Middle East Technical University

Electrical and Electronics Engineering

EE463 STATIC POWER CONVERSION I

Hardware Project: AC to DC Motor Drive

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# Introduction

In this report, detailed information about EE463 Hardware Project, namely, AC to DC Motor Drive is explained. Project requirements, design stages, simulation and test results of the applied method, working principle explanations and calculations will be given.

Design method is selected after some research and brainstorming in between our group members. The best option that is fitted with our concerns is selected to meet the requirements of the project. Chosen topology simulated several times in Simulink environment to obtain the most efficient and the most applicable way.

Implementation of the project has been done step by step. Required equipment and components voltage, current, and power ratings. etc. are calculated precisely. Commercially available component which can be used in our implementation stage is selected and ordered in nicely planned timeline. To achieve successful operation each submodule tested and compared with simulation results and mathematical models.

After implementation, test and verification stage took most of the time and energy, due to nature of the power electronics, EMI, line inductance and resistance effects and importance of the frequency on the component selection and operation of the related components is observed.

## Project Definition

In this project, we are required to make a controlled rectifier that will be used to drive the DC Motor which is shown in figure-1. Rated values of the motor is shown in figure-2.

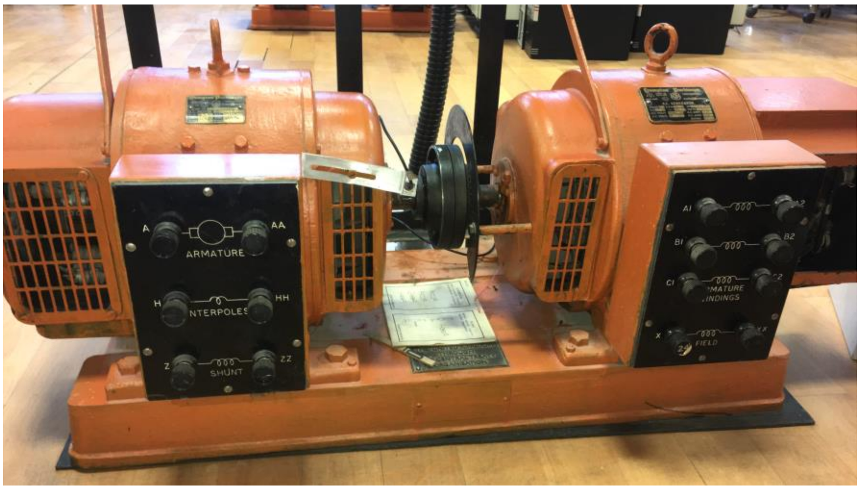


*Figure 1: DC Motor*

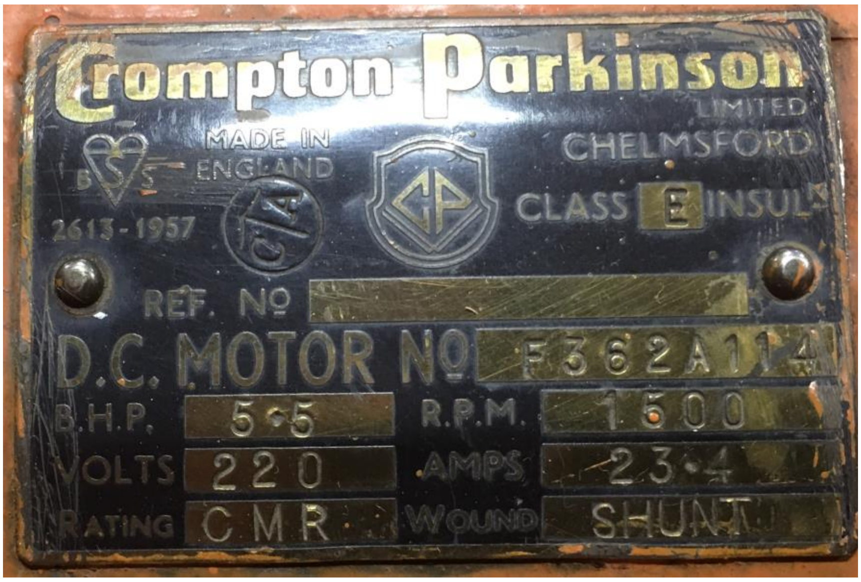


*Figure 2: Rated values of DC motor*

Specs of the all motor windings:

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

We are required to start the DC Motor from standstill to its rated speed with no load condition and control the speed of the motor. Although, variac can be used to apply AC voltage gradually, it cannot be used for control of the output voltage.

## Selection of the Topology

Each topology has its own advantages and disadvantages in power electronics. Following table-1 shows the comparison of these topologies.

*Table 1: Comparisons of topologies*

| Topology Name | Advantages | Disadvantages |
|---|---|---|
| 1-Phase Thyristor Rectifier | ·4-thyristor is needed<br>·Control circuit is less complex than 3-phase thyristor rectifier | ·Average of the output voltage is less than 3-phase thyristor and diode rectifiers<br>·Injects large harmonics into the utility system<br>·Complex gate drive circuitry is needed for thyristors (2-firing angle a and pi+a)<br>·Larger output capacitor is needed to decrease voltage ripple<br>·Slow switching frequency |
| 3-Phase Thyristor Rectifier | ·Low output voltage ripple<br>·High output voltage (average) | ·6-thyristor is needed<br>·Most complex gate drive circuitry<br>·Difficult to implement<br>·Slow switching frequency |
| 3-Phase Diode Rectifier + Buck Converter | ·Low output voltage ripple<br>·High output voltage (average)<br>·High switching frequency<br>·Easy to implement rectifier circuit<br>·Easiest gate drive circuitry<br>·More accessible in the market | ·Number of required components is more than other options<br>·Output filter for buck converter |

As in seen in table-1 3-phase rectifier circuit has less ripple and high output voltage (average) which are decrease the DC-link capacitance value. Because of these reasons using 3-phase rectifier is more logical. Furthermore, gate circuitry of 3-phase thyristor rectifier is the most complex one. However, gate circuitry of buck converter is simple, easy to implement and can be used in high frequency switching. Therefore, considering the difficulty in implementation and complexity of gate drive circuits, 3-phase diode rectifier + buck converter is selected among the 1-phase and 3-phase thyristor rectifiers.

