MIDDLE EAST TECHNICAL UNIVERSITY ELECTRICAL & ELECTRONICS ENGINEERING

EE463: Static Power Conversion I

DC Motor Drive Project Simulation Report Fall 2022

Team: VA Method

Participants:

İrem Bayın 2304145

Ahmet Bilgin 2231488

Nilsu Bora 2304186

Table of Contents

1. Introduction

Different kinds of electrical devices are used in both our daily lives and the industry. In order to drive those devices, the grid voltage should be adjusted to be compatible. In this project, the team is required to design a controlled rectifier that should be available to drive a DC motor. This report is the documentation of the project stages up to and including component selection. First, the possible topologies are researched and compared. After deciding on which topology will be used; analytical, power, and loss calculations are done. Continuing, the simulations of the topology are obtained with respect to the previous calculations. Finally; considering specifications, calculations, and simulations; the components that are planned to use in this project are decided.

2. Project Specifications

The parameters of the DC motor which should be driven are:

- Armature Winding: 0.8 Ω, 12.5 mH
- Shunt Winding: 210 Ω, 23 H
- Interpoles Winding: 0.27 Ω, 12 mH
- BHP: 5.5
- Rated Rpm: 1500
- Rated Voltage: 220 V
- Rated Current: 23.4 V

The input of the DC Motor driver can be 1 or 3-phase AC and the output is a maximum of 180V DC.

3. Topology Selection

3.1. Considered Topologies

In order to satisfy the project specifications, the team has considered using a three-phase diode rectifier with a buck converter, a single-phase thyristor rectifier, or a three-phase thyristor rectifier.

3.1.1. Three-Phase Diode Rectifier with Buck Converter

This topology can be explained in two parts. The first part is a three-phase diode rectifier. Basically, it converts the input AC voltage to output DC voltage. It will be useful in the project as it can take grid AC voltage as input and give DC voltage with decreased ripple as output.

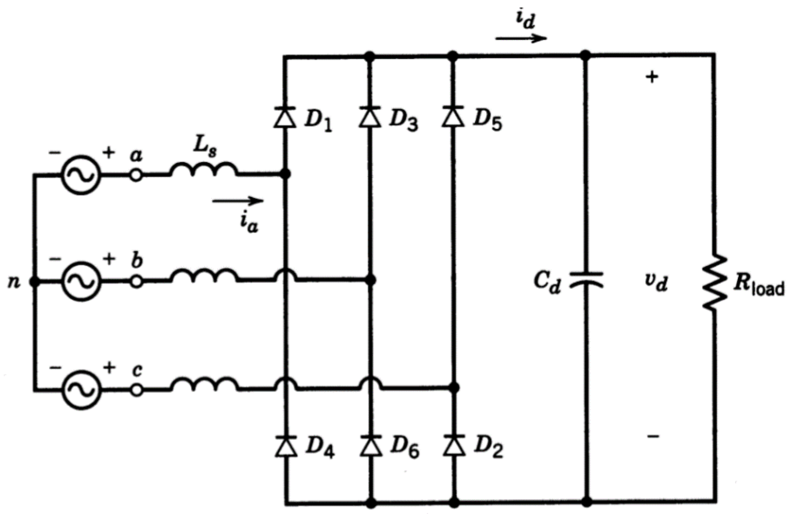

Figure 1. Three-Phase Diode Rectifier Layout

The output voltage of this rectifier with respect to input line-to-line voltage can be calculated by:

$$V_{av} = \frac{3\sqrt{2}}{\pi} V_{ll}$$

Second part is the buck converter. The layout of a buck converter can be observed in Figure 2. It gets DC voltage as input, rectifies it according to the duty cycle and gives the rectified DC voltage as output. The output voltage can be calculated by:

$$V_{out} = V_{in} * D$$

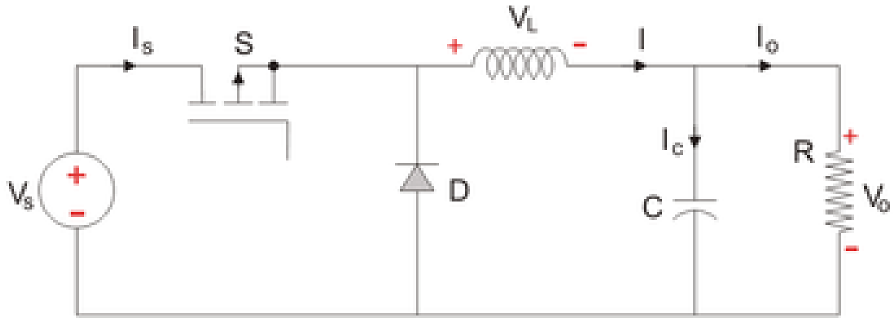

Figure 2. Buck Converter Layout

Advantages

- Three-phase diode rectifier takes grid AC voltage as input and gives DC voltage with decreased ripple as output.
- Even though it consists of a rectifier and converter, this topology is less expensive than the topologies that contain thyristor.
- Only one component needs a gate signal so the layout and synchronization is much simpler than the thyristor-containing topologies.

Disadvantages

- This topology is not suitable for operating in inverter mode.

3.1.2. Single Phase Thyristor Rectifier

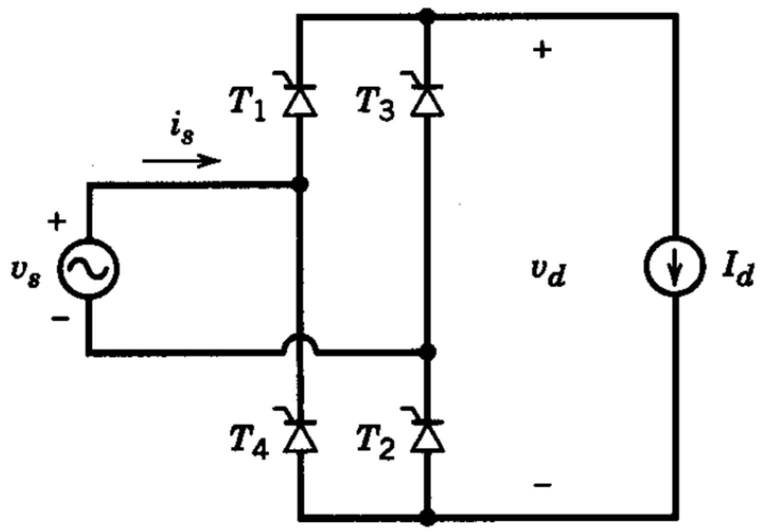

Figure 3. Single Phase Thyristor Rectifier Layout

The output voltage of this rectifier with respect to input line-to-line voltage can be calculated (taking α as the firing angle) by:

$$V_{av} = \frac{2\sqrt{2}}{\pi} V_{ph} \cos cos\ \alpha$$

Advantages

- It contains four thyristors so it is less expensive compared to the three-phase thyristor version.
- Since it has four thyristors, circuit layout and gate signal synchronization are simpler than in the three-phase thyristor case.
- It can operate in inverter mode.
- The output voltage can be fully controlled via the firing angles.

Disadvantages

- It costs higher than the three-phase diode rectifier with a buck converter.
- The output voltage ripple is high.
- The average output voltage is lower than the three-phase version.
- In order to drive the thyristor without a problem, driver circuits are needed. This increases the layout complexity and costs extra components.
- It causes the harmonic problems in input current.

