MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE463 - STATIC POWER CONVERSION I
Hardware Project - AC to DC Motor Drive
Final Report

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1 Introduction

As technology is developed, the necessity for rectifiers and converters increases every day. Three fourth year METU EE Students, named Three Pole Machine introduces AC to DC Motor Drive hardware project.
In this report, first approach and simulation results with component selection for proper operation will be discussed. In the first part of this report, briefly different topologies of AC to DC converters will be compared. Their advantages and disadvantages will be stated. Second part, the topology selection will be announced. Simulation results with ideal cases will be introduced. As there is no ideal cases in hardware implementations, the component selection will be approached by providing a proper margin so that our system does not fail. In the following part, the thermal design specifications and analysis will be reported. Thermal design is crucial since the power losses in the circuit components can cause overheating problems, which can be damaging for the components. In the test results part, the experimental outputs of the driver circuit will be given under resistive load and DC motor load conditions. Finally, in the achievements part, we will share our learning outcomes of the project.
Our main goals from this project are to obtain a robust, simple solution to AC to DC converter. Also, our system should work in longer periods, it should be endurable. To conclude, this project is an implementation of theoretical knowledge of EE463 course. We think that designing such system will develop our engineering skills with problem solution methods.

2 Problem Definition

In the project, it is required to drive a DC motor with AC voltage from variac. Motor will be connected to a DC generator that will be connected to a kettle which will boil water so that we can drink tea.

DC motor can be observed in the Figure 2.1 below:

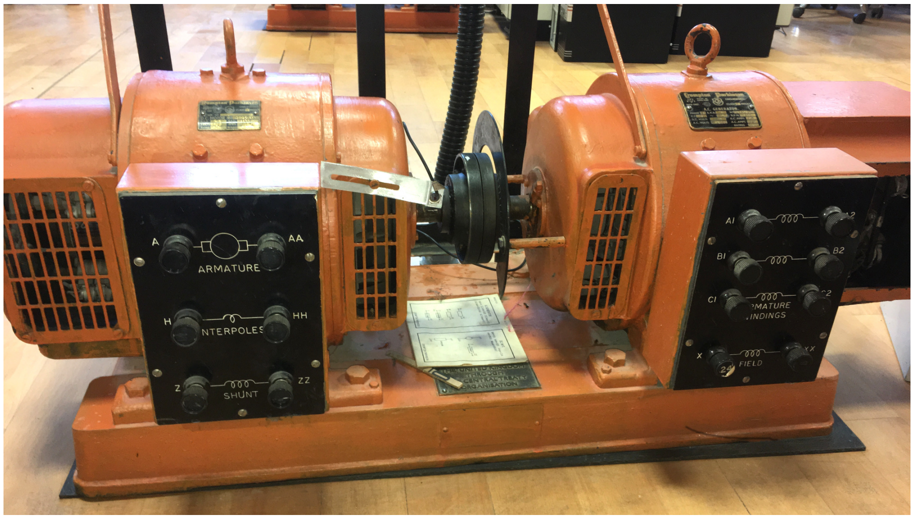

Figure 2.1: DC Motor

Parameters of the DC Motor:

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

Requirements are:

- Input is single-phase or three-phase AC Voltage
- Output, $V_{dc,max} < 180V$

3 A Brief Introduction of Possible Topologies

In the project, topology is chosen among three possible solutions. They are: Single phase fully-controlled rectifier, three-phase fully-controlled rectifier and three-phase diode rectifier with buck converter. In this part, a brief introduction of each topology is provided. Expected theoretical voltage output is calculated.

3.1 Single Phase Thyristor

Thyristor rectifier topologies are generally suitable for high power demanding applications like HVDC transmission systems. The topology consists of 4 thyristors. Its operation is similar to Single Phase Diode Rectifier. However, in contrast to the constant, or in other words uncontrollable, average output voltage characteristic of diode rectifiers, the Single Phase Thyristor Rectifier topology allows controlled operation. The average output voltage of the rectifier can be controlled by adjusting the firing angle of the thyristors. Hence, we can achieve AC to variable DC conversion with this topology. The firing of the thyristors is controlled by applying a pulse signal the gate terminals of the devices. In order to synchronize the firing times of the thyristors, the zero crossings of the input ac waveform should be detected. There should be 180°phase shift between the firing times of the two set of thyristors.

3.1.1 Operation and Structure

The Single Phase Fully-Controlled Rectifier topology is given in Figure 3.1.1.

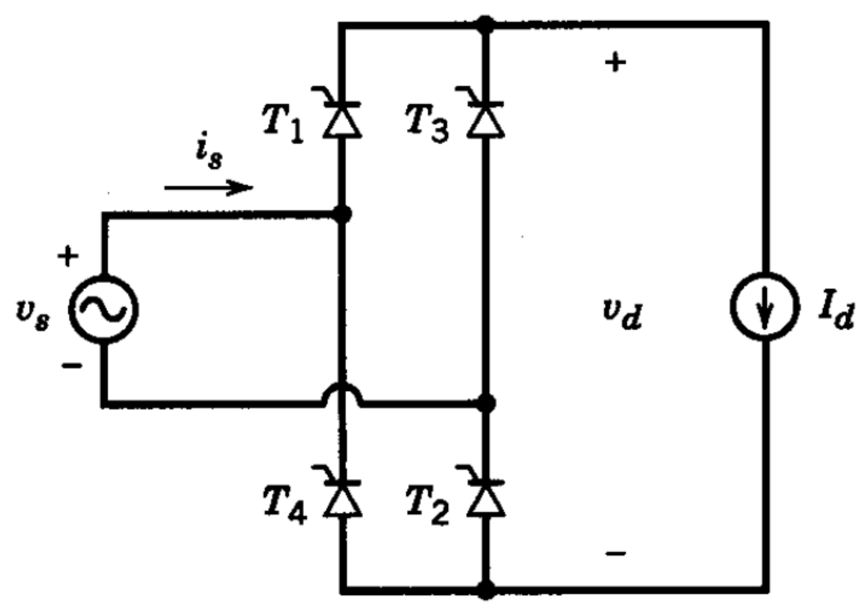

Figure 3.1.1: Single Phase Fully-Controlled Rectifier Structure

During the positive half cycle of the input voltage thyristors T1 and T2 conducts the current after they are fired. In the negative half cycle of the input voltage, the current commutates from thyristors T1 and T2 to thyristors T3 and T4. The zero crossings of the input voltage waveform should be detected to synchronize the firing times of thyristors. By controlling the firing angle of the thyristors, the average of the output voltage can be controlled.

There are basically two operation modes of this rectifier topology: rectification mode and inverter mode. In rectification mode, the average output voltage and current of the rectifier topology is positive. In this mode, power flows from ac (input/grid) side to the dc (output/load) side of the rectifier.

In inverter mode of operation, the average output voltage becomes negative while the output current is still positive. Hence, the power flows from dc (output/load) side to ac (input/grid) side. In other words, the rectifier supplies back power to the grid. In order for this rectifier topology to operate in this mode, there should exist an active source element at the output/load side of the topology.

Theoretical calculation for the average output voltage of the topology is given below:

$$V_{avg} = \frac{2\sqrt{2}}{\pi} V_{ph} \cos\alpha \tag{1}$$

A capacitor with large capacitance value can be connected in the load side of the rectifier in order to filter the output voltage, and reduce the output voltage ripple.

3.1.2 Advantages

- The output voltage can be fully controlled by controlling the firing angles the thyristors.
- The structure of the topology is quite simple. It consists of only 4 thyristors.
- Its operation is also quite simple compared to three phase topologies and buck converter topology.
- It can be operated in four quadrant by connecting two Single Phase Thyristor Rectifier topologies back to back. When it is operated in its inverter mode, the rectifier can supply power back to the grid if an active source is available in the load side of the rectifier. In other words, the output voltage can become negative while the current is still positive.
- Driving the gates of the thyristors in this topology is relatively simple compared to three phase topologies.
- Relatively less number of components are required to construct the topology compared to three phase topologies. Only 4 thyristors and two gate drivers are required. Therefore, the topology is small in size.

3.1.3 Disadvantages

- The output voltage ripple is quite high. The output voltage waveform follows the input voltage waveform. Hence, its ripple is equal to the input voltage ripple depending on the firing angle. In order to reduce the output voltage ripple, a large capacitor should be connected to the output of the rectifier.

- The harmonics in the input current are problematic in this topology. All odd harmonics exist in the input current waveform. This results in high THD value for the input current. In order to reduce the effects of those odd harmonics, a large source inductance should be added to the grid (input) side. However, the addition of the source side inductance effects the commutation time of the rectifier circuit. The commutation time increases with increasing source side inductance.
- In general, driving the gates of the thyristors is quite tedius and troublesome. A driver circuit is required to drive the gates of the thyristors. Also, gates should be fired at precisely correct angles in order to ensure the synchronous operation of the thyristors.
- The zero crossings of the input voltage waveform should be detected to synchronize the firing angles of the thyristors.