# 3-Phase Diode Rectifier with Buck Converter Topology

Circuit diagram of the selected topology 3-phase diode rectifier with buck converter topology is shown in figure-3. 3-phase AC voltage input is rectified to DC voltage (6-pulse voltage waveform with frequency 300Hz) via 3-phase full-wave rectifier circuit and average of the rectifier output voltage is $1.35V_{(l\text{-}l)}$ where $V_{(l\text{-}l)}$ is the line to line voltage of the 3-phase AC input. Output voltage waveform of the rectifier becomes smoother (decreases the ripple) with the help of the DC-link capacitor. Two parallel connected capacitors are used instead of one capacitor with high capacitance value to decrease the loss with paralleling the ESR (equivalent series resistance) of capacitors. In addition to them IGBT is used for switching purpose and fast diode for freewheeling. IGBT is switched according to the gate signal and adjusts the duty cycle of the output voltage PWM (pulse width modulation). As a result, average of the output voltage can be adjusted with gate signal, which is equal to the (D x $V_{DC\text{-}Link}$) where D is the duty cycle of the PWM, and $V_{DC\text{-}Link}$ is the output voltage of the rectifier. Output voltage of the IGBT includes ripples to make the output voltage pure DC voltage (as much as possible) LC filter (low pass filter) can be used. Adding LC filter makes the output voltage and current smoother and also decreases the noise of the output side. However, motor can be considered as RL load which makes the output current smoother also, but ripple of the output voltage does not affect. Because of that inductor of the filter can be ignored for motor drive. However, capacitor cannot be opened with switch, current of the capacitor must be limited. Thus, inductor cannot be ignored separately, but LC filter can be ignored totally. As a result, we ignored the LC filter and output of the switch is directly connected to the motor. In other words, motor is driven by PWM output of buck converter.

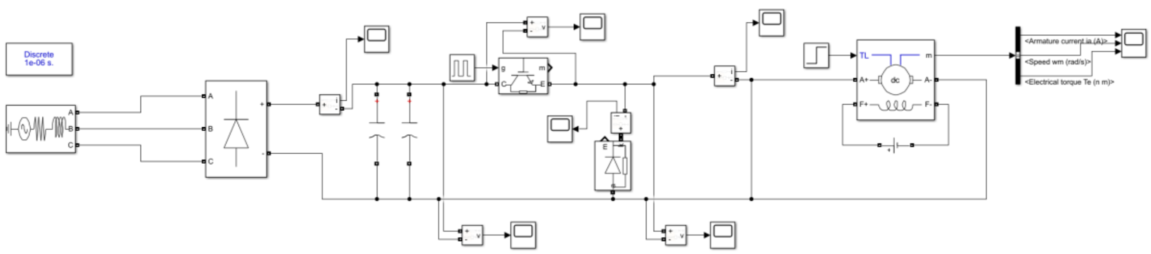

*Figure 3: Overall circuit diagram of the rectifier + buck converter topology with motor load*

Gate signal is produced with Arduino and transferred to the high voltage side with an optocoupler (TLP250) because the magnitude of the signal of the Arduino is not enough. Isolation between high voltage and low voltage side is provided with an optocoupler and amplification of the signal is also provided with an optocoupler. Circuit schematic of the optocoupler is shown in figure-4. In optocoupler circuit we used Arduino PWM for $V_{IN}$, 12V for B2 voltage supply (float-ungrounded) and 10Ω for gate resistance, which affects the rising and falling times of the duty cycle, to decrease the switching losses. Output of the optocoupler is connected to the gate of the IGBT via 10Ω resistance and the negative of the float DC supply is connected to the emitter of the IGBT. By this means the voltage difference between gate and emitter is provided. Frequency of the PWM (500Hz) is adjusted via Arduino which is switching frequency of the IGBT. Also, duty cycle of the PWM can be adjusted with the help of a POT. Furthermore, we add one more feature to our Arduino code to protect our circuit from instantaneous current increase or decrease due to the turning speed of the POT. We provided the final value of the duty cycle with a POT and the duty cycle reaches to that value with an adjusted increasing & decreasing rate. Arduino code can be found in the appendices part of the report.