3.1.3. Three-Phase Thyristor Rectifier

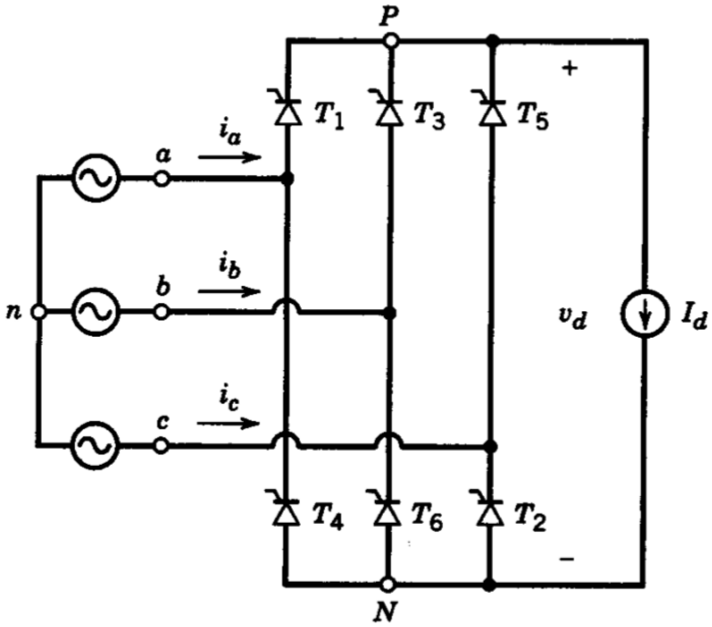

Figure 4. Three-Phase Thyristor Rectifier Layout

The output voltage of this rectifier with respect to input line-to-line voltage can be calculated (taking α as the firing angle) by:

$$V_{av} = \frac{3\sqrt{2}}{\pi} V_{ph} \cos cos\, \alpha$$

Advantages

- This topology results in a lower output ripple voltage compared to the single-phase case.
- The output voltage is fully controlled.
- The average output voltage is higher.
- It is possible to use this topology in the inverter mode.

Disadvantages

- Since six thyristors are used, it is expensive.
- As the thyristor number increases, gate signal complication increases as well.
- Synchronization and simplification is harder.
- The gate signals of thyristors should be given through drivers. This increases the complexity and cost.

3.2. Topology selection

After analyzing all the advantages and disadvantages of the possible topologies, it is decided to use a three-phase diode rectifier with a buck converter. While deciding, its low cost and simple driving are considered. Moreover, its output voltage range is suitable for the project specifications.

4. Rectifier and Converter Calculations

It is decided to use a three-phase diode rectifier to convert AC voltage to DC. The average output voltage of the three-phase diode rectifier can be found as:

$$V_{av} = \frac{3\sqrt{2}}{\pi} V_{ll}$$

Then the average output voltage of the rectifier is equal to the input voltage of the buck converter, $V_{av} = V_{in}$. And the output voltage of the buck converter is:

$$V_{out} = V_{in} * D$$

Where D is the duty cycle. To satisfy the project conditions, V_{out} is equal to 180V. And to work safely and efficiently, the maximum value of the duty cycle is 80%. Because are ignored nonidealities such as the commutation effect.

$$180V = V_{in} * 0.80$$

$$V_{in} = 225\,V$$

$$V_{av} / \frac{3\sqrt{2}}{\pi} = V_{ll} = 225V / \frac{3\sqrt{2}}{\pi} = 166.608\,V$$

To give 225V to buck converter, 166.608 V_{ll} should be supplied to the rectifier. Considering the rectifier is powered through the variac, the variac's working percentage should be calculated. Using the explained equations, several calculations are done in order to decide on the values. The results can be observed in Table 1, the analytical choices are done considering that all calculations done under the knowledge of standard RMS voltage in Turkey is 230V, so the variac's maximum output is $230 * \sqrt{3} = 398,37$ V.

Table 1: Tabulated results and comparison of voltages and percentages

Buck Converter Output = Motor Input (V)	Duty Cycle	Rectifier Output = Buck Converter Input (V)	Variac Output(l-l) = Rectifier Input (V)	Variac Percentage
215,196	0,8	268,995	199,186	0,5
180	0,8	225	166,608	0,418
170	0,8	212,5	157,352	0,395
170	0,79	215,196	159,349	0,4
170	0,63	268,995	199,186	0,5
170	0,6	283,33	209,803	0,527
170	0,5	340	251,763	0,632
170	0,35	485,714	359,662	0,903
134,498	0,5	268,995	199,186	0,5
129,118	0,6	215,196	159,349	0,4
105	0,2	525	388,752	0,976
105	0,5	210	155,501	0,390
105	0,49	215,196	159,349	0,4
105	0,39	268,995	199,186	0,5
43,039	0,2	215,196	159,349	0,4

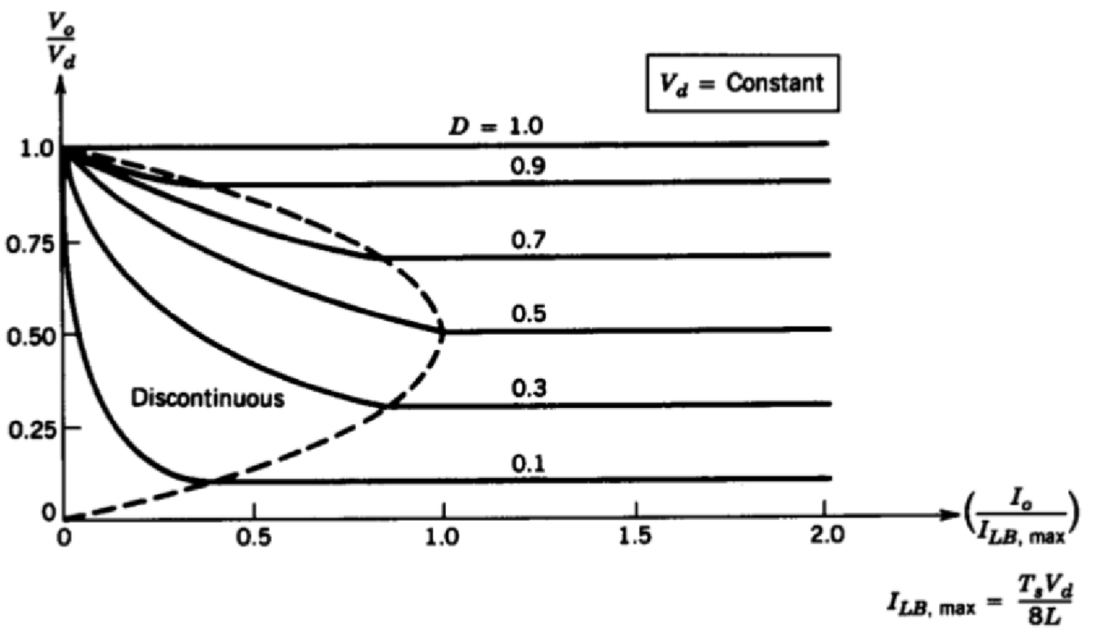

Figure 5. Output voltage and current relations at Continuous and Discontinuous Conduction Modes

Assuming $I_{LB} = \frac{i_{L,peak}}{2} = \frac{t_{ON}(V_d - V_o)}{2L}$ with $t_{ON} = DT_s$

Then $I_{LB} = \frac{DT_s(V_d - V_o)}{2L} = \frac{D^2 V_d}{2Lf_s}$ since $f_s = D * 3280\ Hz$ and $\frac{V_d}{I_{LB}} = Z_{Load} = 0.8\Omega$

L= $\frac{D*0.8}{2*3280} = D * 0.122$ mH, so $L_{min} = 0.122\ mH$

As a result, the additional inductor is not needed since the motor has a 12.5 mH inductor.

5. Power and Loss Calculations

At rated condition

V_T = 220V, I_A=23.4A, BHP=5.5Hp, n=1500rpm

$$P_{out} = 5.5\ HP = 5.5\times745,712\frac{W}{HP} = 4101.416W$$

$$\tau_{out} = \frac{P_{out}}{w_{rated}} = \frac{4101.416W}{1500\times\frac{2\pi}{60}rad/s} = \frac{4101.461W}{157.08rad/s} = 26.13\ N/m$$

$$P_{in} = V_t \times I_a = 220V\times23.4A = 5148W$$

$$P_{c-loss} = I_a^2 \times \left(R_a + R_i\right) + \frac{V_T^2}{R_F} = 816.365W$$

$$E_a = V_T - I_a \times \left(R_a + R_i\right) = 194.962V$$

$$E_a = L_{af} \times I_f \times w_m\ and\ I_f = \frac{V_T}{R_f} = 1.048A$$

$$L_{af} = 1.185H$$

$$P_{loss} = P_{in} - P_{out} - P_{c-loss} = 230.219W$$

$\tau_{loss} = \frac{P_{loss}}{w_{rated}} = 1.466\ N/m$; which are losses due to rotation

At no load condition

At no load condition, all input power is equal to the loss of friction of motor.