3.2 Three Phase Thyristor

Second topology constructed with thyristors is three phase fully controlled rectifier. It is named as it is because with thyristors the output voltage can be controlled without having any dc-dc converter at the output. In the lectures, three phase thyristors are covered, operation philosophy, advantages and disadvantages with explanations can be followed below:

3.2.1 Operation and Structure

In the Figure 3.2.1 below, the topology can be observed:

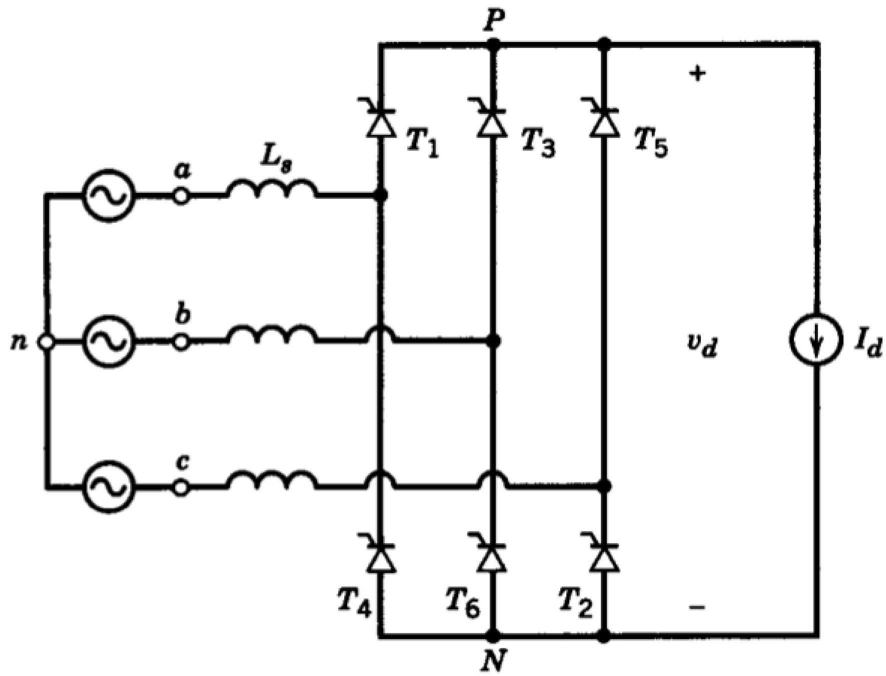

Figure 3.2.1: Three Phase Fully-Controlled Rectifier Structure

In the three phase fully-controlled rectifier, six thyristors are used. Using gate signal generators, thyristors are fired in order to control output voltage. Theoretical calculation of output voltage is below:

$$V_{avg} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha \tag{2}$$

3.2.2 Advantages

- In this topology, output voltage can be controlled without any additional converter.
- Output ripple of this topology is respectively low. In order to decrease the ripple, a lower capacitor can be used in this topology.
- Third harmonic of input current is not observed in this topology. So, THD is respectively low.
- This topology can be used in inverter mode. Therefore, to obtain four quadrant operation, back to back three phase fully-controlled rectifiers can be utilized.

3.2.3 Disadvantages

- This topology is built of six thyristors. Thyristors are expensive components comparing to the normal diodes. Therefore, this topology is more expensive than other options.
- In order to drive this rectifier, six different gate signals have to be used. This requires gate drivers and more components. It increases the cost, and it complicates the structure.
- Synchronization of gate drivers is hard. A zero crossing detector should be used in order to control it, it increases the cost and it makes the topology difficult.

3.3 Three Phase Diode Rectifier with Buck Converter

3.3.1 Operation and Structure

This topology consists of two parts. First part rectifies three phase ac grid voltage to low-ripple dc voltage. In the second part, we apply a buck converter and control our output voltage with duty cycle of switch. The first part of this topology is three phase diode rectifier. In the Figure 3.3.1 below the topology of three phase diode rectifier can be observed.

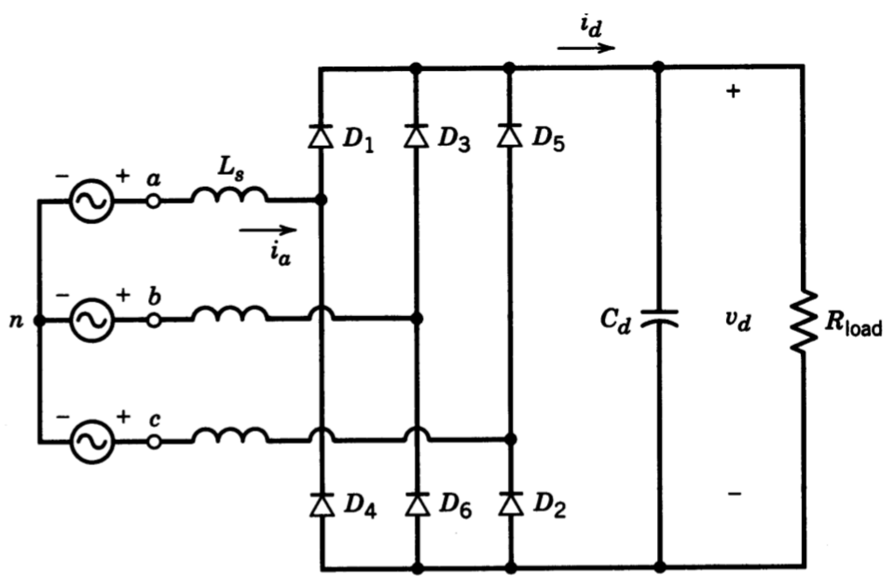

Figure 3.3.1: Three Phase Diode Rectifier Structure

In three phase diode rectifier, one of upper diodes and one of bottom diodes conducts according to the phase voltage levels. In this topology we have no control of average output voltage. Below, theoretical output voltage can be observed.

$$V_{avg} = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{3}$$

In the Figure 3.3.2 below, topology of step down converter can be examined.

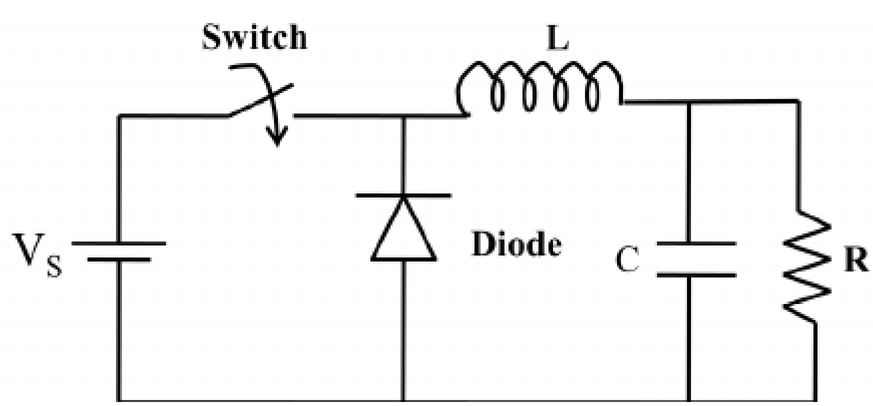

Figure 3.3.2: Buck Converter Structure

Second part of this structure is buck converter. Buck converter basically step downs the input dc voltage to a desired level. In order to control output voltage, a MOSFET driven by a gate signal generator is used. Below, theoretical output voltage can be observed, D stands for duty cycle.

$$V_{out} = DV_{in} \tag{4}$$

Connecting diode rectifier and buck converter results in average voltage:

$$V_{avg} = \frac{3\sqrt{2}}{\pi} V_{LL} D \tag{5}$$

3.3.2 Advantages

- In this topology output voltage ripple is respectively low.
- This topology requires only one gate signal which will be provided to drive buck converter. Thus, this is system is less complicated comparing to other topologies. Also, in this topology there is no need of synchronizing the signals.

- This topology consists of six diodes and a buck converter, this system is less expensive comparing to thyristor rectifiers.
- Since our motor is an LR load, we do not need to construct LC filter at the output of buck converter. This means this topology can be built easier.

3.3.3 Disadvantages

- This topology does not support four quadrant operation. Diode rectifier can work in only one quadrant, so there is no way to obtain four quadrant.
- Theoretically, the expected efficiency is lower than thyristor cases because we use external diode in the buck converter.

4 Topology Selection and Reasoning

In the second part of this report, all possible topologies are discussed. Regarding the advantages and disadvantages of each possible solution, Three Pole Machine decided to continue with three phase diode rectifier with buck converter.

We made this decision because it is easier to drive, less expensive and it is more appropriate for low voltage applications such as motor drive. In the following sections, calculations, simulation results and component selection will be provided.

5 Simulations

In this part, simulations of the selected topology will be provided. Simulations will be provided in three parts, in the first part we provide three-phase diode rectifier simulations and results. In the second part buck converter results and simulations are provided. In the last part, the circuit as a whole will be examined.

5.1 Simulations of Three Phase Diode Rectifier

In the Figure 5.1.1 below, schematic of Simulink simulation can be observed. This simulation is constructed with a single resistance at the output. This simulation does not contain line impedances, and diodes are ideal.

