MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

EE463 Static Power Conversion-I
Hardware Project

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23.01.2019

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I. INTRODUCTION

This report presents the hardware project for the course EE463 Static Power Conversion-I. In this project, a controlled DC motor driver is designed and implemented. For all of the topologies that can be chosen, the power input is 3-phase or single-phase AC grid and the output should be a DC voltage with adjustable value whose maximum is at least 180 V.

In this report, the designed driver is presented and the system description is made by all of its aspects. Firstly, the reasoning of the topology selection will be made. Then the circuit design will be presented with some simulations results in Simulink. The component selection will made accordingly and the behaviour of the implemented system will demonstrated with some test results. Finally, a conclusion part which will highlight the key points will be included at the end.

II. DESIGN DECISIONS

In this project, we are required to design a dc motor driver. The maximum value of the adjustable dc output of the driver must be higher than 180 V. We are expected to the start the motor from standstill to its rated speed under no load and run at rated speed for 2 minutes.

There are three different topologies that can be used for the purpose of constructing a controlled motor driver. Each of these will be examined in the following parts and the topology that we used is also determined.

A. Topology Selection

For a controlled motor drive operation, there are three different topologies that can be used, namely 3-Phase thyristor rectifier, single phase thyristor rectifier and diode rectifier with a Buck converter whose AC-DC converter parts can be seen in Figure 1.

To be able to choose the best topology for our purpose, these three are compared. It can be concluded that even though their ripple at the output voltage will smaller, the topologies which are composed of thyristors need gate driving circuitry which can be utterly difficult to implement. In order to excite the thyristors, 555 timers in astable oscillator mode are considered. However, their duty cycle does not operate from 0% to 100%. Also, it is very tedious to synchronize the firing angle with the grid. Moreover, diode rectifiers are more commercially available and hence there is no need to buy distinct elements and to construct the rectifier circuit.

Consequently, for the purpose of ease of implementation, diode rectifier with buck converter is chosen.

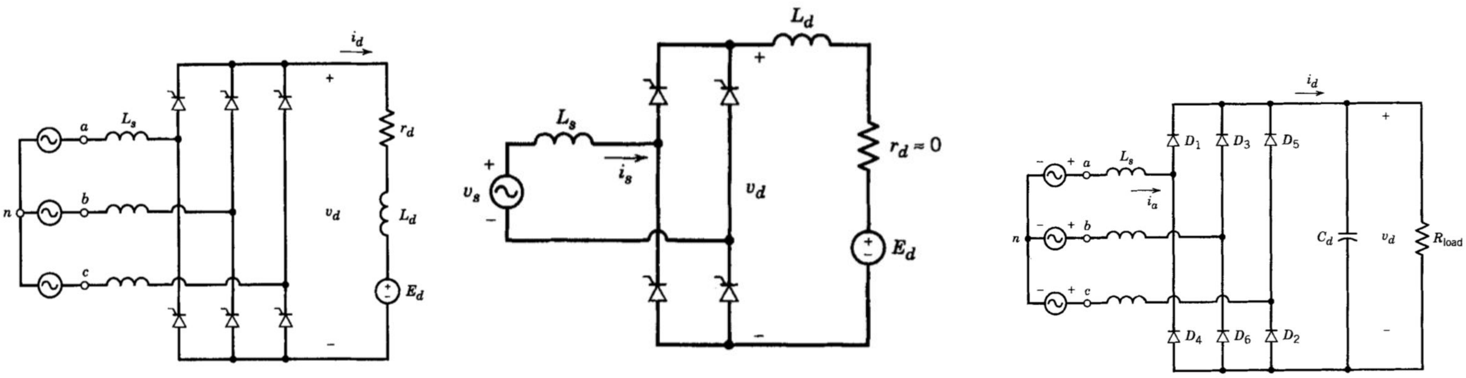

Figure 1: Different topologies for AC-DC converters[1]

B. Rectifier Design

A 3-phase diode rectifier includes 6 diodes. For this part, instead of using 6 discrete diodes to built the rectifier circuit we prefered to buy a single 3-phase diode rectifier package available in the market.

Now having decided the rectifier, we can choose the DC link capacitor at the output of the bridge rectifier. The purpose of this capacitor is to filter out the output of the bridge rectifier in order to reduce the voltage ripple and obtain a more DC-like waveform.

For DC link capacitor, we preferred to use three capacitor instead of one capacitor in order to reduce the ESR and ESL values of the capacitor by paralleling the capacitors.

C. Buck Converter Design

After the 3-phase diode bridge rectifier , there is buck converter which is a DC-to-DC converter which can be seen in Figure 2. The aim of the buck converter is changing the motor speed by adjusting the output voltage. This is achieved by a switching device such as MOSFET or IGBT. IGBT is favored and chosen in our design because of its ability to withstand higher voltage levels than a MOSFET.

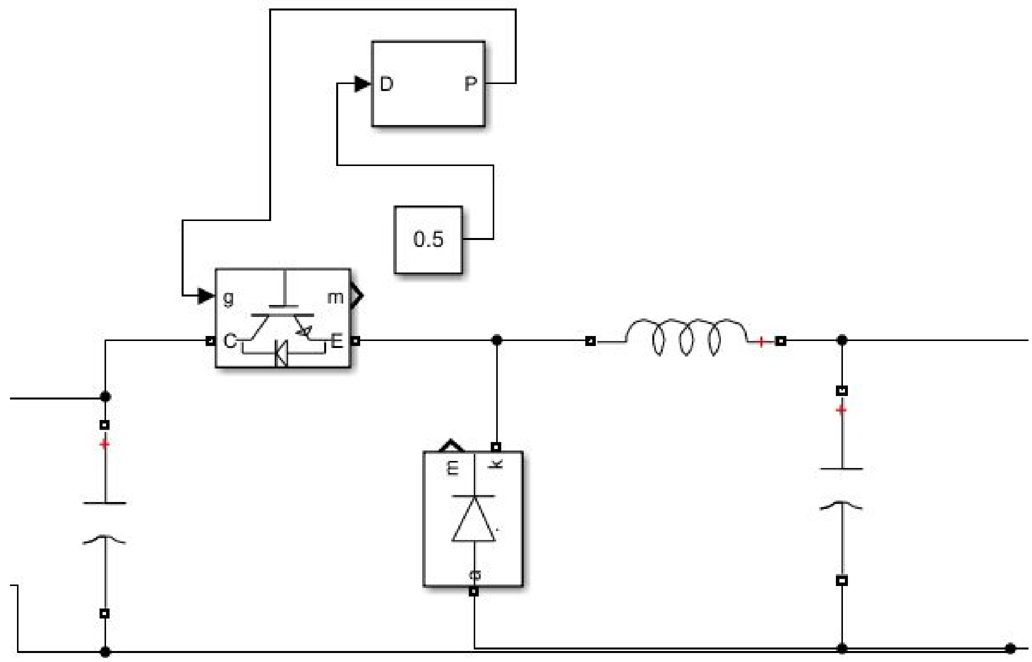

Figure 2: Buck Converter schematic

By applying a PWM signal to the gate of the switching device we can adjust the output voltage. As the on time (or Duty Cycle) increases, the output voltage increases proportionally. Hence, the relationship between the input voltage and output voltage is given by the following equation:

$$V_{out} = D \times V_{in} \qquad (1)$$

In our design, PWM is obtained by using Arduino, which is an microcontroller card. The related Arduino code for PWM generation can be found in Appendix. However, arduino operate at low voltage levels while our driver circuit operates at voltage levels up to 200 V. Hence an isolation is essential in this situation. We preferred use an optocoupler chip as the isolator.