V_T is chosen 170V.

$$E_a = V_T = 170V$$

$$w_m = \frac{E_a}{I_f\times L_{af}} = \frac{170V}{1.048A\times1.185H} = 136.889\ rad/s$$

$$P_{loss} = \tau_{loss} \times w_m = \frac{1.466N}{m} \times \frac{136.889rad}{s} = 200.68N/m$$

At kettle load condition

There is 200.68W loss due to friction. This loss is seen both in the motor and generator. So, the total rotation loss will be 401.36W. As a result, the electromechanical power output will be 2401.36W to boil water in a kettle. In addition, V_T is chosen as 170V.

$$P_{mech} = E_a \times I_a$$

$$E_a = V_T - I_a \times (R_a + R_i)$$

$$P_{mech} = 2401.36W = (V_T - I_a \times (R_a + R_i)) \times I_a$$

$$I_a = 15.671A \text{ and } E_a = 153.232V$$

$$w_m = \frac{E_a}{I_f \times L_{af}} = \frac{153.232V}{1.048A \times 1.185H} = 123.387\ rad/s$$

At start-up

W_m=0 rad/s and E_a=0

V_T is chosen 170V.

$$I_a = \frac{V_T}{(R_a + R_i)} = 158.878A$$

This current rating is too much, and it can damage the motor. As a result, the motor cannot be started with the chosen voltage rating.

6. Calculation and Simulation of Timer

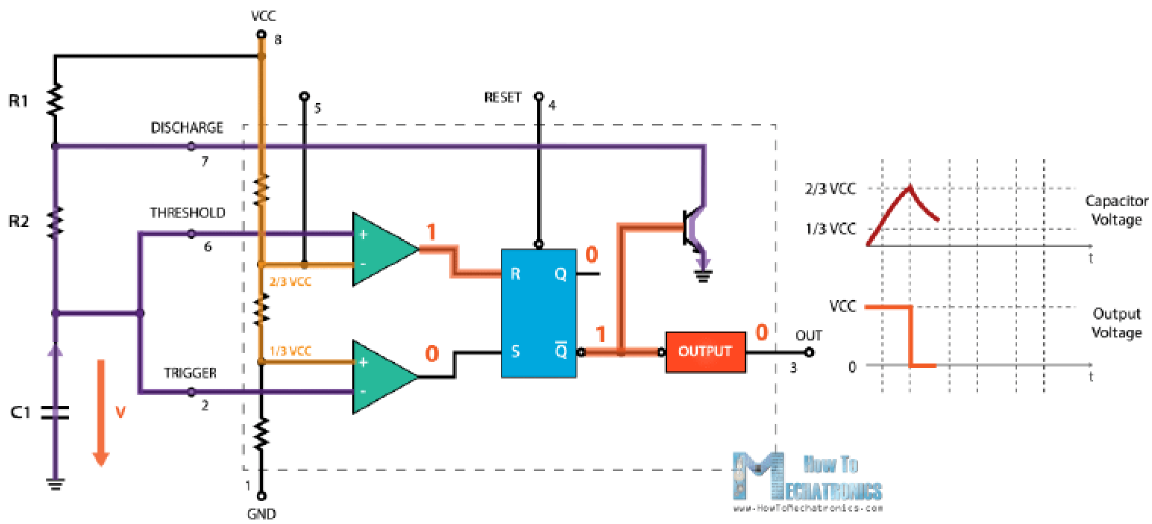

Figure 6. 555 Timer Layout

$$T_{on} = 0.693 * \left(R_1 + R_2\right) * C_1$$

$$T_{off} = 0.693 * R_2 * C_1$$

$$T_{total} = T_{on} + T_{off} = 0.693 * \left(R_1 + 2R_2\right) * C_1$$

$$f = \frac{1}{T_{total}} = \frac{1}{0.693*\left(R_1+2R_2\right)*C_1}$$

$$D = \frac{T_{on}}{T_{total}} = \frac{\left(R_1+R_2\right)}{\left(R_1+2R_2\right)}$$

A duty cycle between 0.2 and 0.8 is needed. Thus, by rearranging the design it was obtained that:

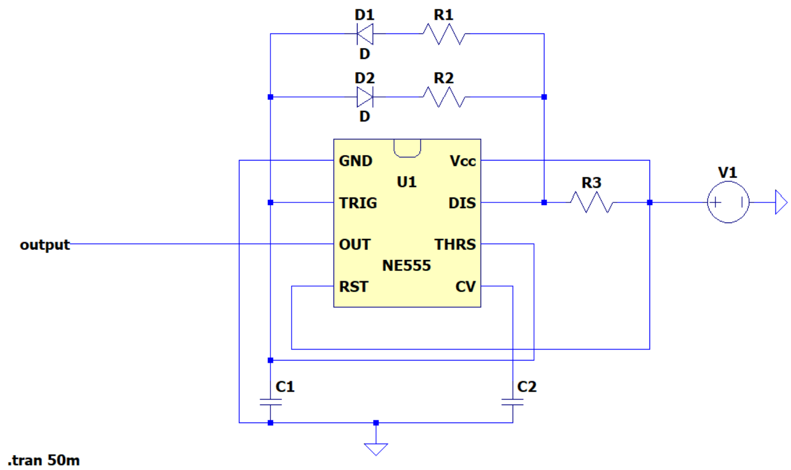

Figure 7. Timer Simulation Layout

Adding two diodes to the system allows us to get a wide range in the duty cycle.

$$T_{on} = 0.693 * \left(R_1 + R_3\right) * C_1$$

$$T_{total} = T_{on} + T_{off} = 0.693 * \left(R_1 + R_2 + R_3\right) * C_1$$

$$f = \frac{1}{T_{total}}$$

$$D = \frac{T_{on}}{T_{total}} = \frac{\left(R_1+R_3\right)}{\left(R_1+R_2+R_3\right)}$$

For D=0.2,

$$\frac{\left(R_1+R_3\right)}{\left(R_1+R_2+R_3\right)} = 0.2$$

$$5 * \left(R_1 + R_3\right) = \left(R_1 + R_2 + R_3\right)$$

$$4 * \left(R_1 + R_3\right) = R_2$$

$$f_{D=0.2} = \frac{1}{0.693*5*\left(R_1+R_3\right)*C_1}$$

For D=0.8,

$$\frac{(R_1+R_3)}{(R_1+R_2+R_3)} = 0.8$$

$$5 * (R_1 + R_3) = 4 * (R_1 + R_2 + R_3)$$

$$\frac{(R_1+R_3)}{4} = R_2$$

$$f_{D=0.8} = \frac{1}{0.693*\frac{5}{4}*(R_1+R_3)*C_1}$$

Hence,

$$4 * f_{D=0.2} = f_{D=0.8}$$

Choosing $R_1 = R_3 = 1k\Omega$, R_2 = 500Ω - 8kΩ variable resistor is needed to get Duty Cycle between 0.2 and 0.8. Since operating at higher frequencies cause higher switching losses, the pulse frequencies should be obtained around 1 kHz which will give us 0.22 µC capacitance value so that

$f_{D=0.2} = 656\ Hz$, and $f_{D=0.8} = 2.62\ kHz$. The simulation results for D = 0.2 and D = 0.8 are shown in Figures 8 and 9.

