MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL – ELECTRONICS ENGINEERING

EE463 – STATIC POWER CONVERSION -1

HARDWARE PROJECT

SIMULATION REPORT

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Introduction

Students enrolled in EE463 – Static Power Conversion 1 course are assign to build a harware project where they can consolidate their theoretical knowledge on the course topics with a practical design. The course project has two parts. In the first part of the project, students build a circuit design by using simulation tools and choose proper components for the hardware part. In the second part of the project, students build a circuit in real life by using their proposed topologies. This report presents the first part of the hardware project.

The hardware project is to build a power electronic circuit to drive a DC motor with an AC source. Properties of the DC motor to be run is given in the table 1. We are expected to run this motor at its rated speed from a standstill for two minutes at no load.

Rated Power	5.5 bhp
Rated Voltage	220 V
Rated Speed	1500 rpm
Rated Current	23.4 A
Armature Winding	0.8 Ω, 12.5 mH
Shunt Winding	210 Ω, 23 H
Interpoles Winding	0.27 Ω, 12 mH

Table 1: Properties of the DC Motor

To perform this operation, we first need to rectify the AC input to DC output and then adjust the DC output at the second stage. To do so, there are several power electronics topologies. However, we focused on two fundamental ones which are *single phase diode rectifier + buck converter* and *three phase diode rectifier + buck converter*.

In this report, we analyze these two topologies. We examine the advantages and disadvantages of them. We compare them with each other and then decide on one of them. After that we list proper components for the circuit and choose among them.

Possible Topologies for Solution

The system mainly focused on two topologies and was evaluated in detail in terms of system requirements.

- **Single Phase Diode Rectifier + Buck Converter**
- **Three Phase Diode Rectifier + Buck Converter**

However, topologies such as single and three phase thyristor rectifier and dimmer were examined, and despite their advantages such as decreasing the output voltage ripple of the system, they were not evaluated due to the fact that our team has less knowledge on this subject and these circuits are more complex.

These 2 topologies are compared in terms of output voltage ripple, efficiency, cost, size and ease of implementation.

Single Phase Diode Rectifier & Buck Converter

Single phase diode rectifier is a preferred topology in applications where less power and cost are aimed. As a trade-off for these features, it requires large LC filters to filter out its high output ripple. This topology, which is simpler than the 3-phase diode rectifier, is generally insufficient for high-power motor drivers.

Advantages

- It can be easily designed and implemented thanks to its simple circuit structure.
- Compact dimensions.
- Lower component cost.

Disadvantages

- It has high output ripple.
- Not suitable for high power loads due to limited current capacity.
- Since it has a lower power factor, it can increase harmonic distortion.

Three Phase Diode Rectifier and Buck Converter

Three phase diode rectifier and buck converter combination offers a more ideal structure in high power applications. A 3-phase AC source used at the input seems to be a more logical topology in terms of providing less output voltage ripple and better harmonic content, as well as operating more efficiently at high powers.

Advantages

- With its high power capacity, it can easily provide the power required for larger engines.
- Output Voltage is less compared to ripple single phase rectifier. In this way, the system can operate more stably.

- It can operate at high efficiency due to low fluctuation and low energy losses.
- The power factor of these rectifiers is generally above 0.95. This allows the system to operate more efficiently.
- Thanks to the low ripple, the deformation time of the system is longer.
- Less low order harmonics are produced.

Disadvantages

- Requires more components and hence calculations. This increases cost and complexity.
- Since it is a system operating at high powers, larger coolers and components may be required.
- As the system is tried to be minimized, problems such as EMI may arise. Therefore, EMI and harmonics may require additional filtering.
- The system inherently requires larger capacitors. The reason for this is that it may be necessary to limit the starting current to avoid problems such as inrush.

Topology Selection

In line with the requirements of the project, **Three Phase Diode Rectifier + Buck Converter** topology was chosen. Factors that play a role in choosing this topology are:

- **Output Stability:** Reduced ripple ensures stable motor operation and reduces electromagnetic noise.
- **High Efficiency:** The topology achieves high power factor and low energy losses, which are critical for industrial applications.
- **Power Handling Capacity:** Sufficient to drive the 220 V, 1500 RPM shunt DC motor.
- **Compliance:** The design adheres to IEEE standards for harmonics and power quality.

Following this, MOSFET was preferred for the switch in the buck converter part of the system, and IGBT was considered as a side option. MOSFET offers higher switching speeds and lower losses in low voltage applications compared to IGBT, while IGBT is more efficient at higher voltages and lower switching frequencies. The use of MOSFET in the buck converter was preferred for the following reasons:

- **High Switching Speed:** Enables operation with 10 kHz frequency, provides smaller LC filters and fast voltage adjustments.
- **Low Losses:** With low RDS(on) and gate charge (Qg) values, both switching and conduction losses are low.
- **High Current and Voltage Capacity:** Safely supports the starting and maximum load currents of the motor.
- **Easy PWM Control:** Output voltage can be adjusted precisely, motor speed and torque are controlled effectively.
- **Good Thermal Performance:** It heats up less, small heatsink is sufficient and extends system life.

In the system established in this way, the design selection of the system can be summarized as follows:

For Rectifier Design:

- Type: Three-phase full-bridge diode rectifier.
- Components: Six diodes (each rated for 20 A, 600 V).
- Output Voltage: 1.35 × V_peak (approximately 310 V DC without filtering).

For Buck Converter Design:

- Switching Element: MOSFET (10 kHz switching frequency).
- LC Filter:
  - Capacitor: 470 µF, 400 V.

- Inductor: 15 mH.
- Control: PWM-based duty cycle adjustment.

With that design topologies, the expected performance metrics are:

- **Output Voltage Ripple:** <2% of the nominal voltage.
- **Efficiency:** >90%.
- **Power Factor:** ≥0.95.
- **Harmonic Compliance:** Meets IEEE 519 standards for THD.