The frequency of switching determines the voltage ripple at the output and they are related by the equation 2 below. Ripple and frequency are inversely proportional, i.e., ripple is reduced when the operating frequency increased. However, increasing the switching frequency will lead an increase in switching losses and hence will increase the temperature of the device which might be harmful after a point. Interpreting all these, we chose our switching frequency as 986 Hz to avoid excessive switching losses.

$$\frac{\Delta V\, out}{V_{out}} = \frac{(1-D)}{8\times L\times C\times f_s^2} \qquad (2)$$

The LC filter at the buck converter is in order to filter the both current and voltage waveforms. The ripple will be reduced by the filter. The important point in the filter design is where to put the corner frequency of the low pass filter. It should be as far as possible from the switching frequency in order to attenuate its value as much as possible. But at the same time, when the frequency gets smaller the filtering component's sizes get bigger according to equation 3 below:

$$f_{corner} = \frac{1}{2\times\pi\times\sqrt{LC}} \qquad (3)$$

Hence a compromise should be made. We have chosen our switching frequency as 986 Hz and put our cut-off frequency at around 60 Hz. To achieve this, we used a 470μF capacitor and an inductor is wrapped to achieve approximately 14 mH which together yields a corner frequency of 62 Hz. The frequency components greater than 62 Hz will be attenuated which will eliminate AC components and DC like waveform will be obtained in motor input.

D. Total AC/DC Driver Circuit

After choosing the rectifier, DC-link capacitors and the parameters of the buck converter such as switching device, switching frequency, LC filter values and freewheeling diode, the whole driver circuit take the form in Figure 3.

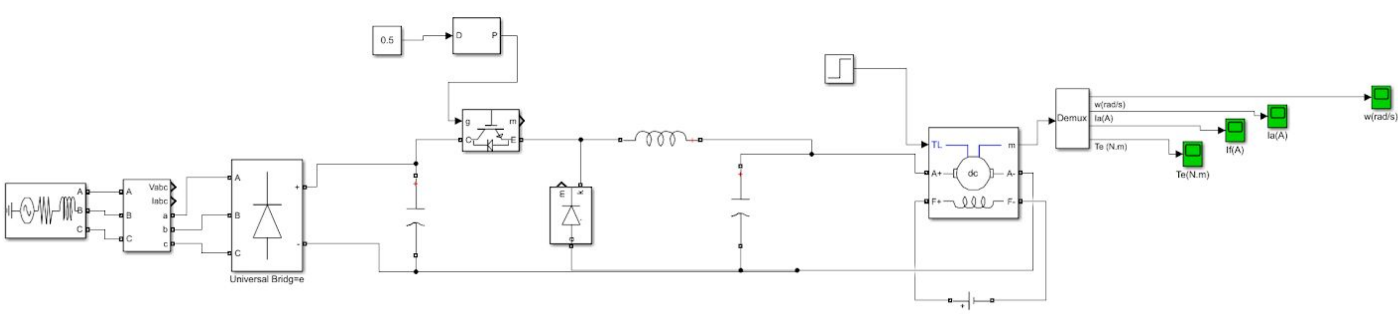

Figure 3: Motor driver circuit

III. COMPUTER SIMULATIONS

After determining the rectifier and buck converter topologies that we used, we simulated the circuit in MATLAB Simulink in order to decide on the component values for proper operation. We simulated the circuit in Figure 3 at 986 Hz in order to measure the voltage values on and current values flow through different components.

A. Three Phase Diode Rectifier

For the first part which is the diode rectifier, the current flows through the rectifier can be seen in Figure 4. The output voltage of the rectifier and the DC link capacitors can be seen in Figure 5.