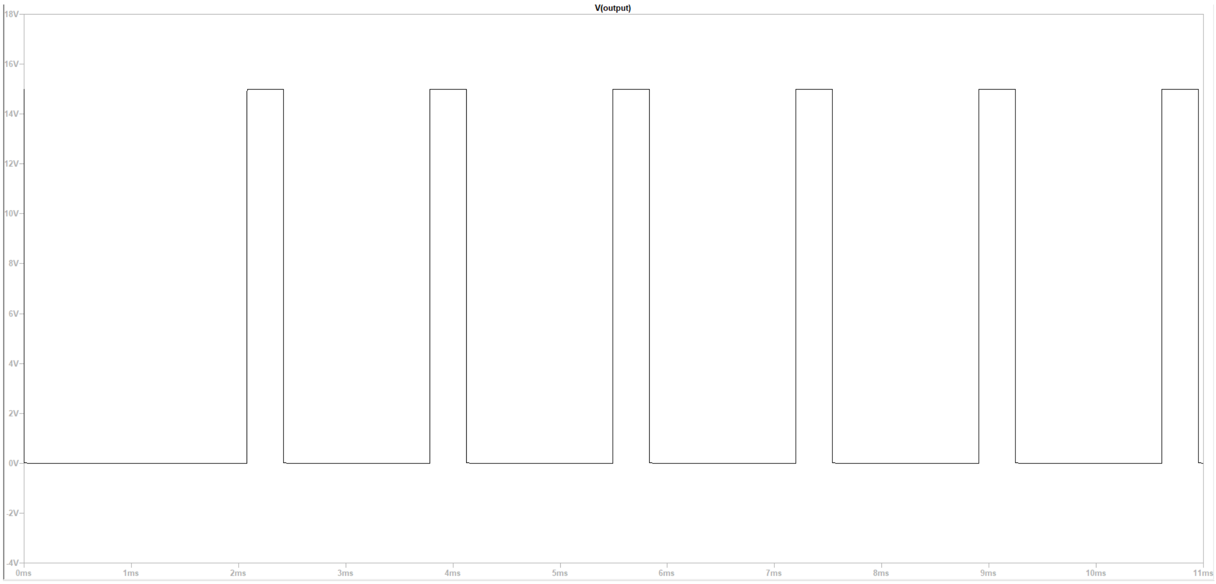

Figure 8. Output of 555Timer for D=0.2

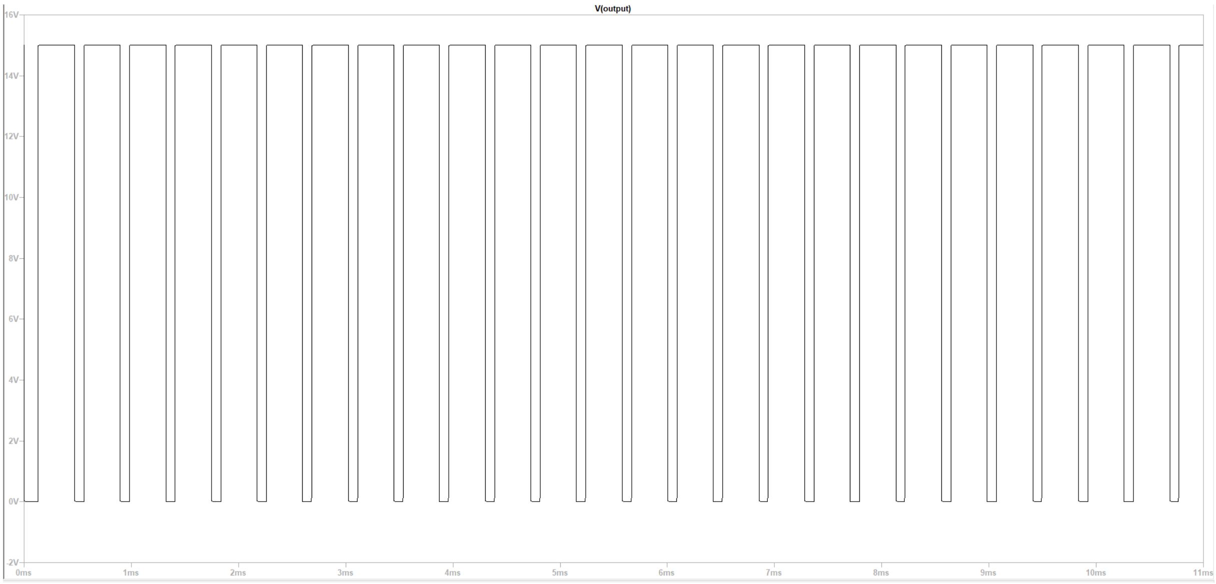

Figure 9. Output of 555Timer for D=0.8

7. Simulation of the Selected Topology

In the simulation, the AC voltage source was selected as 136V line to line. The motor parameters were arranged according to power and loss calculation. The soft starter was used to limit the motor input current. In Figure 10, the layout that is used to simulate the system can be observed.

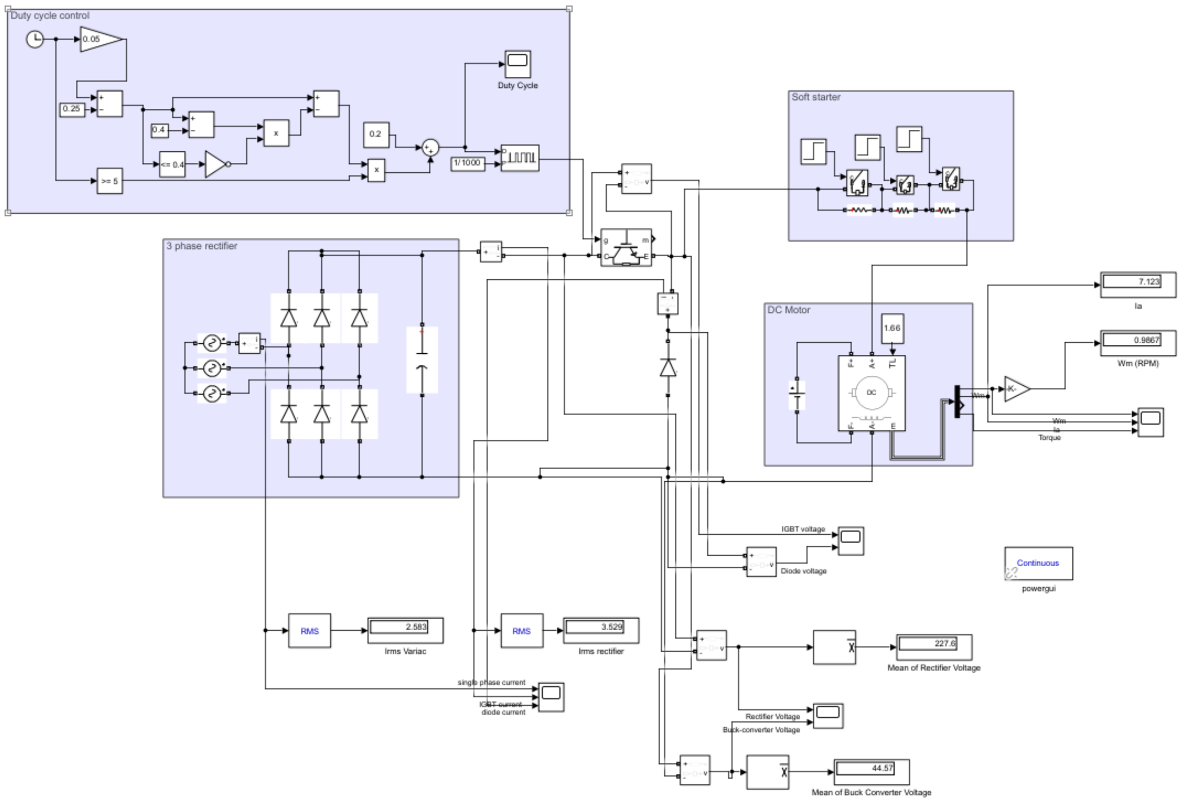

Figure 10. Simulation Layout of the Selected Topology

In Figure 11, it can be seen that the input current rises suddenly when there is no soft starter. This high current can damage the motor and components. As a result, the current must be limited at starting.