In order to minimize the problems that may occur as a result of non-ideality while preparing the system, the system will also include the following consolidations:

- **Thermal Management:**
    - Adequate heat sinks are incorporated for diodes and MOSFET to prevent overheating.
- **Harmonic Mitigation:**
    - A small LC filter on the AC side reduces lower-order harmonics.
- **EMI Control:**
    - Shielded cables and proper grounding are used to minimize electromagnetic interference.
- **Startup Protection:**
    - Inrush current limiters are added to protect the rectifier and upstream equipment.

Simulation Results

Objective

The main goal of the simulations is to test the chosen topology for the DC motor drive system. We use the aforementioned simulations so that the design will meet the requirements specified above such as adjustable DC output voltage in 180V range, soft start up for motor starts, as well as running under different load conditions and performance. Moreover, the simulations allow us to find and solve early issues such as high voltage ripple, imprecise control, or heat stress on parts before transitioning implementation.

Topology Overview

For this project, the topology selected is a *Three-Phase Diode Rectifier with Buck Converter*. We chose this topology because of its simplicity, efficiency and flexibility. Compared to single-phase rectifiers, a three-phase rectifier has more stable, less-rippled direct current (DC), which is important for the regulation of the motor operation. Combine that with a buck converter to have better control of the output voltage and there is a whole range of motor speeds that you can have. This topology maintains compatibility with off-the-shelf components and allows for added control options such as PWM for voltage fine-tunings. In addition, the design trades off performance with construction efficiency, allowing us to choose a cost-effective solution for all the project specifications

Design of the Three-Phase Rectifier

Development of the Three-Phase Rectifier:

The first stage in a DC motor drive system is the three-phase DC rectifier that transforms three phase AC voltage into a DR suitable for a buck converter. The design process had the following steps:

1. Input Specifications:

- Input Voltage: The rectifier has been designed to take in three-phase AC input voltage from a variac such that the supply is strong and can be controlled to any level.
- Operating Frequency: The three phase rectifier has been designed for an operating frequency of fifty hertz.

2. Approach for Selecting Diodes:

- Voltage Rating: The diodes have been selected that have a voltage rating greater than the peak phase voltage of the AC supply.
- Current Rating: These parameters were picked as factors above the maximum sustained load current were chosen to allow possible transitory conditions.

- Type: Such diodes were selected that will minimize the switching losses and thereby increase the efficiency.

3. The Rectifier Circuit:

- The rectifier topology used six diodes arranged in three phase configuration of six diodes.
- The design of full-bridge rectifier will provide continuous DC output across its load with ripple voltage lower as compared to single phase rectifiers and thus will reduce the filtering requirements.
- To reduce the ripple at the output and perform smoother operations, the ordinary capacitor was in this case, added to the DC voltage output of the rectifier. The value of the capacitor was computed.

Input voltage of the system is 150Vrms phase-to-phase and frequency 50Hz, which means output voltage is:

$$Vout = Vin_{l-l} * 1.35 = 150 * 1.35 = 202.5V$$

The input voltage is chosen in a way that to have margin to lower three-phase rectifier output voltage with the help of buck-converter. Due to the efficiency of overall circuit, it is good to choose voltage greater than 180V. A 1000 µF capacitor is used as a smoothing element at the rectifier output. This capacitor value was chosen to strike a balance between cost, size, and ripple reduction.

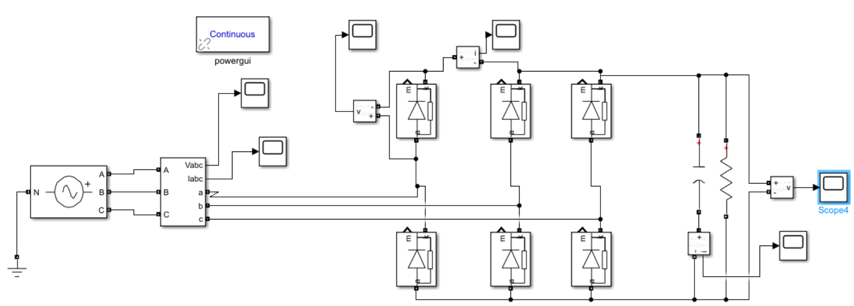

Figure 1: Three Phase Rectifier Setup

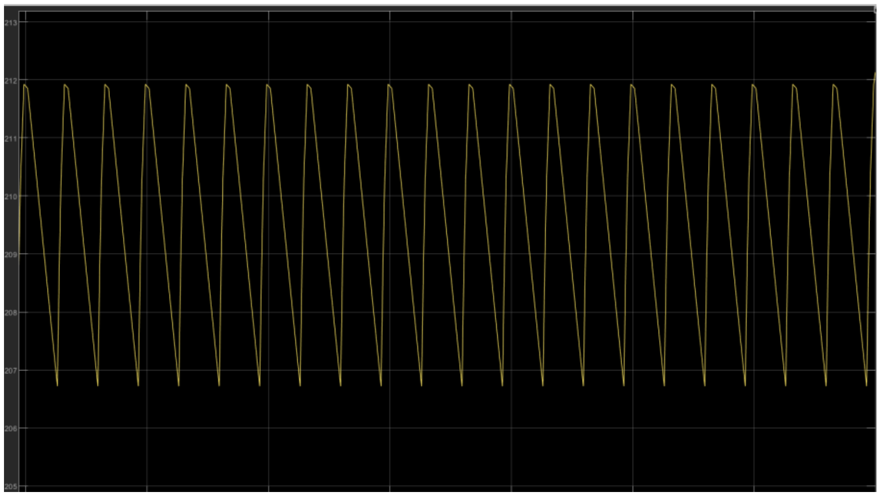

Figure 2: Output Voltage of Three Phase Rectifier

From the figure above, it can be clearly inferred that output voltage of rectifier circuit is **209V and peak-to-peak Vripple=5.4V**. From the calculation our output voltage is really close to the calculated result.

