average power demand of the motor.

The average output voltage reaches a stable level of approximately 175V to 180V after the initial startup phase. This value represents the effective DC voltage seen by the motor after the PWM process. Since the rectified DC bus is approximately 350V, an average output of 175V indicates that the system is operating at roughly a 50% duty cycle during steady-state conditions.

## Component Selection

### 3-Phase Rectifier (VUO36-16NO8) (Figure 9)


*Figure 9. The three-phase rectifier component.*

The VUO36-16NO8 is a standard three-phase rectifier bridge module designed for main rectification and field supply for DC motors. It has a maximum repetitive reverse blocking voltage rating of 1600V and can deliver a bridge output current of 27A at a case temperature of 85 degrees Celsius. This module is highly efficient for three-phase bridge configurations and provides sufficient power handling capabilities for the input stage of the motor driver.

**Power MOSFET (IXFH80N65X2 / IXFK80N65X2) (Figure 10)**

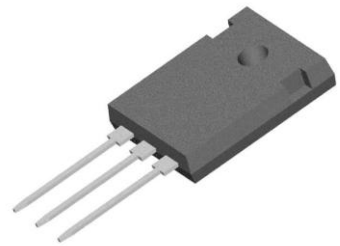

*Figure 10. The MOSFET component.*

These X2-Class HiPerFET power MOSFETs are designed for N-channel enhancement mode operation with a drain-to-source voltage limit of 650V. They support a continuous drain current of 80A and feature a very low static drain-to-source on-resistance of 40 milliohms. These characteristics make them ideal for AC and DC motor drives, providing more than enough current capacity and thermal efficiency for high-performance switching.

**Gate Driver (TLP250) (Figure 11)**

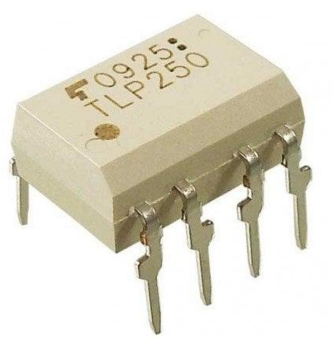


*Figure 11. The gate driver for the MOSFET.*

The TLP250 is used for gate driving circuits of power MOSFETs or IGBTs. It operates with a supply voltage between 10V and 35V and provides a peak output current of plus or minus 1.5A. With an isolation voltage of 2500$V_{rms}$ and a maximum switching time of 0.5 microseconds, it is sufficient to ensure fast and safe signal transmission between the control logic and power stage of the driver.

**DC/DC Converter (ROE Series) (Figure 12)**


*Figure 12. The isolating DC/DC converter.*

The 5V to 12V converter is picked to isolate microcontroller and and motor driver. Converter provides 1-watt unregulated power conversion with up to 80 percent efficiency. These converters offer 1kVDC isolation and are typically used for general-purpose power isolation and voltage matching. They are perfectly sufficient for providing the necessary isolated power supply to the gate drivers of motor driver circuit.

**Fast Recovery Diode (DSEI30-06A) (Figure 13)**


*Figure 13. The diode component.*

The DSEI30-06A is a Fast Recovery Epitaxial Diode (FRED) with a repetitive reverse voltage rating of 600V and an average forward current of 30A. It features an extremely short recovery time of 35 nanoseconds, which significantly reduces power dissipation and turn-on losses in the commutating switch. This component is an excellent choice for use as a free-wheeling diode in the motor drive. The ratings are sufficient for the motor driver Project.

**Filter Capacitor (K054004710PM0E040) (Figure 14)**


*Figure 14. The DC-link capacitor component.*

The Kendeil electrolytic capacitor used in this project has a capacitance of 470uF and a maximum voltage rating of 400V. It is designed for a long operating life of 5000 hours, which ensures the durability of the system. The input voltage of 260V is reduced to 180V and during the on and off times capacitor is providing the voltage. To do that this capacitor is well enough to satisfy the controller needs.