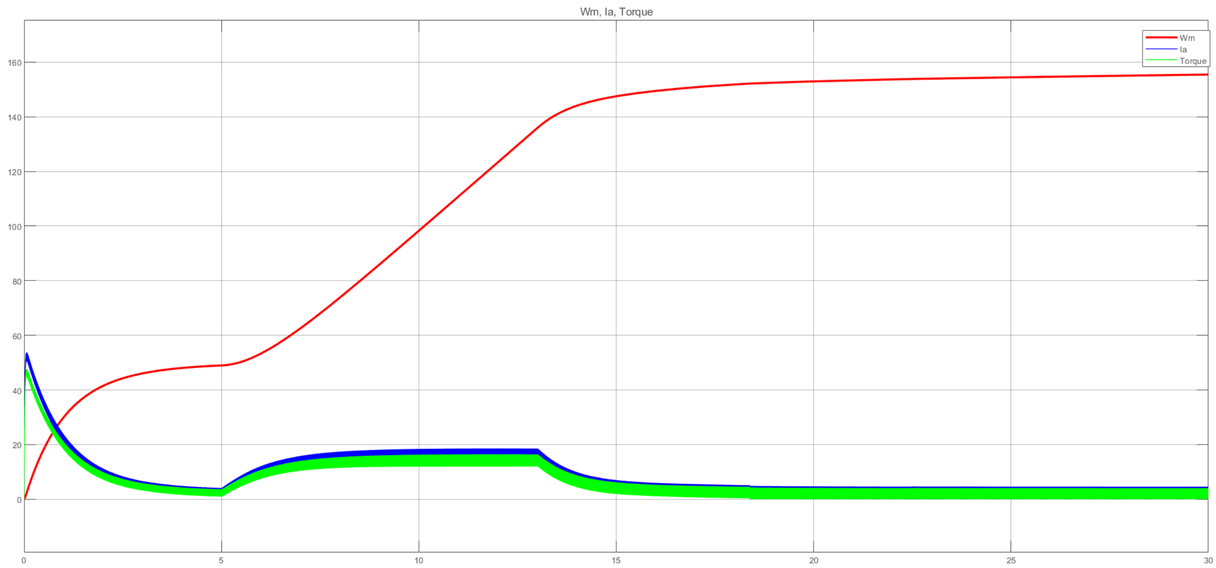

Figure 11. Wm, Ia, and Torque of the motor without soft starter, timespan 0 to 30 seconds

In the soft starter system applied in the simulation, extra resistances are connected to the system, so the current reach lower values. As Ea increases, current decreases. So the resistance is gradually reduced to increase the current. Thus, the motor is enabled to operate before the current rises to dangerous levels. In Figures 12, 14,15 and 16, the effect of the soft starter on the current can be seen.

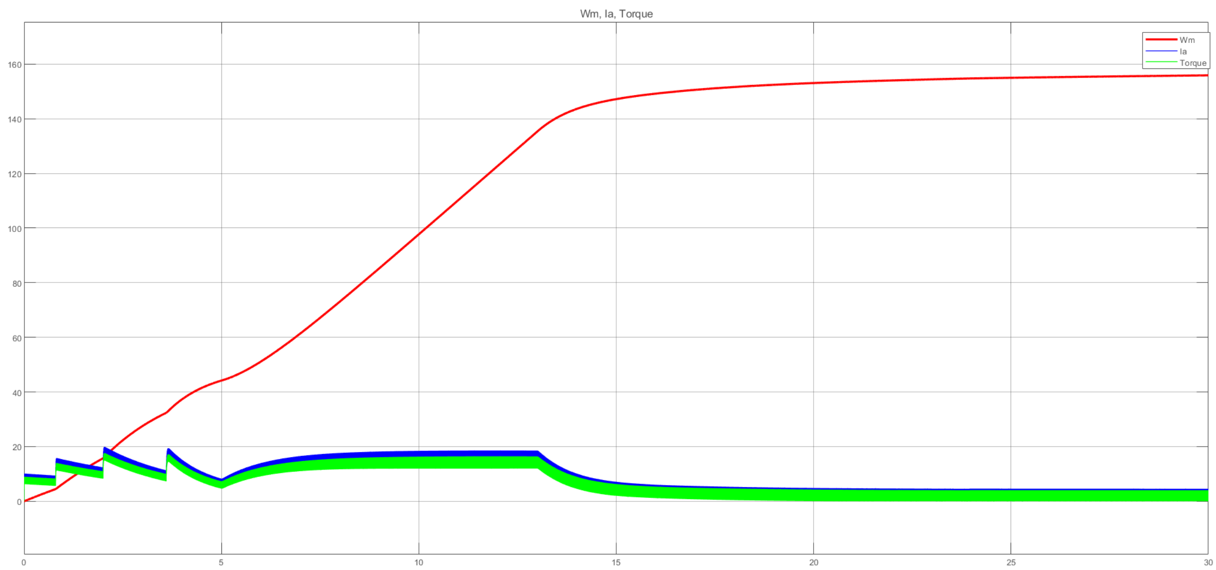

Figure 12. Wm, Ia, and Torque of the motor with soft starter, timespan 0 to 30 seconds