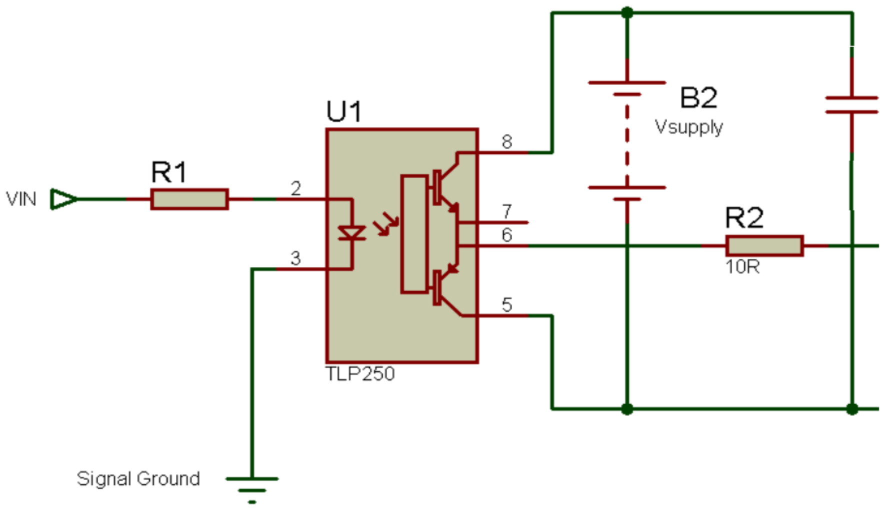


*Figure 4: Circuit schematic of the optocoupler circuit*

# Component Selection

## 1) Three Phase Diode Rectifier

The first aim was transforming three-phase AC input to a DC output. In order to overcome this situation, we used a three-phase diode rectifier. The simulation results show that the average output current value as 12.8A. The ratings of the rectifier are:

$V_{RRM} = 1800V$ : maximum repetitive reverse blocking voltage

$I_{DAV} = 45A$ : bridge output current

## 2) DC-Link Capacitor

In order to reduce the ripples at the output of the rectifier, the DC link capacitor is used. There are two 330uF capacitors at the output of the rectifier. The simulation results show that the average voltage of the DC link capacitors is 297V. The ratings of the capacitors are:

$V_{rated} = 400V$

$C = 330uF$

$ESR = 240m\Omega$

### 3) IGBT

The IGBT is the switching element in the design. The output of the DC link capacitor is connected to the collector of IGBT. As the IGBT opens, the collector voltage goes through the emitter terminals. In order to adjust the average voltage at the emitter terminal, the switching is important. This switching PWM is applied to the gate terminal. The simulation results show that the peak overshoot voltage value is 445V and the output current is approximately 15A. The ratings of the chosen IGBT are:

$V_{CES} = 1200V$

$I_C = 40A$

$V_F = 2.2V$

We did not connect the snubber circuit with the help of an high voltage IGBT.

### 4) Diode

The freewheeling diode is used in order to make a path for current to flow when the IGBT is closed. The important parameter is the reverse recovery time of the diode. As the switch operates at kHz ranges, the diode should respond as quickly as possible. The simulation results show that the reverse voltage applied on the diode is 300V and the current is 6A. The ratings of the diode are:

$V_{RRM} = 600V$

$I_F = 70A$

$t_{rr} = 20ns$

### 5) Optocoupler (TLP250)

The PWM inputs in gate terminals of IGBT comes from TLP250. This component isolates the decision unit (Arduino in this case) and the converter. The working principle is simply based on a light indicator inside of it. It receives a PWM signal at the input terminals and gives an output PWM with a peak voltage of applied $V_{cc}$. The output PWM is built by taking the collector voltage as a base in order to create a voltage difference between the gate and the emitter. The isolation voltage of this component is:

$V_{iso} = 2500V_{rms}$

### 6) Arduino

The Arduino is a decision mechanism in order to create PWM signals. The topology behind this is reading a POT's value and mapping it logically. By comparing the read value, the duty cycle of the PWM signal is determined. Also, by changing the POT's position while running the circuit, the duty cycle and the average output voltage can be changed.

## Simulation Tests Results

There are two different simulation is completed for R-load and motor-load because firstly we did the R-load test and then the motor-load test experimentally. R-load test (both experimental and simulation) is done in small voltage and current ratings since functioning of the circuit is tested but motor-load test (both experimental and simulation) is done for full-load.

### 1) R-Load Test

In R-load simulation, we used 50Ω resistance as an R-load, two 330μF capacitors and $38V_{(l\text{-}l)}$ AC input which corresponds to rectified 50V DC. Also, following simulation results are done with 50% duty cycle at 500 Hz switching frequency. Following figure-5 shows the overall circuit diagram of the resistive load circuit. Ripple of the output voltage waveform of the full-wave rectifier becomes more smoother with the help of an DC-link capacitors. As in seen in figure-6, mean of the output voltage is 50V and peak to peak of the ripple is 2.7V with the help of an 660μF DC-link capacitors. In figure-7 output PWM waveform can be seen whose mean voltage is 25V which is expected due to the 50% duty cycle. Source of ripple seen in output voltage is rectifier circuit.