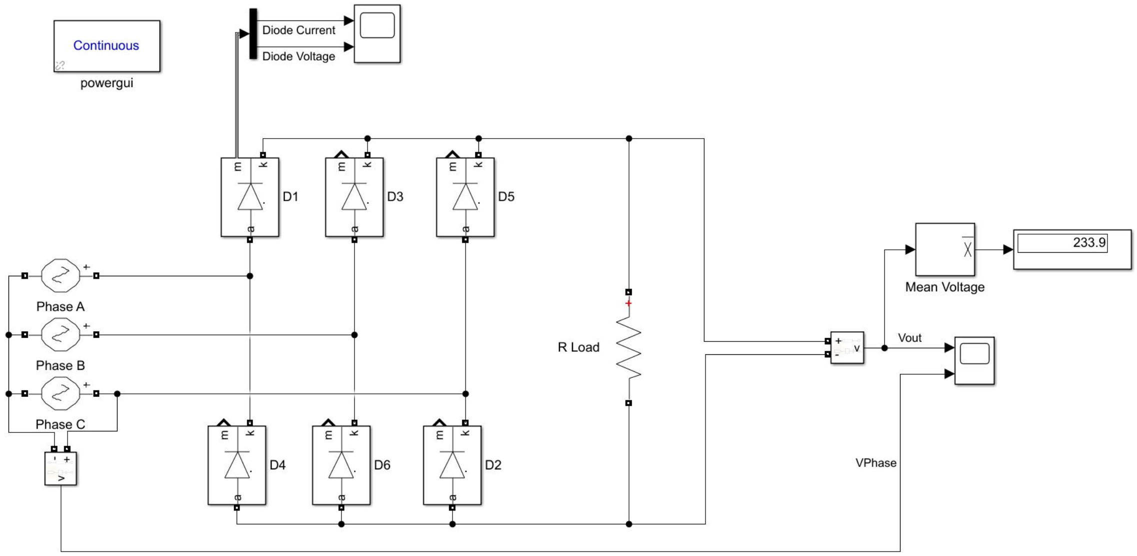

Figure 5.1.1: Schematic of Three Phase Diode Rectifier

It is given that the output voltage of the whole converter V_{max} must be less than $180V_{dc}$. We limited the duty cycle of buck converter to 80%. Then, $V_{rectifier,av}$ can be calculated as below formula.

$$V_{in,buck} = V_{rec,ac} = \frac{V_{out}}{D} = 225V$$

V_{RMS} can be calculated as:

$$V_s = 225\frac{\pi}{3\sqrt{6}} = 96.2V_{rms}$$

So, the input voltage was chosen as $100V_{rms}$

In the Figure 5.1.2 below, input phase voltage and output voltage can be observed.

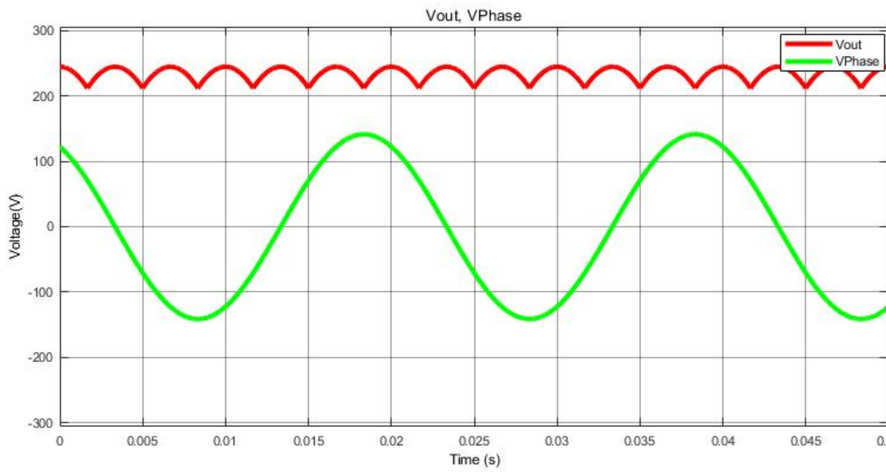

Figure 5.1.2: Voltage Output and Voltage Input of Three Phase Diode Rectifier

Input voltage of a three-phase diode rectifier has frequency of 50, Turkish Grid Frequency. However, as we observe in the output, output has six times of input frequency. Thus, this topology can be named as six pulse diode rectifier. Output voltage ripple is respectively low in this case. It can be simulated as 32.8 V. Moreover, this topology does not have triplen harmonics in input current. This results in lower THD, and better power quality. THD of this topology is simulated as 31.8%

Input and output current waveforms can be observed from Figure 5.1.3 below.

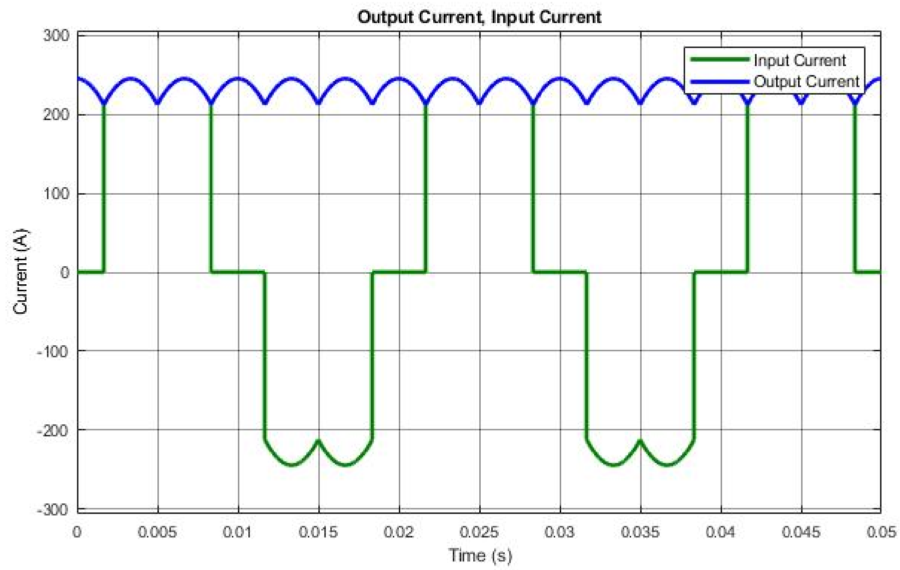

Figure 5.1.3: Input Current and Output Current of Three Phase Diode Rectifier

Component selection will be based on stresses and limits. In the Figure 5.1.4 below, diode stresses can be observed.

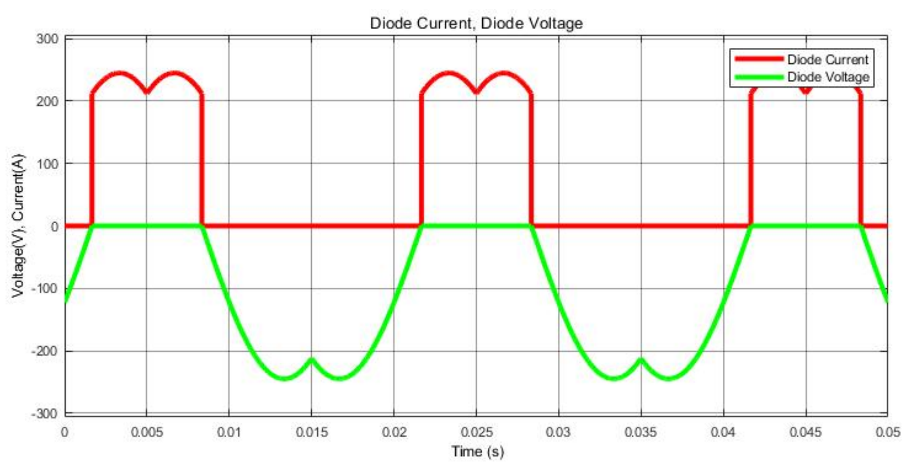

Figure 5.1.4: Diode Current and Diode Voltage of a Diode

It is obvious that our diodes have to be able to carry peak current of 250A. However, this stress is for the ideal case with output resistance of 1Ω. This value will be less when we add the buck converter, and the DC Machine. Also, our diodes should have reverse voltage of minimum -250V.

5.2 Simulations of Buck Converter

The Simulink simulation schematic of the Buck Converter circuit topology is given in Figure 5.2.1. The topology is simulated to observe the output voltage and current waveforms, diode current and voltage waveforms and MOSFET voltage and current waveforms.

In the simulations, the switching frequency of the MOSFET is chosen 1 kHz with 10% duty cycle. Since initially dc motor is at standstill, there is no back emf produced by the motor, which will limit the output current of the Buck Converter. Therefore, we should be careful about the start-up current of the dc motor. In order to limit the output current at start-up, we have decided to initially set the duty cycle of the control signal to be 0.1 . Thus, it is ensured that the output current does not exceed the rated current of the dc motor, which is provided 23.4 A. We plan to steadily increase the duty cycle of the control signal from 0.1 (10%) to 0.8 (80%) in a finite duration until the back emf of the motor builts up while it is reaching its rated speed, and hence reach steady state condition. Thereafter, we can control the output dc voltage of the converter circuit to obtain variable DC output converter. The input voltage is applied from a dc voltage source with 225 V as computed in the subsection 4.1. Since the dc motor itself is a big RL load, it is thought to be unnecessary to add an LC filter at the output for the Buck Converter. Hence, we have modelled the buck converter without LC filter at the output. The output of the Buck Converter circuit is loaded with the resistance (R) and inductance (L) ratings of the DC Motor to be driven. A dc voltage source representing the back emf voltage of the dc motor is also added at the output. However, it is set to 0.1 V in order to obtain the start-up current and voltage waveforms of the output load, MOSFET and freewheeling diode. The observed peak and average values of the current and voltage waveforms across the MOSFET and diode in simulations will be used in the component selection part to select the components with the suitable ratings to our circuit.