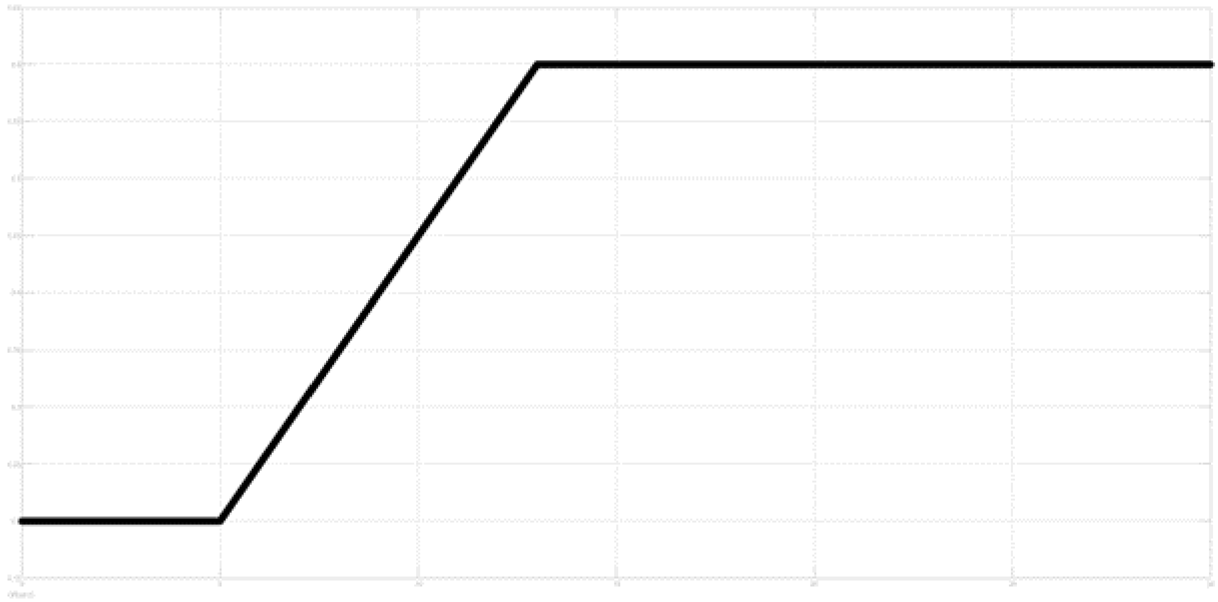

Figure 13. Duty Cycle Change at No Load Case

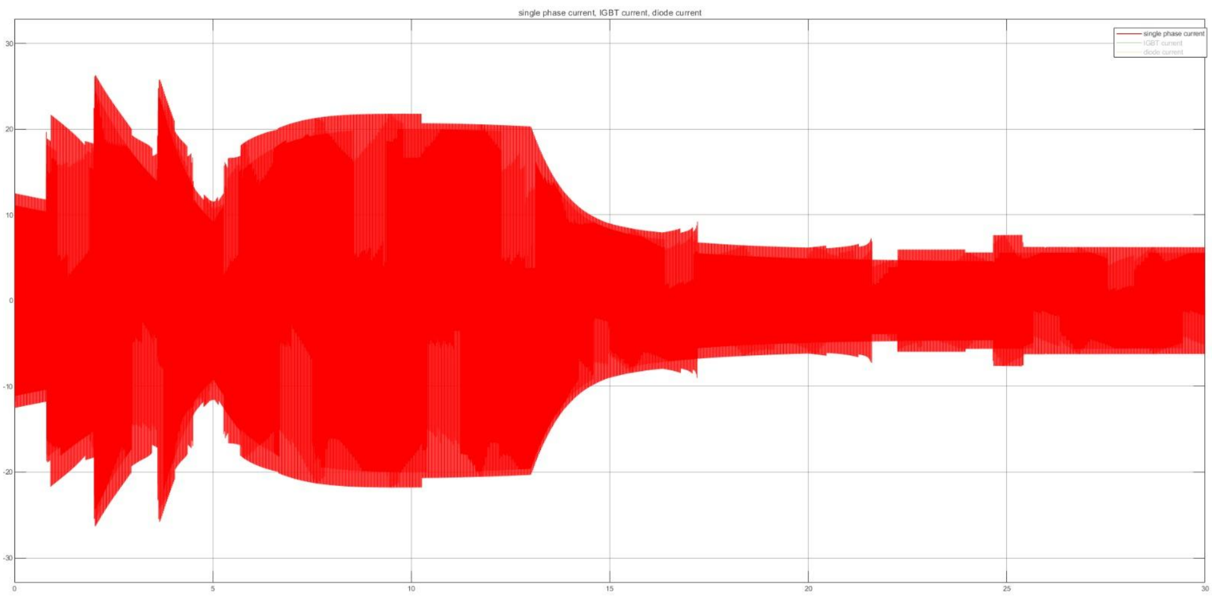

Figure 14. Phase Current at No Load Case

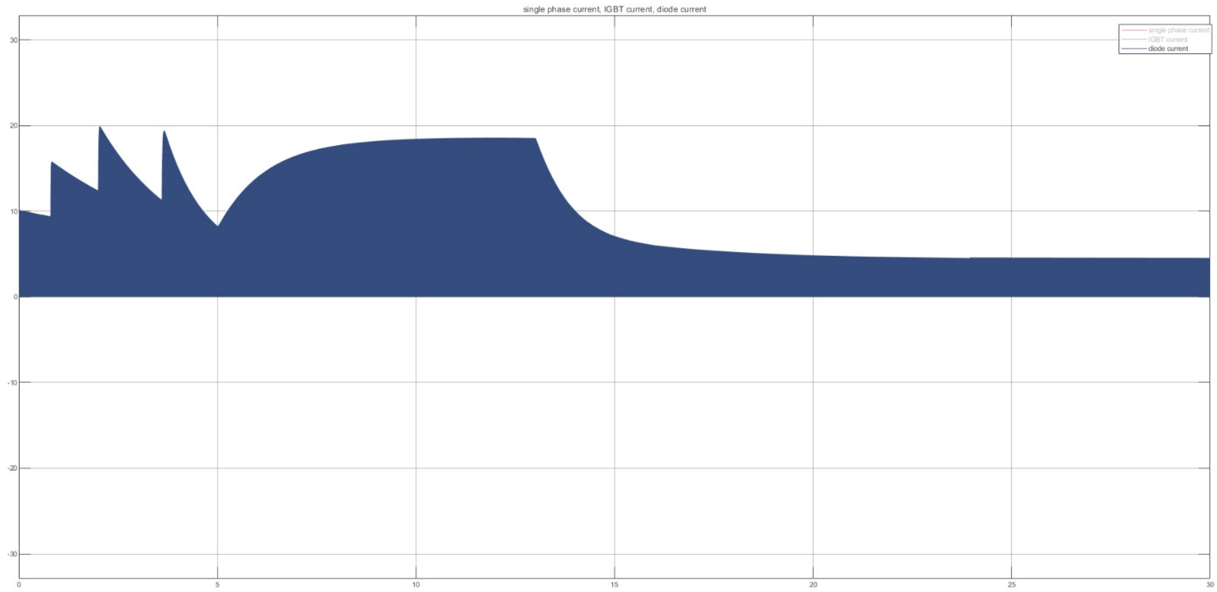

Figure 15. Diode Current at No Load Case

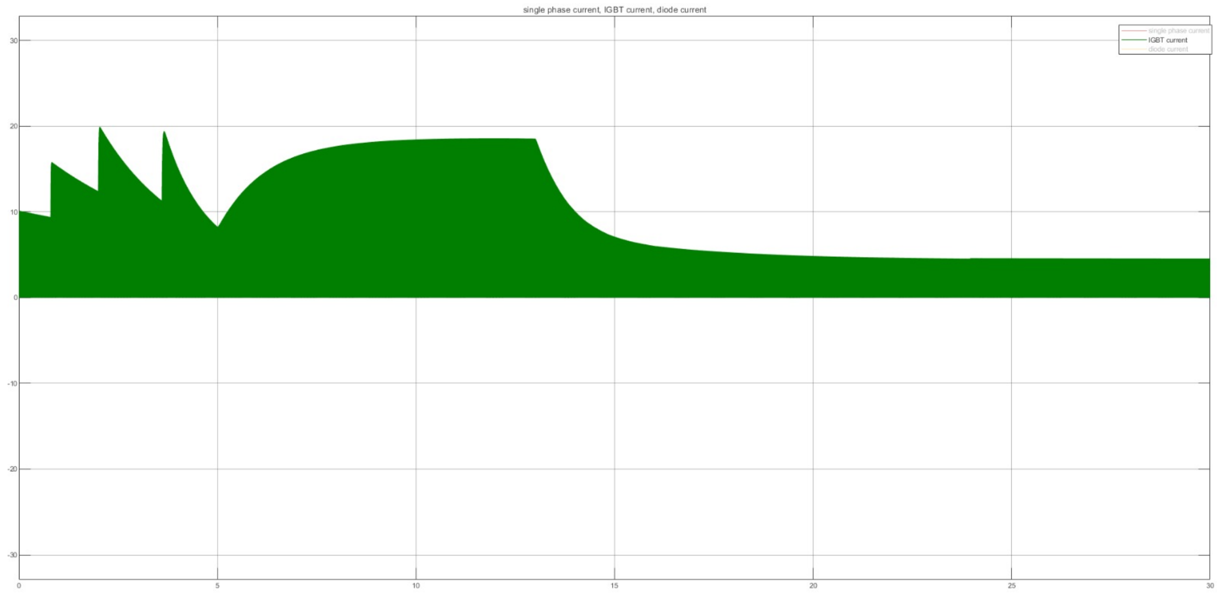

Figure 16. IGBT Current at No Load Case

The average voltage at the DC motor can be adjusted by changing the duty cycle value. In Figure 17, adjusting D to 0.2 makes the mean voltage of the DC machine equal to %20 of the output voltage of the rectifier circuit. On the other hand, in Figure 18, the DC machine input average equals 80% of the output voltage of the rectifier circuit by adjusting D to 0.8.