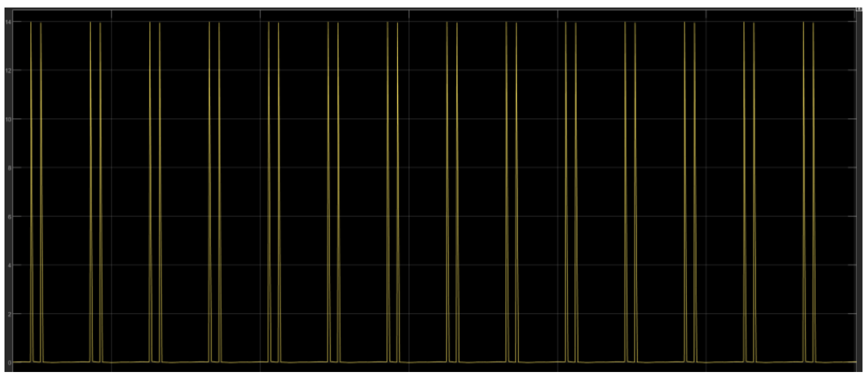

Figure 3: Diode Current

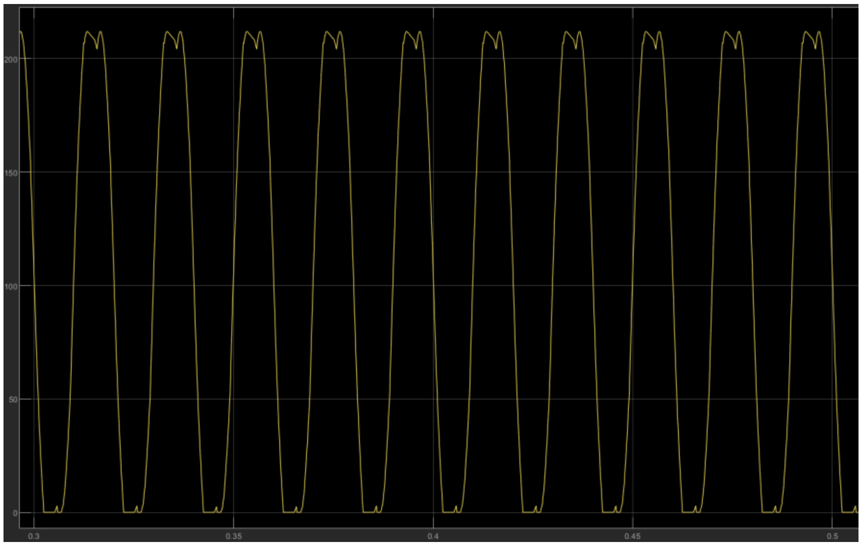

Figure 4: Diode Voltage

Design of the Buck Converter

The design of the buck converter is driven by the need to convert the processed raw DC to any desired lower DC voltage with minimal losses. The rectified voltage of 203 V is further regulated to the required level employing a PWM switching scheme at 10 kHz frequency. The buck converter is built with a duty cycle of 0.85, which in ideal cases translates to an output voltage of about 172.55 V. The inductor, capacitor, switching element, and diode are all rated to operate in Continuous Conduction Mode (CCM) with minimum output ripple.

An inductor of 3 mH was selected to prevent excessive ripple during the switching action. Calculated values show an inductive current ripple at 5.755 A. This ripple is very much acceptable so as not to distort the current supplied to the load. The intensity of the inductor is also considered in defining the core and wire diameter so as to avoid the losses at maximum load current.

The output capacitor which is sized at 680 µF was chosen in order to limit the voltage ripple to about 1.06 V. This value guarantees that the output voltage is quite steady thus making it appropriate in driving the DC motor. The capacitor's voltage and ripple current ratings are meant to withstand the operational requirements without any time ageing.

In the circuit, the switched element is a MOSFET and it has a voltage rating greater than the input voltage to account for voltage spikes. A MOSFET is chosen with low on-resistance to eliminate conduction losses. The free wheeling component is a diode.

MOSFET switching is controlled by the use of PWM, keeping the duty cycle at 0.85 as desired. In this way, the output voltage is well regulated. Switching frequency of up to 10 kHz is selected to ensure balance between efficiency of the circuit and stress on the components to the extent of minimizing electromagnetic interference while retaining small sizes of the components.