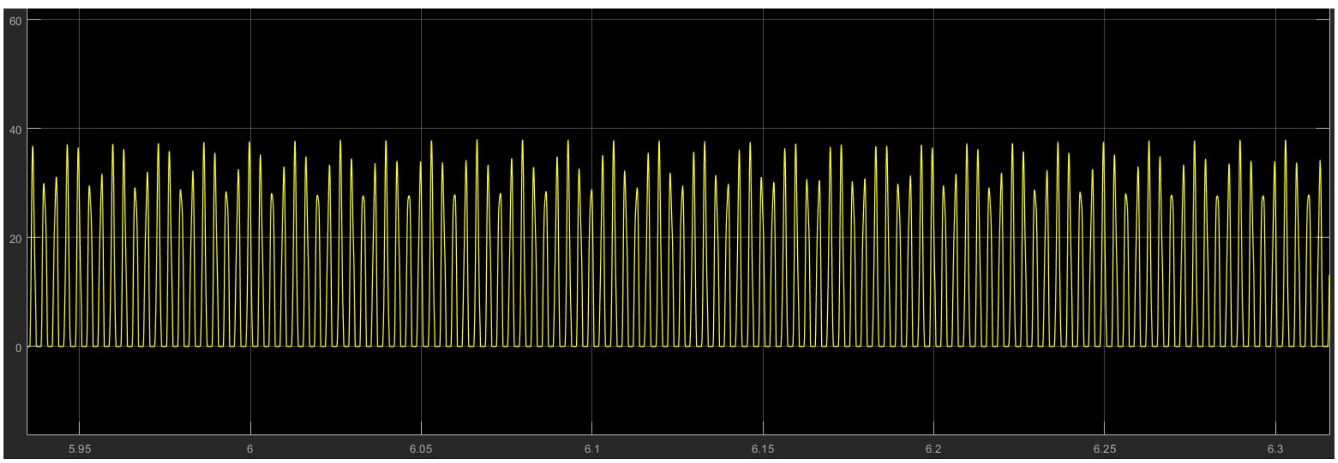

Figure 4: Current on Diode Rectifier

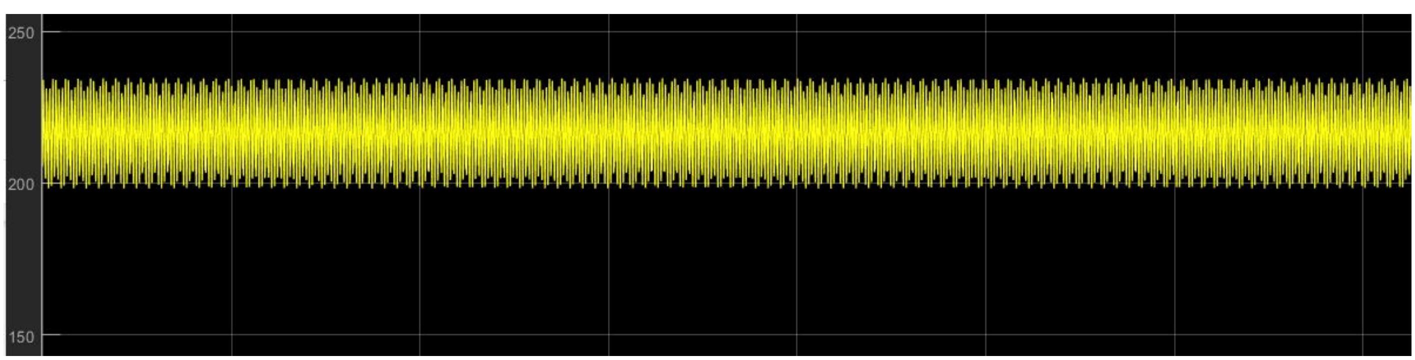

Figure 5: Output Voltage of Diode Rectifier

B. IGBT and Diode

In order to be able to choose the right component with proper ratings, the voltage across the IGBT and the current flows through it are measured. The simulation results can be seen in Figure 6 and Figure 7.

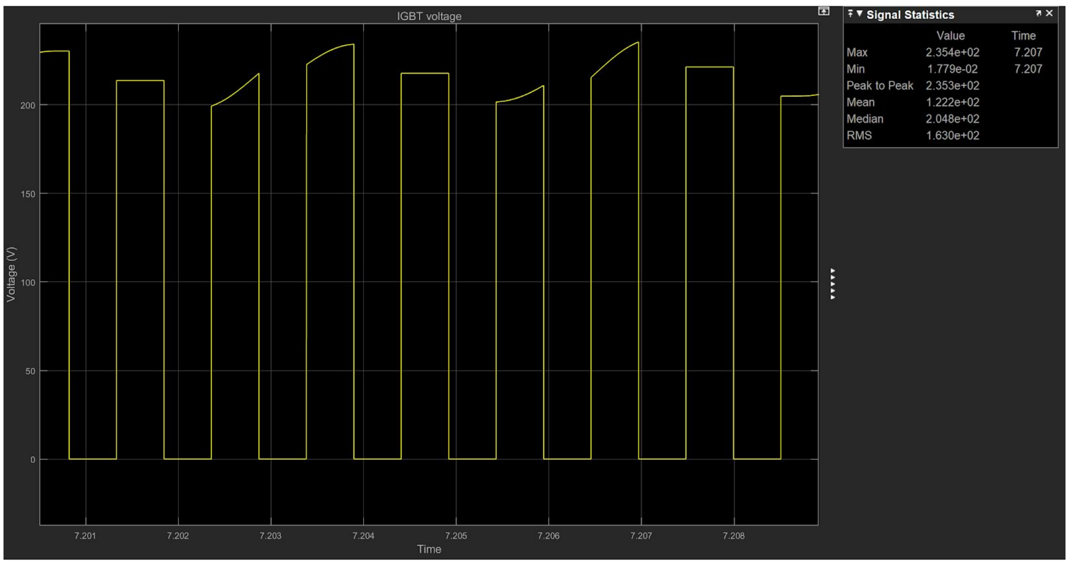

Figure 6: Emitter Voltage

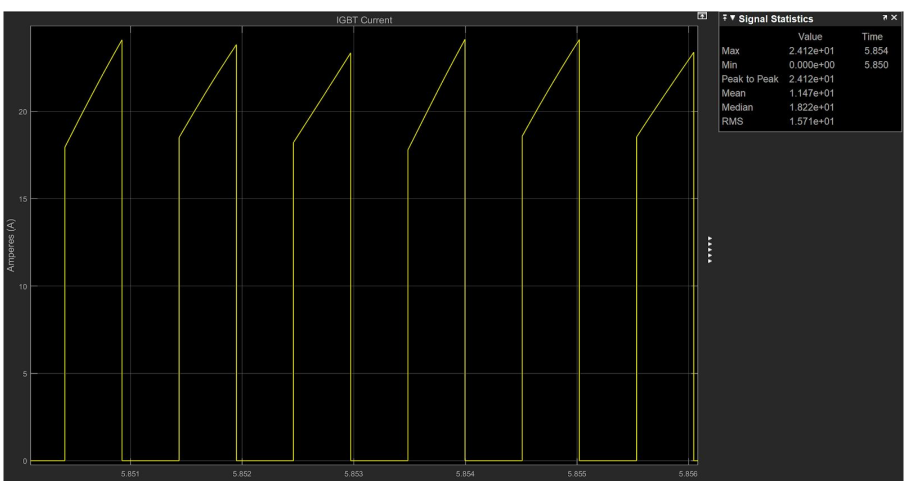

Figure 7 : Collector Current

As one can see from the above figures, IGBT voltage becomes 235 V maximum and IGBT current is 24.12 Amps maximum at the steady state operation. In practical cases, there will be high starting voltages and current values because of the capacitive and inductive elements in the circuit. However, this will be overcomed by increasing voltage slowly and gradually.

C. LC Filter

The output waveforms of the LC filter, which is the output of the Buck Converter can be seen below in Figure 8 and figure 9.