**Arduino UNO R3 (Figure 15)**

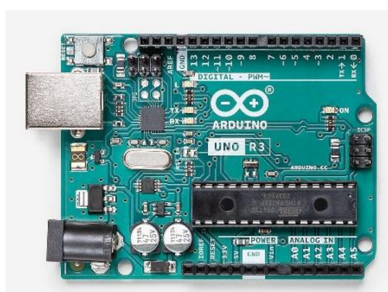


*Figure 15. Arduino Uno for the PWM input.*

The Arduino microcontroller serves as the primary controller responsible for generating high-frequency Pulse Width Modulation (PWM) signals to regulate the motor's operating speed. By varying the duty cycle of these pulses, the Arduino controls the average output voltage, maintaining a stable steady-state level of approximately 180V. It specifically manages the soft-start sequence by linearly increasing the PWM duty cycle over a six-second period.

## Test Results

Before the results are presented, due to the health concerns caused by the solder smoke and the tightness of the schedule, we decided not to implement the control loop. We settled with just implementing a gate driver, utilizing an isolator to make sure Arduino is safe from any possible circuit faults. The final circuit diagram is in Figure 16.

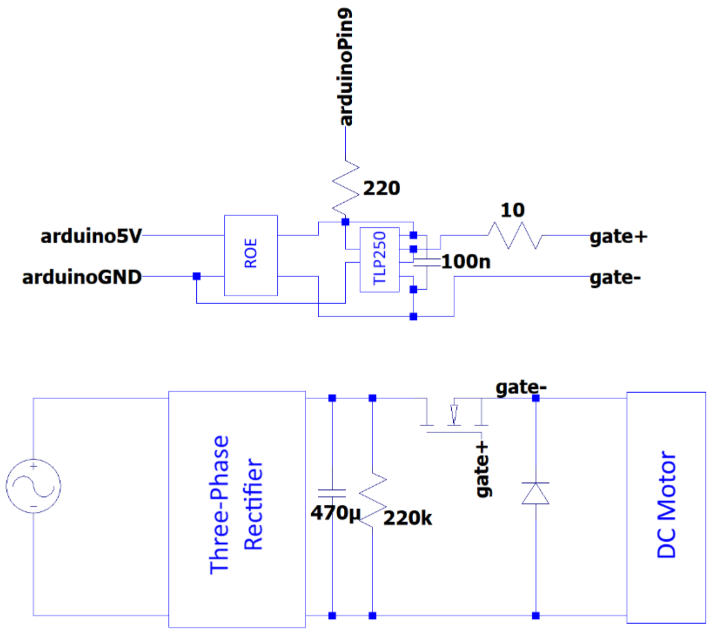


*Figure 16. The final circuit diagram.*

The physical circuit is given in Figure 17.

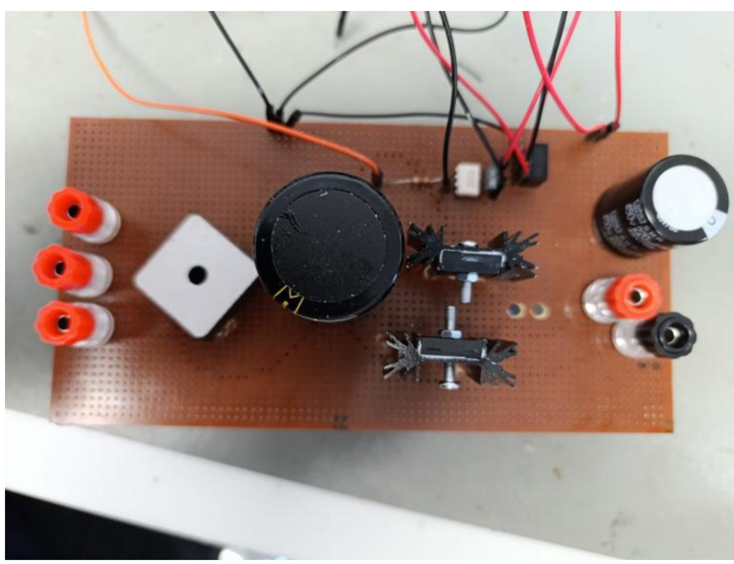

*Figure 17. The physical circuit.*

Note that there is an output capacitor in this implementation. We ended up cutting the wires under the stripboard to disconnect it from the circuit, but for health reasons, we did not want to desolder it.