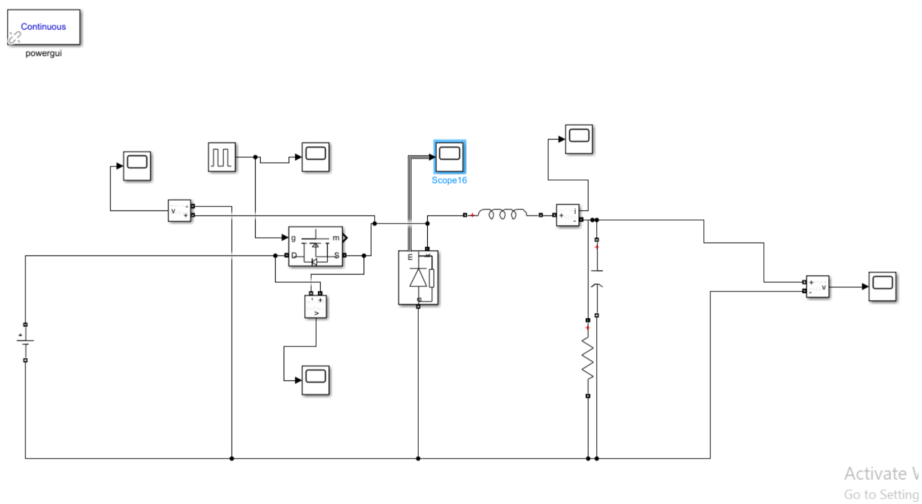

Figure 5:Buck Converter Design

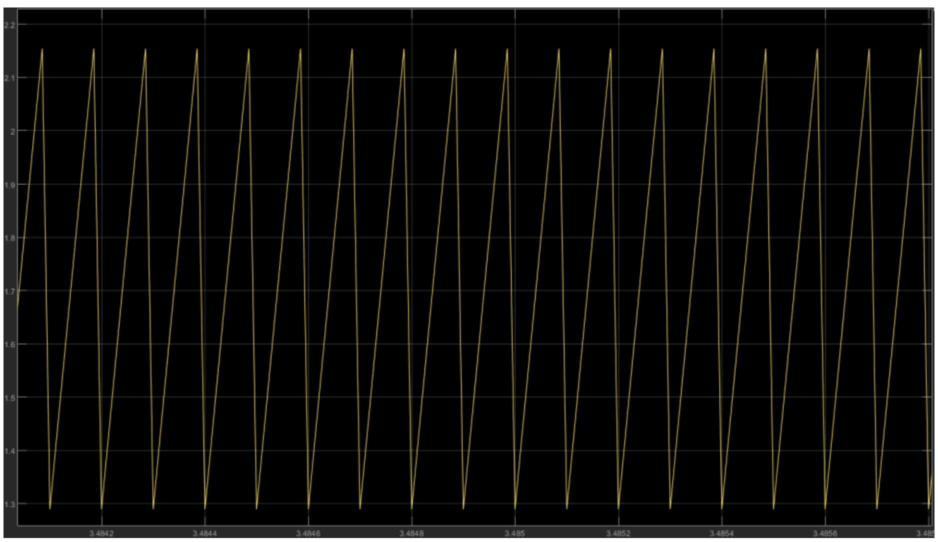

Figure 6:Inductor Current

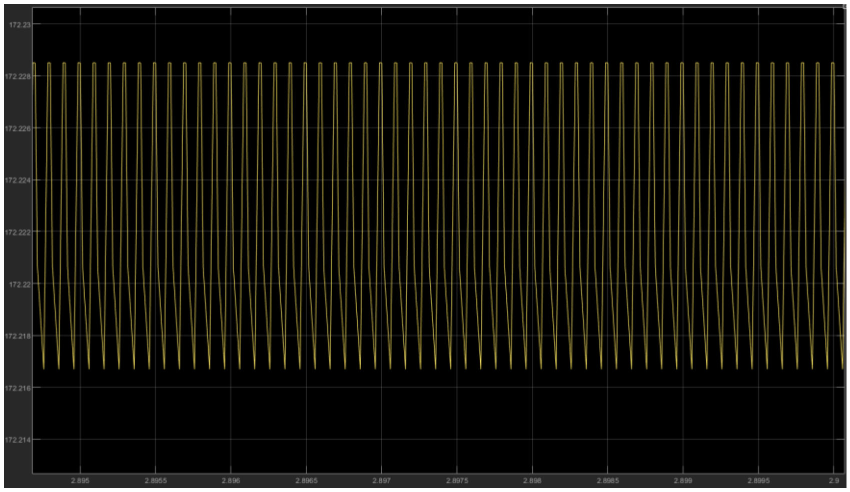

Figure 7: Buck Converter Output Voltage

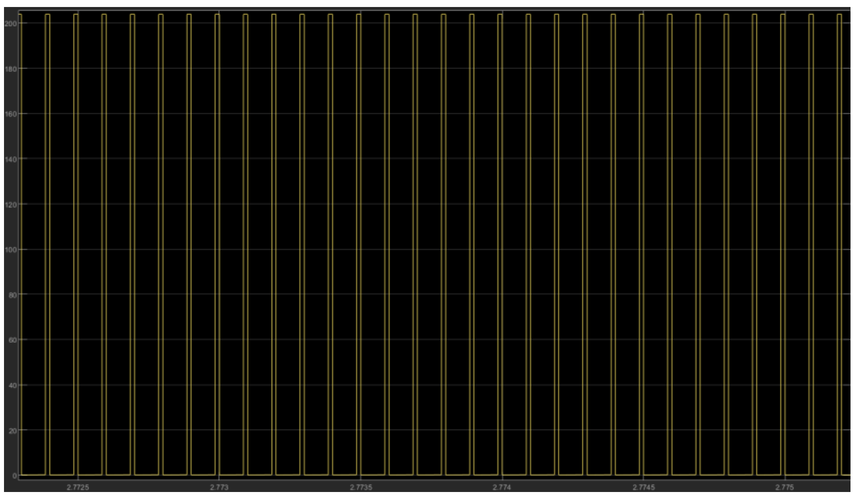

Figure 8: Voltage around MOSFET

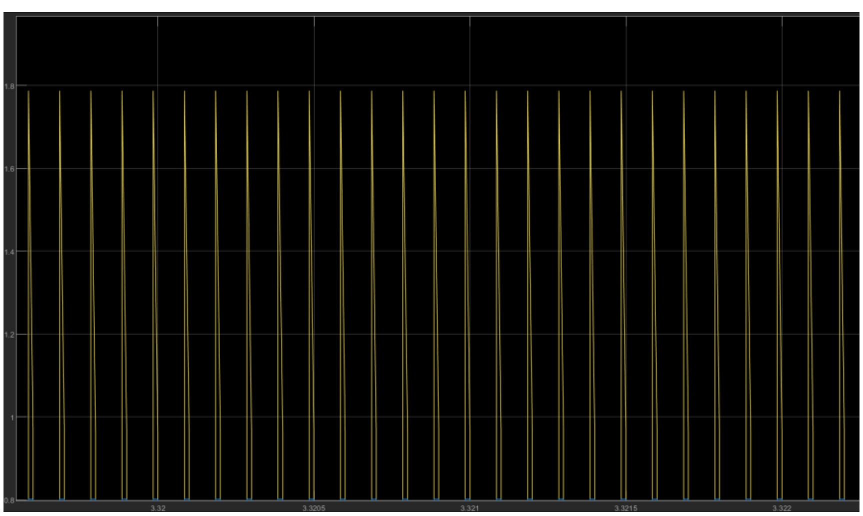

Figure 9: Diode Current

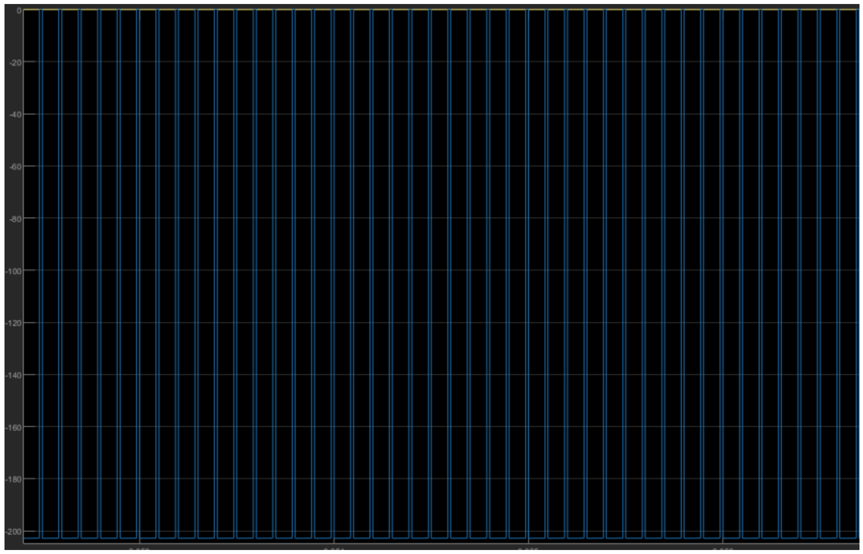

Figure 10: Diode Voltage

Simulation of the Overall Design