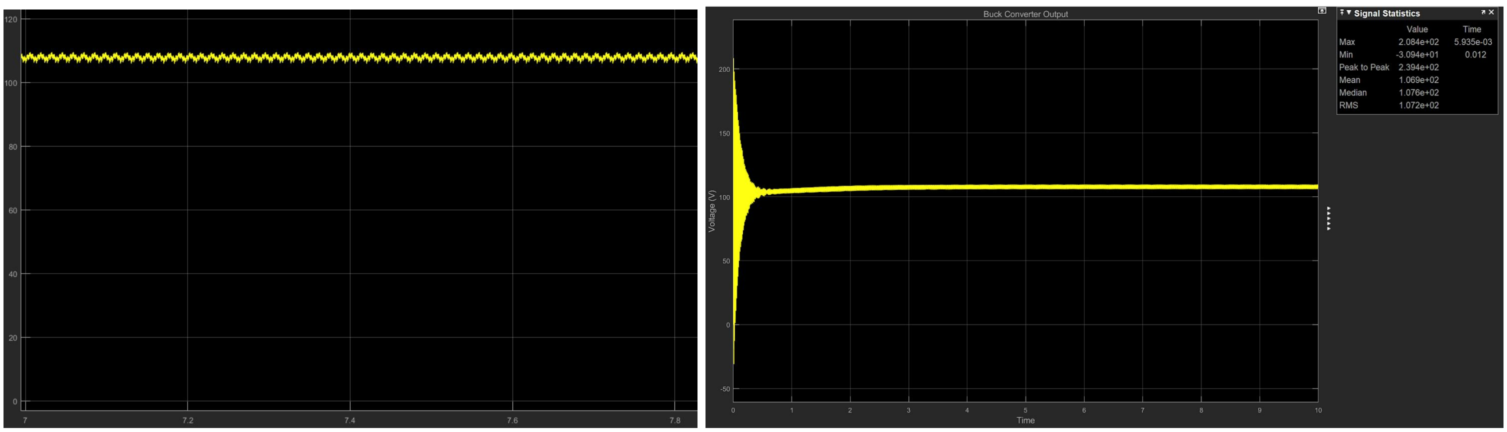

Figure 8: Output Voltage

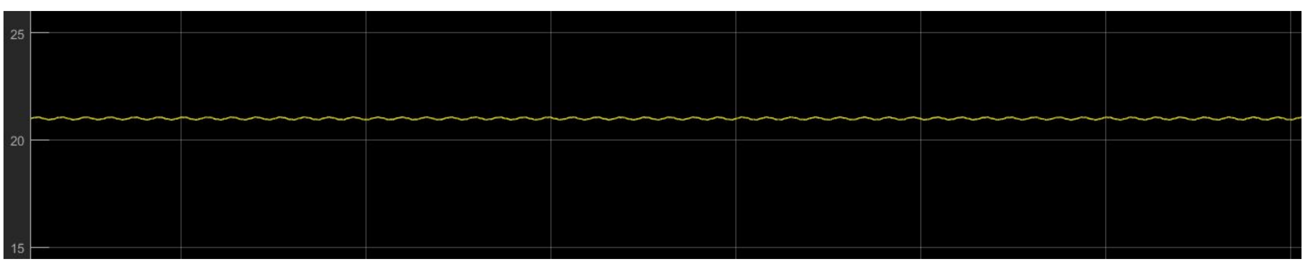

Figure 9: Output Current

Since, it is required that the maximum voltage value at the output should be greater than 180 V, we determined our input voltage value in a way that when full duty cycle is given a voltage of minimum 180 volts is obtained at the output. The output voltage of the buck converter when the duty cycle is 100% can be seen in Figure 10.

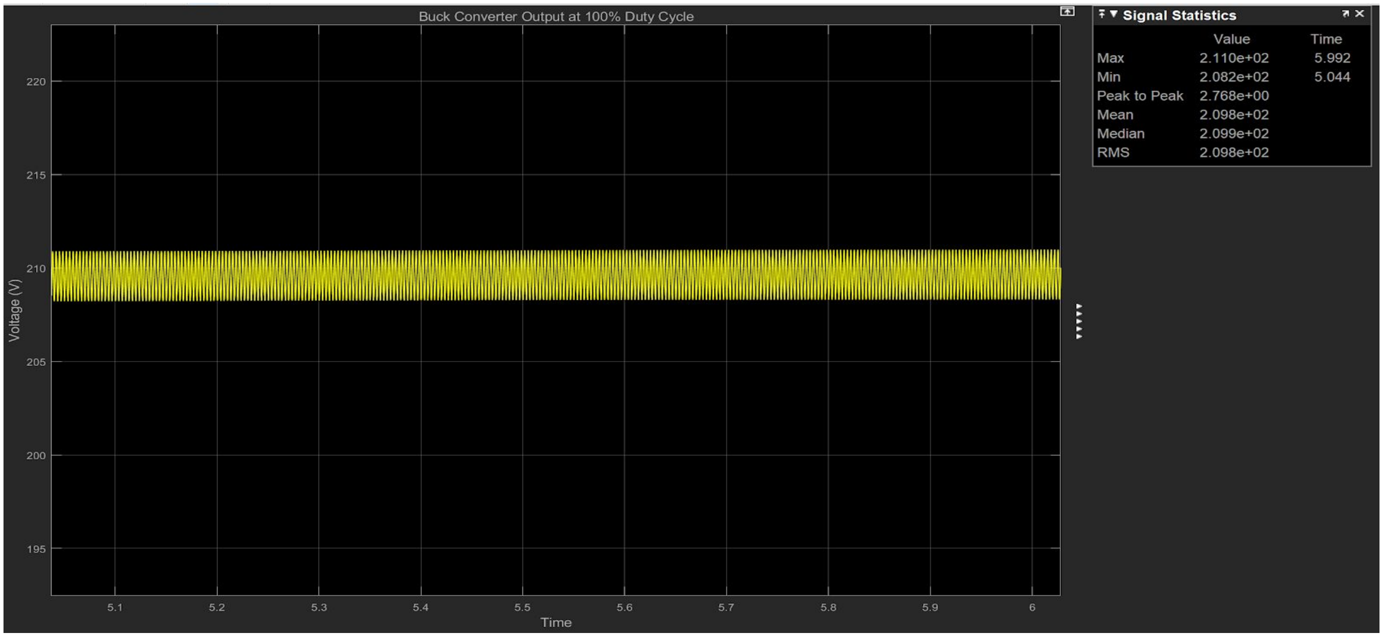

Figure 10 : Output voltage at full duty cycle

D. Motor waveforms at Full Duty Cycle

We are also required to start the DC motor from standstill to rated speed under no load. Hence, we should be able to obtain rated speed when full duty cycle is given.

It can be seen from Figure 11 that the motor speed is 157 rad/s which is approximately 1500 RPM (rated speed of the motor that is being used) at 100% duty cycle. The armature current at that instant can also be seen in in Figure 12.