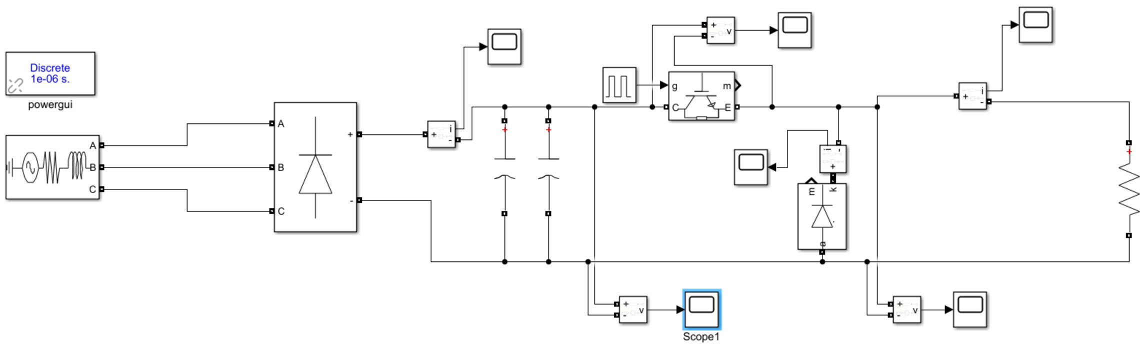


*Figure 5: Overall circuit diagram with resistive load*

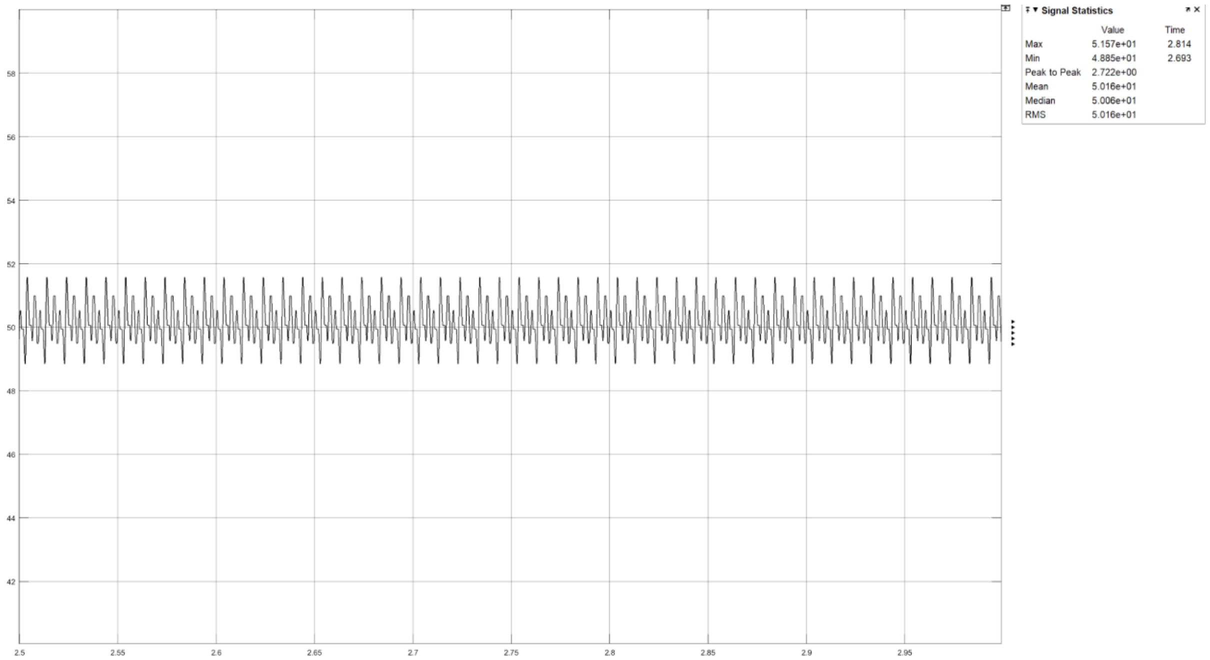


*Figure 6: DC-Link voltage waveform*

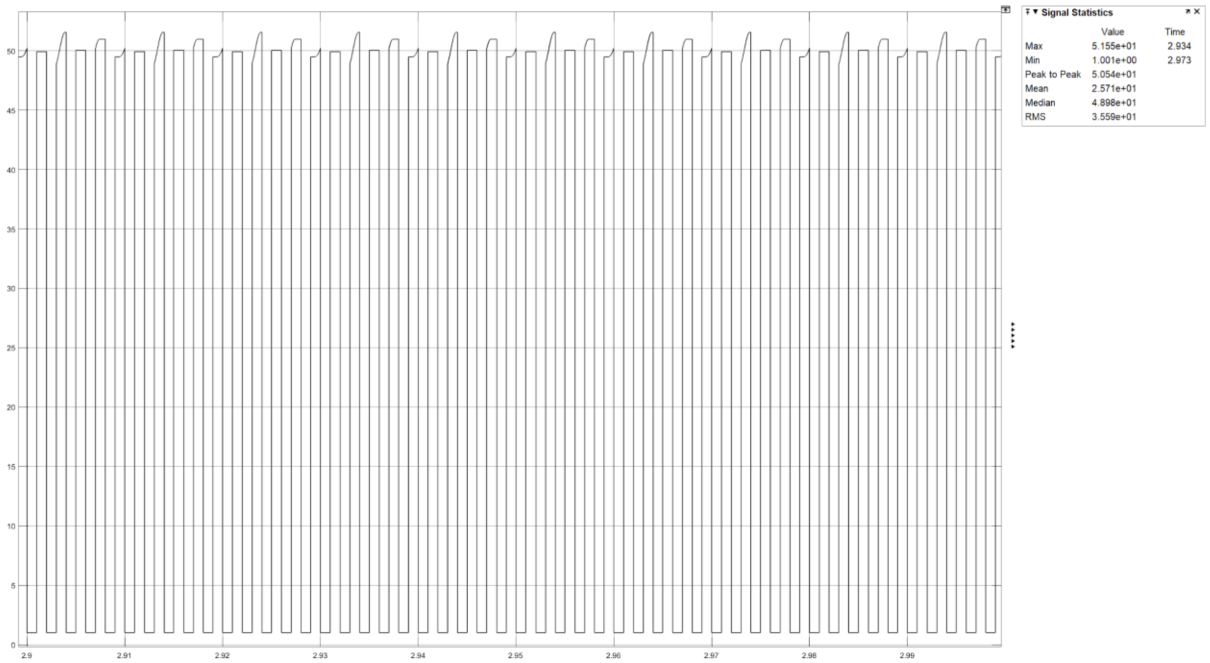


*Figure 7: Output voltage waveform (PWM)*

### 2) Motor-Load Test

The only difference between R-load simulation and motor-load simulation is that, separately excited DC motor is used as a load. Following motor-load simulation is done with %50 duty cycle at 500 Hz switching frequency and $220V_{(l-l)}$ AC input. Also, motor parameters used in simulation are:

- Armature Winding: 1.07 Ω, 24.5 mH (includes interpoles winding)
- Shunt Winding: 210 Ω, 23 H
- Inertia: 2 kg.m$^2$

Following figure-8 shows the overall circuit diagram of the motor-load circuit. Also, the voltage of the field excitation is 220V and the torque is 13Nm (which corresponds a 2kW load at rated speed for robustness bonus). Magnitude of ripple of the output voltage waveform of the full-wave rectifier is increase because of the increase in input voltage as in seen in figure-9. Armature current, speed and electrical torque graphs of the motor can be seen in figure-10. High inrush current is drawn at the armature of the motor due to the starting torque of the motor. Furthermore, motor reaches to 78.5 rad/s speed which corresponds to 750 rpm with an 50% duty cycle as expected. It means that speed of the DC-motor is controlled with armature voltage.

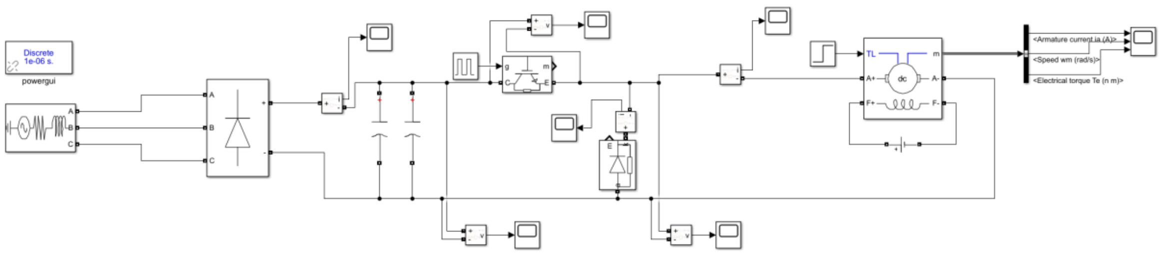


*Figure 8: Overall circuit diagram of motor-load*