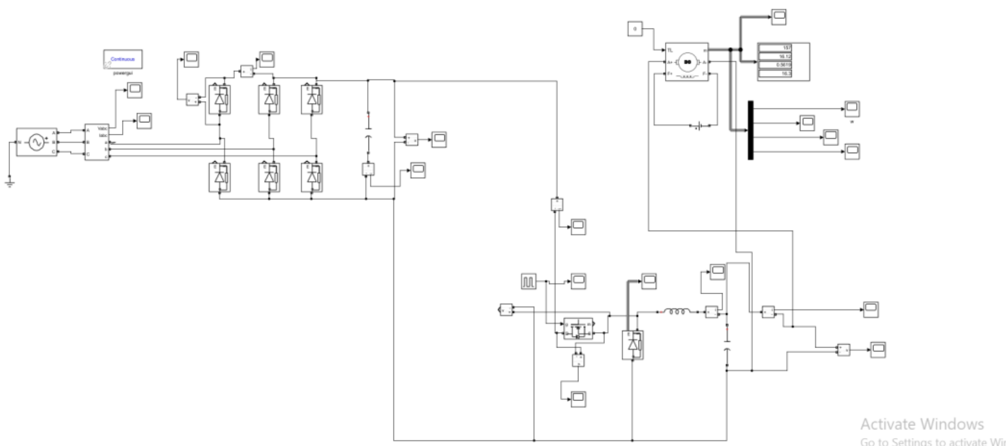

Figure 11: Overall System Design at Simulink

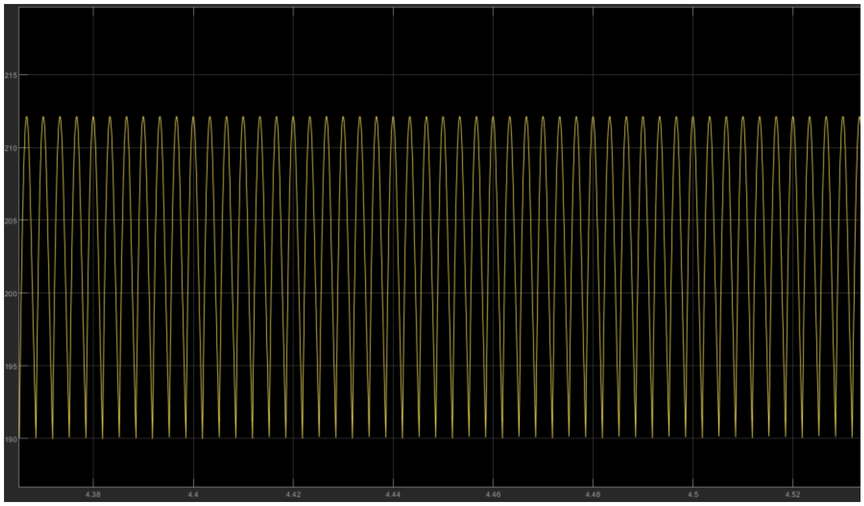

Figure 12: Output Voltage of Three Phase Rectifier Circuit

From the figure above, it can be inferred that our output voltage at three phase rectifier circuit is **205Vrms** which is roughly same as we calculated beforehand. Otherwise, the voltage ripple is **22.18V**. This voltage ripple is not a problem because it will be handled by the filter of buck converter.