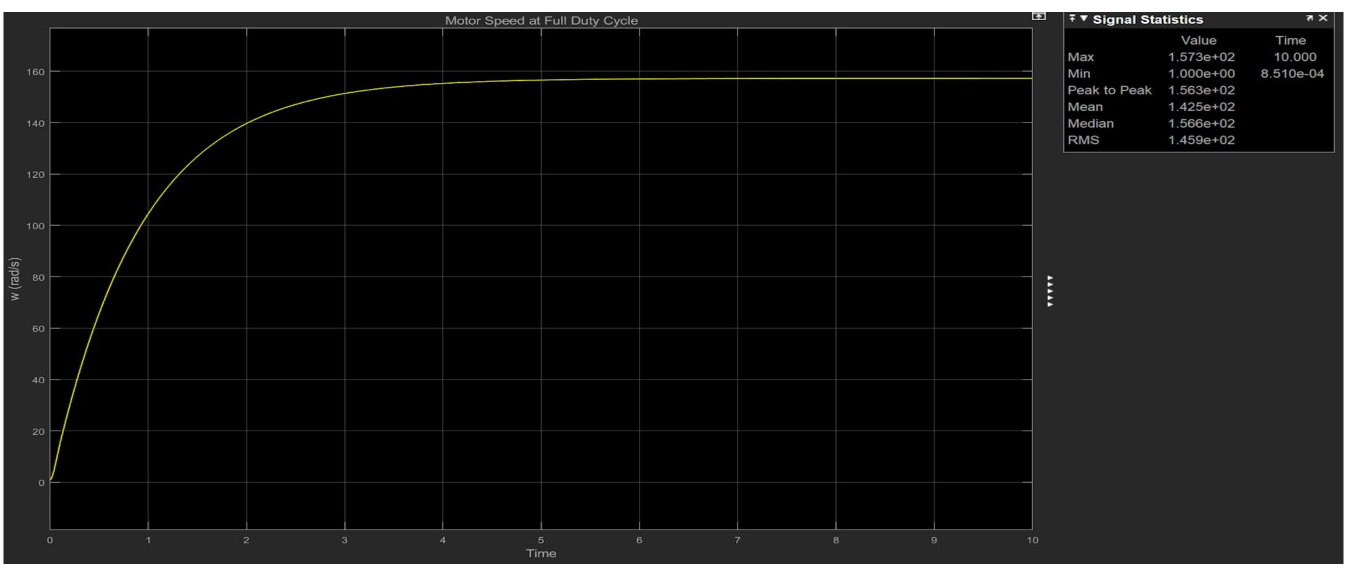

Figure 11 : Motor speed at Full Duty Cycle

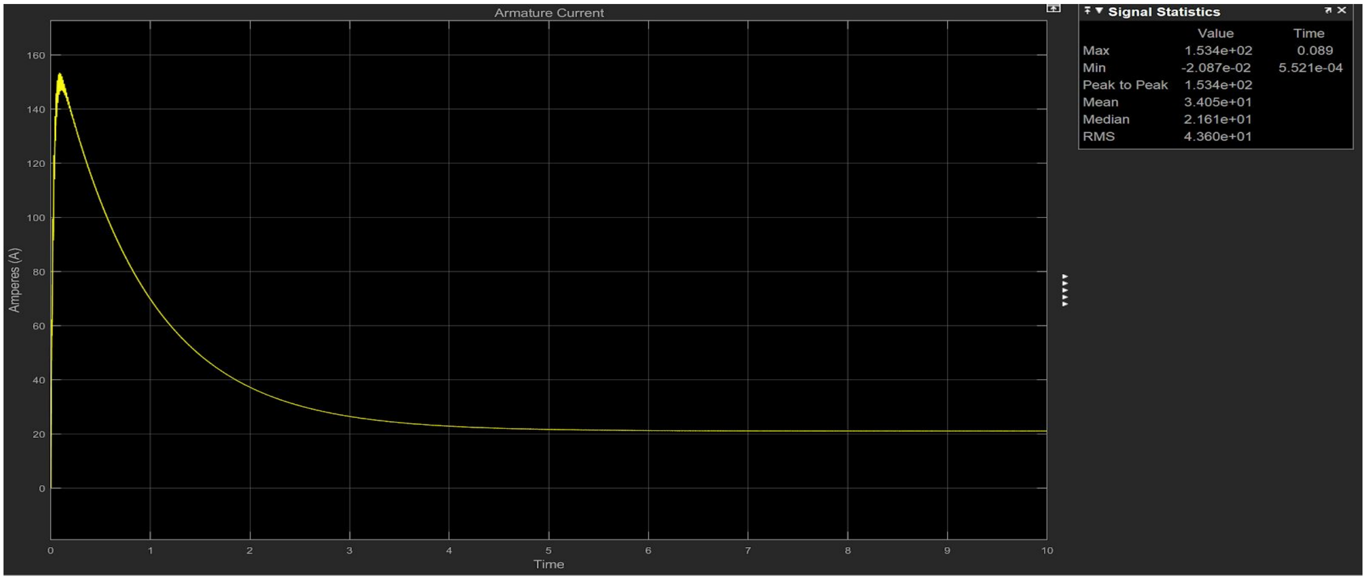

Figure 12 : Armature current at Full Duty Cycle

IV. COMPONENT SELECTION

The component selection for buck converter includes selecting an optocoupler, a three-phase full-bridge diode rectifier, DC link capacitors, an IGBT, a diode, inductor and capacitor for LC filter and an RC snubber. The selections are made according to the simulations above and experimental results.

A. Three Phase Full-Bridge Diode Rectifier

Two parameters which are the maximum peak reverse voltage and maximum average output current are main determinants for selecting a diode rectifier. Considering the maximum peak reverse voltage to be 540V and maximum output current to be 20A for full 100% input of VARIAC, VUO34-18NO1DSP [1] model rectifier is used which has a maximum peak reverse voltage of 1800V and maximum average output current of 45A which are more than enough for the design. Its operational maximum temperature is 150℃ which is not expected to create a problem.

B. DC Link Capacitors

DC Link capacitors are selected among aluminum electrolytic capacitors. For a safe operation, the capacitors are selected way beyond the potential maximum voltage rating. Moreover, to achieve low equivalent series resistance rate, three capacitors with lower capacitance are planned to be paralleled. Therefore, instead of one big capacitor, three smaller capacitors are used. For this purpose K05 SNAP-IN KENDEIL 220uF and 450V capacitors are selected.

C. IGBT

The main element amongst the components of buck converter is the IGBT. It is selected over MOSFET for its higher voltage and current handling capacity for cheaper price. Because of the improved durability, STGW30NC120HD is used which has 1200V voltage rating and 30A current rating which are beyond sufficient for the operation. The IGBT selection is not feasible normally. A 650V rated IGBT should have been enough, however, the voltage spikes pushed the design to this choice.

D. Diode

A diode which has a durability of at least the peak value of the emitter voltage of IGBT and at least the current flowing through the circuit when the IGBT is off is needed. Therefore, 30A 600V ISOPLUS247-2 is selected as freewheel diode. The heat dissipation on the diode is important. As a result, a standard heatsink is needed to be mounted on the diode.

E. LC Filter

A capacitor and an inductor is needed for an LC filter. Therefore, a capacitor that has a voltage rating of the output voltage and an inductor which should not saturate between no-load and full-load operations. For this purpose, K05 SNAP-IN KENDEIL 470uF and 400V is used. Since an appropriate inductor could not be found and flexibility of values for handmade inductors, a coil is wrapped and an inductor is made. An inductance of 14mH is achieved.