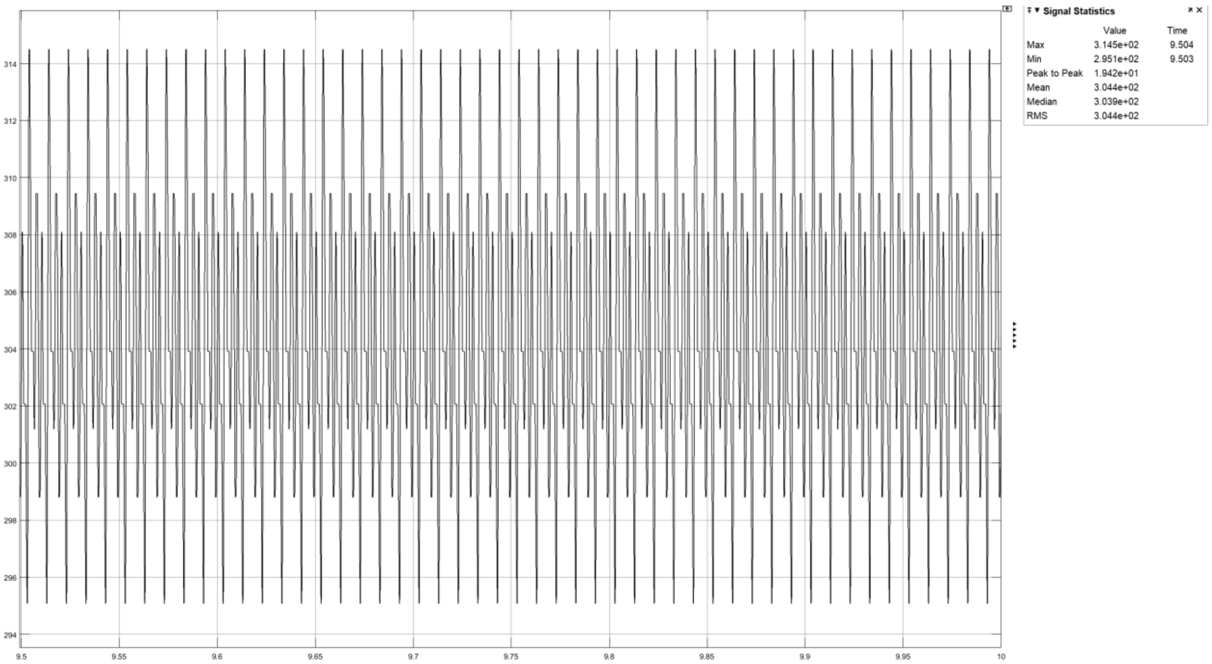


*Figure 9: DC-Link voltage waveform*

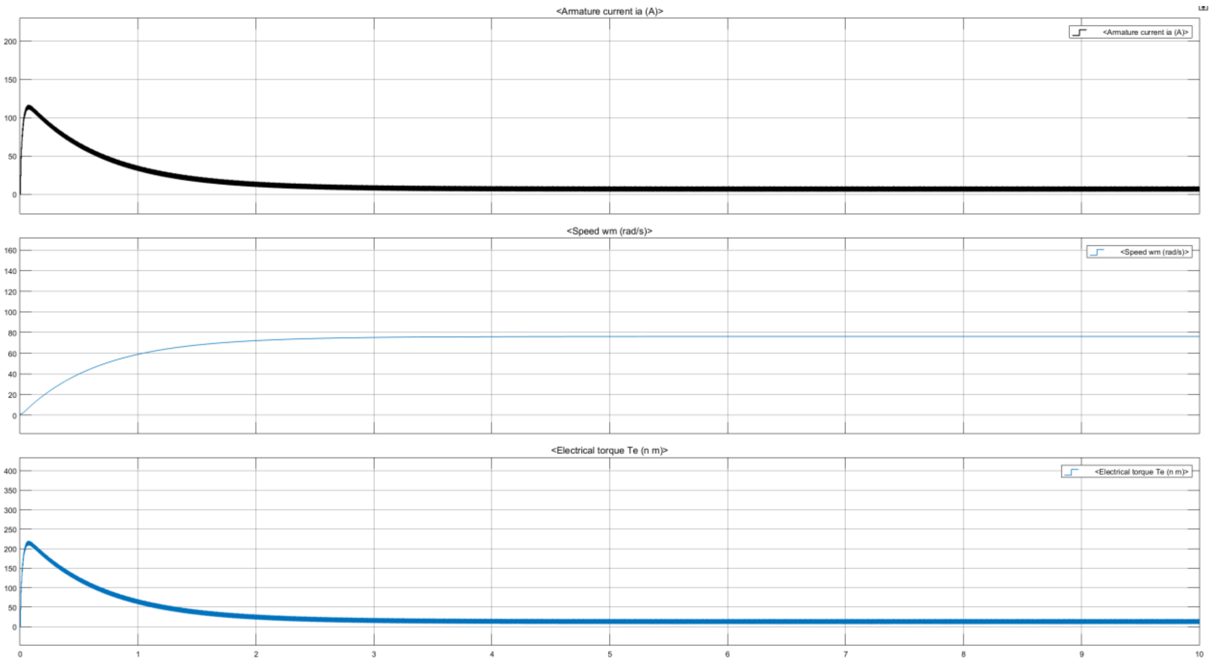


*Figure 10: Armature current, speed and electrical torque graphs of the motor*

## Experimental Test Results

We did R-load and motor-load tests experimentally and following figure-11 shows our prototype photos. Position of the components is shown in the appendices part.

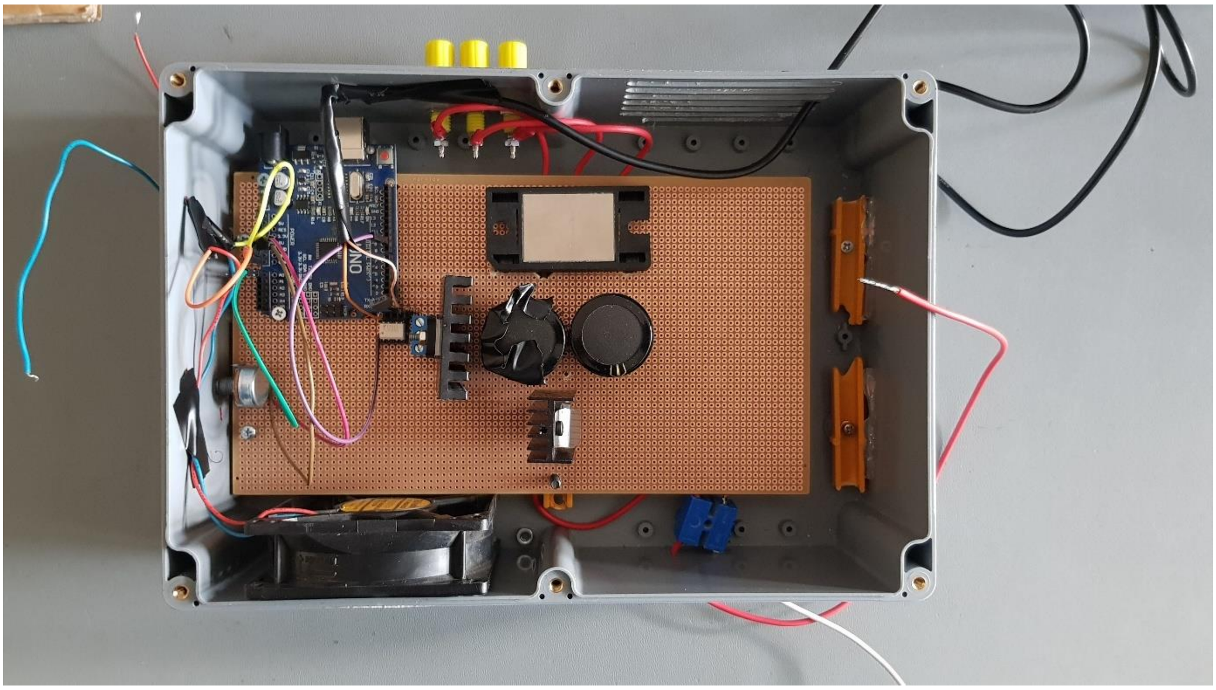

*Figure 11: Prototype of the circuit*

### 1) R-Load Test

In this test we used 50 Ω resistance as a load and $38V_{(l-l)}$ AC input which corresponds to rectified 50V DC. Also, following tests are done with different duty cycle at 500 Hz switching frequency. Figure-12 shows the output voltage of the full-wave 3-phase diode rectifier which is a 6-pulse DC voltage (300 Hz). More smoother voltage waveform after adding DC-link capacitors is shown in figure-13 which is approximately ripple free DC voltage.

