ORTA DOĞU TEKNİK ÜNİVERSİTESİ

MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE463 – STATIC POWER CONVERSION 1

HARDWARE PROJECT: AC/DC Converter for DC Motor Drive

FINAL REPORT

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INTRODUCTION

The converters and rectifiers are crucial for the motor drive system in the power electronics area. In this project, the AC/DC converter is designed by APPE. This simulation report discusses the possible topologies that can be used, and a selection is made between them. Also, the selection criteria are explained. After the topology selection, the calculation and simulations are presented. The calculations contain both motor side and rectifier, converter side calculations. The simulations include both ideal and non-ideal cases. After analyzing simulations and calculations, the required components are chosen by using the result of these analyses. In the following part, implementations and improvemens to the systems explained. Later part, updated thermal analysis is made for updated real life application of our system. When design fully implemented to the real life R-load and RL-load tests are conducted, moreover, the outputs from these tests are explained. Hereafter, in the demo day DC motor is drived successfully. Finally, our cost analysis and final product are shown with learning outcomes of ours.

Problem Definition and Requirements

In this project, it is required to design a controlled rectifier to drive a DC Motor. As input, the adjustable AC source (variac) is used. This DC motor is connected to a kettle used to boil water. The DC motor is given in Figure 1:

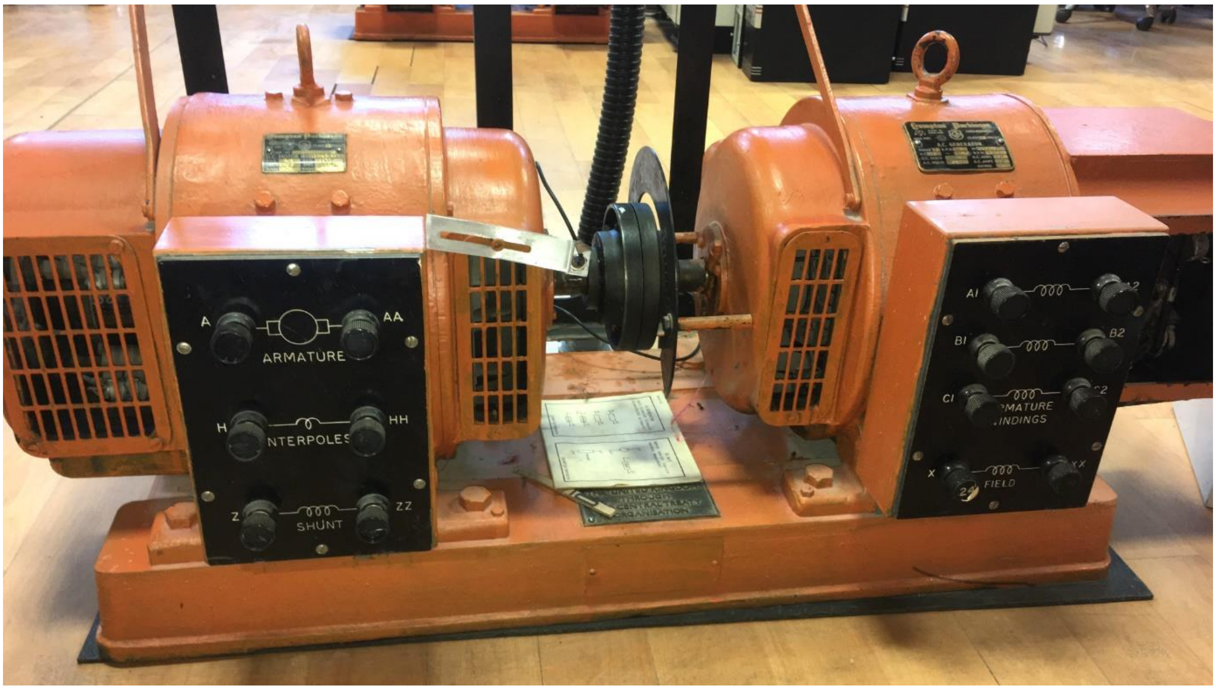

Figure 1: The DC Motor

The specifications of this motor are as follows :

Table 1:Motor Specifications

Parameter	
Armature Winding	0.8 Ω, 12.5 mH
Shunt Winding	210 Ω, 23 H
Interpoles Winding	0.27 Ω, 12 mH
Mechanical Power	5.5 HP
Rated Voltage	220 Volts
Rated Current	23.4 Amps
RPM	1500 RPM

Input and output requirements are as follows :

- Input : 3 phase or 1 phase AC Grid (Adjustable with variac)
- Output : Adjustable DC Output (Vmax <180 Vdc)

In the next section, the following three possible topologies are discussed in terms of disadvantages and advantages :

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

TOPOLOGY SELECTION:

To drive the given motor, many different solutions and topology can be used; however, in this part, one explained 2 thyristors topologies and diode rectifier with buck converter and these topologies advantages and disadvantages

1)Thyristor Topologies

Thyristors are controlled rectifiers that are used for HVDC applications. Power output and voltage output are controlled by changing the firing angle by sending controlled pulses to gate terminals. Moreover, thyristor has the advantage of working two quadrants as rectifiers which power flows from the grid to load and as an inverter (needs active source at load), which power flows from load to grid. The first thyristor topology is Single-phase fully controlled rectifier.

a) Single Phase Fully Controlled Rectifier

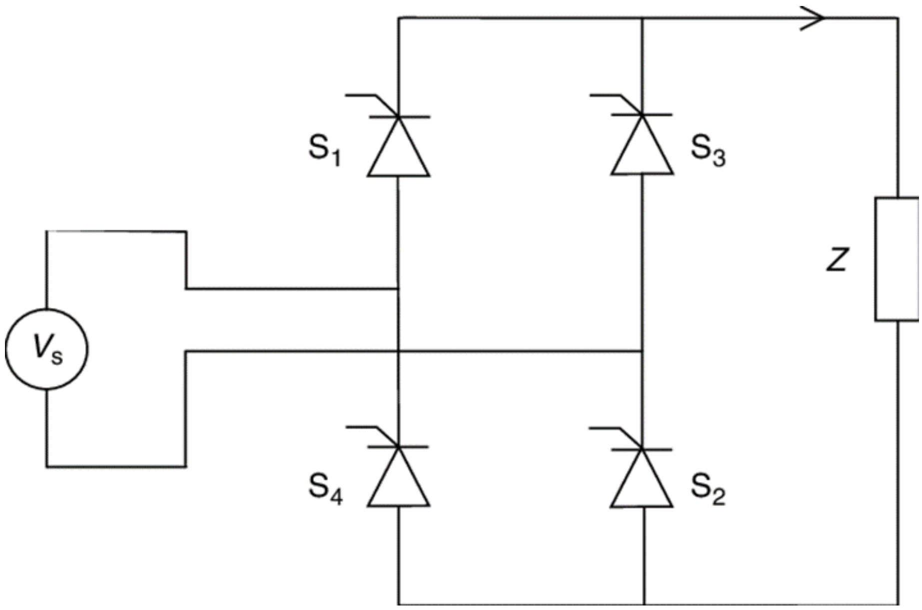

Figure 2: The Single Phase Controlled Rectifier Schematic

The single-phase fully controlled rectifier topology can be observed in Figure 2; 4 thyristors are working with 2 phases which need 180-degree phase difference between firing angles at the first S1, and S4 opened at second phase S3 and S2 open and conduct. The output phase voltage formula is:

$$Vavg = \frac{2\sqrt{2}\,Vph}{\pi} cos\alpha$$

Due to a single-phase, a high voltage ripple at the output can be reduced by adding a high capacitor with high capacitance.

Advantages:

- Two quadrants work both as inverter and rectifier.

- With another single phase-controlled rectifier connected in the reverse direction, the rectifier can work at all four quadrants.

- It is cost-friendly comparing the three-phase due to the lower number of the thyristor (4) used.

Disadvantages:

- High voltage ripple at the output.

- Hard to arrange firing angles simultaneously and needs for additional circuits and sources to open thyristors

-Lower average output voltage compared to three-phase one.

-Large harmonics in the input current

-Low power factor and DPF (Displacement Power Factor) for smaller output voltage.

b) Three Phase Fully Controlled Rectifier

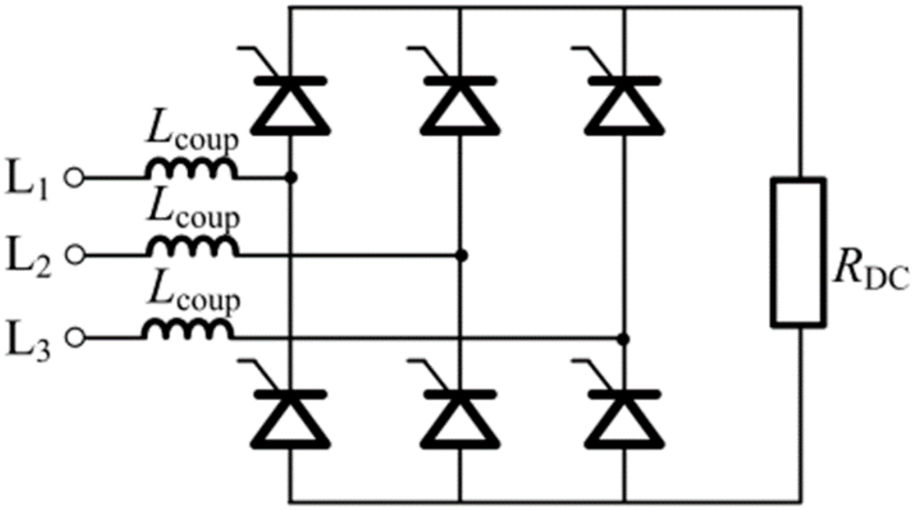

Figure 3:The Three Phase Thyristor Rectifier Schematic

In a three-phase, fully controlled rectifier, there are 6 thyristors with 3 phases; there are 120 degrees between each phase. There is output voltage ripple, but it is less than the output voltage ripple of single-phase topology.

$$Vavg = \frac{3\sqrt{2}}{\pi} * Vll * cos\alpha$$

Advantages

- Two quadrant operation, with additions it can be increased to work at 4 quadrant operation

- Lower voltage ripple compared to single-phase rectifier.

- Higher average output voltage.

- Controlled output voltage and power flow

Disadvantages

- More complicated compared to a single phase due to 6 thyristors.

- Desynchronization problem since 6 thyristors gate signal must be synchronal.

- More expensive due to the increasing number of thyristors.

2) Three Phase Diode rectifier with Buck Converter Topology

There are two-part in this topology first one is a three-phase diode rectifier, and the second part is a buck converter with control of duty cycle; the schematic can be seen in the figures below.

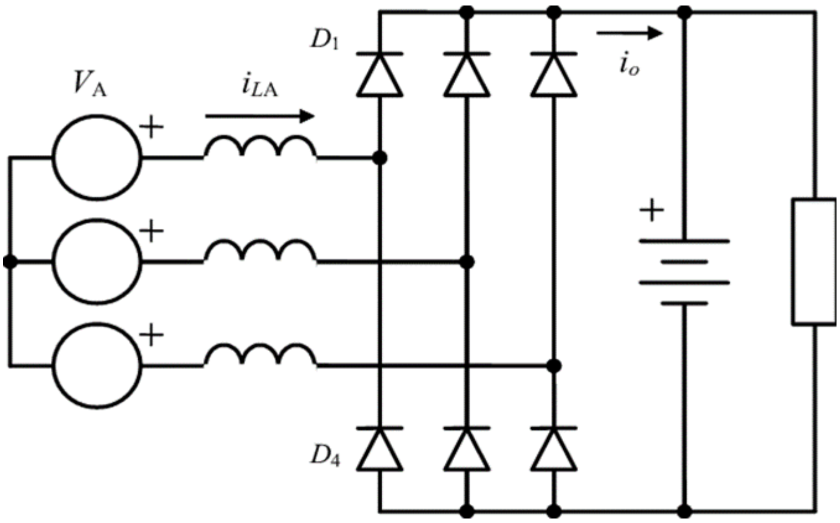

Figure 4:The Three Phase Diode Rectifier Schemeatic

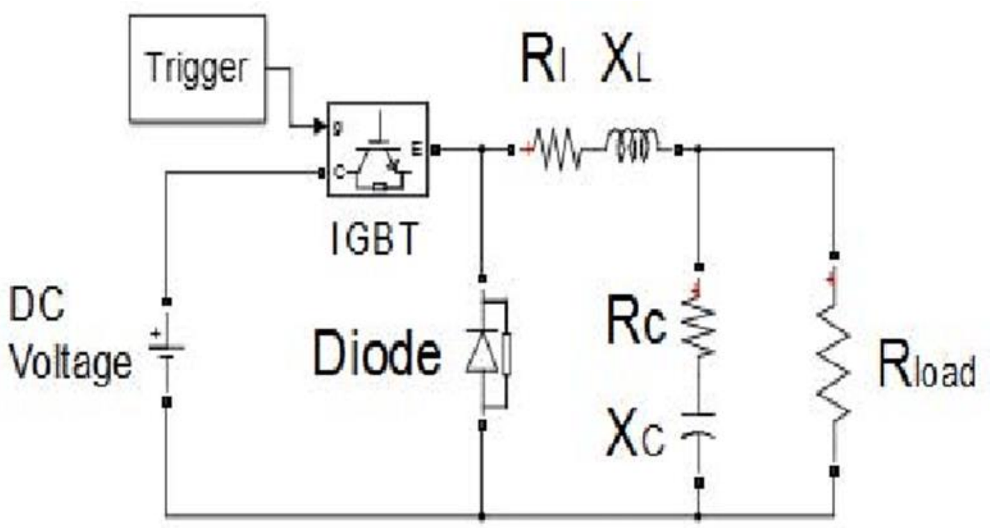

Figure 5:The Buck Converter Schematic

Three-phase diode rectifiers contain 6 diodes. Therefore, the output voltage cannot be controlled like thyristor rectifiers. Moreover, diodes cannot work at two-quadrant; however, due to the diodes working principle, no gate signal or synchronization is needed, reducing design complexity. The average output voltage of a three-phase diode rectifier is :

$$Vavg = \frac{3\sqrt{2}}{\pi} V_{ll} = \frac{3\sqrt{6}}{\pi} V_{ph}$$

The buck converter is used to control output voltage with controlled gate signal created by PWM to adjust the duty cycle of the IGBT switch to control output. The output voltage formula of the buck converter is:

$$Vavg = \frac{3\sqrt{2}}{\pi} V_{ll} \times D = \frac{3\sqrt{6}}{\pi} V_{ph} \times D$$

D is the duty cycle.

Advantages:

- Low output voltage ripple.

- Motor has high inductance; therefore, no need for inductance or capacitance at the output of the buck converter.

- Easy to construct; it just needs a one-timer as an extra since diodes do not require gate signals or synchronization signals.

Disadvantages:

- Four quadrant operations cannot be obtained due to the diodes working principle.

- Switching losses increase with increasing switching frequency.

After the discussion, we decided to implement a third topology: a 3-phase diode rectifier and buck converter. One reason for that is that synchronization of the gate signals of thyristors is so problematic in practical design. The following parts show required calculations and simulations or this topology.

ANALYTICAL CALCULATIONS

Motor Calculations

In this project, the parameters are given in the nameplate of the DC motor. The nameplate can be found in Figure 6. Also, specifications of the motor windings can be found in Table 1.

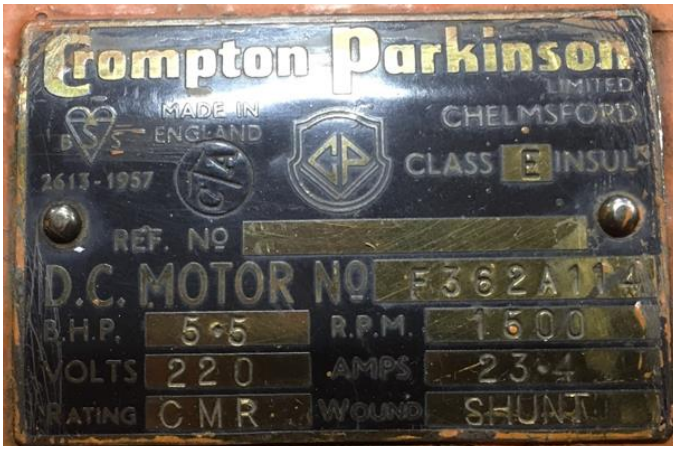

Figure 6:The Nameplate of the DC motor

It is stated in the project definition that any type of connection can be done. We have chosen to connect the motor with a shunt connection. A model of this representation can be found in Figure 7.