We first performed tests with R and RL loads. Figure 18 is for the R load, and Figure 19 is for the RL load. The yellow waveform (CH1) is the output voltage, the light blue waveform (CH2) is the output current, and the pink waveform (CH3) is the switching voltage.

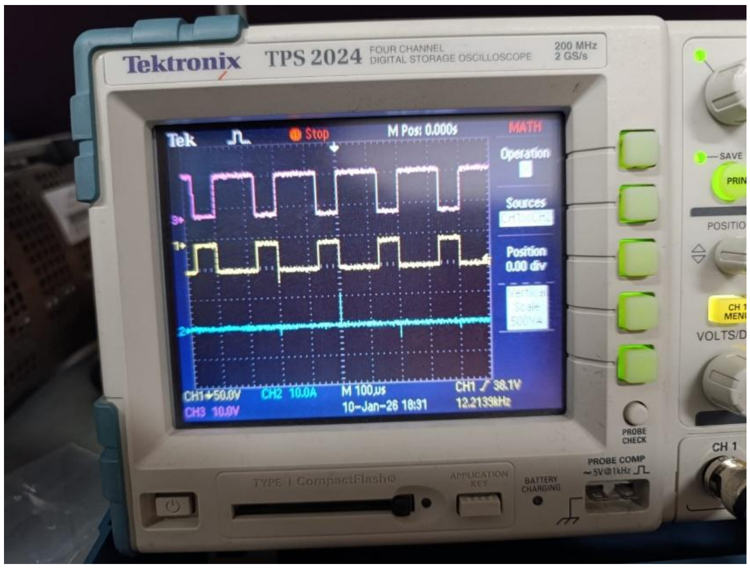


*Figure 18. R load test with R approximately 4.9Ω.*

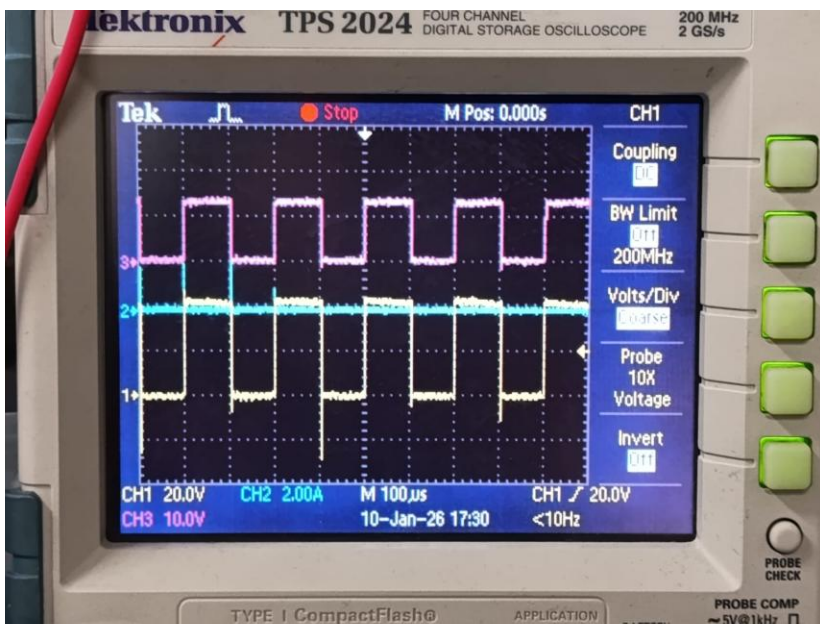


*Figure 19. RL load test with R approximately 27Ω, L approximately 50mH.*

We did not do any high voltage tests since we were afraid we could burn the circuit and have nothing to show during the demonstration day.