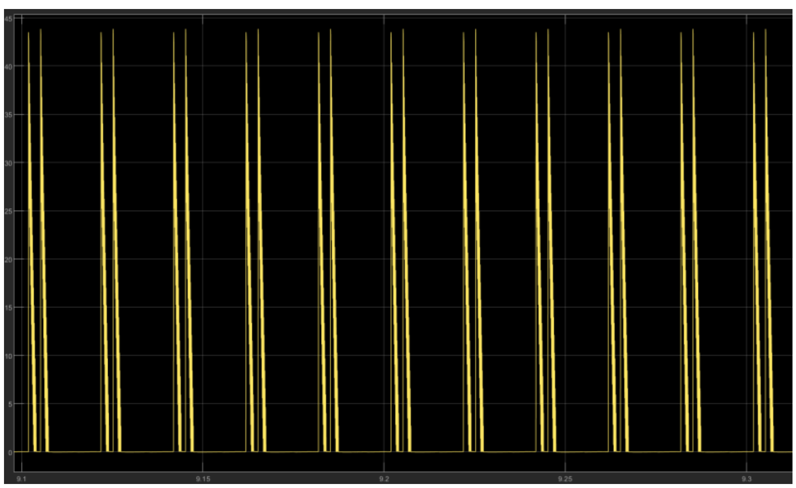

Figure 13: Diode Current of Three Phase Rectifier Circuit

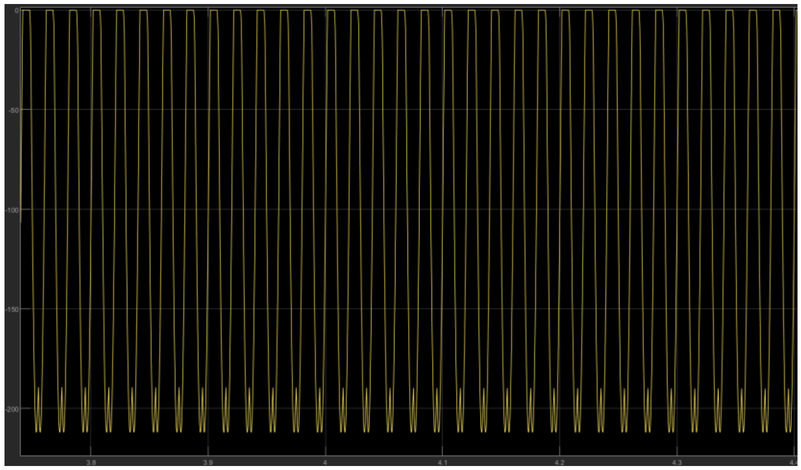

Figure 14: Diode Voltage of Three Phase Rectifier Circuit

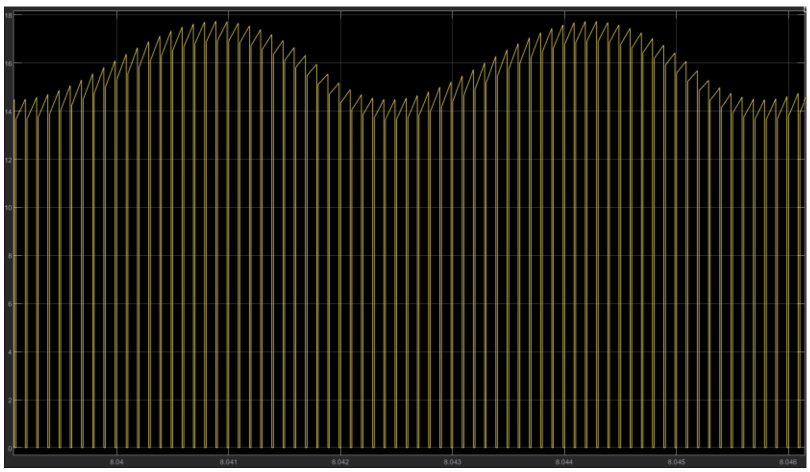

Figure 15: Current of Mosfet of Buck Converter

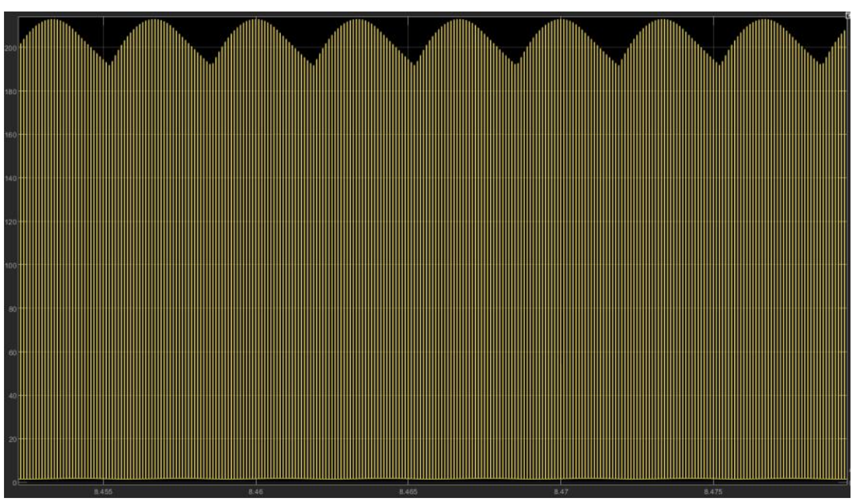

Figure 16: Voltage of Mosfet of Buck Converter

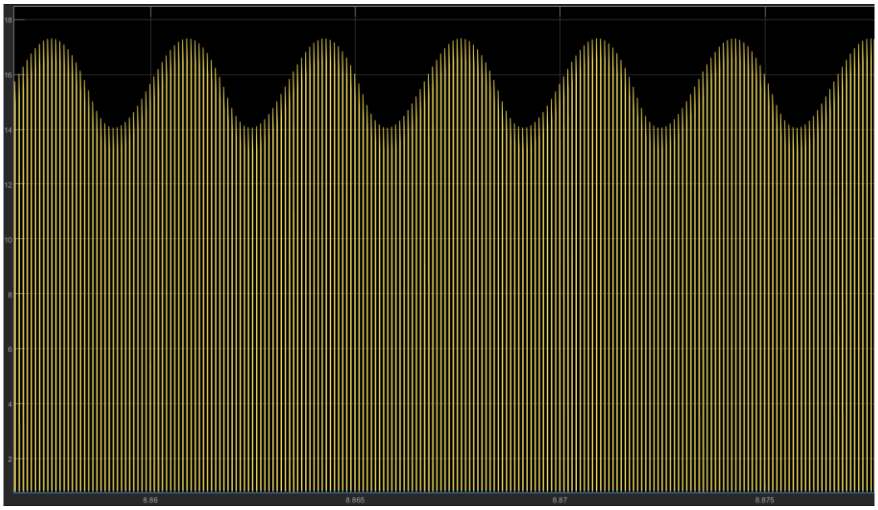

Figure 17: Current of Freewheeling Diode of Buck Converter

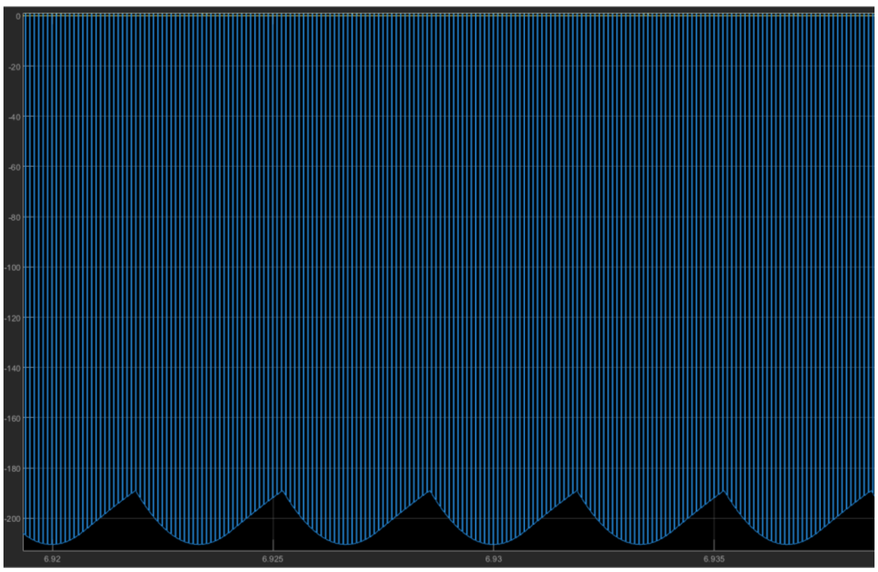

Figure 18: Voltage of Freewheeling Diode of Buck Converter

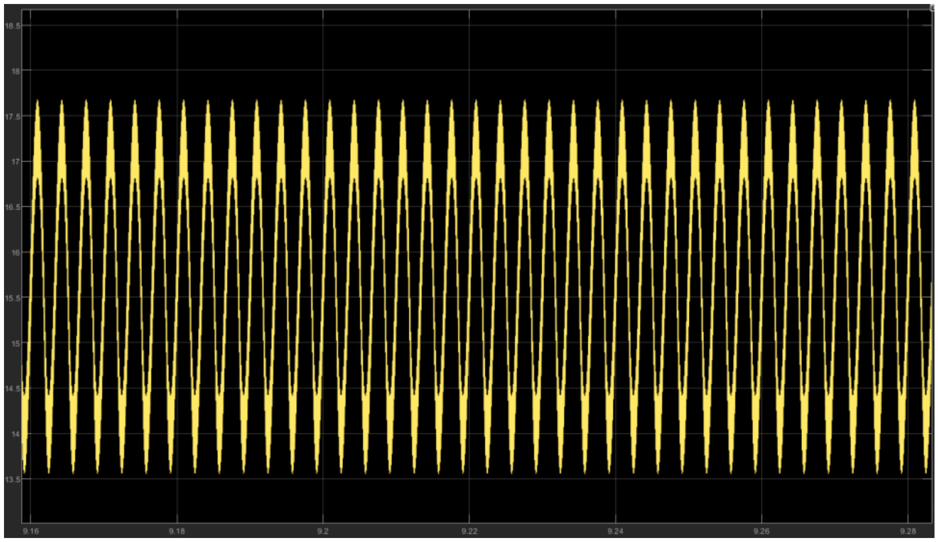

Figure 19: Current of Buck Converter

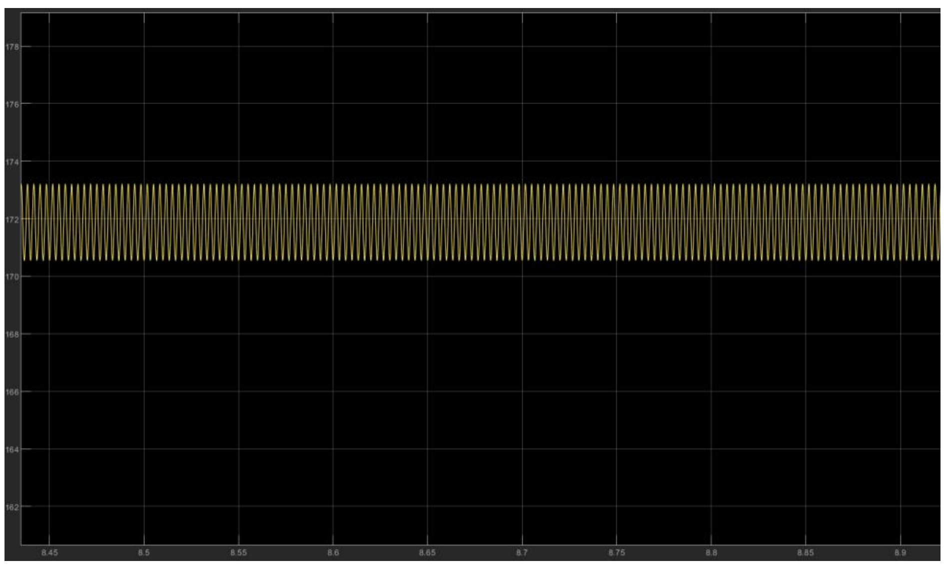

Figure 20: Output Voltage of Overall System

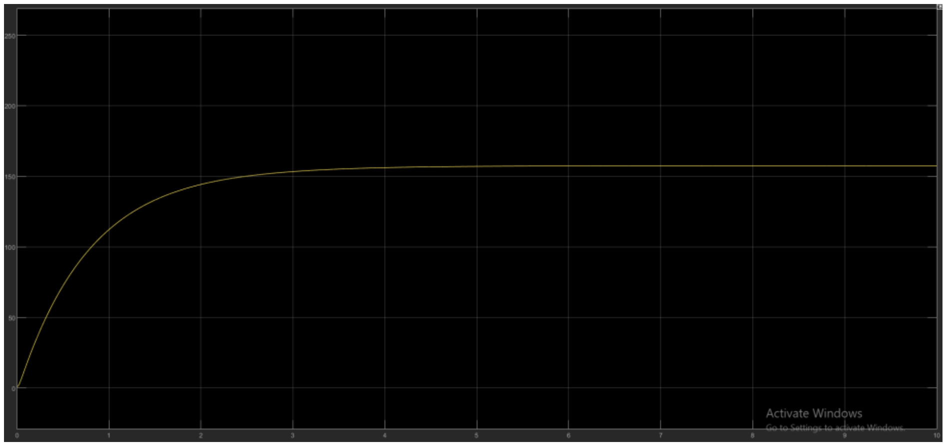

Figure 21: Speed of Motor

Component Selection

Three Phase Rectifier

STMicroelectronics STTH6003CW:

- Reverse Voltage (VR): 300 V
- Forward Current (IF): 60 A
- Forward Voltage Drop (VF): 1.25 V
- Why it's Suitable: Balances a high current rating and a sufficiently high reverse voltage margin, with a reasonably low forward voltage drop.

MOSFET

FCH47N60F (ON Semiconductor)

- Voltage Rating (VDS): 600 V
- Current Rating (ID): 47 A (max)
- RDS(on): 0.078 Ω
- Gate Charge (Qg): ~96 nC
- Why It's Suitable: High current capability and very low RDS(on) minimize conduction losses, making it ideal for high-efficiency designs.

IPP60R180P6 (Infineon)

- Voltage Rating (VDS): 600 V
- Current Rating (ID) :30 A (continuous)
- RDS(on): 0.18 Ω
- Gate Charge (Qg): ~64 nC
- Why It's Suitable: Optimized for high-frequency operation with low gate charge, offering excellent performance at 10 kHz.

Freewheeling Diode

MUR3040WT (ON Semiconductor)

- Reverse Voltage (VR): 400 V
- Forward Current (IF): 30 A
- Forward Voltage Drop (VF): 1.1 V
- Recovery Time (tr): 50 ns