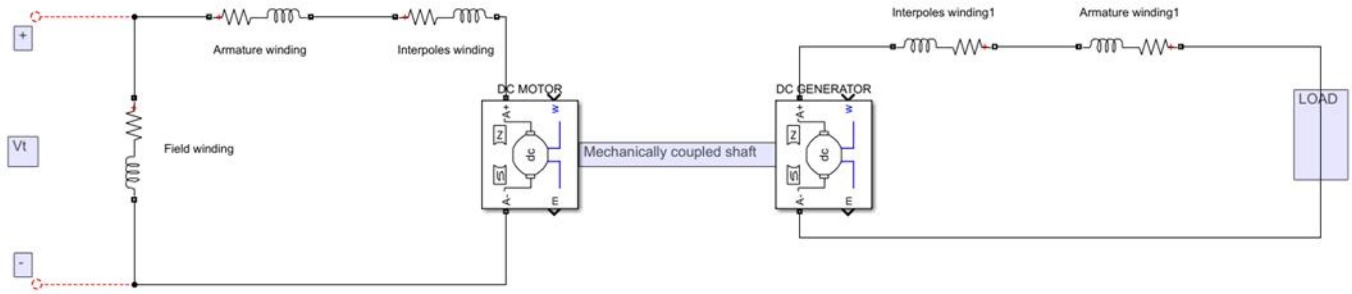

Figure 7: Shunt connection of DC motor mechanically coupled to DC generator

Required values to calculate motor parameters at full load can be found using the nameplate in Figure 6.

$$P_{rated} = 5.5\ (HP) * 746\ \left(\frac{W}{HP}\right) = 4103\ (W)$$

$$w_{rated} = \frac{1500*2*\pi}{60} = 157\ (\frac{rad}{s})$$

$$I_{f,rated} = \frac{V_{rated}}{R_f} = \frac{220}{210} = 1.0476\ (A)$$

The rated electrical input to the system is $P_e = V_{rated} * I_{a,rated} = 220\ (V) * 23.4\ (A) = 5148\ (W)$. So, the total loss of the system can be calculated as $P_{loss} = P_e - P_{rated} = 5148\ (W) - 4103\ (W) = 1045\ (W)$. There are losses in the system introduced by the armature resistance, field resistance, and interpole resistance.

$$P_{armature,loss} = I_{a,rated}{}^2 * R_a = 23.4^2\ (A^2) * 0.8\ (\Omega) = 438\ (W)$$

$$P_{interpole,loss} = I_{a,rated}{}^2 * R_i = 23.4^2\ (A^2) * 0.27\ (\Omega) = 148\ (W)$$

$$P_{field,loss} = I_{f,rated}{}^2 * R_f = 1.0476^2\ (A^2) * 210\ (\Omega) = 230\ (W)$$

So, after subtracting these losses from the total loss, we can obtain resistance losses in the motor.

$$P_{resistance,loss} = P_{loss} - P_{armature,loss} - P_{interpole,loss} - P_{field,loss} = 1045 - 438 - 148 - 230 = 230\ (W)$$

Now, Coulomb friction loss ($T_f, which\ is\ a\ parameter\ in\ Simulink\ DC\ machine$) must be found to obtain the friction losses at a different speed. To obtain that value $P_{resistance,loss} = T_f * w_{rated}$ formulization will be used.

$$T_f = \frac{230\ (W)}{157\ (\frac{rad}{s})} = 1.465\ (N.m)$$

It is stated in the project that the output voltage of the DC motor drive (V_t) should be less than 180 V. After analytical calculations; we have decided to have 170 V at the output voltage. Beyond that point, $V_t = 170\ V$ will be used in the calculations.

- Assuming motor at start-up,

$V_t = 170\ (V)$

$I_f = \frac{V_t}{R_f} = \frac{170}{210} = 0.8095\ (A)$ (Since the motor is shunt connected)

$I_a = \frac{V_t}{R_a+R_i} = \frac{170}{0.8+0.27} = 158.8785\ (A)$

As seen from the above calculations, the start-up current is high, and this start-up current can damage the motor since the full load current of the DC motor is 23.4 A. To decrease the start-up current low $V_t$should be applied by changing the duty cycle of the operation. By doing so, we have managed soft-start operations.

- Assuming motor is working at no load condition,

At no load, mechanical power come from the friction losses (T_e = T_f). So, using the obtained Coulomb friction loss, total mechanical power required for no-load operation can be found. By using $E_a = L_{af} * w_m$ equation, speed of the no-load condition can be calculated. After that, by multiplying T_f with speed will result in total friction loss. In our calculations, we have assumed $L_{af} = 1.8\ (H)$ also we have neglected the losses in the armature and interpole windings ($E_a = V_t = 170\ (V)$).

$$w_m = \frac{170}{1.8} = 94.5\ \left(\frac{rad}{s}\right)$$

So, friction losses can be calculated as,

$$P_{friciton,loss} = 1.465\ (N.m) * 94.5\ \left(\frac{rad}{s}\right) = 140\ (W)$$

Since the motor and generator are the same and coupled, we can conclude that total friction losses in the no-load case are approximately 280 (W).

- Assuming motor is working at kettle load,

To obtain the Tea Bonus, our driver should supply a minimum of 2kW for at least 5 minutes. We are required to find the power that is transmitted to the motor. The motor will be working at 2000 (W); also, additional friction losses are calculated for the no-load condition, which is 280 (W). So, without armature, field, and interpole losses, 2280 (W) power is required. To find the exact value, armature current must be found.

$E_a = \frac{2280}{I_a}$, $\quad E_a = V_t - I_a * (R_a + R_i) = 170 - I_a * 1.07$

By equating these two equations, armature current can be found.

$\frac{2280}{I_a} = 170 - I_a * 1.07 \rightarrow \quad 2280 = 170 * I_a - 1.07 * {I_a}^2$

$I_a = 14.8\ (A)$

$$P_{armature,loss} = {I_a}^2 * R_a = 14.8^2\ (A^2) * 0.8\ (\Omega) = 175\ (W)$$

$$P_{interpole,loss} = {I_{a,rated}}^2 * R_i = 14.8^2\ (A^2) * 0.27\ (\Omega) = 59\ (W)$$

$$P_{field,loss} = {I_{f,rated}}^2 * R_f = 1.0476^2\ (A^2) * 210\ (\Omega) = 230\ (W)$$

So, the total power required can be calculated as follows.

$$P_{in} = 2280\ (W) + 175\ (W) + 59\ (W) + 230\ (W) = 2744\ (W)$$

Based on our simulation results, where all components are ideal, we can generate almost 3.5 (kW) power at the input side of the motor.

SIMULATIONS OF SELECTED TOPOLOGY

As explained in the previous section, the three-phase diode rectifier and buck converter topology is selected due to their advantages. Then, the simulations of this topology are presented in this section. First, the three-phase diode rectifier is simulated; after that, the voltage-current waveforms of the buck converter are analyzed. Last, the entire topology is simulated for the ideal case, and the stress values are determined for rectifier diodes, MOSFET or IGBT, and free-wheeling diode.

1. The Three-Phase Diode Rectifier

The circuit schematic of the three-phase diode rectifier is given in Figure 8.

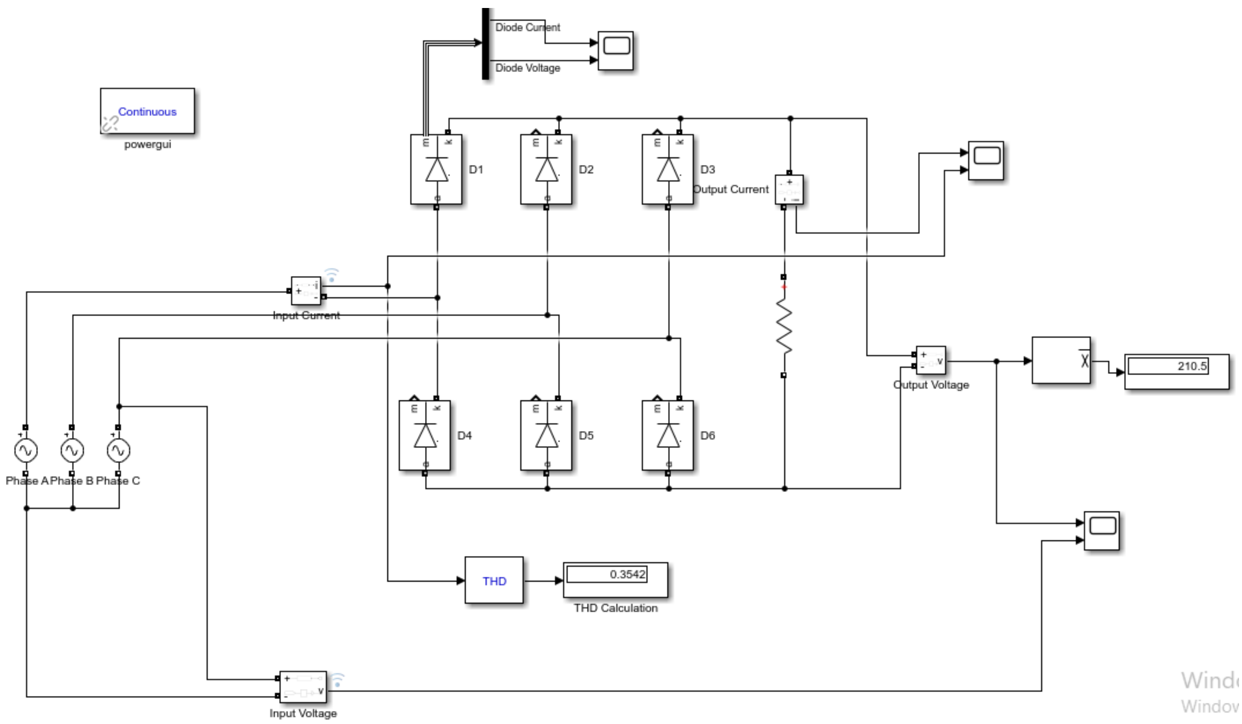

Figure 8: Circuit Schematic of Three-Phase Diode Rectifier

As a requirement of the project, the output voltage of all systems must be less than 180 V_{dc}. Then, we decided to limit the output voltage as 170 V_{dc}. Also, the duty cycle of the buck converter must be between $0 < D < 1$, so we decided to limit the duty cycle to 0.8, the higher the duty cycle values may not be possible in a non-ideal world. According to the following calculations, the required input voltage is found :

$$V_{out} = \frac{3\sqrt{6}}{\pi} \times D \times V_{ph}$$

$$170\ V = \frac{3\sqrt{6}}{\pi} \times 0.8 \times V_{ph}$$

$$V_{ph} = 90.8473\ Volts$$

According to calculations, the input voltage can be between 90 – 100 Volts for at most 180 V_{dc}. The precise value of input voltage will be determined when the tests are done. Now, we applied 90 Volts to the input for simulations.

The output and input voltage waveform of the three-phase diode rectifier for 90 Volts phase voltage is given in Figure 9.

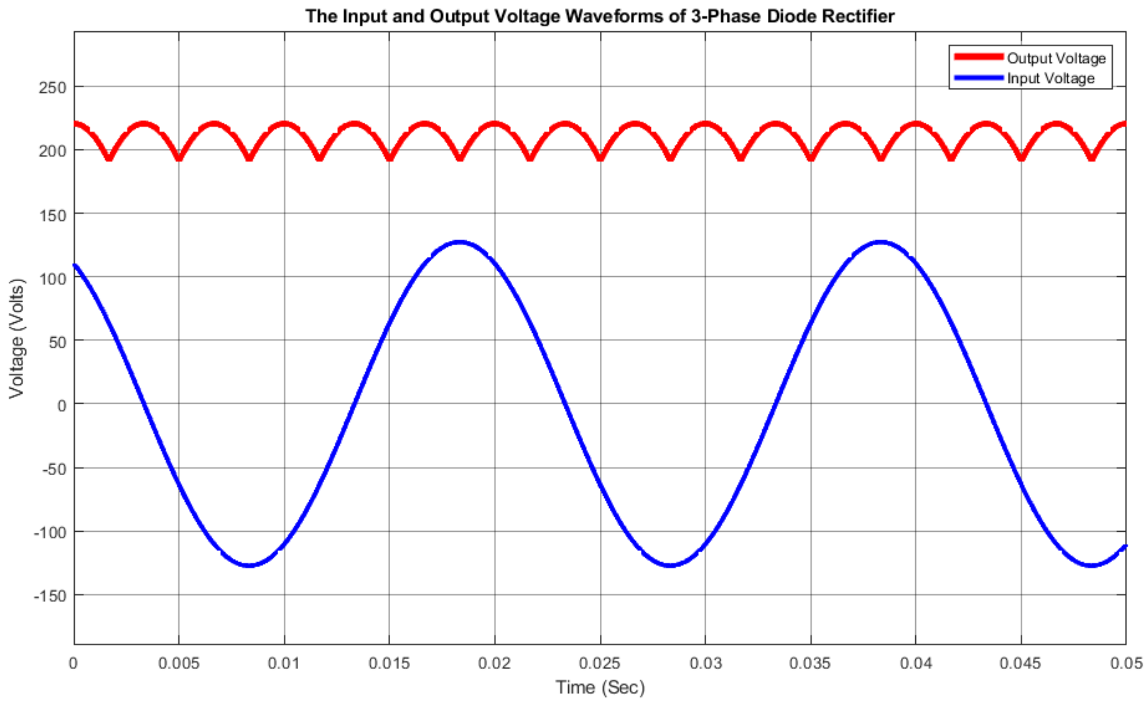

Figure 9: The Input and Output Voltage Waveforms of 3-Phase Diode Rectifier

The output and input current waveform of the three-phase diode rectifier for 90 Volts phase voltage is given in Figure 10.

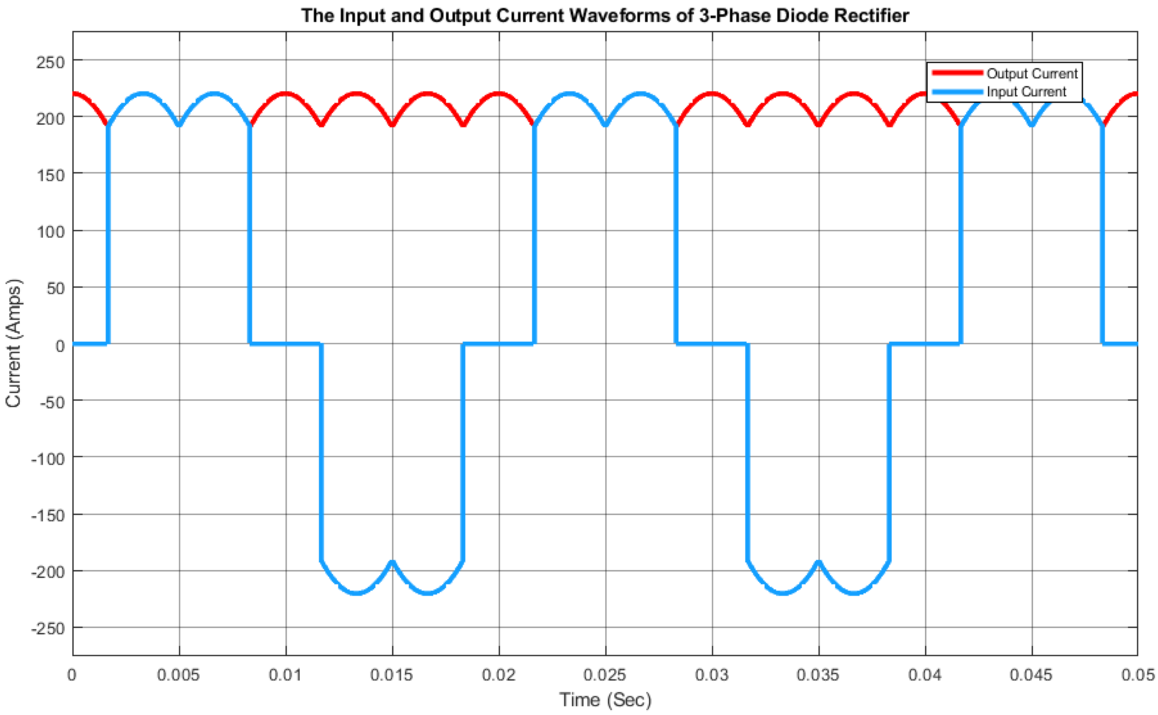

Figure 10: The Input and Output Current Waveforms of 3-Phase Diode Rectifier

The waveforms in Figures 2 and 3 are as expected for the ideal case with no line inductance and diodes. Also, the rectifier load is a resistor without capacitance, so the ripple voltage is higher than the capacitance case.

The diode current and voltage of the rectifier are given in Figure 11.