F. RC snubber

An RC snubber with 1600V 4.7nF and 22Ohm is designed according to the application note[2].

G. Optocoupler

An optocoupler is used to separate low voltage side (microcontroller circuit) and high voltage side. For this purpose, TLP250 IGBT driver which has an ability to drive the gate of IGBT. It has 10-35V supply voltage and 2500V isolation voltage. The circuit in its application form is used to drive optocoupler which can be seen from Figure 13.

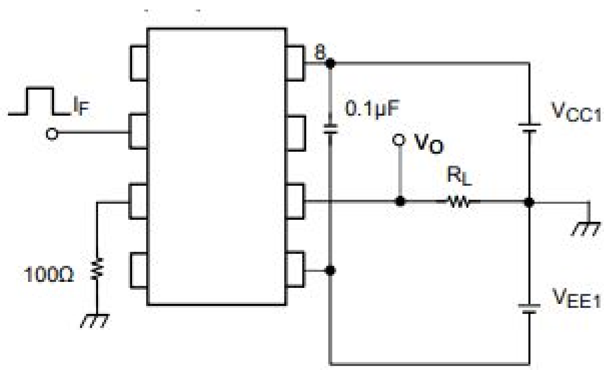

Figure 13 : Optocoupler Driver Circuit

V. FAILURES, ERRORS AND IMPORTANT POINTS

The first error that is face throughout the design process was the sensitivity of TLP250. For an unknown reason, the gate driver circuit had offset of a 6.6Vpp which provided a constant gate signal to the IGBT Gate. Since the opening voltage of IGBT was 4.3V, it remained open during the tests with faulty TLP250 optocouplers. This fault was overcome by changing the optocoupler which costed a lot. Apart from the financial problems, the time consumed by finding the fault was a bigger issue.

Another problem is about the cable lengths. It turned out that the inductances of cables are beyond the modest expectations. Especially, cable length between the IGBT gate driver circuit and the IGBT gate created a big problem. Tests with R load did not reflect the real experiment with the motor. During the experiments with the motor, gate of IGBT burned because of the length of the cable. As a result, it is a very good practice to keep the cable between the gate and gate driver circuit as small as possible. Also, cable length between the diode and the emitter must be as small as possible as well.

The main problem that creates even more problems during the debugging of a mistake is the poor soldering of cables and components. The location of components must be predesigned and reviewed during the soldering process so that when a fault occurs, any kind of problem such as loose contact, wrong connection etc. can be found easily. Also, it prevents unwanted contacts. Therefore, it is understood that working clean is a very important concept for hardware projects such as this.

The switching frequency is one of the main determinants of power loss. It is proportional with the temperature rise on the IGBT. During the experiments, an IGBT is lost to high temperature after 5th minute of running. If the circuit is designed thermally poor, then the switching frequency must be low. However, high frequency makes the output smoother.

VI. TEST RESULTS

A. PWM Signal

As mentioned earlier, in order to switch the IGBT a PWM signal generated at arduino will be used. However since isolation is needed and the output capacity of arduino is not enough to excite the gate an optocoupler is used. The output of the optocoupler, i.e., the gate signal of the IGBT can be seen in below in Figure 14.

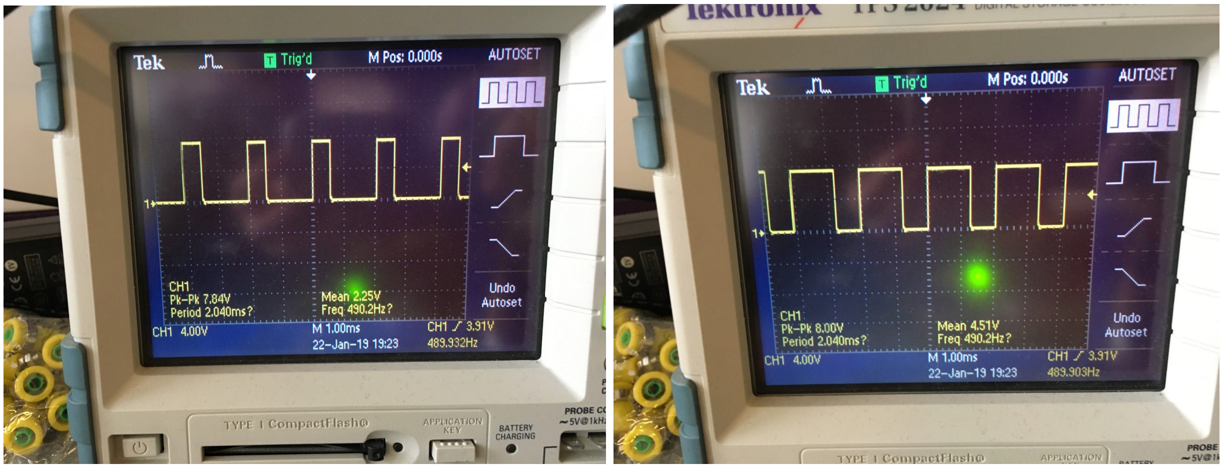

Figure 14 : Optocoupler output for different duty cycles

B. Rectifier Output

We tested rectifier circuit with a resistive load while the buck converter was not operating. The test environment can be seen in Figure 15.