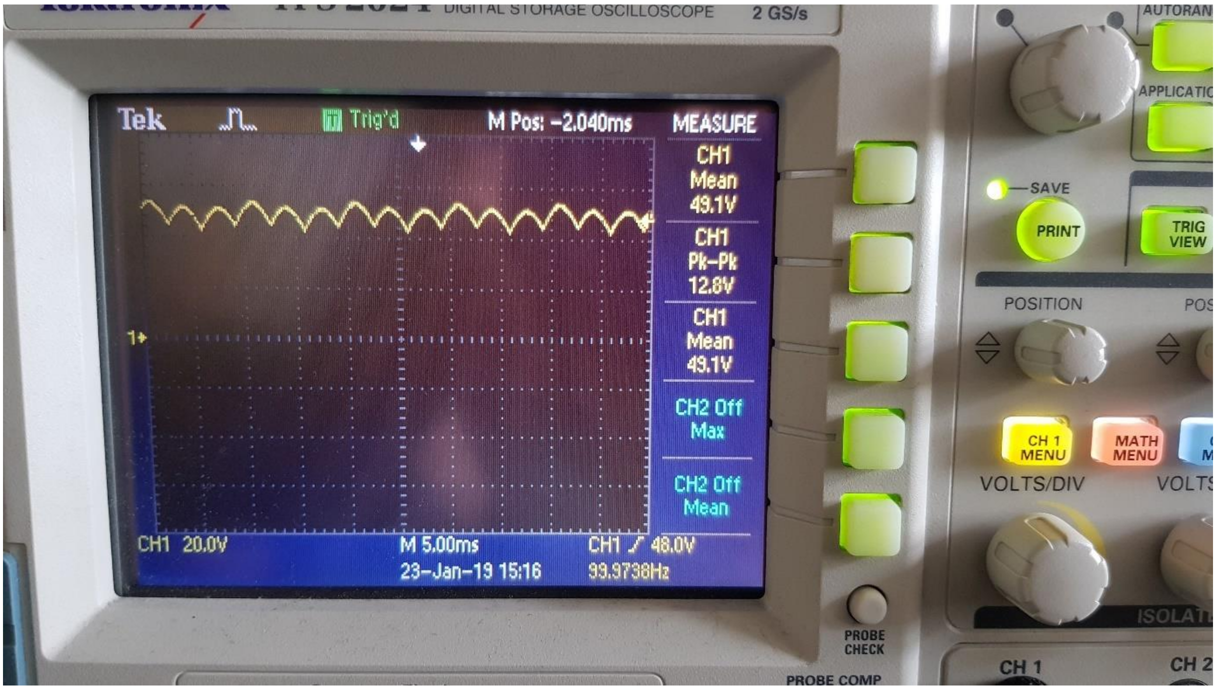


*Figure 12: Output voltage waveform of full-wave 3-phase diode rectifier*

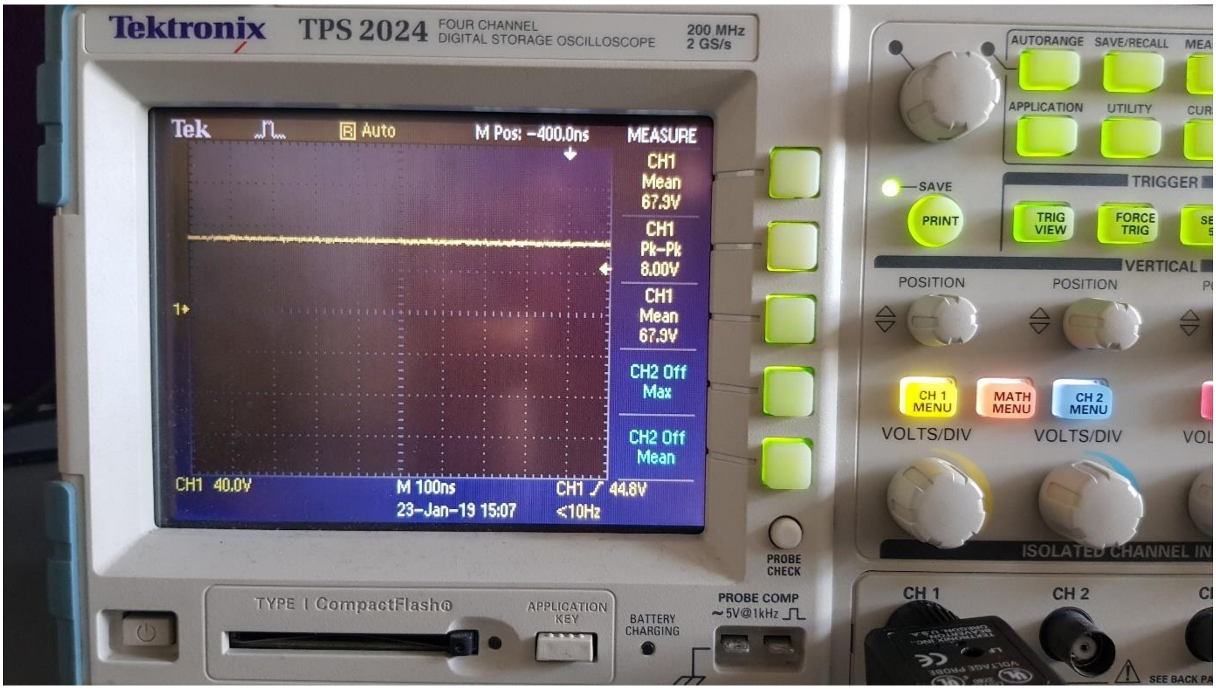


*Figure 13: Voltage waveform of DC-link capacitors*

After producing DC voltage, we produced the PWM at 500 Hz with Arduino for switching the IGBT (via optocoupler) which can be seen in figure-14 & figure-15 for different duty cycles. Also, the maximum voltage value of the Arduino PWM is approximately 5V. This voltage is increased with TLP250. Output voltage waveform of the optocoupler is shown in figure-16 & figure-17 for different duty cycles.