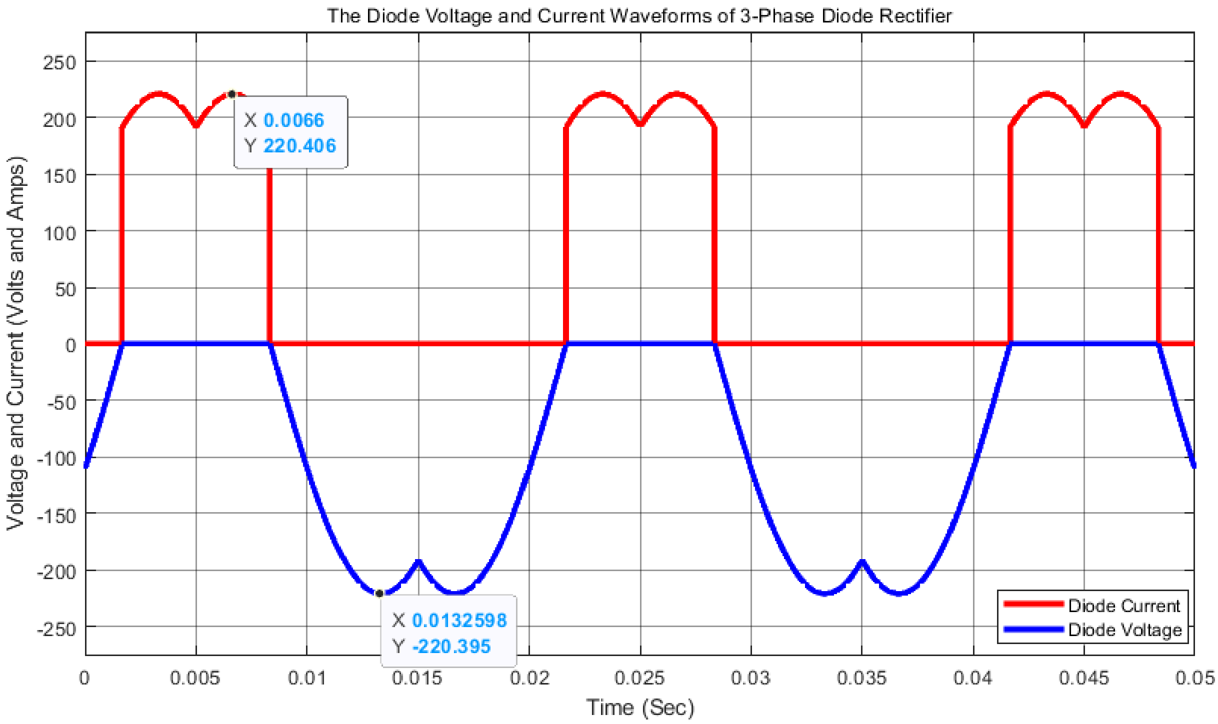

Figure 11: Voltage and Current of Diode in 3-Phase Diode Rectifier

Figure 11 shows the stresses of the diodes. As can be seen, the maximum blocking voltage of the diode is 220 Volts, and the maximum current that the diode can carry is 220 Amps. However, these values are only valid for the resistor load case. We have a buck converter and DC motor in the entire topology,so the component selection is made using later simulations.

2. Buck Converter

The circuit schematic of the buck converter is given in Figure 12. For the switch, the MOSFET is used in the simulation, but IGBT can also be chosen.

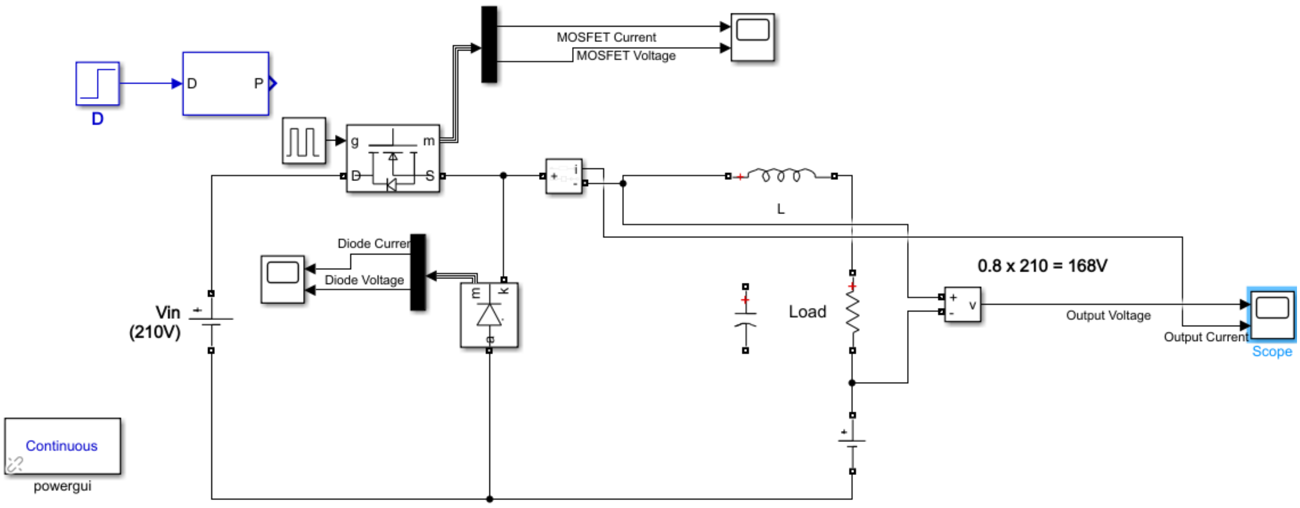

Figure 12: Circuit Schematic of Buck Converter

We also considered the DC motor when we decided on the duty cycle. Since the DC machine is standing at the beginning, applying a high duty cycle at the initial may damage the machine. Hence, we slowly increased the duty cycle by using a potentiometer in the controller. The controller is used the determine the gate signal of MOSFET or IGBT. Therefore, at the start-up, the duty cycle is arranged as 0.1 and increases gradually until 0.8. In this buck converter simulation, the duty cycle is 0.1 to see the stresses of the components at start-up. Initially, there is no back emf in the motor; we gave the 0.1 Volts to the load side of the buck converter. Also, we did not add an LC filter since the DC motor itself is already a huge RL load. Then we don't need another filter in these simulations. The load variables are given as in the motor parameters. Also, we decided to apply 10 kHz as a switching frequency to the MOSFET or IGBT. The following figures show voltage, current waveforms of output, MOSFET, and free-wheeling diodes at the start-up; the duty cycle is given as 0.1.

The voltage and current waveforms of the output are given in Figure 13.

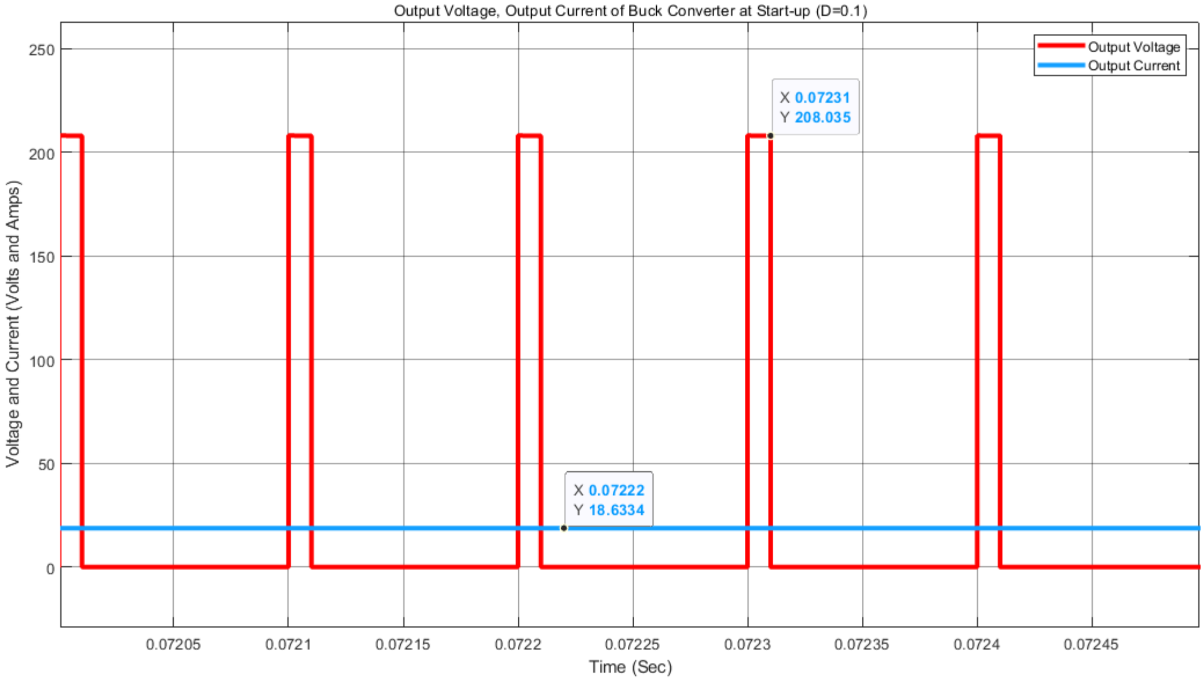

Figure 13: The Output Voltage and Current Waveforms of Buck Converter

The voltage and current waveforms of MOSFET at the start-up can be seen in Figure 14.

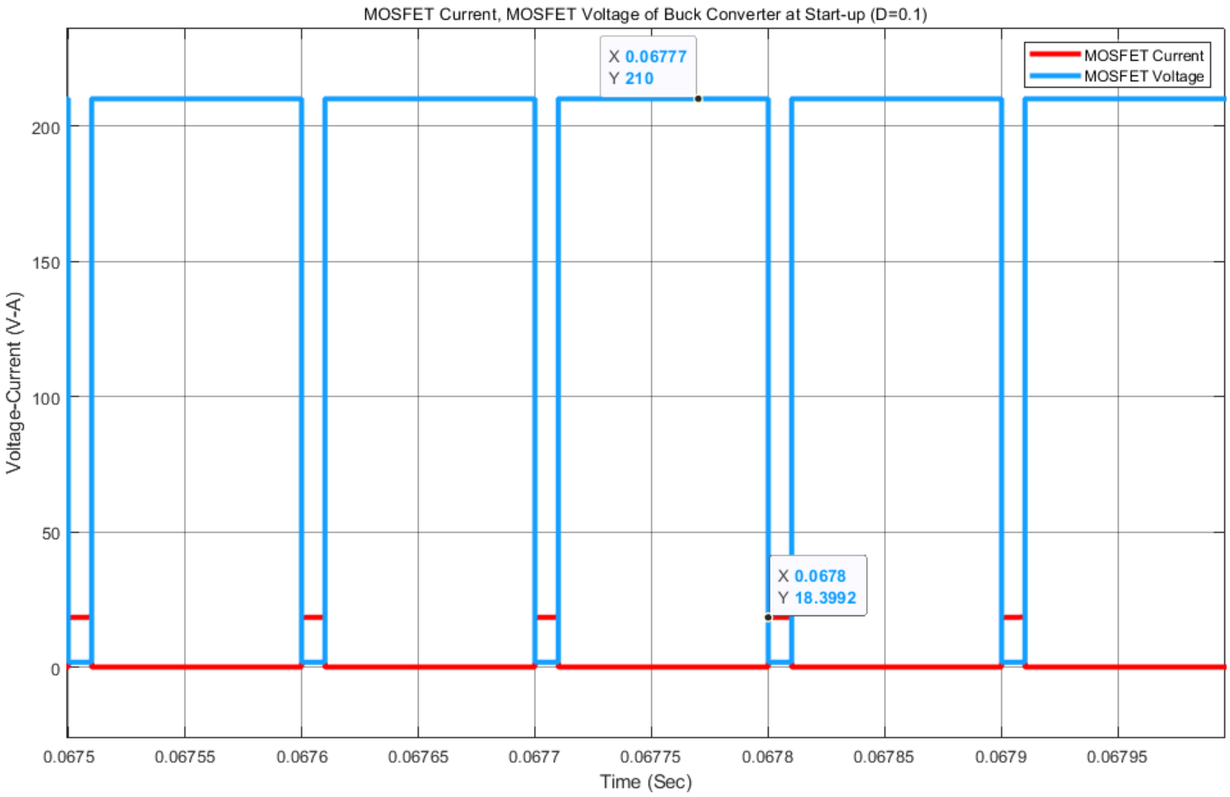

Figure 14. The Voltage and Current Waveforms of MOSFET in Buck Converter

As shown in Figure 14, the maximum blocking voltage of MOSFET is about 210 Volts, and the maximum current value is 18 Amps for a start-up.

The voltage and current waveforms of the free-wheeling diode in the buck converter at the start-up can be seen in Figure 15.

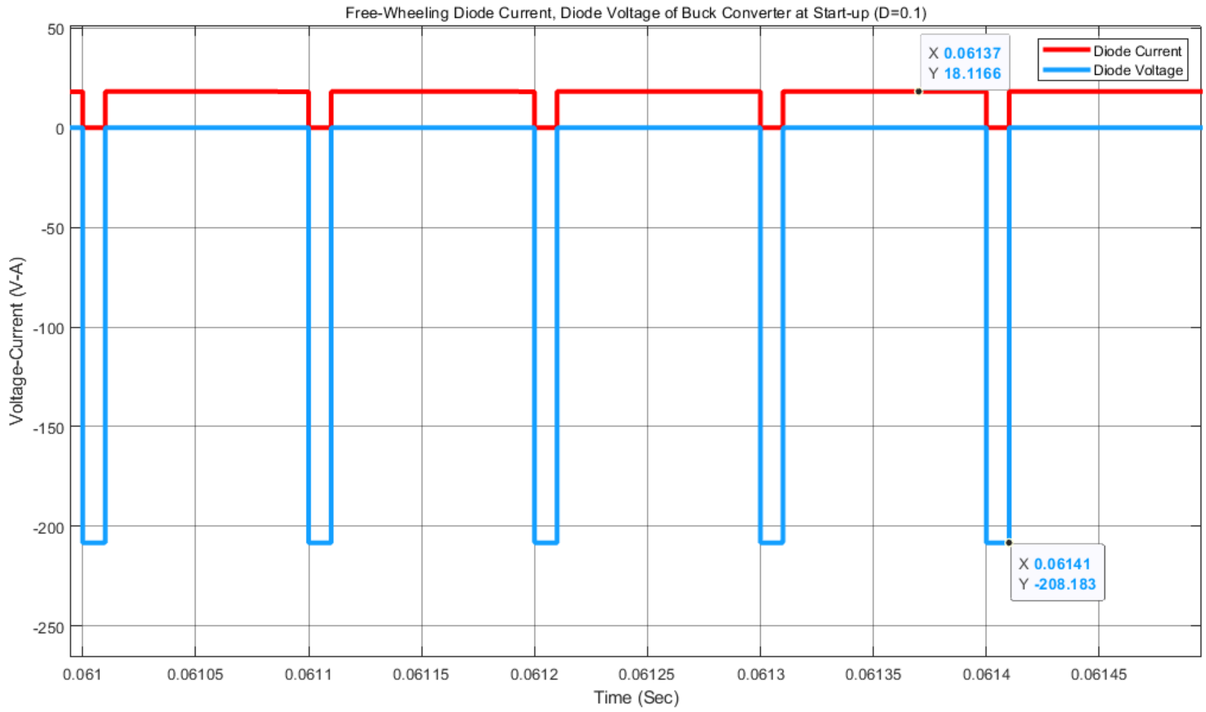

Figure 15:The Voltage and Current Waveforms of Free-Wheeling Diode in Buck Converter

As can be seen from Figure 15, the blocking voltage at the free-wheeling diode is about 210 Volts. And, the maximum forward current value is 18 Amps.

3. Three Phase Diode Rectifier and Buck Converter

The circuit schematic of the three-phase diode rectifier and buck converter model is given in Figure 16.

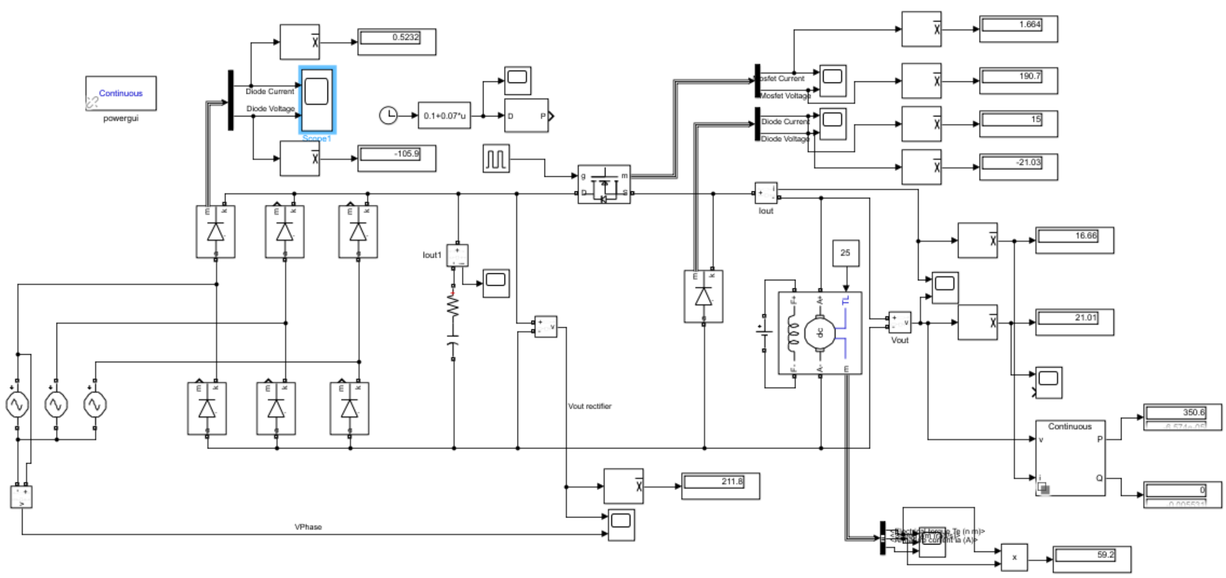

Figure 16: Circuit Schematic of 3-Phase Diode Rectifier and Buck Converter

The rectifier diodes and free-wheeling diode are chosen ideal. Also, DC motor parameters are given in Figure 17. Also, we added 10^{-4} Farad capacitance at the load of the rectifier in order to decrease output voltage ripple.