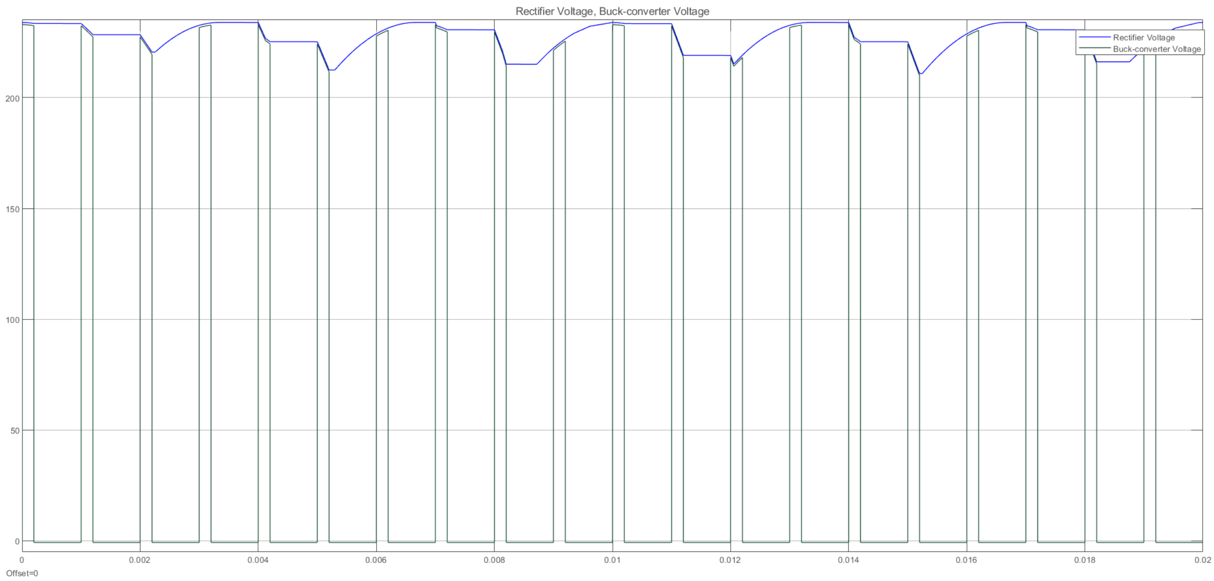

Figure 17. Three-Phase Rectifier and Buck Converter Output Voltage at D=0.2

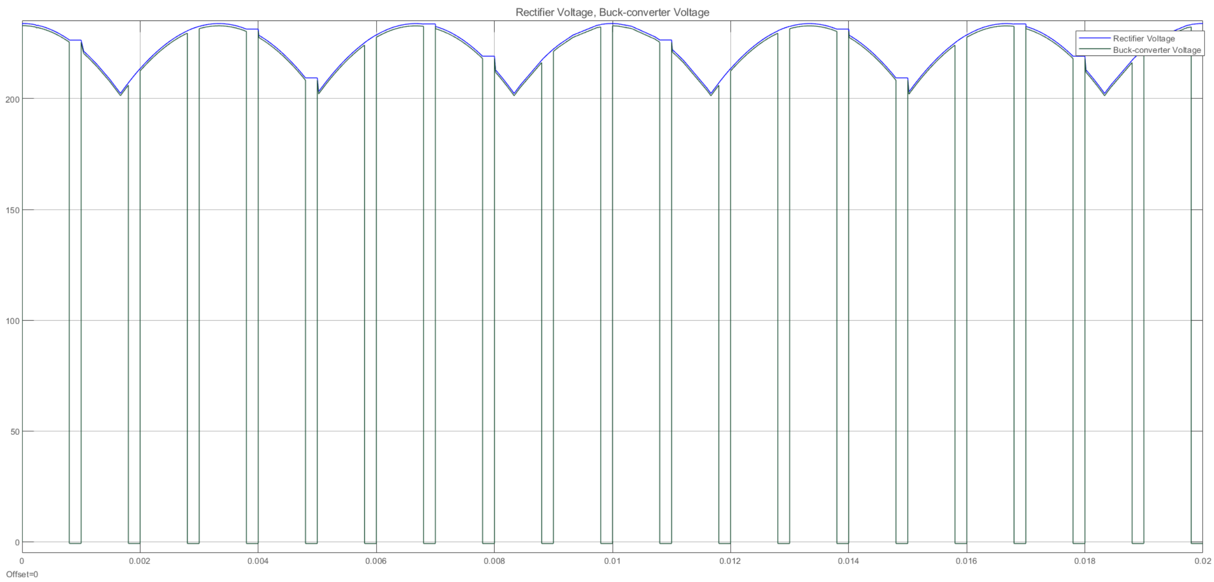

Figure 18. Three-Phase Rectifier and Buck Converter Output Voltage at D=0.8

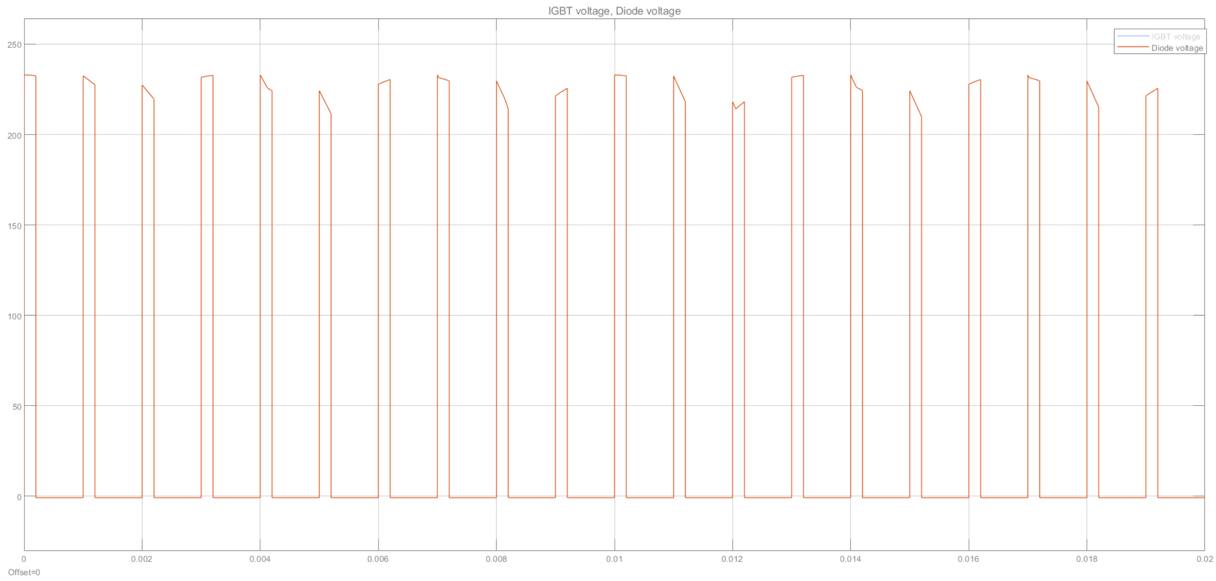

Figure 19. Diode Voltage at D=0.2

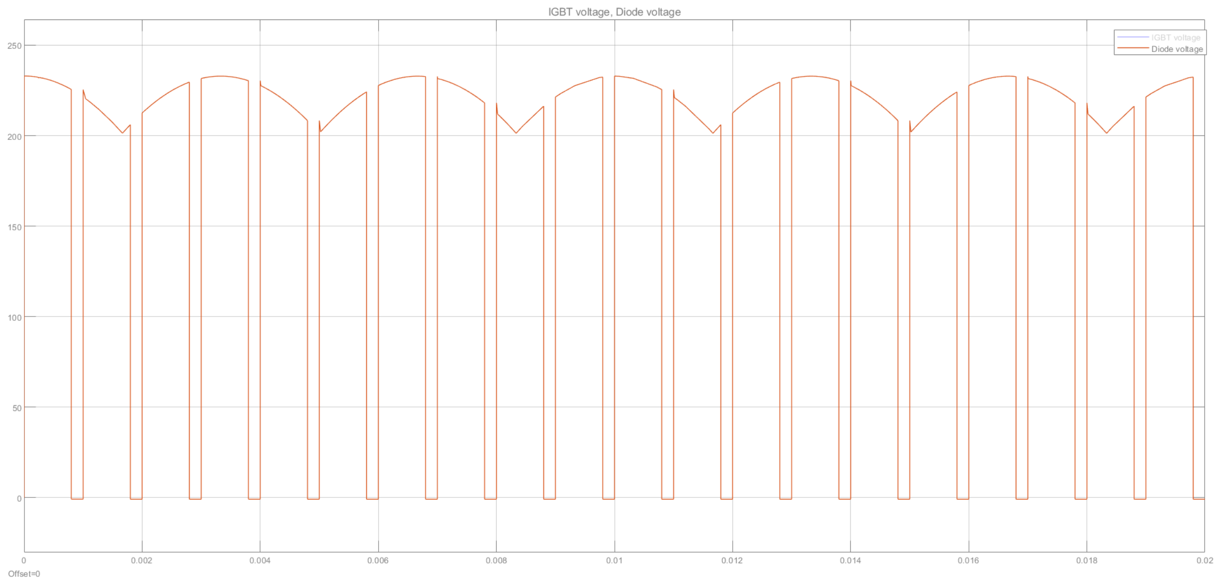

Figure 20. Diode Voltage at D=0.8

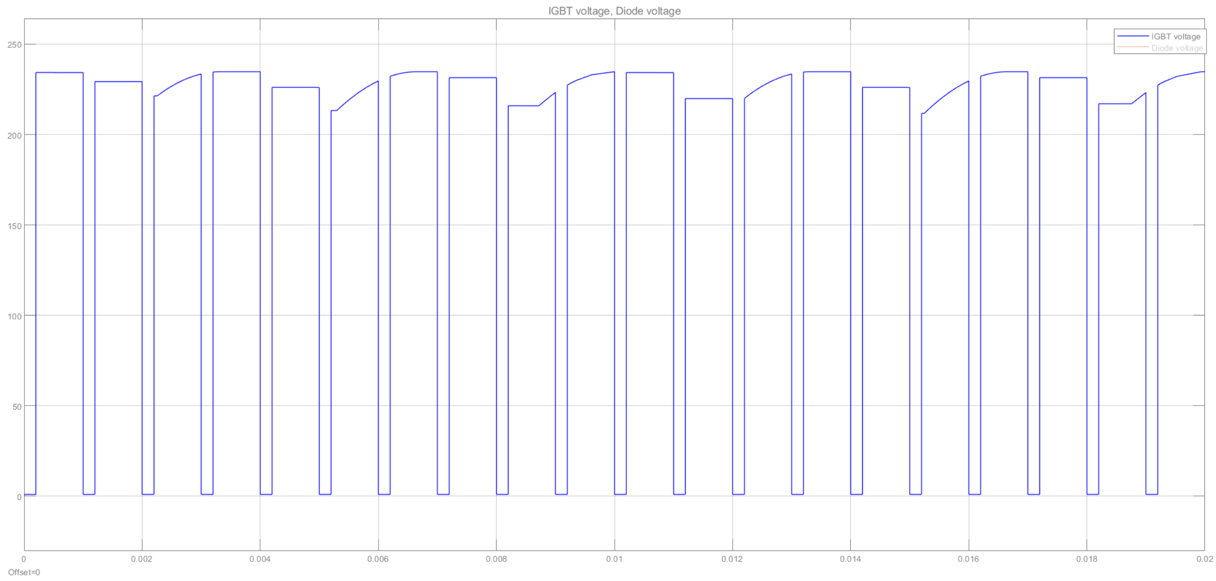

Figure 21. IGBT Voltage at D=0.2

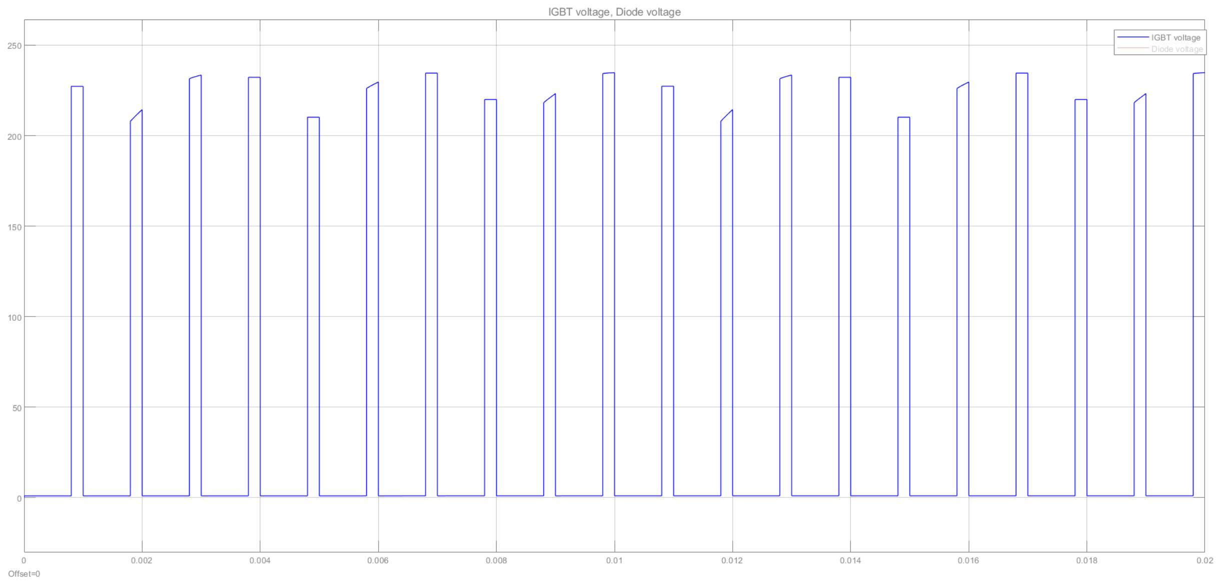

Figure 22. IGBT Voltage at D=0.8

8. Component Selection

Bridge Rectifier

It was decided to use 3 phase full-bridge rectifier module due to its size being smaller than the rectifier built with six diodes. In addition, this is a more economical solution.

From simulations, the variac voltage was decided to be 136V. However, choosing a rectifier that can stand grid voltage is more appropriate. In simulations, the peak current was found to be 25.7 A. As a result, it was decided to choose a rectifier that could stand 30 A and 300V reverse voltage.

Table 2: Features of selected bridge rectifiers

Product name	Bridge Output Current	Max repetitive reverse blocking voltage	Forward Voltage Drop
GUO40-12NO1	40A	1200V	1.28V
GUO40-16NO1	40A	1600V	1.28V
FUO50-16N	50A	1600V	1.50V

IGBT

In the simulation, IGBT that has a 30A collector current and 600V collector-emitter voltage was used. Then it was observed that the peak collector current of IGBT is 26.11A. The team decided that the IGBT must have a minimum 30A collector current capability, and the IGBT in the laboratory has this property.

Table 3: Features of IGBTs

Name	Collector current	Collector-Emitter Voltage	Gate Charges
IXGH24N60C4D1	45A at 25C 39A at 100C	600V	167nC