We initially wanted to control our duty cycle actively from Simulink. The model for this purpose can be found in Figure 20.

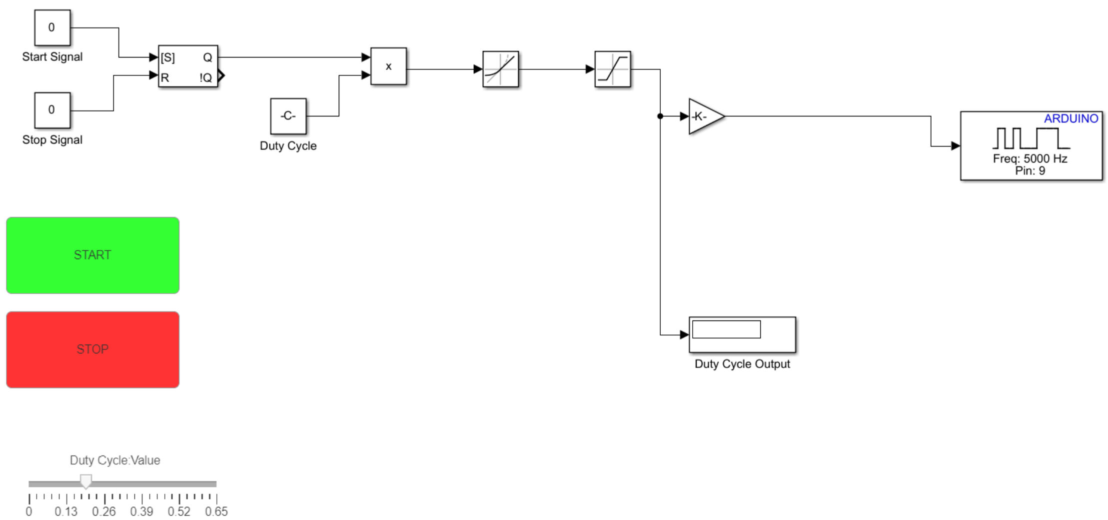


*Figure 20. The initial Simulink model for duty cycle control.*

Unfortunately, our Arduino would keep disconnecting from the computer in terms of communication, and the model would no longer be able to update the duty cycle. This is most likely caused by the noise in the circuit. Because of this, we instead settled with a Simulink model that does not require any communication once uploaded into the Arduino. Figure 21 shows the model used in the demonstration day.