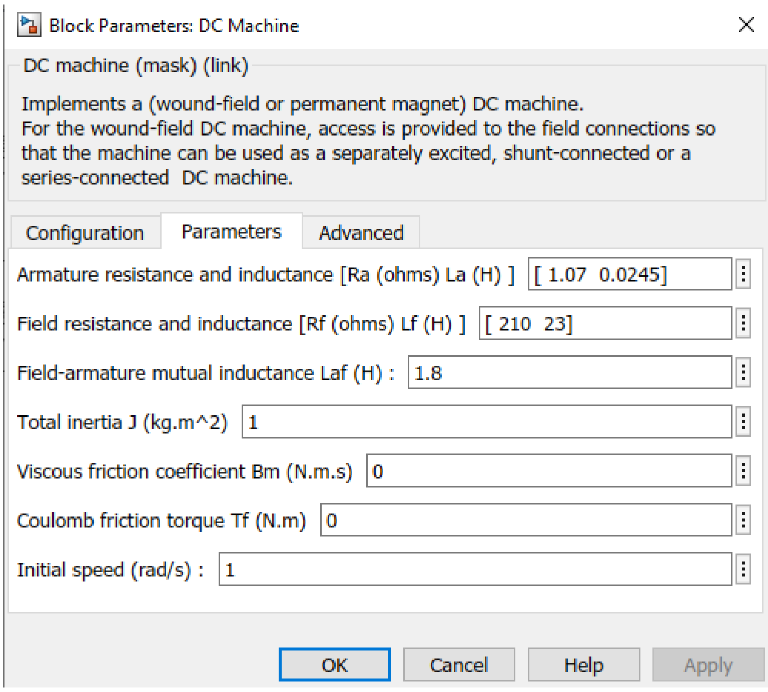

Figure 17: The Motor Parameters

For each component, the maximum and minimum values of voltage and current at the start-up are observed and the mean values are calculated by Simulink blocks as shown in Figure 9. According to these values, the selection of components is decided.

The rectifier diodes voltage and current waveforms are given in Figure 18.

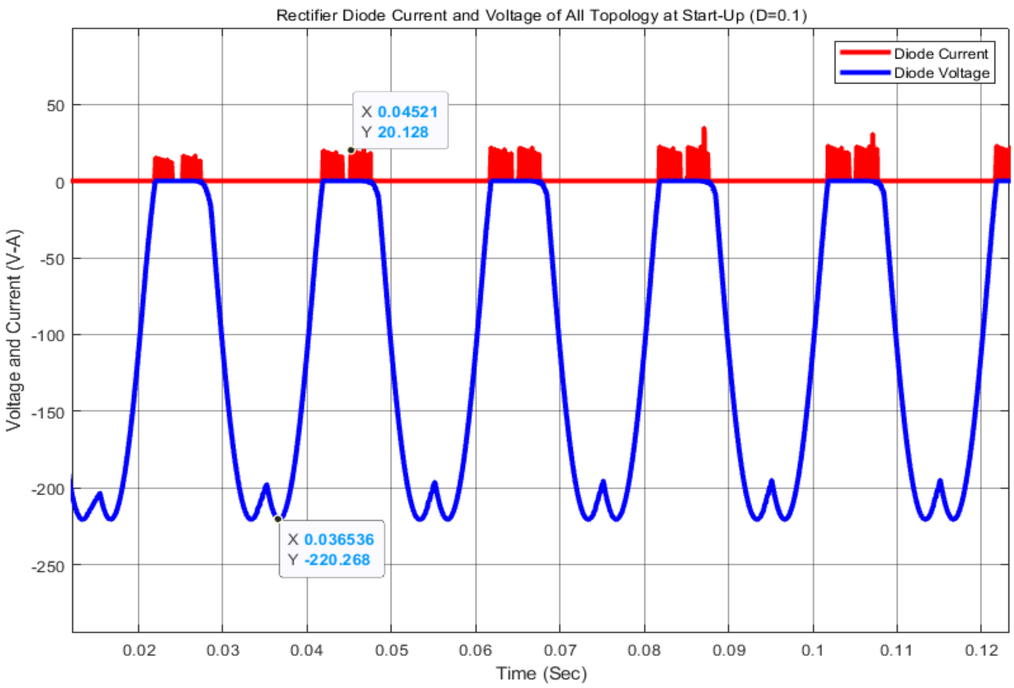

Figure 18: The Rectifier Diode Voltage and Current Waveforms at Start-Up (D=0.1)

As shown in Figure 18, the blocking voltage of rectifier diode should be at least -220 Volts. The maximum current at the start-up is about 20 Amps when the duty cycle is 0.1. Also, at the initial there is no back emf.

MOSFET voltage and current waveforms at the start-up are given in Figure 19.

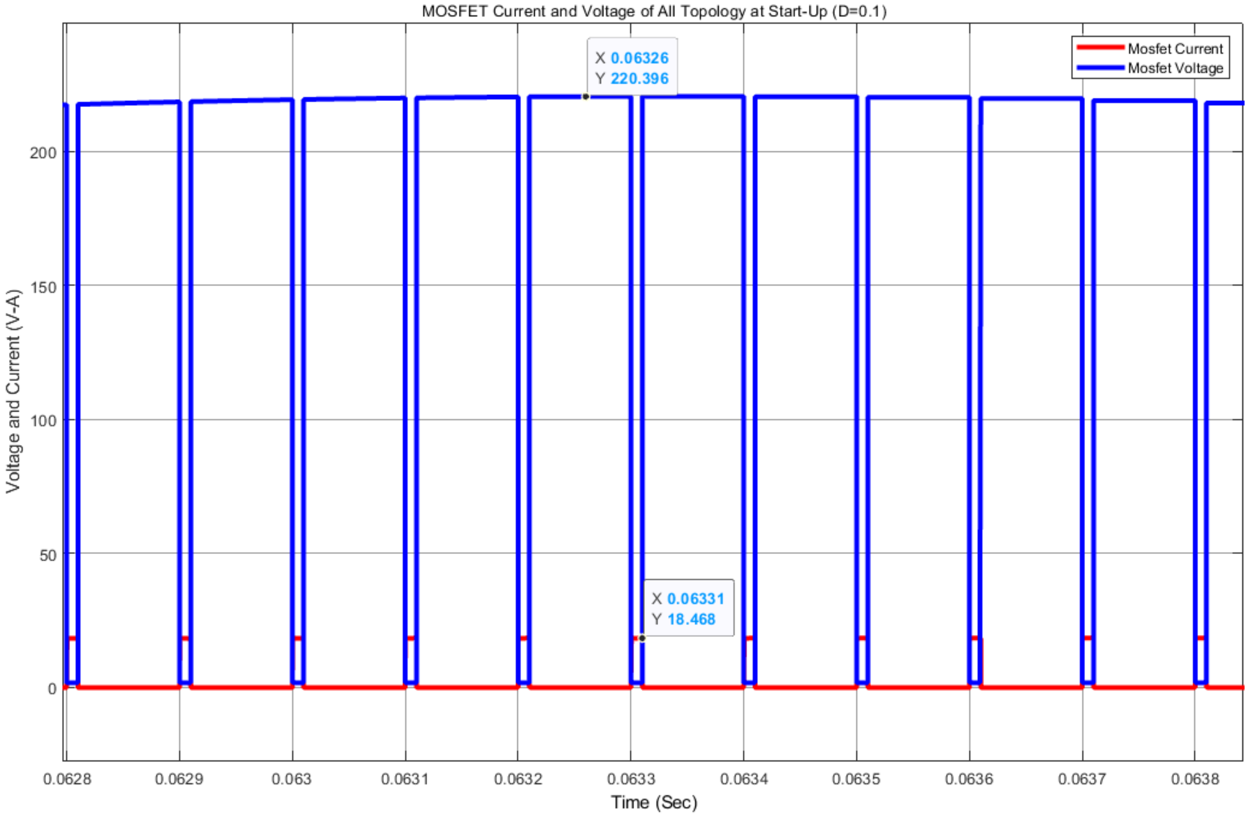

Figure 19:The MOSFET Voltage and Current Waveforms at Start-Up (D=0.1)

As shown in Figure 19, the blocking voltage of MOSFET at the start-up is 220 Volts, and the maximum current is about 18 Amps. The MOSFET or IGBT selection is made by using these values. Also, the average current is calculated as about 2 Amps.

The free-wheeling diode voltage and current waveforms at the start-up are given in Figure 20.

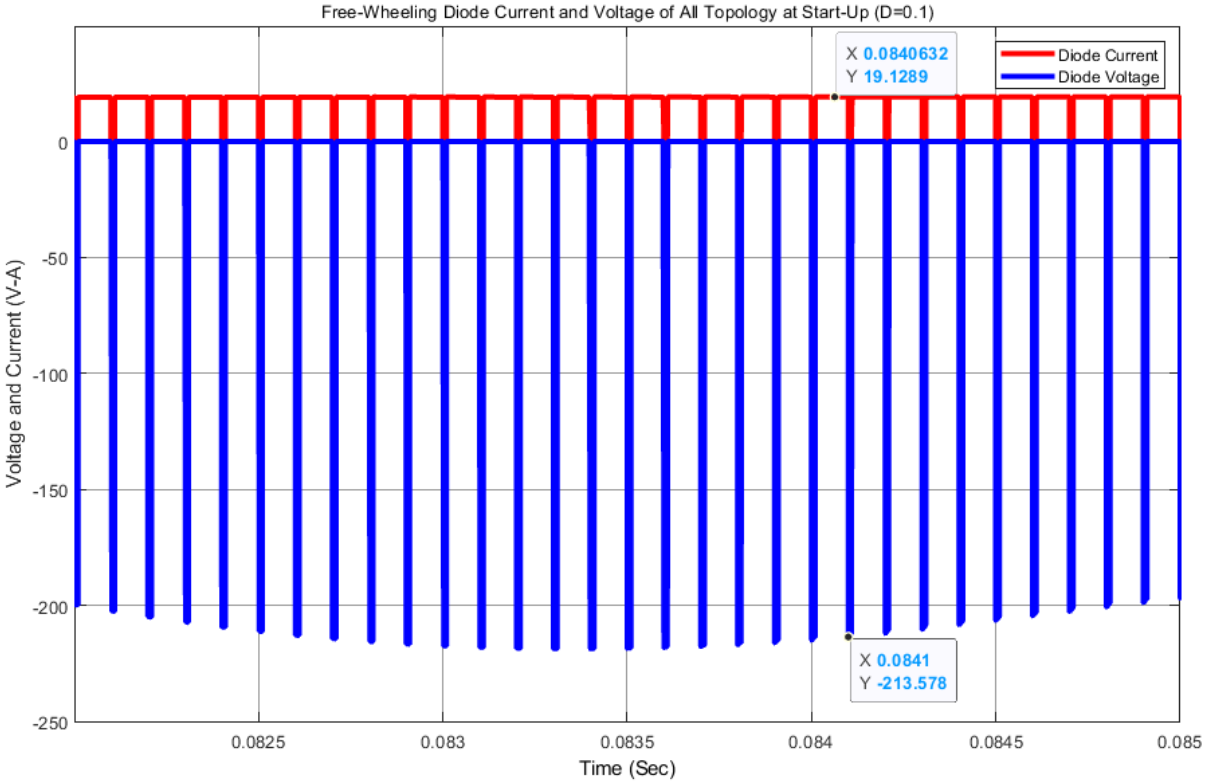

Figure 20:The Free-Wheeling Diode Voltage and Current Waveforms at Start-Up (D=0.1)

As shown in Figure 20, the blocking voltage of the free-wheeling diode is about -220 Volts. Also, the maximum current is about 20 Amps.

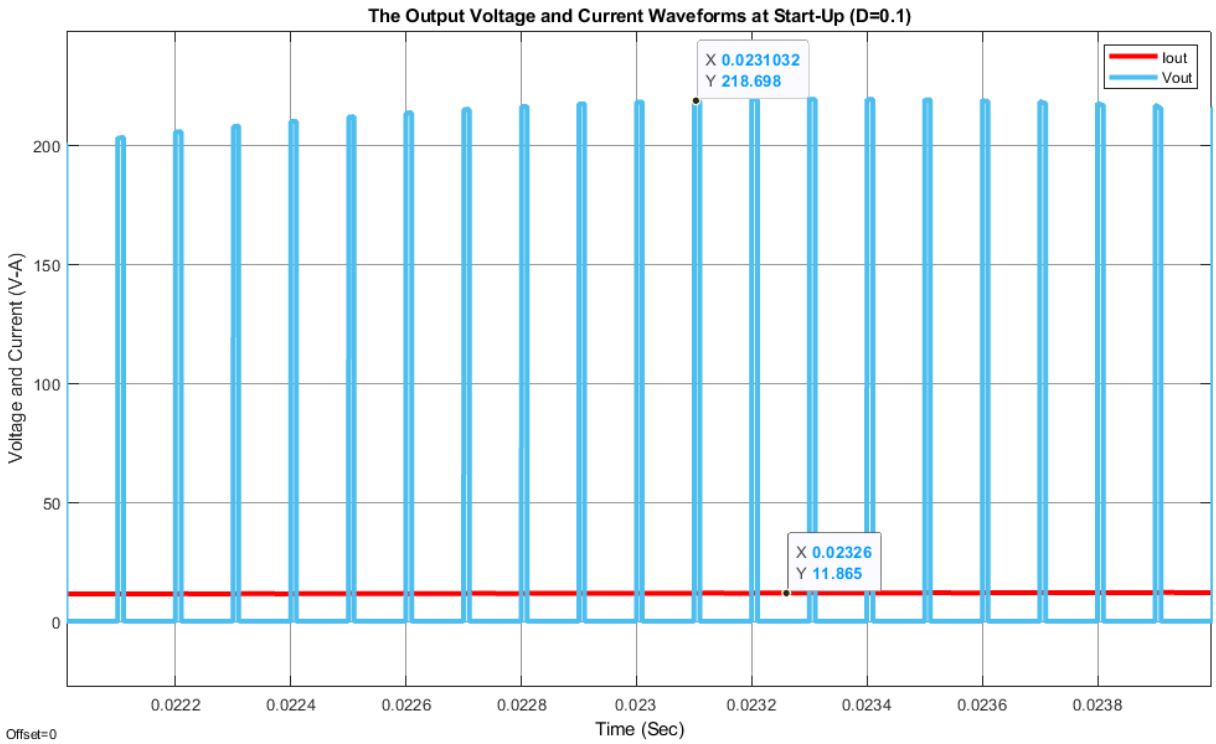

Figure 21: The Output Voltage and Current Waveforms at Start-Up (D=0.1)

The output voltage and current waveforms at start-up are given in Figure 21. The average voltage and current values are calculated as shown in Figure 16.

After doing start-up simulations, the simulation results for steady state are observed. The rectifier diode voltage and current waveforms are shown in Figure 22.