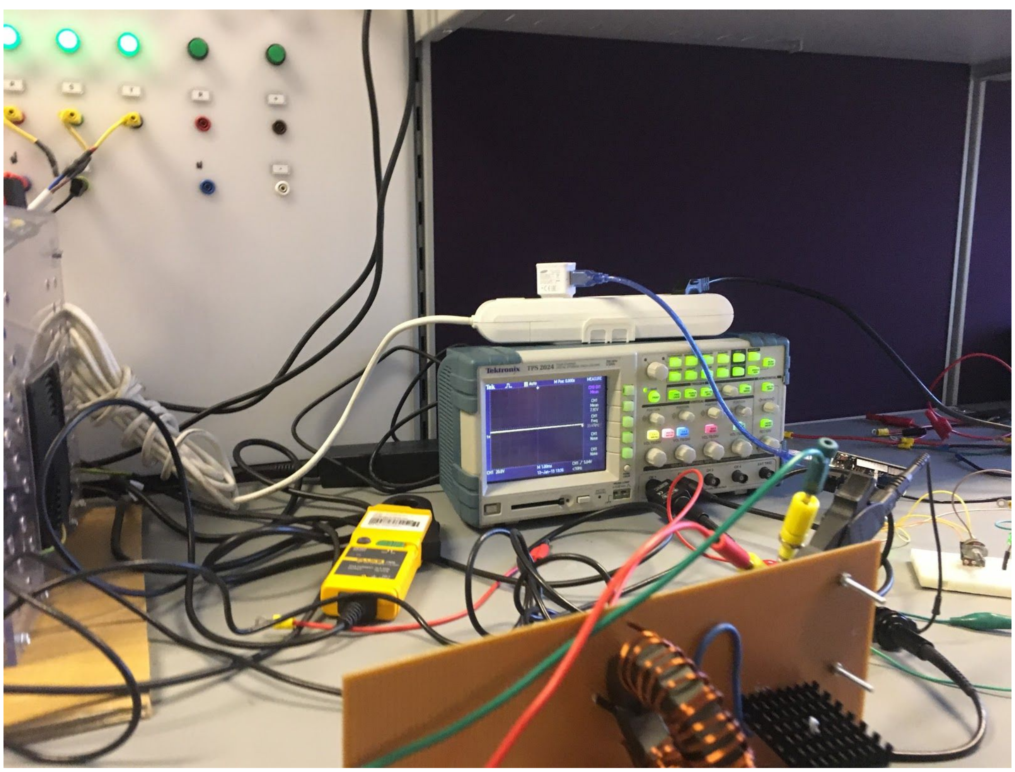

Figure 15 : 3-phase rectifier test

C. Buck Converter Test

Before trying with 3-phase rectified output, we first test our Buck converter by giving a DC voltage from a DC source (up to 35 Volts) to its input and observing the output voltage. We were able to control the output dc voltage level by changing the duty cycle using a potentiometer. Hence, we conclude that our buck converter is operating successfully for the theoretical case (pure DC in DC out). The output voltage can be seen in Figure 16.

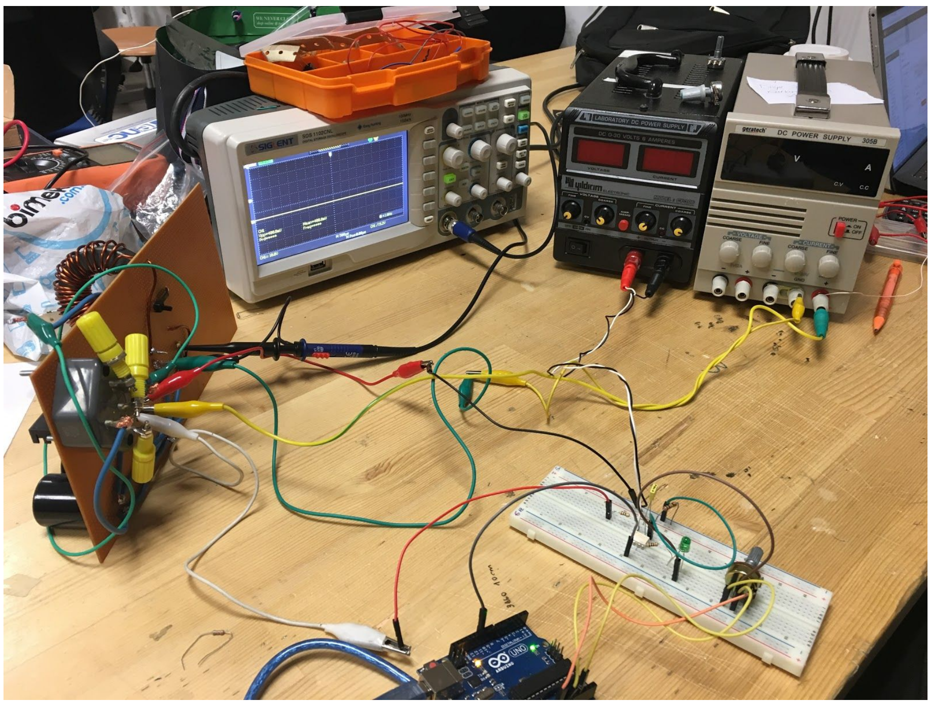

Figure 16 : Buck Converter Test environment

Buck converter test result also proved that we can effectively switch the IGBT since we were able to obtain variable dc output.

D. Driver Test with R load

Instead of connecting the driver circuit directly to the DC motor, it is beneficial to test with a R load beforehand. We connected 3 phase grid to the rectifier input and connected an R load to the output. This allowed us to see the behaviour of the circuit at high voltages and effect of non-idealities to the circuit. The test environment can be seen in Figure 17.