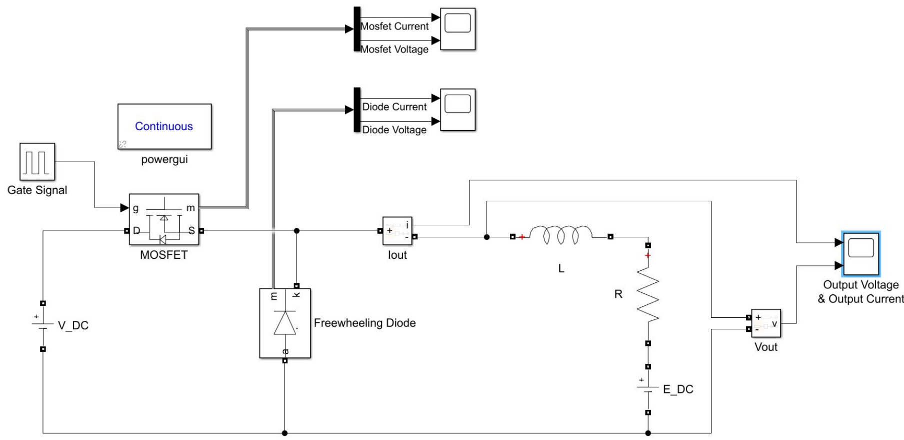

Figure 5.2.1: Schematic of Buck Converter

In the Figure 5.2.2, the output voltage and current waveforms of the Buck Converter circuit, obtained from simulations, are given.

At the output of the Buck Converter, a square wave voltage waveform is observed. The ripple in the output voltage is measured to be close to 225 V. However, the ripple in the output current of the circuit is quite small.

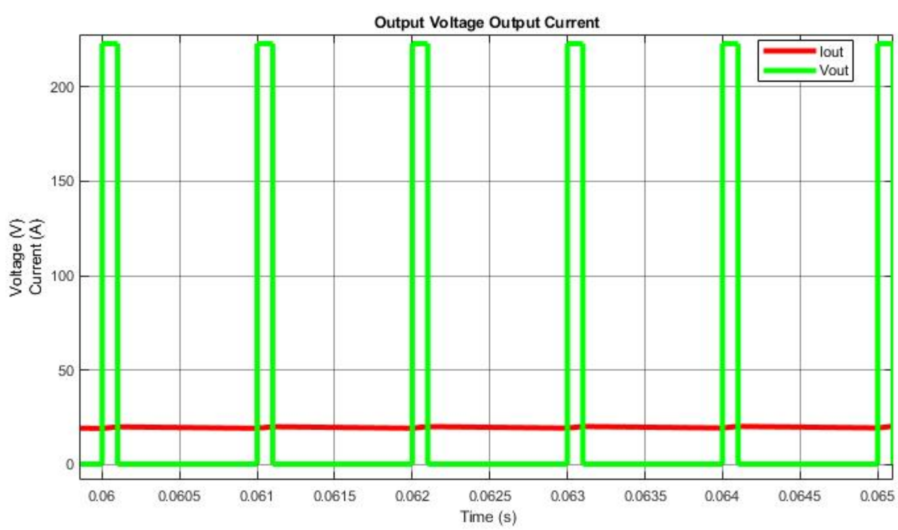

Figure 5.2.2: Buck Converter Output Voltage and Output Current Waveforms

MOSFET voltage and current waveforms are given in Figure 5.2.3 below.

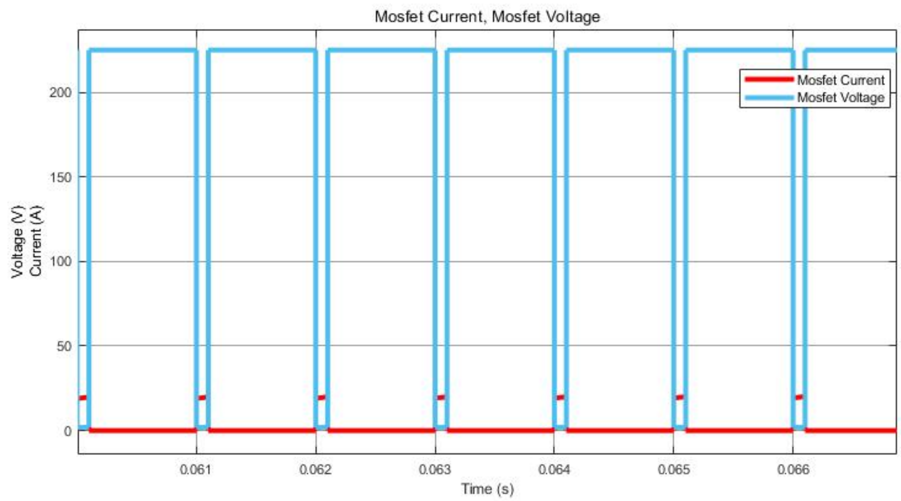

Figure 5.2.3: MOSFET Voltage and Current Waveforms

The Figure 5.2.4 shows the voltage and current waveforms across the freewheeling diode.

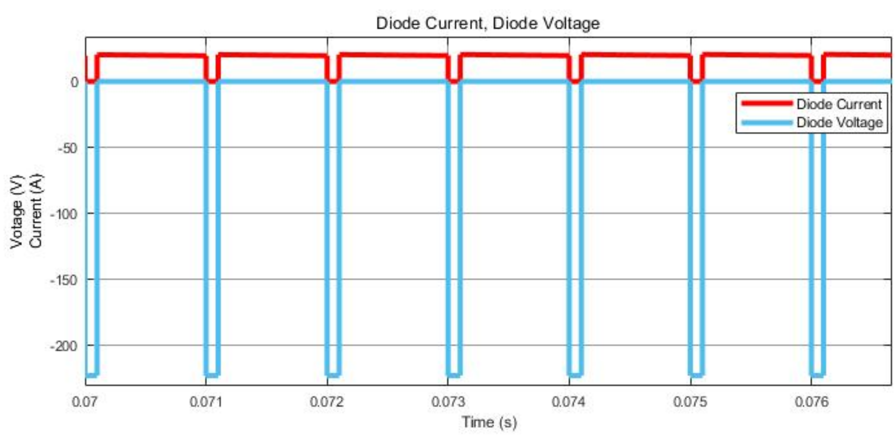

Figure 5.2.4: Freewheeling Diode Voltage and Current Waveforms

5.3 Simulations of Rectifier & Buck Converter

In the Figure 5.3.1 below, we can observe the whole circuit consists of diode rectifier and buck converter. In the schematic, we used an RL load with dc voltage, it is basically a motor model. Displays show average values of diode voltage and inputs. This values are critical for component selection.

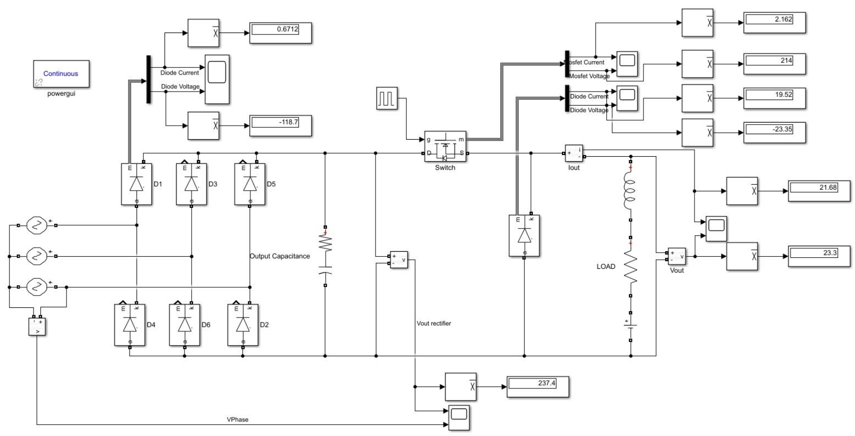

Figure 5.3.1: Schematic of Whole Circuit

In the Figure below 5.3.2, output voltage and current for start up can be observed. It is taken at duty cycle of 0.1

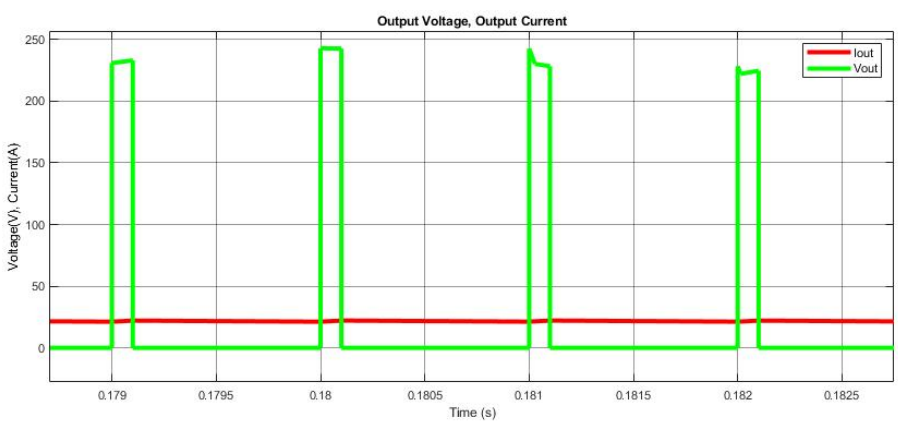

Figure 5.3.2: Output Voltage and Current Waveforms of Converter

In the Figure 5.3.3 below, we can see transient waveform of the input diode. At start-up, maximum current is around 24 Amperes, and reverse voltage is around -250 Volts.