FGW40N65WE	56A at 25C 40A at 100C	650V	180nC

Diode

In the simulation, it was found that the peak current is 20A when 140V is applied. However, this voltage can increase up to 180V. As a result, the team decided to choose a diode with 25A current rate and 200V reverse blocking voltage.

Table 4: Features of selected diodes

Name	Forward Current	Reverse Blocking Voltage	Reverse recovery time	Forward Voltage Drop
DSEI30-06A	37A	600V	35ns (max 50ns)	1.6V
DHG 30I600PA	30A	600V	40ns (max 60ns)	2.27V
MBR40200PT_T0_10001	40A	200V	-	0.9V

Capacitor

In the simulation, a 100µF capacitor was used, and this gives a 22V ripple. In addition, it operated under 183.67V. However, it was calculated that if 170V is supplied to the motor with a 0.6-duty cycle, the capacitor operates on 283V. So a capacitor with 100uF and 400V was chosen.

9. Conclusion

In this project, a DC motor driver that takes AC voltage as input will be made and this report includes to solution approach. To do that, a full bridge rectifier and buck converter topology was selected by analyzing all topologies. This topology is more economical and the control of the system is more effortless. After the topology selection was made, power and loss calculations of the motor and voltage calculations of the rectifier and converter were made. According to these, the variac output voltage was selected as 136 V and the duty cycle was selected as 0.8. In simulations, voltage and current values on a component were obtained, and the component for implementation was made according to these.

After this step, the design will be implemented into hardware. In the implementation process, there may be changes according to real-life standards.