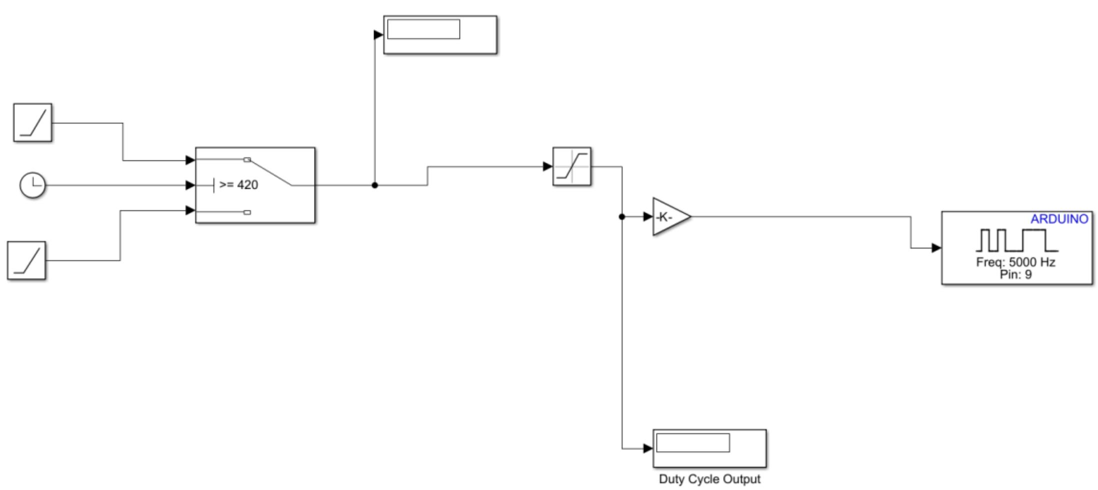


*Figure 21. The Simulink model that worked during the demonstration.*

When we did this, we were able to drive the motor almost effectively. Our average voltage output kept fluctuating between 170V and 190V, instead of hanging around 180V. In the demo, we were able to run the motor at rated voltage as well as run the kettle for 5 minutes. During the operation, the hottest component was our three-phase rectifier, which is to be expected. It did not have any heat sink on it. It reached up to 85°C. Figure 22 shows the heatmap during operation.

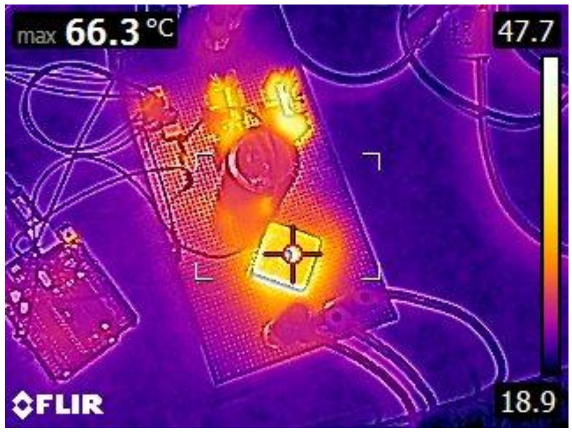


*Figure 22. Heat map of our circuit.*

The waveforms taken when the circuit operated the kettle can be seen in Figure 23.

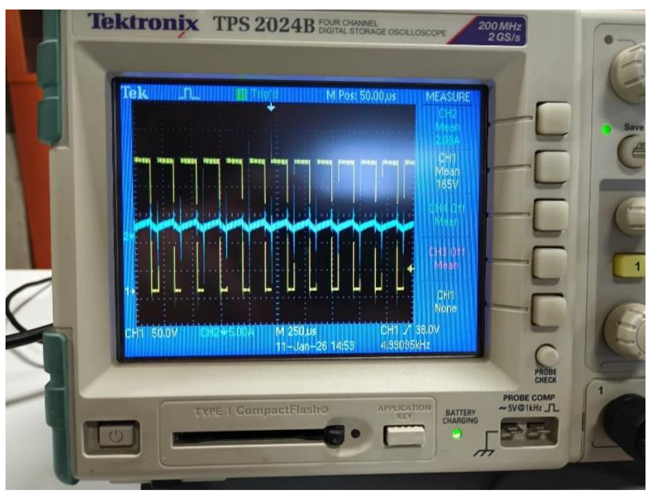


*Figure 23. The waveforms during kettle operation.*

The yellow waveform (CH1) corresponds to the output voltage, and the blue waveform (CH2) is the output current.

In the end, our circuit did not blow up, and we were able to perform the tea bonus, as well as the single supply bonus.

## Conclusion

In conclusion, we managed to design a circuit that was able to run the DC motor at the rated voltage and speed without blowing up. For us, the most critical parts were soldering carefully and selecting components with proper rating. The former required us to keep the thick cables far apart from each other to take precautions against high-voltage arcing. Due to unexpected health concerns and time struggles, we had to abandon closed-loop implementation. Our circuit did not fail, but we had fluctuation on the output voltage average even though the output was a proper square wave. This may have been due to the noise in the drivers, causing the duty cycle to change slightly. Nonetheless, it was a valuable experience for us as it showed us the importance of safety considerations and possible parasitics, affecting the communication between digital components.