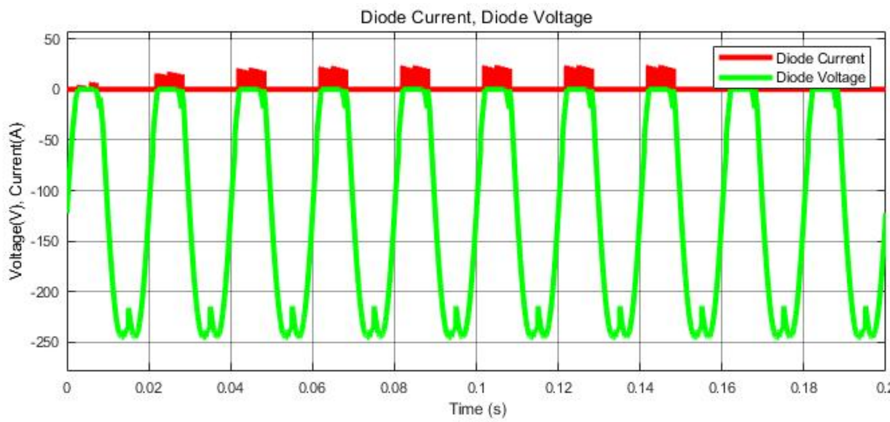

Figure 5.3.3: Rectifier Diode Voltage and Current Waveforms

In the Figure 5.3.4 below, we can observe MOSFET stresses, average current is around 3 Amperes and blocking voltage is around 214 Volts at start-up.

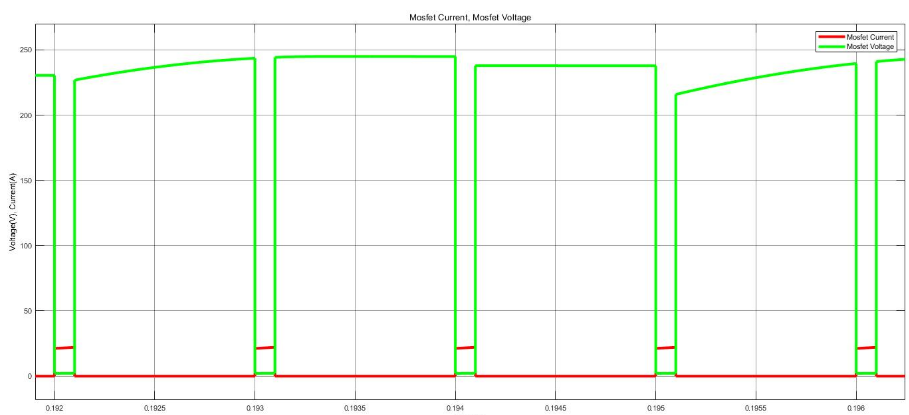

Figure 5.3.4: MOSFET Voltage and Current Waveforms at Start-Up, D=10%

In the Figure 5.3.5 below, we can observe the freewheeling diode stresses, average current is around 25 Amperes and blocking voltage is around 220 Volts at start-up.

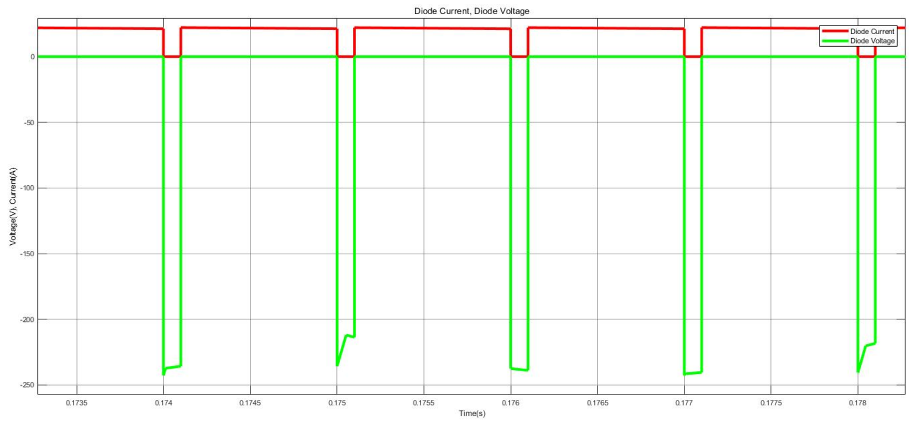

Figure 5.3.5: Freewheeling Diode Voltage and Current Waveforms at Start-Up, D=10%

In the Figure 5.3.6 below, we can observe the freewheeling diode stresses, average current is around 20 Amperes and the reverse voltage is around 25 Volts at steady-state.

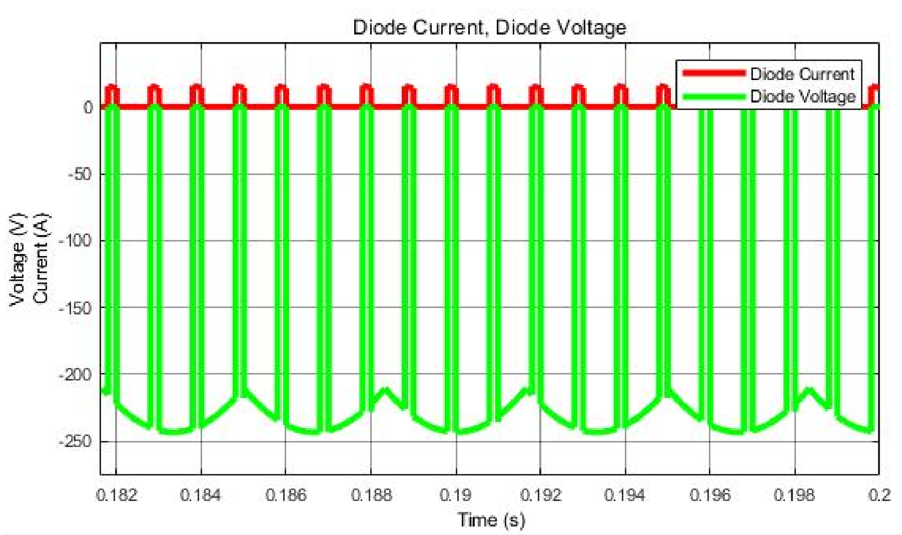

Figure 5.3.6: Freewheeling Diode Voltage and Current Waveforms at Steady State, D=80%

In the Figure 5.3.7 below, we can observe the MOSFET stresses, average current is around 12 Amperes and the reverse voltage is around 50 Volts at steady-state.

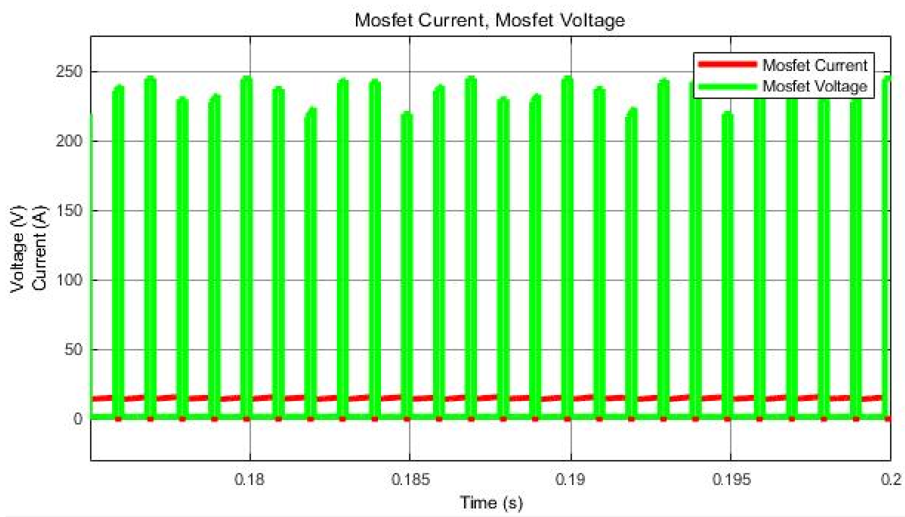

Figure 5.3.7: MOSFET Voltage and Current Waveforms at Steady State, D=80%

Simulations show that, critical points that need attention is:

- At start-up, current of freewheeling diode and voltage of MOSFET is critical. We paid attention when we select the components.
- At steady-state, voltage of freewheeling diode and rectifier's diode current is critical. Also, MOSFET's current is critical. We paid attention to these parameters

6 Component Selection

We have simulated the Simulink Model such that input voltage and currents are similar to rated values. After completing the simulations, we have selected the components that we are going to use in the project.

Since the "Buck Converter" MOSFET will conduct at around 80% duty cycle after reaching rated speed, we decided to select a MOSFET that can carry up to 25-30 A average current. The voltage rating of the MOSFET must be bigger than 250V according to the simulation results. When we looked at the available components in the laboratory, we thought that IXGH24N60C4D1 N Channel IGBT Transistor can be a good selection for us.

To decide which diode that we will use, we have followed the same procedure. The free-wheeling diode in the buck converter will carry at 90% duty cycle at start up. Therefore, it can carry 25 A current. The reverse voltage of this diode reaches up to 200 V average at rated speed and has 250V peak value. Providing required voltage and current rating, DSEI30-06A has been selected for the free-wheeling diode of the buck converter.

The simulation results imply that diodes on the rectifier will carry average 10 A current which has 20-25 A peak value. Reverse voltage of rectifier diode has peak value of 245 V which is the peak of applied line to line voltage. By considering all these requirements, DSEI12-06A is a good selection for rectifier diodes.