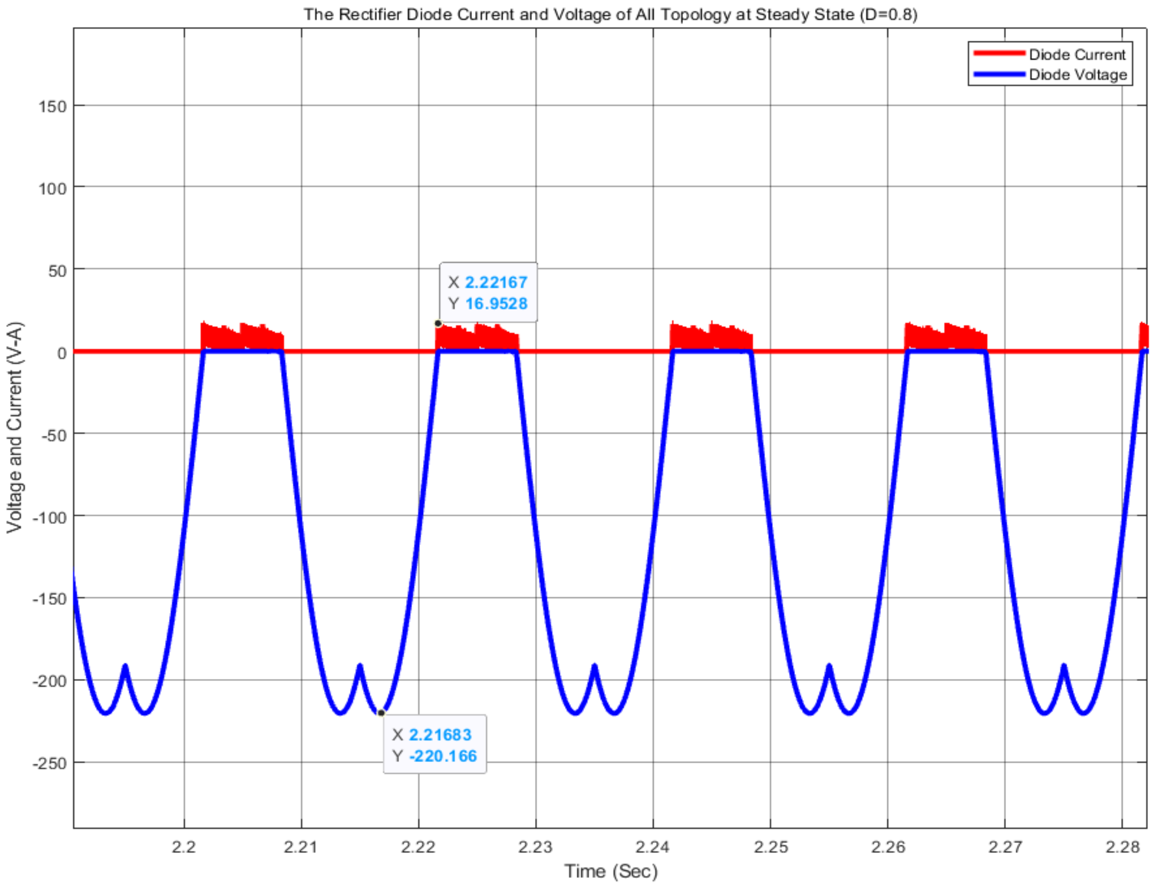

Figure 22:The Rectifier Diode Voltage and Current Waveforms at Steady State (D=0.8)

The blocking voltage of the rectifier diode is the same as the start-up case, -220 Volts. The maximum current is about 16 Amps, but this is valid for the ideal case; therefore, the component selection is made by using this value and error margin.

The MOSFET voltage and current waveforms are given in Figure 23. As shown from the figure, the blocking voltage at steady state is not much changed with start-up case. The average values for current and voltage are calculated. The average current is equal to 10.6 Amps.

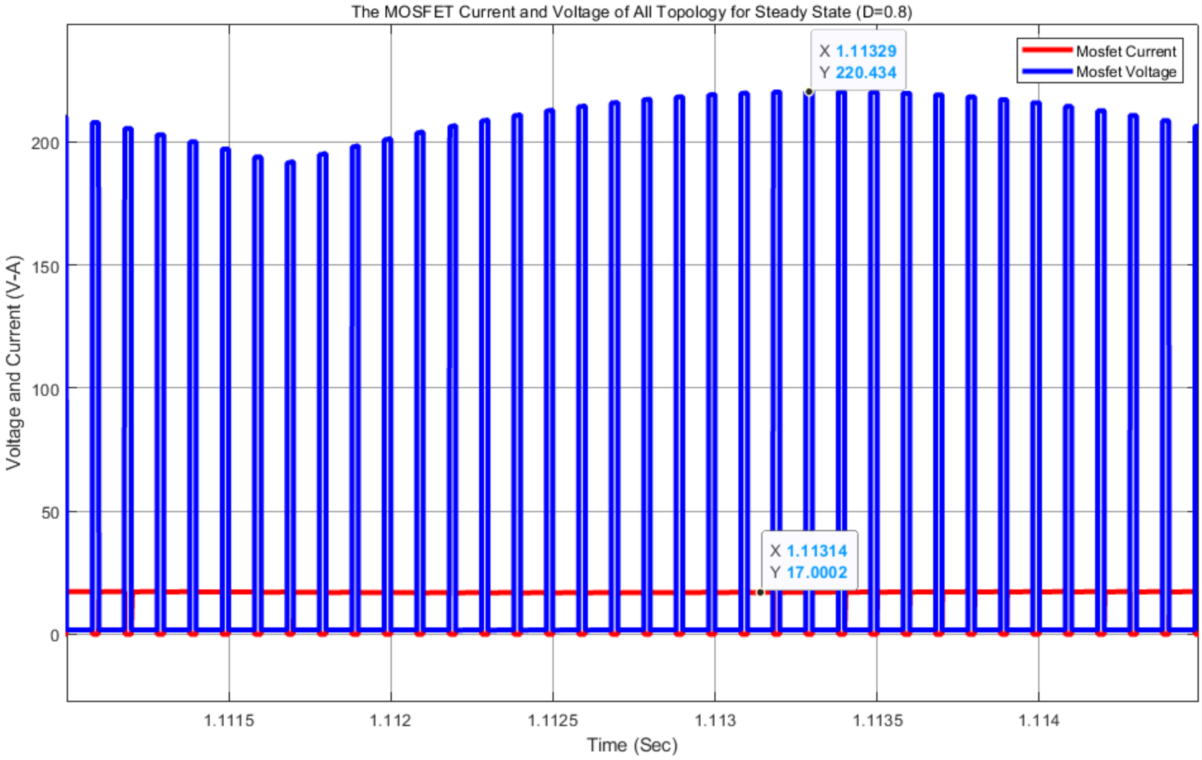

Figure 23:The MOSFET Voltage and Current Waveforms at Steady State (D=0.8)

The free-wheeling diode voltage-current waveforms for the steady-state are given in Figure 2

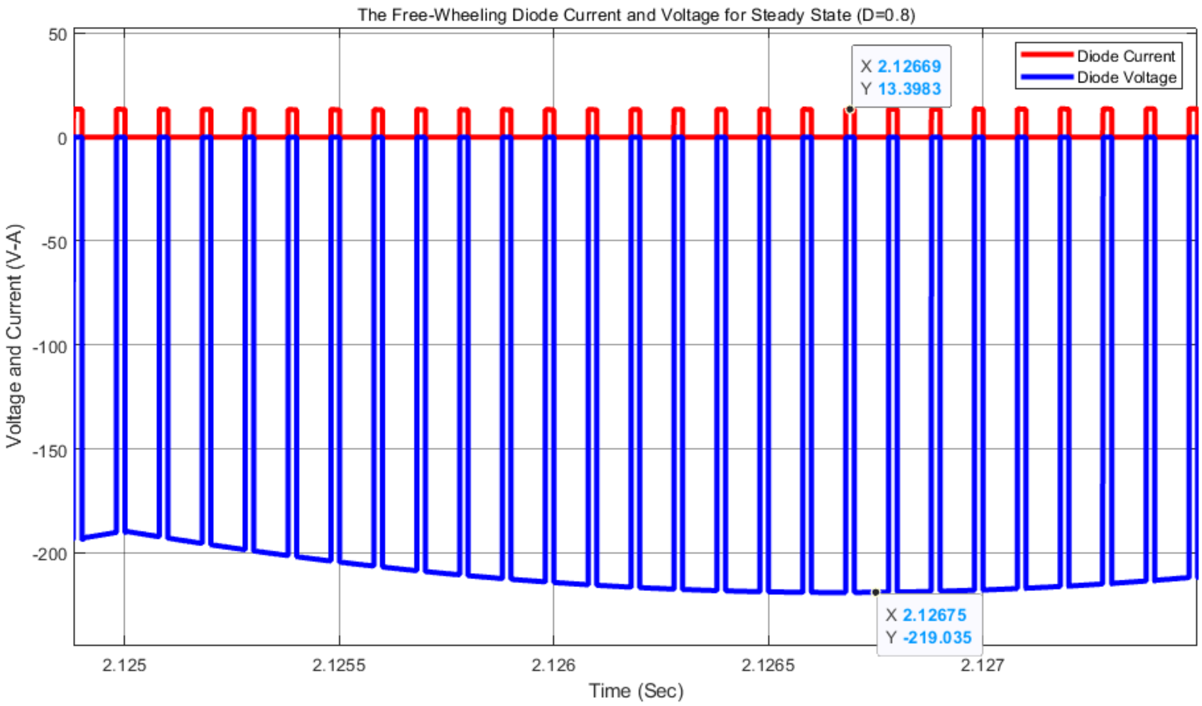

Figure 24:The Free-Wheeling Diode Voltage and Current Waveforms at Steady State (D=0.8)

The stresses at the steady-state of the free-wheeling diode are shown in Figure 24.

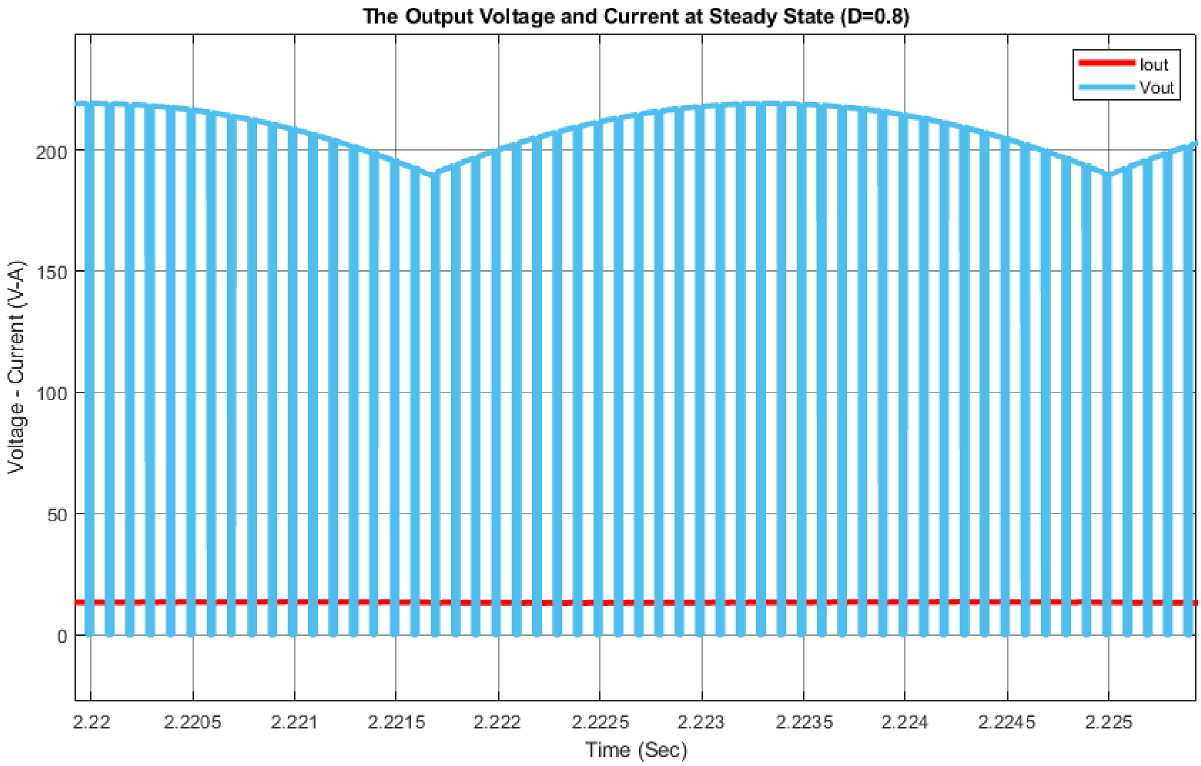

Figure 25:The Output Voltage and Current Waveforms at Steady State (D=0.8)

The output voltage and current waveforms are shown in Figure 25. The average output voltage is 167.4 Volts for a 0.8 duty cycle, 5-sec simulation.

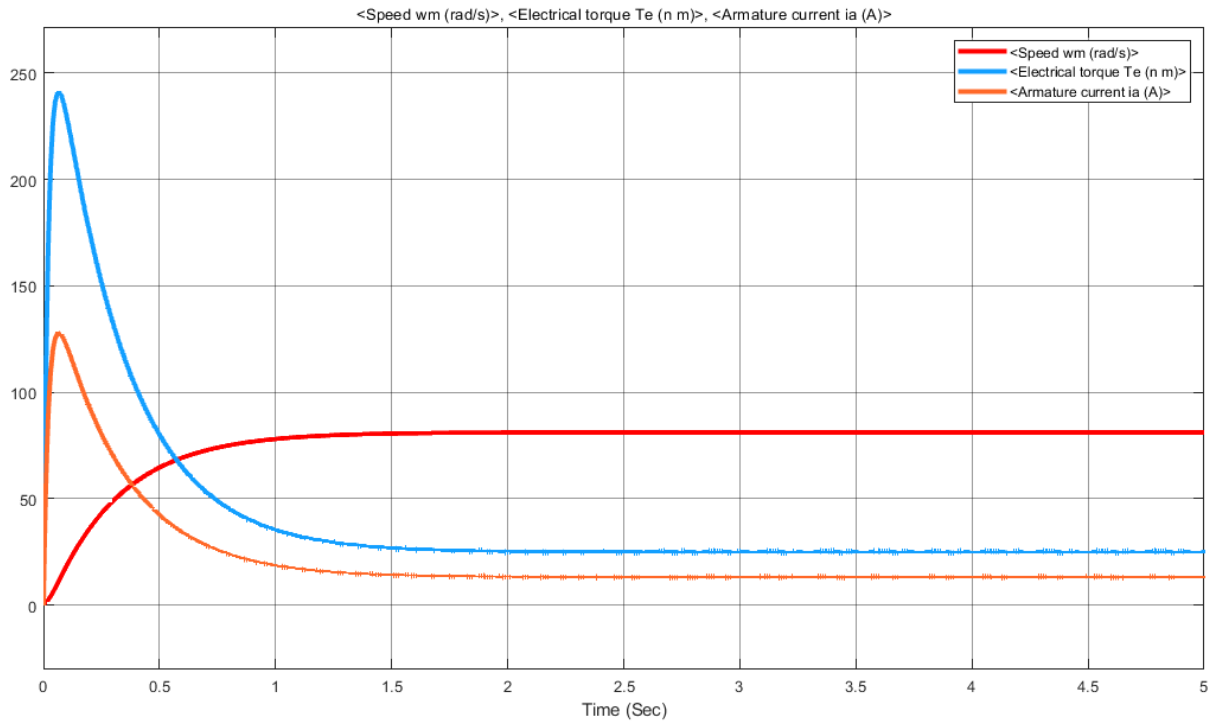

Figure 26: Speed, Torque and Armature Current Graphs of DC Motor at D=0.8

The speed, torque, and armature currents graphs are given in Figure 26. Since the duty cycle is equal to 0.8, the armature current has a peak at the start-up. We decided to make soft-starting which is starting to lower duty cycle and increase steadily to eliminate high current at the beginning.

After doing simulations, component selection will be made in the next section using critical MOSFET/IGBT and diodes.

SIMULATION OF CONTROLLER

In order to provide a gate signal to MOSFET or IGBT, we need to generate pulses. To do that, we need both a controller and gate driver. As APPE, we decided to implement an analog controller to our final design. However, initially, the pulses are generated with a digital controller which is 555 Timer.

With the help of 555 Timer, we can generate pulses with desired period using pulse width modulation tecnique (PWM). The duty cycle of PWM signal is defined as the amount of time which is high or 1. It can be calculated as follows:

$$D = (\frac{T_{high}}{T}) \times 100$$

We succeed to generate pulses by using NE555 Timer in LT Spice, the circuit schmeatic is given in Figure 27.