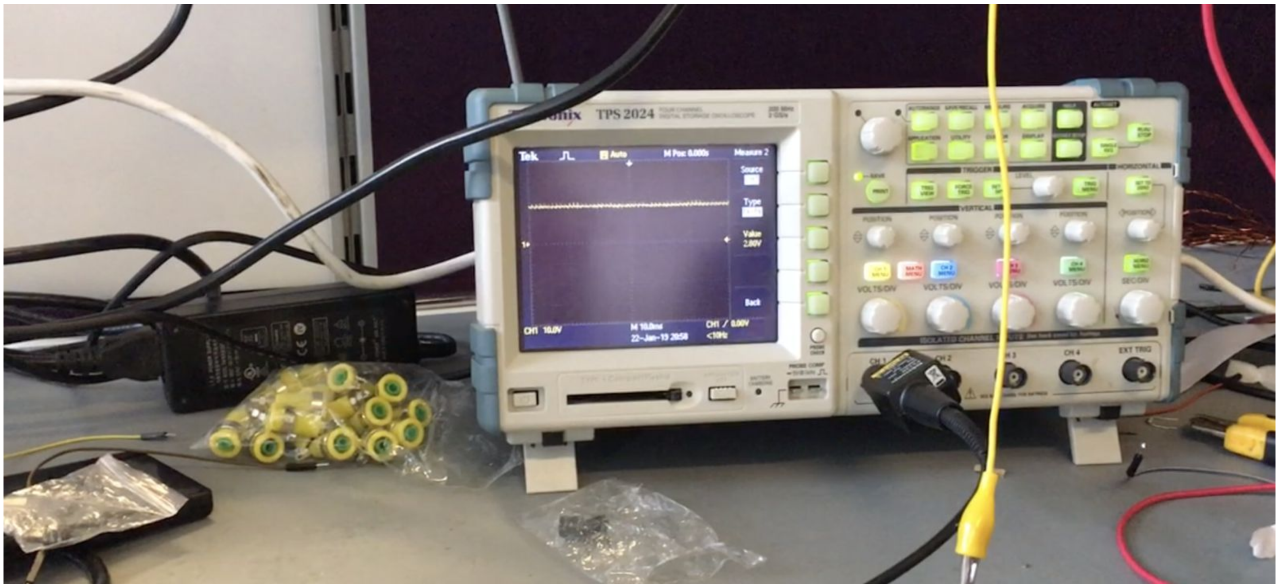

Figure 17: R load test

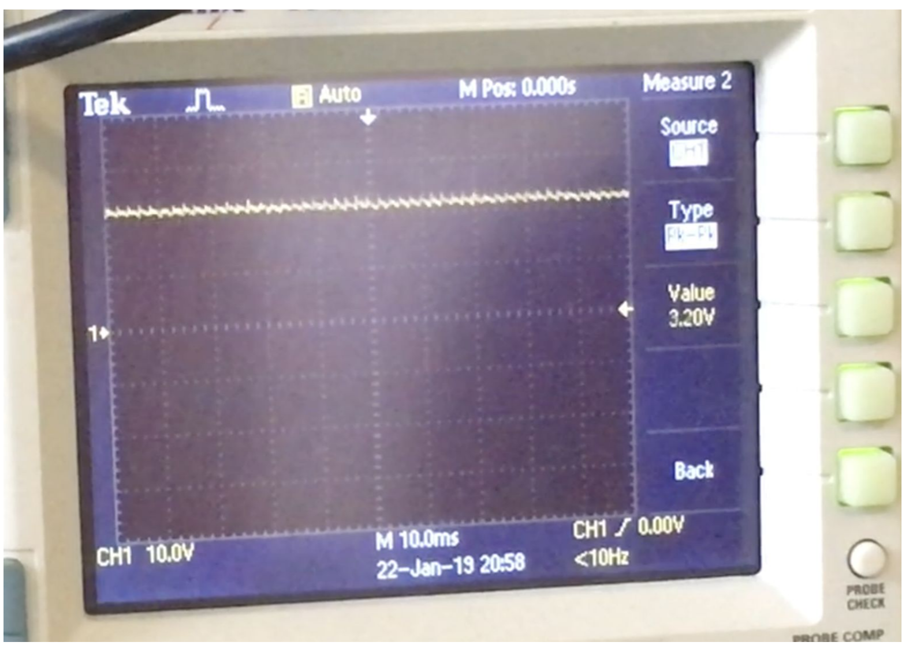

Figure 18: R load test output voltage

The voltage output of the driver can be seen in Figure 18. As one can see, the waveform resembles a DC voltage as expected but there is still some ripple which are not very important since the motor can tolerate them.

E. Motor Test

Unfortunately, we were not able to drive the motor since our IGBT failed each of the three times we tried. Consequently, we could not collect any data while the motor is running.

Our overall design of the circuit can be seen in Figure 19.

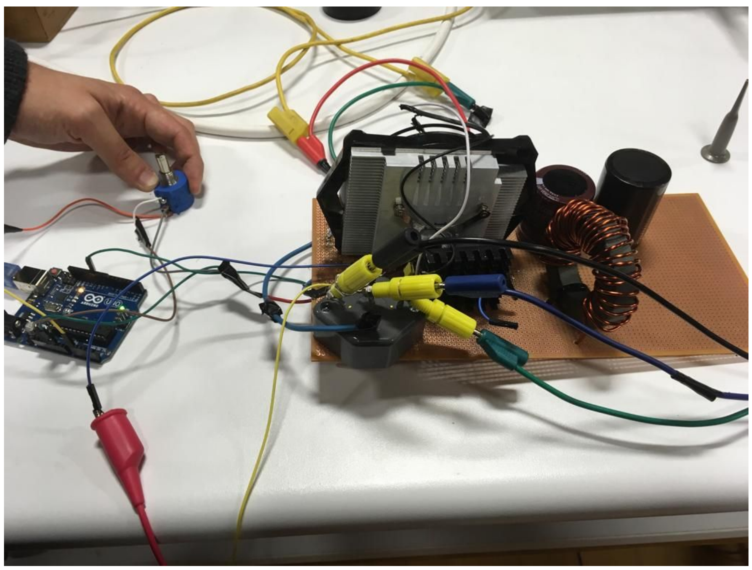

Figure 19: Overall circuit

VII. COST ANALYSIS

The cost analysis of the final design can be found in the Table 1 below.

Table 1: Cost analysis

Component	Quantity	Price ($)
Optocoupler	1	1,28
220 uF Capacitors	3	2,3
IGBT	1	1,85
Diode Bridge Rectifier	1	10,2
Diode	1	1,73
470 uF Capacitor	1	2,4
Inductor	1	2,0
Fans	2	5,0
Total		31,36

VIII. CONCLUSION

In this project an AC/DC Motor Drive was tried to be designed using a three phase diode bridge rectifier. However, the design failed during experiments with real motor where it worked smoothly with R and RL loads at the laboratory. Throughout the project, it is understood that design rules such as using short cables to connect, placing power,ground and signal routes accordingly, using twisted cables etc. are very useful. Also, selecting the right component is one of the most important points even though it can be compensated by other components. For example, voltage spikes which are caused by parasitic elements can be endured by selecting higher voltage rated IGBT or using RC snubber. In order to understand the behaviour of the circuit in a very deep manner, it is important to test the circuit in each design step. For instance, after soldering one more component if something goes wrong, the reason is obvious. Thermal design is another concept that is vital during the operation. Throughout the project, thermal design was not a major concern until when IGBT burnt with smoke. Then, it is understood that temperature is one of the important and costly problem. As a result of this project, the design failed. However, the learning outcomes from all the failures helped us improve and strengthen our conceptual knowledge. We are glad to have participated in this project.

IX. REFERENCES

[1] Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power electronics: Converters, applications, and design*. Hoboken, NJ: Wiley.

[2] CDE Cornell Dubilier. (n.d.). Designing RC Snubber Networks. Retrieved January 23, 2019, from https://www.alliedelec.com/images/Products/mkt/pb/cornelldubilier/pdfs/snubberguide.pdf

X. APPENDIX: Arduino PWM Generator

```
const int analogInPin = A1;  // Analog input pin that the potentiometer is attached to
const int analogOutPin = 11; // Analog output pin that the LED is attached to

int sensorValue = 0;        // value read from the pot
int outputValue = 0;        // value output to the PWM (analog out)
void setup() {
  // initialize serial communications at 9600 bps:
  Serial.begin(9600);
  TCCR2B = TCCR2B & 0b11111000 | 0x02; // Set frequency
}

void loop() {
  // read the analog in value:
  sensorValue = analogRead(analogInPin);
  // map it to the range of the analog out:
  outputValue = map(sensorValue, 0, 1023, 0, 255);
  // change the analog out value:
  analogWrite(analogOutPin, outputValue);

  // print the results to the Serial Monitor:
  Serial.print("sensor = ");
```

```
  Serial.print(sensorValue);
  Serial.print("\t output = ");
  Serial.println(outputValue/2.55);

  // wait 2 milliseconds before the next loop for the analog-to-digital
  // converter to settle after the last reading:
  delay(2);
}
```

Link to Video : https://www.youtube.com/watch?v=jpYy6RgigcY&feature=youtu.be