We decided to use two 3300uF 400V capacitor in parallel at the output of the rectifier. 330 uF Capacitor.

7 Gate Driver Design

For the IGBT of the buck converter, a gate driver circuetry is required. We have created the required PWM signal using Timer555 IC. PWM generating circuitry can be seen in Figure 7.0.1. As shown in the Figure 7.0.1, we have used a potentiometer to control duty cycle of the timer output. Then, we have connected a TLP250 gate driver IC to provide enough current for the gate of the IGBT. Connections of the TLP250 can be seen in figure 7.0.2.

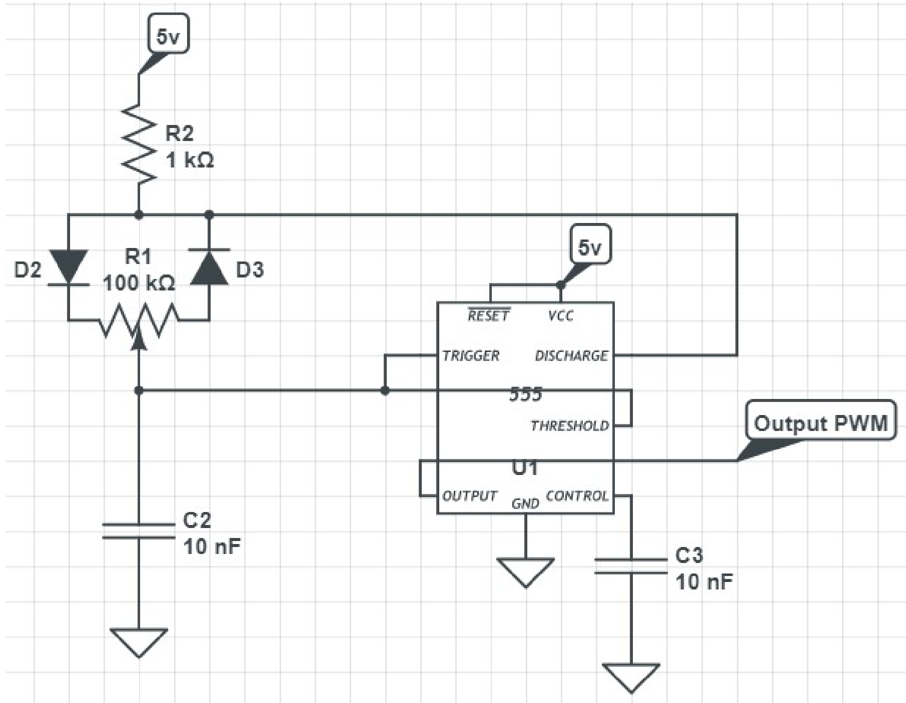

Figure 7.0.1: Timer 555 PWM Generator Circuit

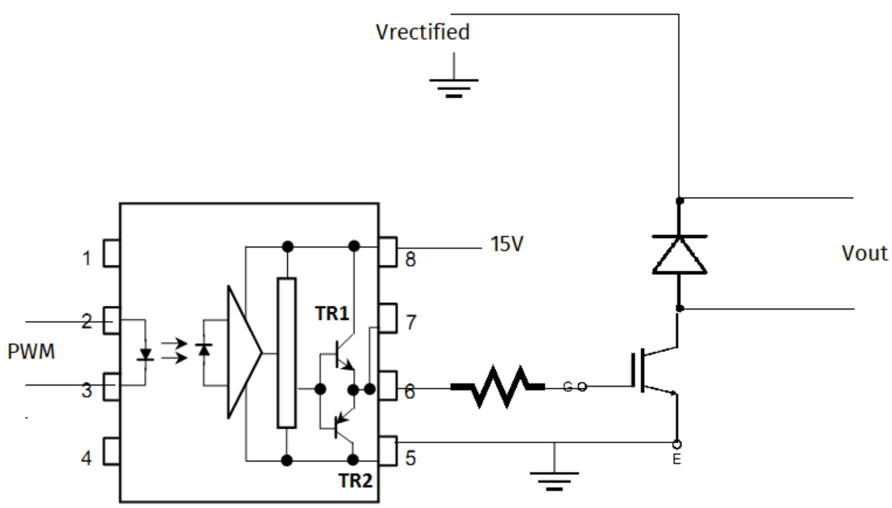

Figure 7.0.2: TLP250 Gate Driver Circuit

8 Thermal Analysis

In this part of the report, thermal analysis of the selected components are presented. We have first determined the losses of each component, then we have modelled them to find required heat sinks to obtain reasonable component temperature. Conduction and switching losses of the IGBT and freewheeling diode is calculated using below formula.

$$P_{conduction} = V_{on} I_{on} D \tag{6}$$

$$P_{switching} = (E_{on} + E_{off}) f_s \tag{7}$$

Output current I_o=10A for full load operation. For this current value, V_{CE}=1.5V, E_{on}=0.4mJ, E_{off}=0.3mJ are obtained from data-sheet. P_{IGBT} can be calculated as:

$$P_{IGBT} = 1.5V * 10A * 0.8 + (0.3mJ + 0.4mJ) * 1kHz = 12.7W$$

$V_{D,on}$=1.5V is given in the data-sheet of the diode. However, E_{on} and E_{off} parameters are not specified. Hence we have only considered the conduction losses. 10A current conducts when duty cycle is 0.8, so we take D=0.2 for the diode. P_{diode} can be calculated as:

$$P_{diode} = 1.5V * 10A * 0.2 + = 3W$$

Maximum junction temperature of T_j=150°C is allowed for both diode and IGBT.$R_{j-c,IGBT}$=0.65°C/W and $R_{j-c,diode}$=2°C/W. Taking T_{amb}=30°C and T_j=120, we have calculated the required heatsink thermal resistances as follows:

$$R_{th,IGBT} = \frac{(120-30)^{\circ}C}{12.7W} = 7.09^{\circ}C/W$$

$$R_{heatsink,IGBT} = 7.09^{\circ}C/W - 0.65^{\circ}C/W = 6.44^{\circ}C/W$$

$$R_{th,diode} = \frac{(120-30)^{\circ}C}{3W} = 30^{\circ}C/W$$

$$R_{heatsink,diode} = 30^{\circ}C/W - 2^{\circ}C/W = 28^{\circ}C/W$$

The heatsinks that we have found does not have datasheets. Therefore, we have selected a relatively large one and tested it with low output currents. It worked fine with 2-3A output current which is the required current to drive DC motor at no load. On demo day, when DC motor was driven at no load, temperatures of the components were fine. However, at full-load temperature of the IGBT increased so fast and we have cooled it by creating air flow on the heatsink.

9 Test Results

In this section, we provide the test results and observations of the overall circuit under different conditions.
In our circuit board design on pertinax, we decided to implement the IGBT switch at the low voltage side although the simulations results are provided with the switch implemented at the high voltage side. Both configurations provides the same input & output characteristics, but the low voltage side implementation is advantageous in terms of isolation requirements. For this reason, we thought that the low voltage side implementation of the IGBT switch would be more convenient solution.

9.1 R-Load Test

We, first of all, tested the gate driver circuit of the IGBT. After being sure that the gate driver circuit is operating properly, the overall circuit is tested under low voltage with resistive load. The test results of the gate signal, output voltage and output current of the circuit is given for both 80% and 10% duty ratio in Figure 9.1.1 and Figure 9.1.2, respectively. In the figures, CH1 shows the gate signal of the IGBT, CH3 shows the output voltage of the Buck Converter and CH4 represents the output current of the Buck Converter.

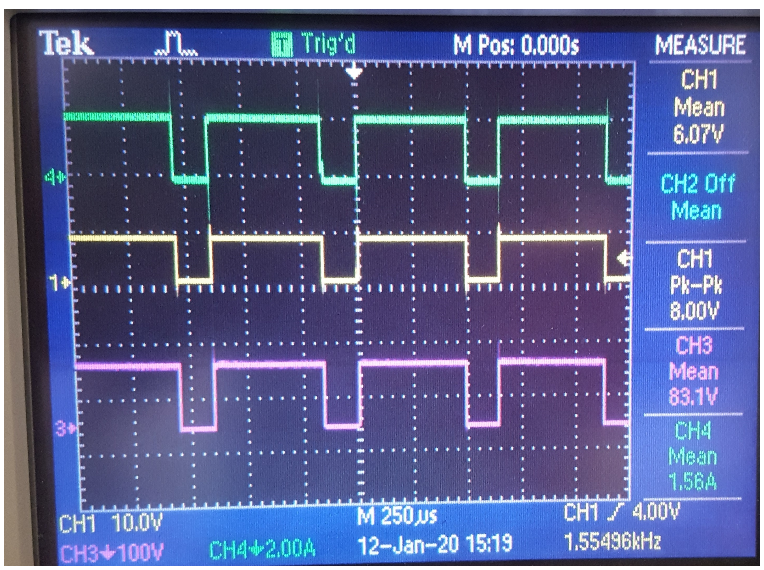

Figure 9.1.1: Gate Signal and Output Voltage & Current Waveforms for 80% Duty Ratio

Figure 9.1.2: Gate Signal and Output Voltage & Current Waveforms for 10% Duty Ratio

The DC-Link voltage at the output of the Three Phase Rectifier is provided in Figure 9.1.3, below.