- Why It's Suitable: Low forward voltage drop reduces conduction losses, and the recovery time is well-suited for 10 kHz operation.

1. STTH30R04 (STMicroelectronics)

- Reverse Voltage (VR): 400 V

- Forward Current (IF): 30 A
- Forward Voltage Drop (VF): 1.2 V
- Recovery Time (tr): 70 ns
- Why It's Suitable: Fast recovery, 400 V rating with a good safety margin, and adequate current handling.

For the **MOSFET:**

The operational range of the system is approximately 20 Amps. Although this system range is suitable for two MOSFETs, as the IPP60R180P6 heats up (100°C), the system may not be able to deliver the desired current. Therefore, while the system is being implemented, the heat sync status of the system will be examined and considering the uncontrollable heating, **FCH47N60F** will be preferred first. Although this system is expensive compared to other MOSFETs, it is much more suitable for the system and has made it preferred.

For the **MOSFET DRIVER:**

The voltage of the PWM signal must exceed the gate threshold voltage of the MOSFET. A gate drive voltage of 10V-15V is generally required for most MOSFETs to operate properly. If the PWM signal voltage is low, the MOSFET will not turn on fully and may overheat. To prevent this, an **IR2110** MOSFET DRIVER was selected for the system.

For the **Freewheeling Diode:**

Although MUR3040WT seems more suitable among the two diodes, unfortunately it could not be preferred as it would challenge our team in terms of transportation to Turkey and availability. For this reason**, STTH30R04** diode, which meets the system conditions very well, will be used.

For the **Three Phase Rectifier:**

STTH6003CW was chosen because it was close to the operating values we used in the project.

For the **Three Phase Rectifier Capacitor:**