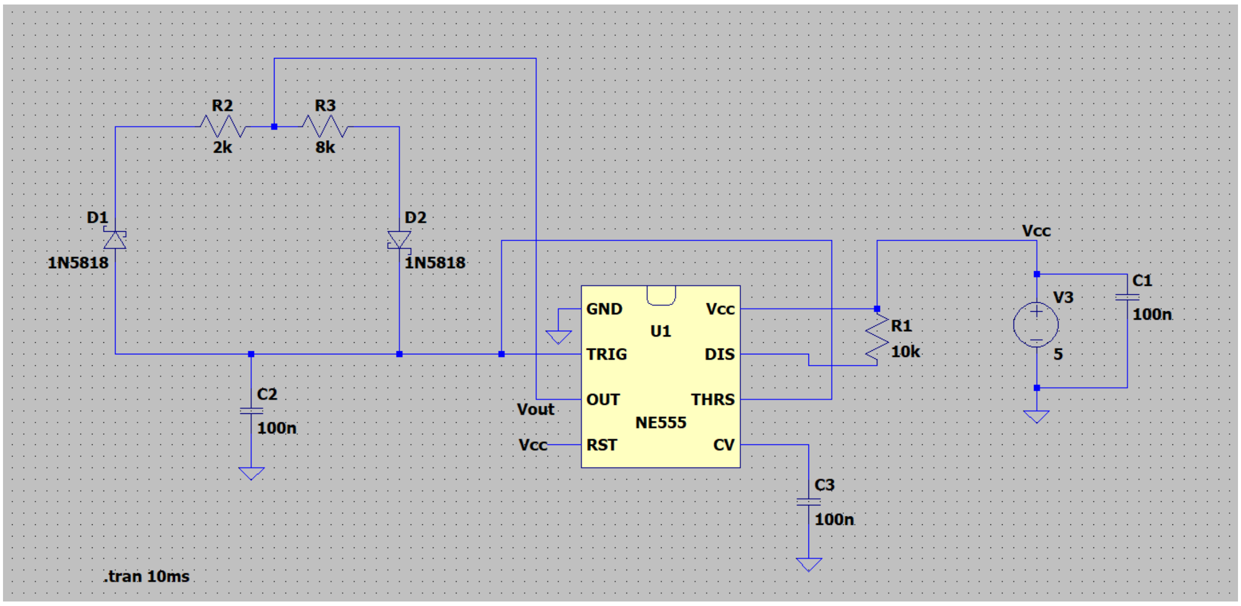

Figure 27:The Circuit Schematic of 555 Timer PWM Generator

In this schematic, the circuit produces pulses with duty cycle about %50. Because R2 and R3 are fixed value. In the practical design, we are planning to use potentiometer in order to change resistance value so we can change the duty cycle as we want. The duty cycle can be calculated as follows:

$$D = ((R_2 + R_3)/(R_2 + 2R_3)) \times 100$$

The pulses that generated by this circuit is given in Figure 28.

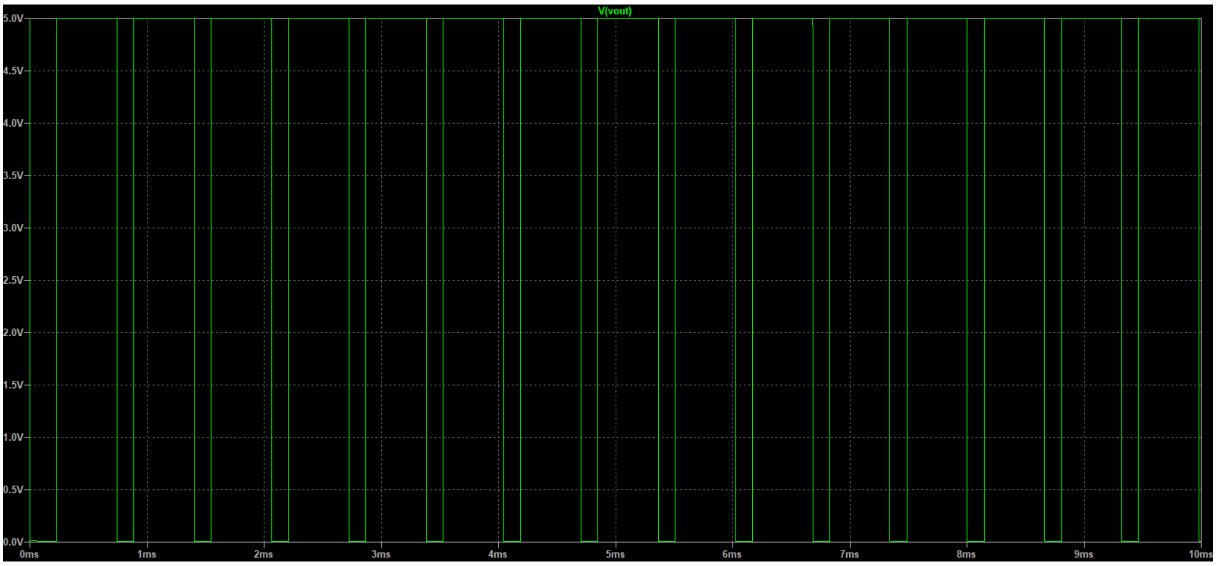

Figure 28: The Pulse Generation with 555 Timer (D=0.5)

In addition to controller, the gate driver IC is required to drive MOSFET or IGBT. Therefore, as a gate driver will be simulated as possible in computer environment, also controller and gate driver will be tested in laboratory. For now, we decided to use TLP250 Optocouple as a gate driver.

However, the 555 Timer calculations are not enough now, the switching frequency should be also considered. In the next step, we will test LM555 Timer with potentiometer and observe which duty cycle can we produced.

COMPONENT SELECTION

Based on our investigations on our model, we have selected the following components.

- GUO40-12NO1 Bridge Diode
- IXGH24N60C4D1 N IGBT
- 100 µF 400 V Electrolytic Capacitor
- DSEP30-06B (HiperFRED 30A 600V 30ns) diode

Bridge Diode

For rectifying diodes in the input side, we have decided to use 1 bridge diode rather than six different normal diodes to increase compactness after our discussions. Based on our simulations, rectifier diodes must be capable of working at least 220 V reverse blocking voltage and 23.4 A forward current. GUO40-12NO1 bridge diode has 40 A, 1200 V specifications which enables us to operate safely.

IXYS **GUO40-12NO1**

Rectifier				Ratings			
Symbol	Definition	Conditions		min.	typ.	max.	Unit
V_{RSM}	*max. non-repetitive reverse blocking voltage*		T_{VJ} = 25°C			1300	V
V_{RRM}	*max. repetitive reverse blocking voltage*		T_{VJ} = 25°C			1200	V
I_R	*reverse current*	V_R = 1200 V	T_{VJ} = 25°C			40	µA
		V_R = 1200 V	T_{VJ} = 150°C			1.5	mA
V_F	*forward voltage drop*	I_F = 10 A	T_{VJ} = 25°C			1.06	V
		I_F = 30 A				1.28	V
		I_F = 10 A	T_{VJ} = 150 °C			0.92	V
		I_F = 30 A				1.23	V
I_{DAV}	*bridge output current*	T_C = 90°C rectangular d = ⅓	T_{VJ} = 175°C			40	A
V_{F0}	*threshold voltage*	*for power loss calculation only*	T_{VJ} = 175°C			0.74	V
r_F	*slope resistance*					16.3	mΩ
R_{thJC}	*thermal resistance junction to case*					4.3	K/W
R_{thCH}	*thermal resistance case to heatsink*				0.50		K/W
P_{tot}	*total power dissipation*		T_C = 25°C			35	W
I_{FSM}	*max. forward surge current*	t = 10 ms; (50 Hz), sine	T_{VJ} = 45°C			370	A
		t = 8,3 ms; (60 Hz), sine	V_R = 0 V			400	A
		t = 10 ms; (50 Hz), sine	T_{VJ} = 150°C			315	A
		t = 8,3 ms; (60 Hz), sine	V_R = 0 V			340	A
I^2t	*value for fusing*	t = 10 ms; (50 Hz), sine	T_{VJ} = 45°C			685	A^2s
		t = 8,3 ms; (60 Hz), sine	V_R = 0 V			665	A^2s
		t = 10 ms; (50 Hz), sine	T_{VJ} = 150°C			495	A^2s
		t = 8,3 ms; (60 Hz), sine	V_R = 0 V			480	A^2s
C_J	*junction capacitance*	V_R = 400 V; f = 1 MHz	T_{VJ} = 25°C		10		pF

Figure 29: Datasheet of GUO40-12NO1

IGBT

After observing the simulation, it was concluded that MOSFET/IGBT must work at least 220 V and 18 A. IXGH24N60C4D1 N IGBT can operate properly until 600V, 30 A.

Type	V_{CE}	I_C	$V_{CE(sat),Tj=25°C}$	$T_{j,max}$	Marking Code	Package
IGW30N60T	600V	30A	1.5V	175°C	G30T60	PG-TO247-3

Maximum Ratings

Parameter	Symbol	Value	Unit
Collector-emitter voltage, $T_j \geq 25°C$	V_{CE}	600	V
DC collector current, limited by T_{jmax} T_C = 25°C, value limited by bondwire T_C = 100°C	I_C	 45 39	A
Pulsed collector current, t_p limited by T_{jmax}	I_{Cpuls}	90	
Turn off safe operating area, V_{CE} = 600V, T_j = 175°C, t_p = 1µs	-	90	
Gate-emitter voltage	V_{GE}	±20	V
Short circuit withstand time[2)] V_{GE} = 15V, $V_{CC} \leq$ 400V, $T_j \leq$ 150°C	t_{SC}	5	µs
Power dissipation T_C = 25°C	P_{tot}	187	W
Operating junction temperature	T_j	-40...+175	°C
Storage temperature	T_{stg}	-55...+150	
Soldering temperature, 1.6mm (0.063 in.) from case for 10s	-	260	

Figure 30:Datasheet of IXGH24N60C4D1 N IGBT

DC Link Capacitor

We have added a capacitor after the rectifier part to decrease the voltage ripple. This capacitor should work properly at almost 250 V so after adding a safety margin, we have concluded to use 100µF 400 V Electrolytic Capacitor.

Free-Wheeling Diode

Reverse blocking voltage of free-wheeling diode is observed as 220 V and forward current observed as 20 A. Also, free-wheeling diode should be fast, so we have chosen to work with DSEP30-06B (HiperFRED 30A 600V 20ns) diode diode. This diode can work until 600 V, 30 A.

IMPLEMENTATION and IMPROVEMENTS

555 Timer Controller

After selection of components, these components are bought and implementation process is began. First, we decided to implement controller and gate driver circuit since it is critical to give gate signal to the IGBT. Therefore, first we constructed the controller circuit that is shown in Figure 27. However, we observed it is not suitable for changing duty cycle gradually. Hence, we changed our controller design as follows:

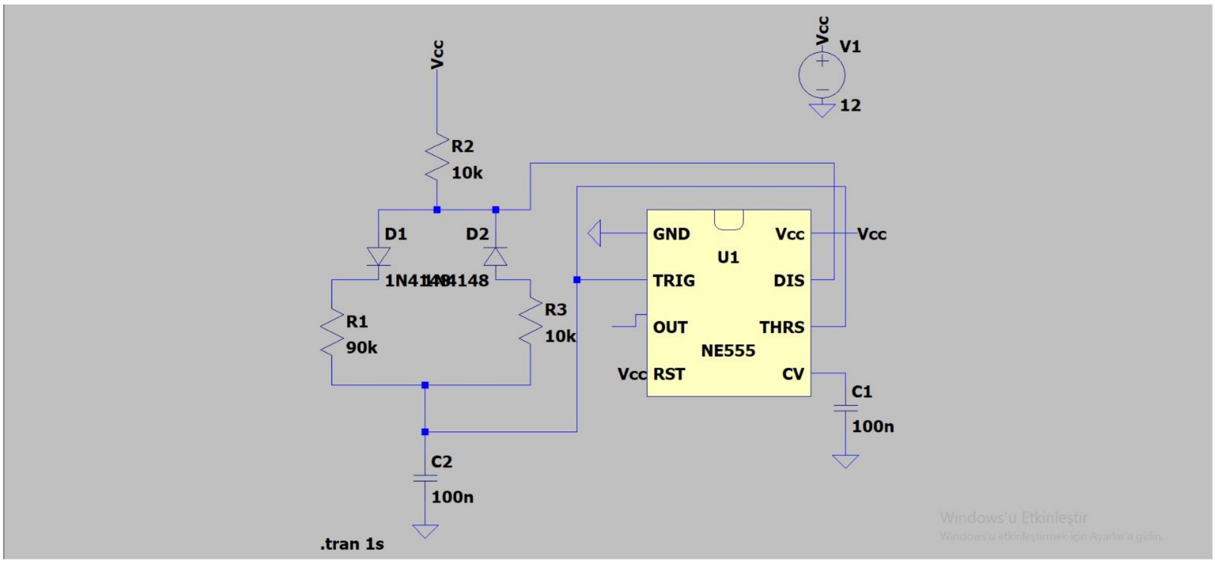

Figure 31: The Circuit Schematic of 555 Timer Circuit

First, we simulated the circuit in Figure 31. In this circuit, when the resistor R1 and R3 are fixed as shown, the duty cycle of the circuit is fixed too. In order to change duty cycle steadily, we decided to use 2 potentiometers instead of resistors. We used 2 potentiometers which are connected in series, one of them is 10k and other one is 100k. 10k potentiometer is used for 5%-20% duty cycle, it changes the duty cycle slowly, therefore, we avoid to sudden increase of duty cycle. The other potentiometer 100k is used from 20% to 80-90% duty cycle. However, in this circuit, operating frequency changes with varying duty cycle from 250Hz to 1kHz.

Optocoupler

As mentioned before we decided to use TLP250 Optocoupler as a gate driver in order to isolate the high and low voltage sides. The pin configuration of TLP250 is given in Figure 32.

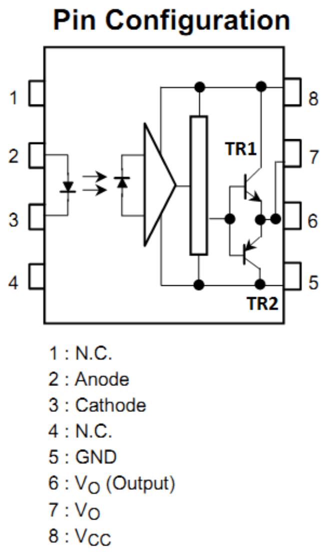

Figure 32: The Pin Configuration of TLP250

The connections between optocoupler and IGBT are shown in Figure 33. It is important to give isolated Vcc input to optocoupler. Also, a small resistor is connected between Vcc and ground. In order to isolate low voltage and high voltage side, the ground for optocoupler must be same in IGBT ground.

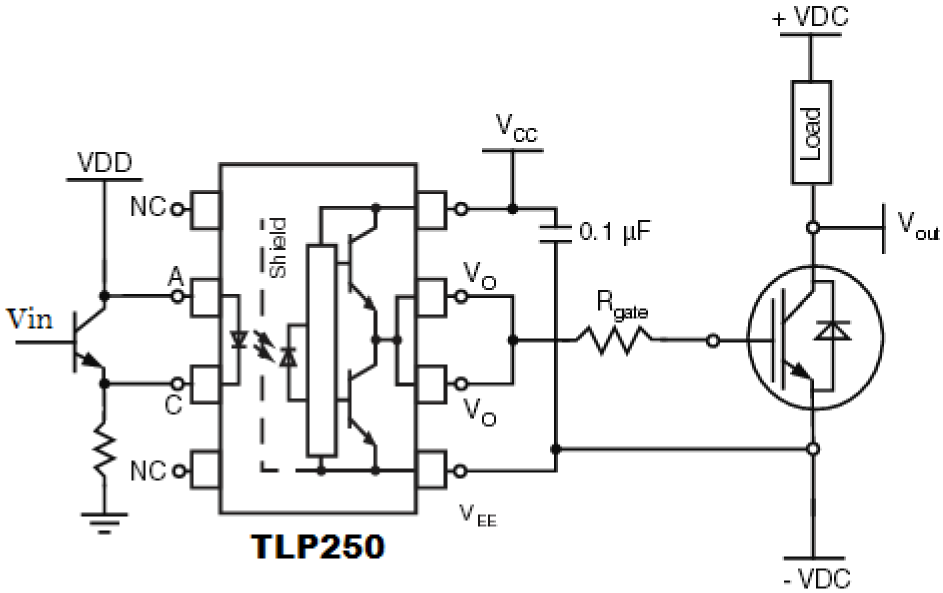

Figure 33: The Connection of Optocoupler

After implemented both controller and gate driver, we generated pulses with changing duty cycle succesfully.

The Three-Phase Diode Rectifier

After implementation of gate driver and controller, we started to implement 3-phase diode rectifier. After some discussion about the component, we decided to use another bridge rectifier for this part. We bought SBR3516 Bridge Diode as shown in Figure 34. This component is suitable for our purpose.

Figure 34: SBR3516 Bridge Diode

The DC Link Capacitor

In our simulations, we used 100 µF capacitance at the end of the diode rectifier in order to reduce ripple voltage. First, we tried to this capacitance value, but we observed that this value is not suitable for the real case, the capacitor was damaged. Hence, we decided to use much larger capacitance value. Then, we decided to use 470 µF 400 V capacitor as shown in the Figure 35.

Figure 3510:The DC Link Capacitor

After implemented bridge diode and DC link capacitor, we connected it 3-phase voltage source and observed the result. We opened the source slowly and increased gradually until 35-40% value. In the calculation part we decided to use input as this value. The output at DC link capacitor shown in the Figure 36.