Figure 9.1.3: Three Phase Rectifier Output Voltage Waveform

In order to decide whether we need a snubber design for the IGBT, we observed the collector to emitter voltage of the IGBT under resistive load conditions. The collector to emitter voltage waveform of the IGBT is given in Figure 9.1.4. As shown in Figure 9.1.4, the voltage ripple between the collector and emitter terminals of the IGBT is observed to be around 4 V for 60 V DC-Link input voltage. If we scale this ripple value for the maximum DC-Link input voltage in our design, which is 225 V, it is expected to have around 15 V ripple over the IGBT terminals. As a result, in total, our IGBT should be able to block at least 240 V. Since the IGBT we used in our design has a voltage rating of 600 V, which is safely over 240 V, we concluded that it was not necessary to design an snubber circuit for the IGBT.

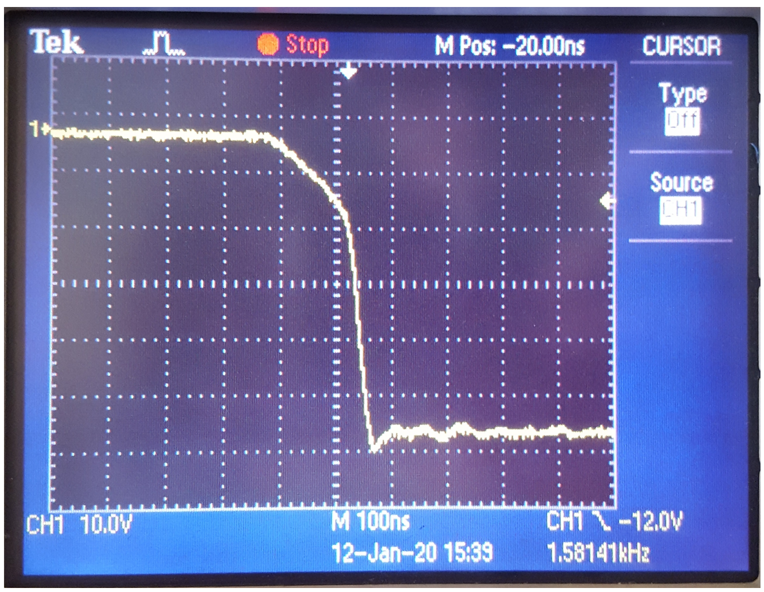

Figure 9.1.4: Collector to Emitter (V_{CE}) Voltage Waveform of the IGBT

9.2 Demo Day Test Results

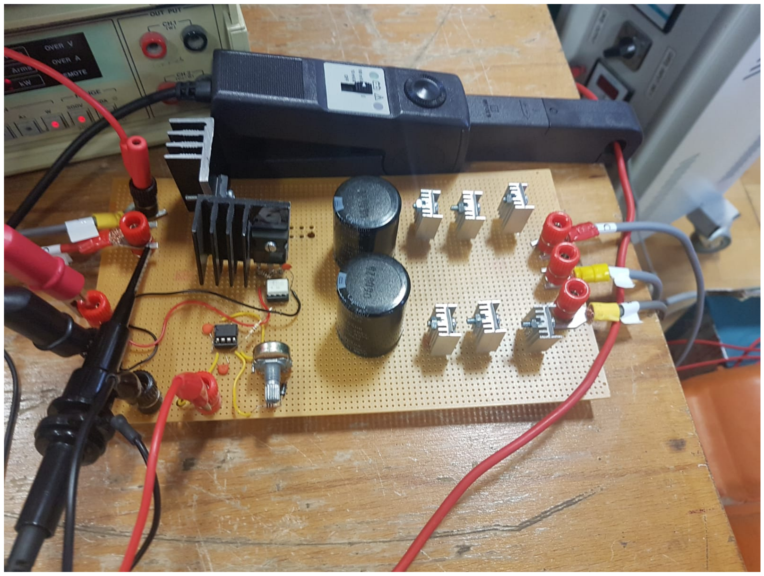

Figure 9.2.1: Demo Day Test

On the Demo Day, we tested our converter circuit connected to DC motor under both no-load and full-load conditions.

9.2.1 DC Motor No-Load Test

In order to test the converter circuit connected to DC Motor under no-load conditions, we applied three phase AC voltage from the variac to the three phase input of the rectifier circuit at the input side. We applied soft start by increasing the variac voltage slowly from zero to 150 V line-to-line. Hence, the DC-Link capacitors, connected in parallel, at the output of the three phase rectifier are allowed to charge gradually at the start-up. In addition, for the soft start of the DC motor, initially we set the duty ratio of the gate signal of the IGBT to nearly zero. Then, the duty ratio is increased gradually to 80% in order to let the back emf voltage of the DC motor to built up slowly without drawing dangerously high currents. The output voltage waveforms of the converter circuit under testing conditions are given in Figure 9.2.2 and Figure 9.2.3 for two different duty ratio values.

During testing sessions, for 180 V average output DC voltage, the rotational speed of the DC motor is measured as 1310 rpm.

Figure 9.2.2: Output Voltage Waveform for Low Duty Ratio

Figure 9.2.3: Output Voltage Waveform for High Duty Ratio

9.2.2 DC Motor Full-Load Test

While running in the no-load, suddenly a load "kettle" is attached to the output. The rated power consumption of the load is 2kW. As it is expected, the rotational speed of the DC motor decreased. The decrease in the rotational speed was $1310 - 1220 = 90rpm$, which is approximately %7. This decrease is expected because input power did not change even if we added a load to the output side. Output power of a DC motor is defined as $P = T * \omega$ so increasing torque means a decrease in the speed. Our full-load rotational speed was $1220rpm$.

Efficiency of a motor drive is so vital. In practical cases it is observed that almost %98 efficiency can be achieved by motor drives. So, it is expected to have a high efficiency. In our tests, we experimentally observed that at full-load $\frac{P_{out}}{P_{in}} = \frac{1.652W}{1.73W} = \%95.5$ This results can be seen in the Figure 9.2.4 below.

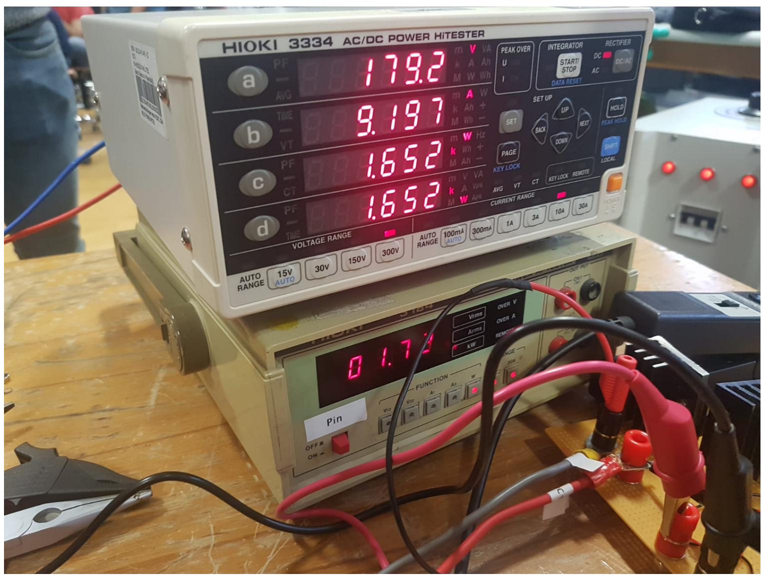

Figure 9.2.4: Input and output power of the motor drive, experimentally

The output voltage and current waveforms of the drive circuit can be observed from Figure 12.0.4.

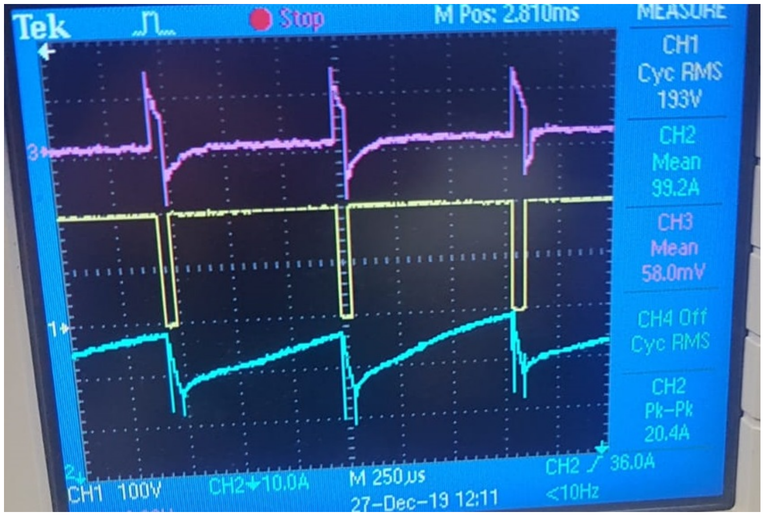

Figure 9.2.5: Output Voltage and Current Waveforms

In the demo sessions, thermal concerns were the number one problem. As load connected to the system and duty cycle increased, the heat dissipated on the IGBT is increased. The maximum temperature that IGBT can operate was 150°C, so it was crucial not to exceed that temperature. In the demo, the temperature of the IGBT kept at 80 °C. Figure 9.2.6 can be observed below.