It is chosen high to prevent the system's output ripple and to prevent damage to the MOSFET. Which is **9mH** for now.

For the **Buck Converter Inductor:**

$$L = \frac{V_{out} \times (1 - D)}{(\Delta IL \times fs\ )}$$

Based on the formula, the system was calculated, and it was decided to use a value above **1.2mH**. This value has been selected as 4.7m for now to increase the filtering ability of the system and minimize output distortion. This value, chosen by taking into account effects such as system losses and ESR, will be reduced to 3m and 1.5m respectively, according to observations in the implementation.

For the **Buck Converter Capacitor:**

In the system created by considering the Ripple effect, the buck converter capacitor value of the system is currently determined as **4.7uF**.

Conclusion

In this report, we design a power electronic circuit in simulation environment to run a DC motor at its rated speed from standstill for two minutes. We first examine different topologies such as single phase diode rectifier + buck converter and three phase diode rectifier + buck converter. We decided on three phase diode rectifier + buck converter topology because it has less voltage ripple at the output and higher average output voltage. After topology selection, we work on building the circuit on simulation environment. We decide on the values of capacitors, inductors, proper MOSFETs and diodes, and switching frequency of the MOSFETs and duty cycle. We first build the circuit considering everything is ideal. Then, we enter the non-idealities of the components to the simulation. Due to non-idealities, the output of the circuit did deviate from the ideal solution. Therefore, we iterate the previous step with different components until we reach the desired outcomes. With these iterations, we get closer to build a proper circuit that would operate in practice.