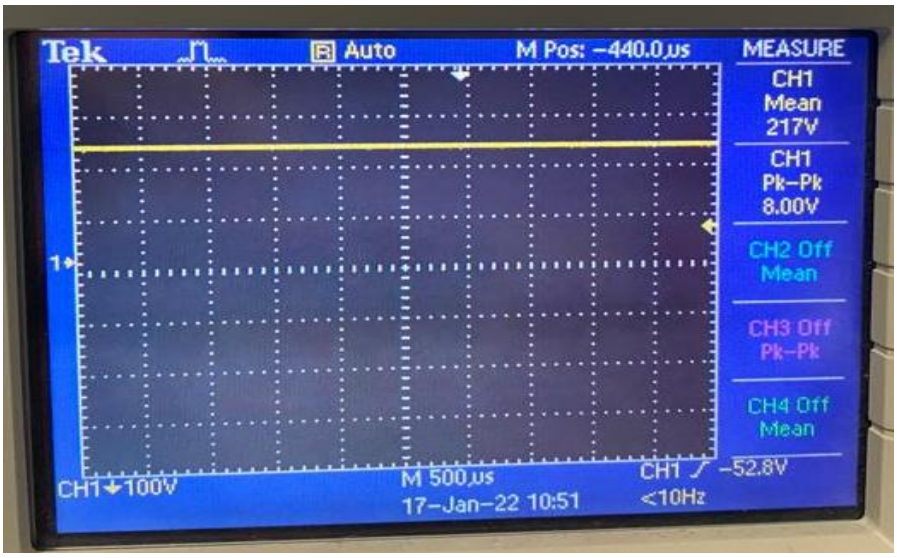

Figure 36: Output of DC Link Capacitor

As can be seen from Figure 36, the output ripple is suitable. Hence, 470 µF 400 V capacitor is enough for this application.

IGBT and Free-wheeling Diode

The IGBT that we used is the same as mentioned about component selection. However, because of logistics problems the free-wheeling diode is changed. But, it has same values as the old one. Since, these components are sensitive with temperature, we need to use heatsinks for IGBT, free-wheeling diode and bridge diode. The thermal analysis for each component includes chosen heatsinks is given next section. The circuit includes all parts and connections are given in Figure 37

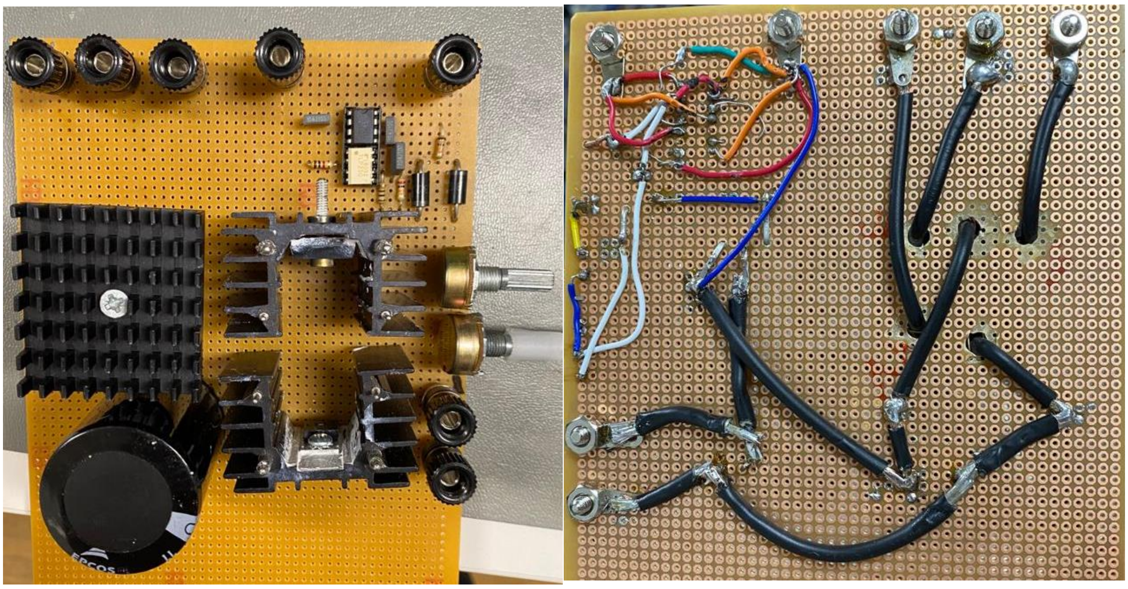

Figure 37: The Final Circuit Design and Connections

THERMAL ANALYSIS

Since, our design consists switch and diodes, we need to consider thermal properties of these components. In this section, the thermal analysis are explained. After the calculations, the required heatsink is determined. As mentioned in the controller part, frequency of operation changes with varying duty cycle. At 0.9 duty cycle, frequency becomes 1kHz and calculations are done accordingly

1. IGBT

Conduction and switching losses can be calculated for IGBT as follows:

$$P_{conduction} = V_{on} I_{on} D$$

$$P_{switching} = \left(E_{on} + E_{off}\right) \times f_s$$

In order to calculate these losses, the information of component datasheet is used [1]. For $T_j = 25°C$, E_{on} is given 0.40 mJ and E_{off} is given 0.30 mJ. The switching frequency can be 1kHz at maximum. Then:

$$P_{switching} = (0.40 + 0.30) \times 1k = 0.7\ W\ \ at\ T_j = 25°C$$

For $T_j = 125°C$, E_{on} is given 0.63 mJ and E_{off} is given 0.50 mJ. The switching frequency can be 1kHz at maximum. Therefore:

$$P_{switching} = (0.63 + 0.50) \times 1k = 1.13\ W\ \ at\ T_j = 125°C$$

In order to find conduction losses, we need to know voltage and current values when rated load case (steady state). I_{on} is average current that passes the IGBT calculated by Simulink.

$$I_{on} = 10.6\ A$$

$$V_{on} = V_{CE(sat)} = 1.95\ V\ at\ T_j = 125°C$$

$$V_{on} = V_{CE(sat)} = 2.70\ V\ at\ T_j = 25°C$$

Hence, the conduction loss for IGBT can be calculated as follows:

$$P_{conduction} = 1.95 \times 10.6 \times 0.9 = 18.603\ W$$

$$P_{conduction} = 2.70 \times 10.6 \times 0.9 = 25.758\ W$$

Therefore, at the room temperature the total IGBT losses are:

$$P_{IGBT} = P_{conduction} + P_{switching} = 0.7\ W + 25.758\ W = 26.458\ W\ at\ T_j = 25°C$$

2. Free-Wheeling Diode

For the free-wheeling diode at the end of buck converter, the losses can be calculated as follows:

$$P_{conduction} = V_F I_F D$$

$$P_{switching} = V_{reverse} \times f_{sw} \times t_{rr} \times I_{rr} \times \frac{1}{2}$$

The required information for the calculations is given in datasheet of the selected diode[2]. In our case, $V_{reverse}$ is the maximum voltage on the free-wheeling diode and it is shown in simulations as 220 Volts.

$$P_{switching} = 220\,V \times 1kHz \times 25ns \times 2.5A \times \frac{1}{2} = 6.875\,mW\ at\ T_{VJ} = 25°\mathrm{C}, I_F = 30\,A$$

$$P_{switching} = 220\,V \times 1kHz \times 70ns \times 4.5A \times \frac{1}{2} = 34.65\,mW\ at\ T_{VJ} = 100°\mathrm{C}, I_F = 30\,A$$

In our case, the maximum current flow on the free-wheeling diode is about 15 Amps. From the datasheet:

At $T_{VJ} = 25°\mathrm{C}$:

$$V_F = 2.51\,V\ at\ I_F = 30\,A$$

$$V_F = 3.19\,V\ at\ I_F = 60\,A$$

At $T_{VJ} = 150°\mathrm{C}$:

$$V_F = 161\,V\ at\ I_F = 30\,A$$

$$V_F = 2.24\,V\ at\ I_F = 60\,A$$

The conduction loss of free-wheeling diode can be calculated as follows:

$$P_{conduction} = V_F I_F D = 2.51 \times 15 \times 0.9 = 33.885\,Watt\ at\ T_{VJ} = 25°\mathrm{C}$$

$$P_{conduction} = V_F I_F D = 1.61 \times 15 \times 0.9 = 21.735\,Watt\ at\ T_{VJ} = 150°\mathrm{C}$$

3. Rectifier Diode

We decided to use diode rectifier module, its datasheet can be found [3]. The conduction loss of this module diode can be calculated same as free-wheeling diode. The required information is given in datasheet [3].

At $T_{VJ} = 25°\mathrm{C}$:

$$V_F = 1.06\,V\ at\ I_F = 10\,A$$

$$V_F = 1.28\,V\ at\ I_F = 30\,A$$

At $T_{VJ} = 150°\mathrm{C}$:

$$V_F = 0.92\,V\ at\ I_F = 10\,A$$

$$V_F = 1.23\,V\ at\ I_F = 30\,A$$

In our case, the maximum current flow on the rectifier diode is about 20 Amps. Therefore, conduction loss can be calculated as follows:

$$P_{conduction} = V_F I_F D = 1.28 \times 20 \times 0.9 = 23.04\,W \text{ at } T_{VJ} = 25°\mathrm{C}$$

$$P_{conduction} = V_F I_F D = 1.23 \times 20 \times 0.9 = 22.14\ W \text{ at } T_{VJ} = 150°\text{C}$$

The switching losses are not applicable for this diode module now, however; we are trying to find a method to find switching losses.

After completing the thermal analysis, we chose heatsink with respect to the current thermal losses for freewheeling diode, bridge rectifier and IGBT. To be on the safe side, we chose larger heatsinks. Also, we added a fan for cooling down the circuit for operating at kettle load. Adding fan decreases the temperature of the circuit excessively.

TEST RESULTS

R Load

After implementation overall circuit, we started to test it with R load. We connected R-load at the output of buck converter instead of DC motor. The variac was started and increased slowly until about 35% which is nearly 140 Volts input. We simulated our circuit with 90-100 Volts input. However, after the observation of behaviour at R load, we decided to use higher value as an input. Since we chose our components considered error margin, these components can work at this input value. In order not to have high current values, we used the R load at maximum resistance value which is equal to 192 Ω.

After reaching to desirable input value, we started to increase duty cycle with potentiometer. Since R load is connected we accepted that the output voltage and current have same shape, there won't be lag and lead between them. The output voltage and current for 10% and 80% duty cycle are given in Figure 38 and 39.

Also, after observing that the circuit worked properly with high resistance, we decreased the load resistance value to observe the increased input and load current. After that, we continued using minimum load resistance value.

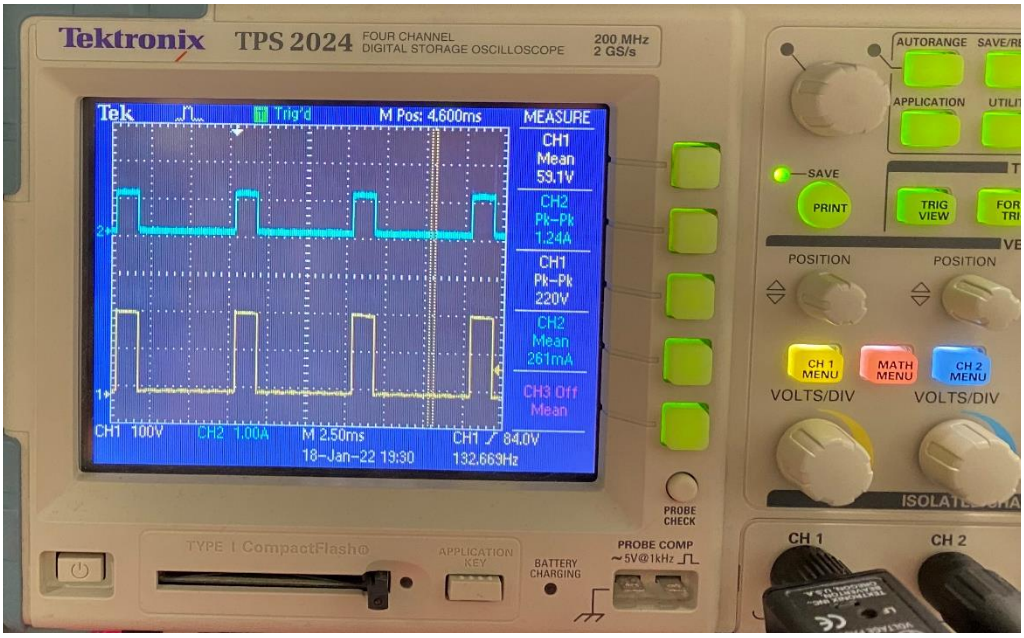

Figure 3811: R Load Test Results for 10% Duty Cycle

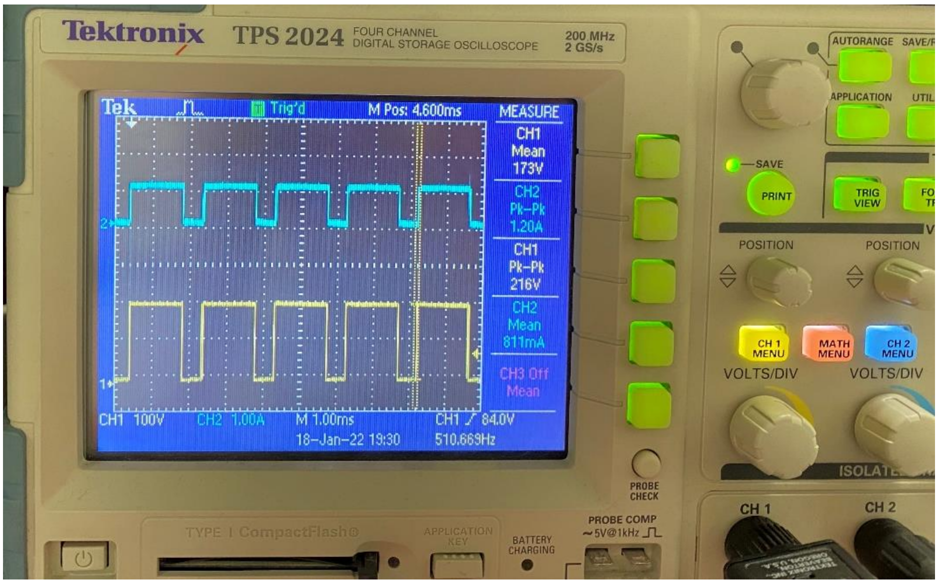

Figure 39:R Load Test Results for 80% Duty Cycle

The output voltage and current for 10% and 80% duty cycle are given in Figure 38 and 39. The CH1 shows output voltage and CH2 shows output current. As expected, voltage and current are in same shape. The frequency is changed with changing duty cycle because of our controller design. But it is not exceeded 1k therefore, our design is working as expected for R-load.

R-L Load

After R load tests, we connected to R-L load to the circuit. Since DC motor is also one big R-L load, this test is critical for design. Inductor load is adjusted so that minimum inductance is present at the load. Inductor load and resistance load connections can be found in Figure 40.

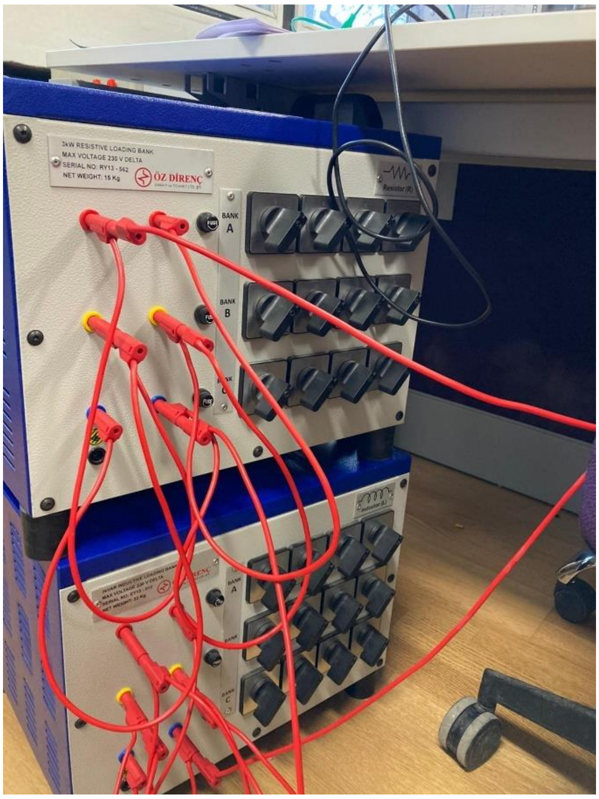

Figure 40: R-L Load Connections

This time, to be on the safe side, we adjusted the variac to give almost 90V of input voltage and tested the R-L load. The crucial part about R-L load test was to exceed the 2A output current limit since the motor to be driven starts to rotate after exceeding 2A output current limit. We started at %10 duty cycle and observed DCM mode of operation. After increasing the duty cycle to almost 50%, we observed 2A output current. As we increase the duty cycle, we observed increased output current at the load side and we held it at that duty cycle value for almost 5 minutes to ensure that the circuit can operate smoothly after some time. Also, we observed the temperature increase after 5 minutes and relieved that the circuit is not overheating. In Figure 41, 42 and 43, R-L test results for %10, %50 and %80 duty cycle can be found.