Figure 9.2.6: Thermal capture of the motor drive, experimentally

10 Achievements

1. Firstly, we learnt how to design circuits at the high voltage and high current.
2. We learnt that ratings of electronical components are so crucial in power electronics. All components should be selected according to the needs of the circuit that is going to be developed. Any worst case should be taken into account with a proper margin in order not to have burn-outs and circuit failures.
3. All team members, especially Emre, learnt how to do proper soldering on pertinax.
4. Gate drivers of IGBT and MOSFET are analyzed in order to find a proper solution in the drive circuit. In this gate driver design we encountered with several problems. While dealing with these problems, we learnt that
   (a) Isolation is important in power electronics, all circuits that need isolation should be designed properly.
   (b) Parasitic inductance of the gate of IGBT and MOSFET can be dangerous and problematic in some ways. In order to avoid this problems, the distance between gate driver and gate pin should be minimized as much as possible.
   (c) Gate driver output resistance is important because the transient time during switching the IGBT results in switching losses. Longer switching period creates higher losses and higher heat dissipation in the circuit.

5. Thermal design is so important in the power electronics, proper heat sink selection and implementation on the circuit plays an essential role in the design. It is obvious that a nice layout and a successful positioning increase thermal performance. During the tests that we conducted with our circuit, we observed that the IGBT was the most problematic component in terms of overheating since it had to carry high current for longer periods at steady-state operation (at high duty ratio), which resulted in high conduction losses as well as switching losses.

6. In order to decrease inductive effects of the cables, the distances between all the component should be minimized. If possible, PCB is more proper.

7. Overshoots at the switching node voltage due to ringing effects of the parasitic capacitors and inductors should always be taken into account so that no problem occurs in the operation. The overshoot can be dangerously high and give severe damage to the semiconductor devices like IGBTs and diodes. Therefore, a proper snubber design can be needed in some circuits. Although it was possible to design a snubber circuit, our design was already working properly since the voltage and current ratings of our components were well over the critical overshoot voltage and current levels that occur in the circuit. So, we did not build one.

8. Capacitors with high voltage ratings should always be left discharged. A high resistance can be used in order to discharge the capacitor.

9. It is generally a good practice to connect multiple capacitors in parallel at the rectifier output instead of connecting single huge capacitor. This helps to reduce the ESR value of the capacitors and hence improve DC-Link voltage at the output of the rectifier circuit. Also, it provides more secure operation. In case of a faulty condition occuring in one of the capacitors, the other capacitor(s) can maintain the proper operation of the circuit.

11 Conclusion

In this project, our goal was to drive a DC motor with AC input. In this report, we, first of all, compared and evaluated different driver topologies. Then, we explained our topology selection and provided the simulation results of the selected topology. The required components were selected according to the simulation results with proper voltage and current ratings. The necessary gate driver circuitry for the switch was explained in detail. Thermal analysis of the power components was conducted. The test results for the overall drive circuit were provided. Finally, we presented the achievements that we obtained during the implementation of this project.

Starting with the comparison of different topologies, we acquired general information about AC to DC converter topologies and their working principles. We learnt how to utilize simulation results in the design process and component selection of the project. During the implementation process, we experienced that the hardware design requires more attention and effort than software simulations. Hence, this experience helped us to learn practical tips and how to implement them in our design. In general, it has been a learn-by-doing process for us. In conclusion, by implementing this project, we have improved our practical skills by utilizing the theoretical knowledge obtained from the EE463 course.

12 Appendix

The project video link is provided below.

Video Link: https://youtu.be/YZUBasKc0Og

The photos of the overall circuit taken from various angles are provided in the following figures.

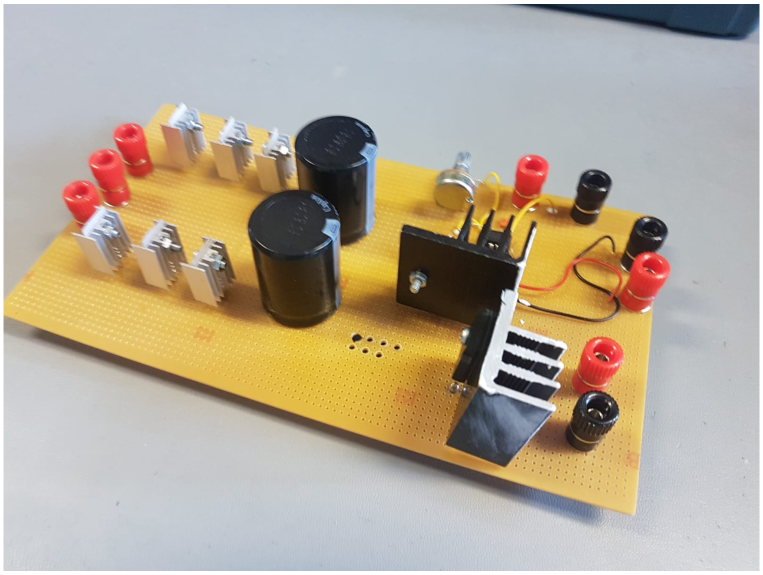

Figure 12.0.1: Isometric view of the overall driver circuit on pertinax

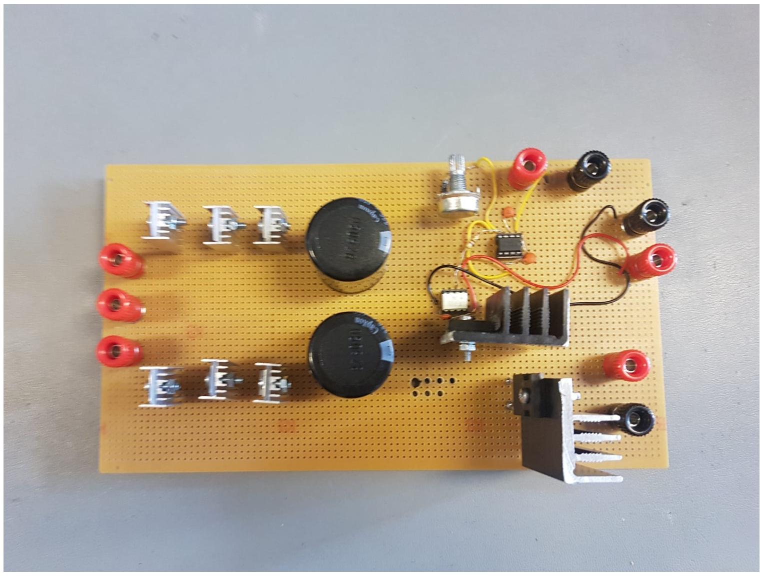

Figure 12.0.2: Top view of the overall driver circuit on pertinax

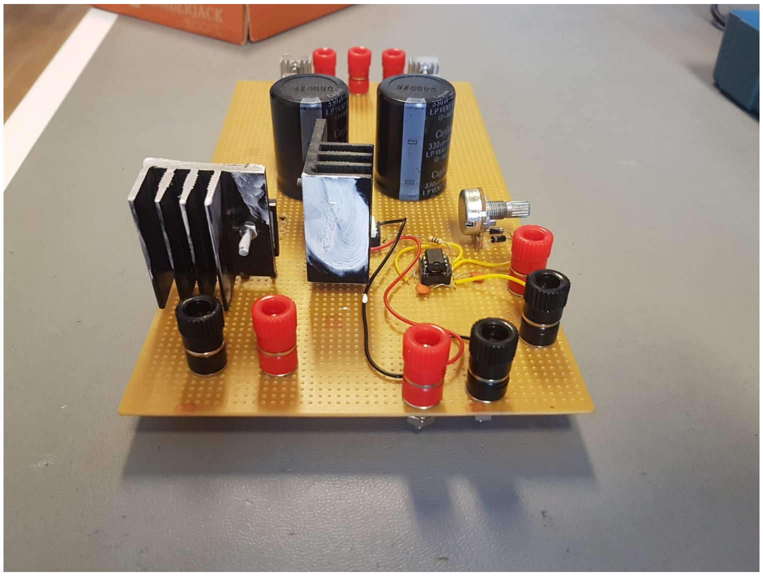

Figure 12.0.3: Back view of the overall driver circuit on pertinax

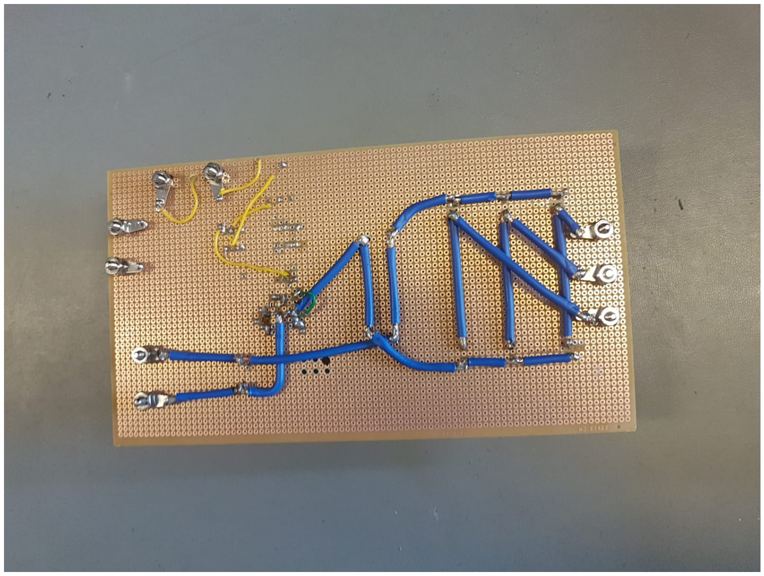

Figure 12.0.4: Bottom view of the overall driver circuit on pertinax