Ch2: Output Voltage

Ch3: Input Voltage RMS

Ch4: Output Current

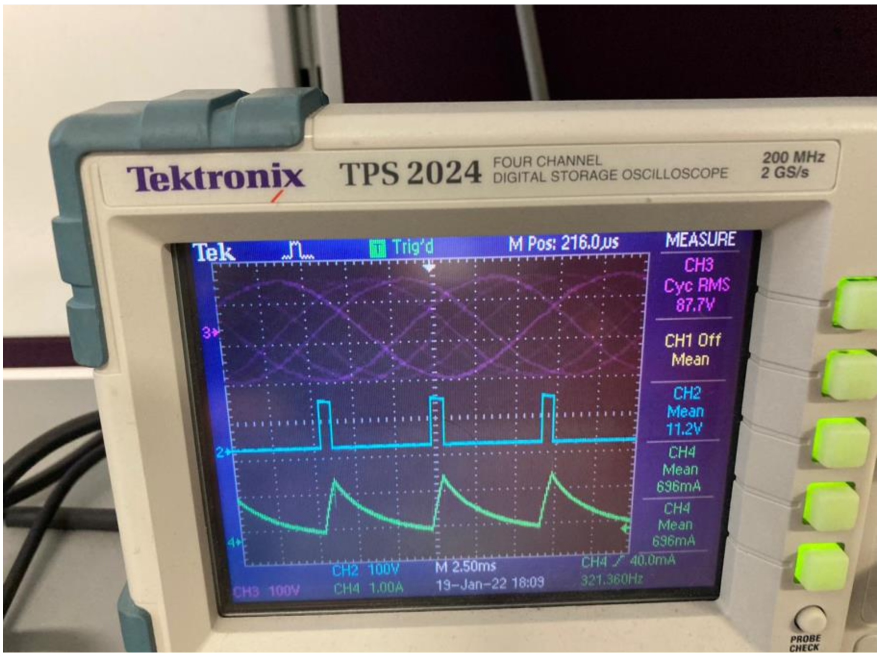

Figure 41: R-L Load Test Results for 10% Duty Cycle

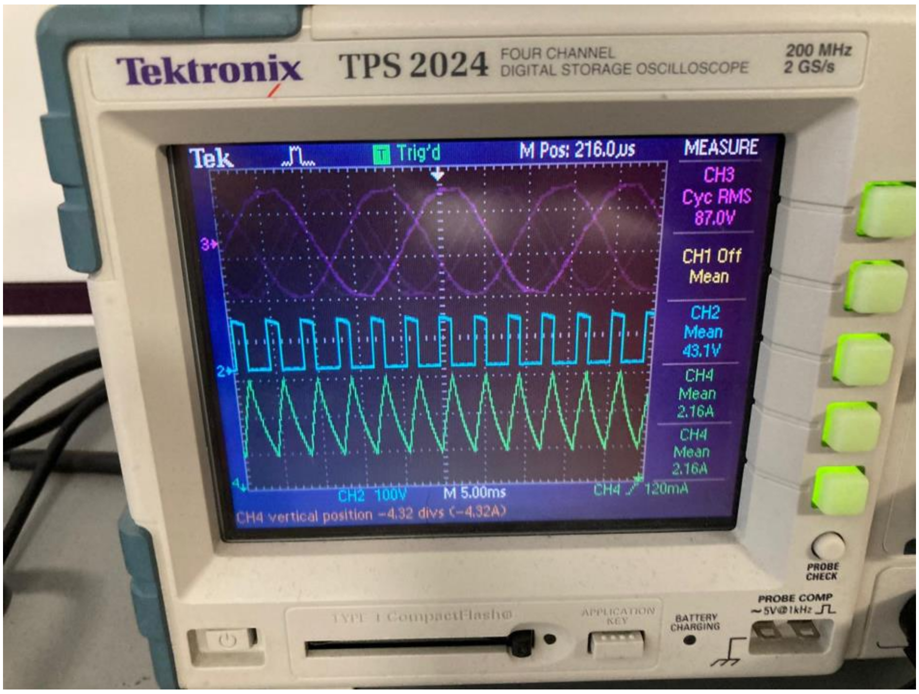

Figure 42: R-L Load Test Results for 50% Duty Cycle

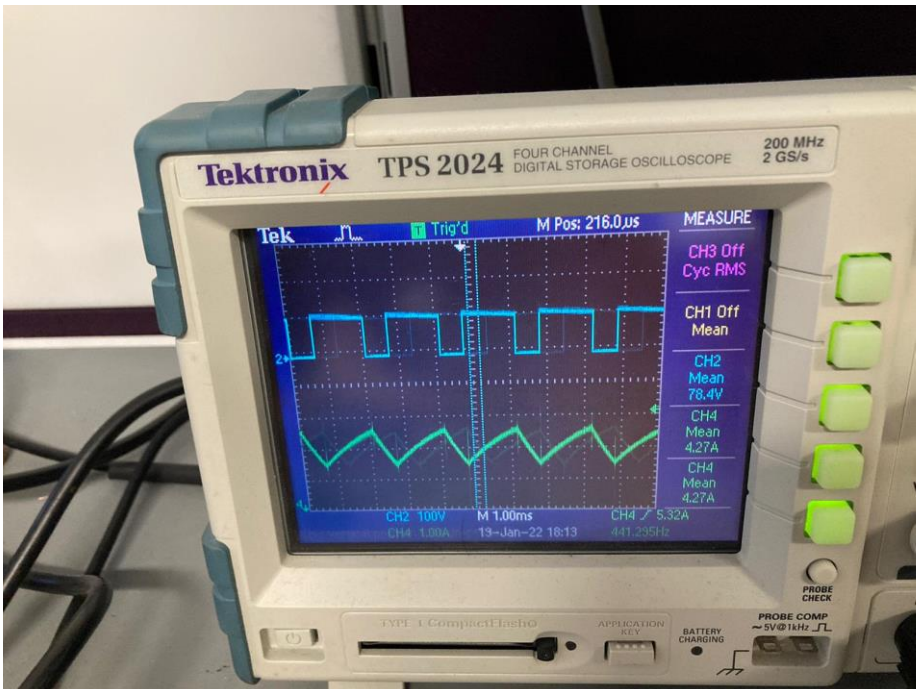

Figure 43: R-L Load Test Results for 80% Duty Cycle

In R-L load test, the output current does not have the same shape as the voltage with the introduction of the load inductance. Output current increases when switch is on and decreases when switch is off. Also, output voltage have low ripple since we used a high capacitance value.

Demo Day

In the demo day, we tested our design with no-load and full-load cases. First, we made all necessary connection between the DC motor and our design. Then, we set the AC voltage source at

140-150 Volts level by soft-starting. By this way, the DC link capacitor is charged. After fixing the input voltage we started to increase duty cycle gradually and slowly in order to prevent high in-rush currents.

At low duty cycle, we observed discontinuous current mode due to low current level as shown in Figure 44.

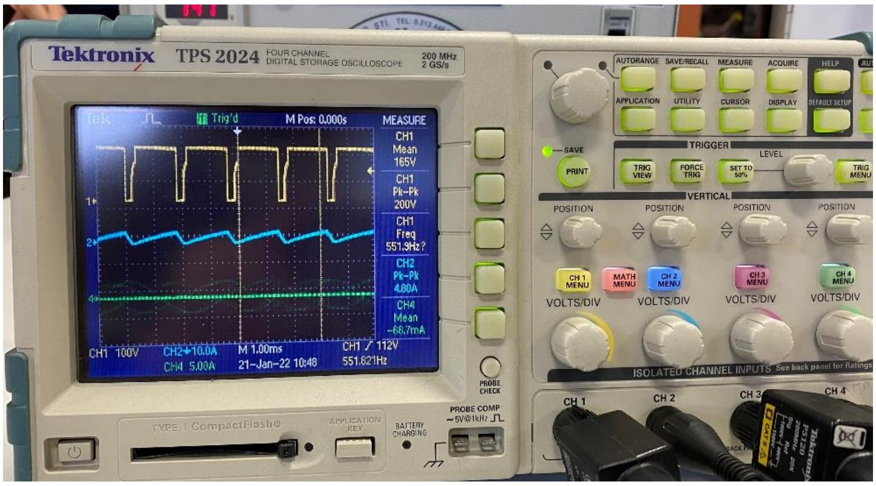

Figure 124: The Voltage and Current Waveforms with No-Load (DCM) from Demo Day

However, the problem solved with increasing duty cycle.

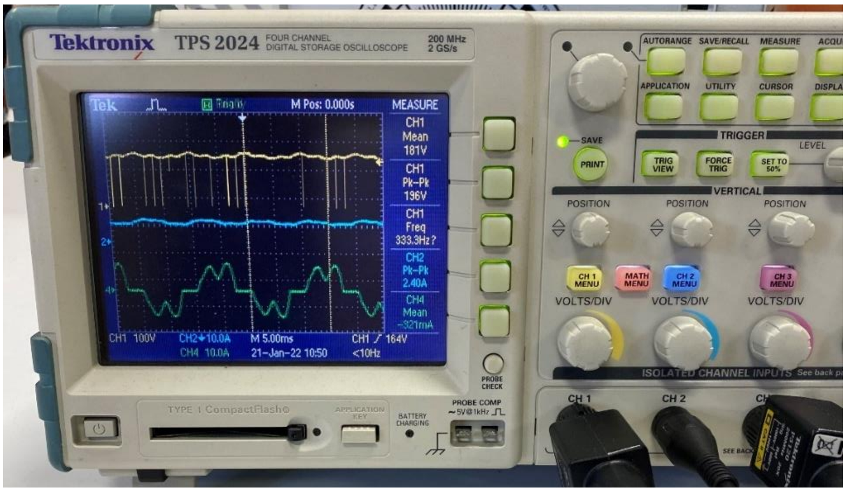

Figure 135: The Voltage and Current Waveforms with No-Load (CCM) from Demo Day

THD analysis of input current can be found in Figure 45.

Figure 46: THD analysis of input current with kettle load from Demo Day

After increasing the duty cycle to achieve 2A output current, motor started to turn and the input voltage, input power, output power and output current values can be found in Figure 47.

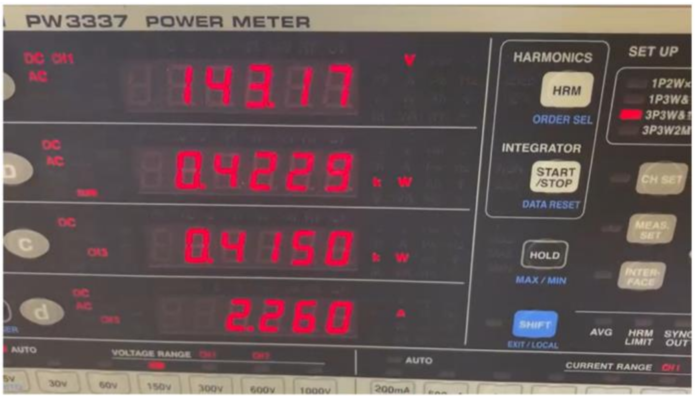

Figure 4714: The Voltage, Current and Power Measurements with No-Load (CCM) from Demo Day

After observing that the motor works with no load case, we connected the motor to kettle load. We increased the input voltage to obtain 2kW of power and to reduce the waiting time. We increased the input voltage to 180V. We obtained 2.1kW of output power and almost 10A output current. Also, efficiency is calculated to be 98%. These values can be found in Figure 48 and Figure 49.

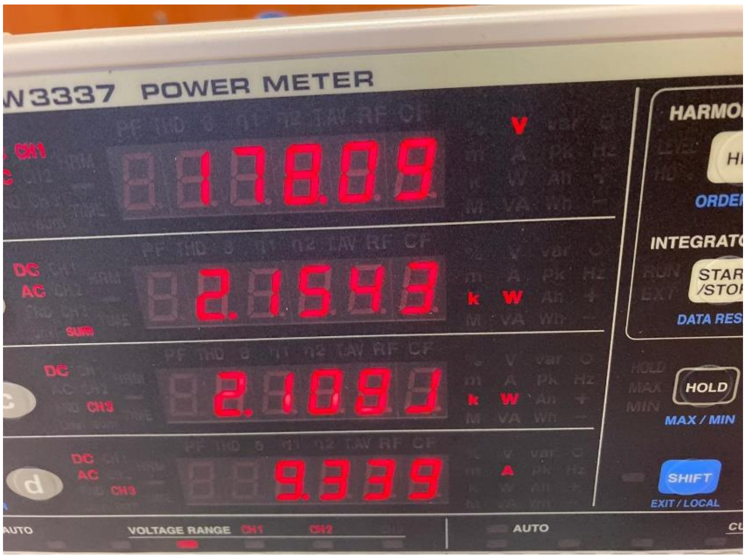

Figure 4815: The Voltage, Current and Power Measurements with Full-Load (CCM) from Demo Day

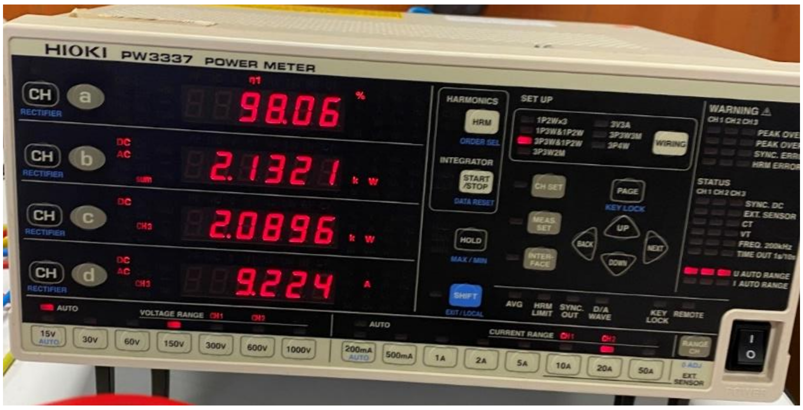

Figure 4916: The Voltage, Current and Power Measurements with Full-Load (CCM) from Demo Day

With these values, we managed to boil the water inside the kettle in 7 minutes and gained the kettle load bonus.

CONCLUSION

In this project we aimed to design a converter that transform AC input to DC and drive the motor positioned at the output of the DC. Firtsly, we analyzed the different topologies and selected the suitable and easy to implement topology. After topology selection, we constructed a gate driver circuit to drive the IGBT which drives the motor. Then, simulations are completed with and without losses. Also, thermal losses are calculated according to the switching frequency. After simulations components are selected according to the simulation results. After this point, hardware implementation part started and test results after implementation is provided in the report.

During the implementation process, some challenges occurred. We have learned that implementation process is harder than the simulation process. In conclusion, this project helped us not to stay only in theoretical knowledge but working on the hardware part also.

APPENDIX

Cost Analysis

# of comp	Component	Model	Price (Dolar)
1	Fan		3.38
1	12.5x12.5 cm Stripe board		0.58
1	3 Heat Sink	Aluminium	1.95 in total
1	3-Phase rectifier diode	Sbr3516a	1.96
1	Igbt	IXGH24N60C4D1	2.79
1	Fast diode	dsep30-06b	1.71
1	Optocoupler	TLP250	0.26
1	Timer	LM555	0.2
1	Capacitor	470mikroFarad	0.043
3	Capacitor	100 nanoFarad	0.129 in total
4	Resistor		0.0094 in total
2	Diode		0.043 in total
2	Potentiometer	10k,100k	0.26 in total
1	Box	3-D	0 (Thanks to Ozan hoca)
7	Connector	black, 4cm,1.1 diameter	1.68 in total
	Total Cost		14.994 Dolar

Important links

3 phase rectifier diode 1.96 dolar

https://www.newark.com/multicomp/sbr3516/diode-bridge-rect-3ph-35a-1-6kv/dp/16AC3472

Igbt **IXGH24N60C4D1** 1.95 dolar(from trendyol) / 2,79 dolar

https://www.ozdisan.com/guc-yari-iletkenleri/igbt/discrete-igbt/IXGH24N60C4D1

https://www.trendyol.com/oemparcaal/ixgh24n60c4d1-p-100768759

Fast diode **dsep30-06b** 2.37/1.71 dolar

https://www.digikey.com/en/products/detail/ixys/DSEP30-06B/1651360

https://www.makermarketim.net/dsep30-06b-hiperfred-30a-600v-30ns-hizli-diyot

Optocoupler TLP250, $0.26 dolar

https://tr.aliexpress.com/item/33022554977.html?spm=a2g0o.search0304.0.0.4da64be0JsTDh0&algo_pvid=c577f12d-a6a6-46ea-8a88-438b5b262575&aem_p4p_detail=2022020704010913997420123009360073640749&algo_exp_id=c577f12d-a6a6-46ea-8a88-438b5b262575-1

Final Product

Final images of the product can be found here.

Project Video Link

Below the link of the project video can be found.

https://youtu.be/wvtaae2TDvc