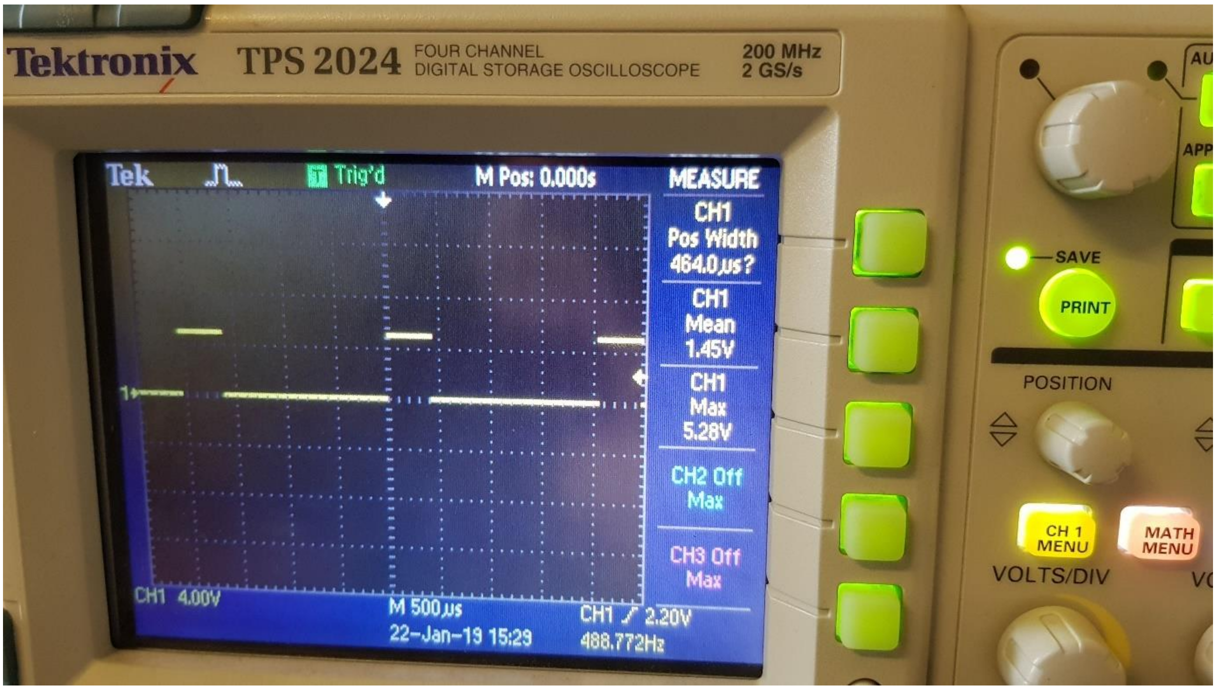


*Figure 14: Arduino PWM (23% duty cycle)*

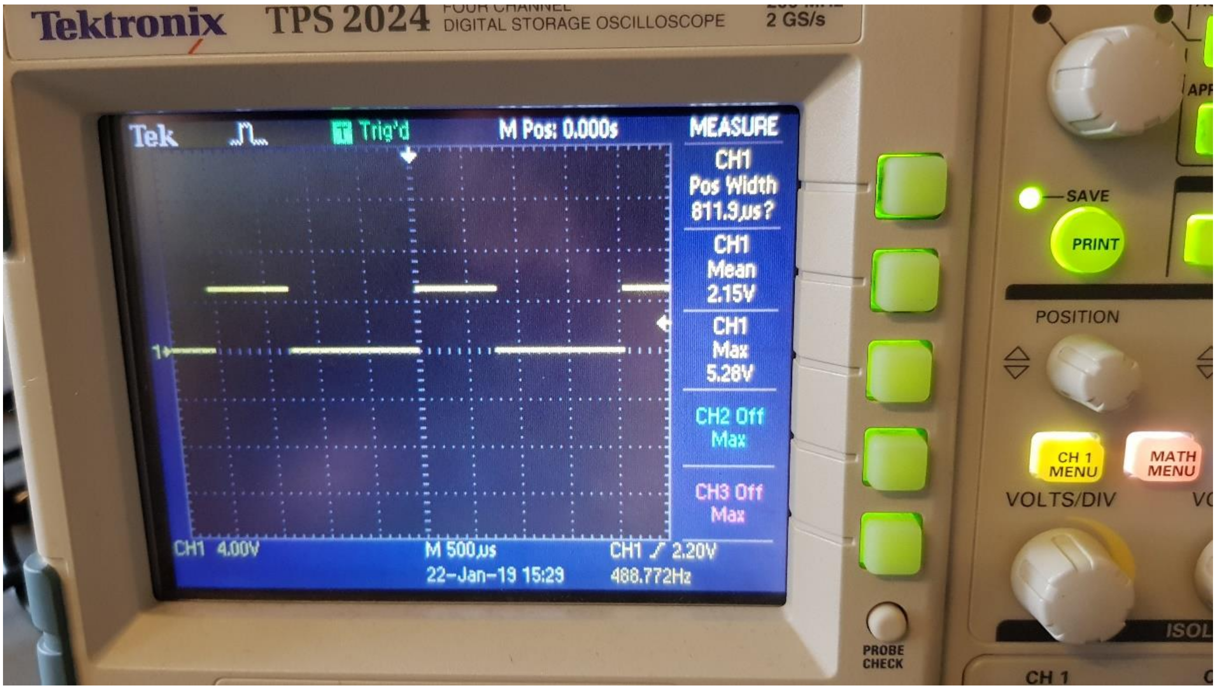


*Figure 15: Arduino PWM (40% duty cycle)*

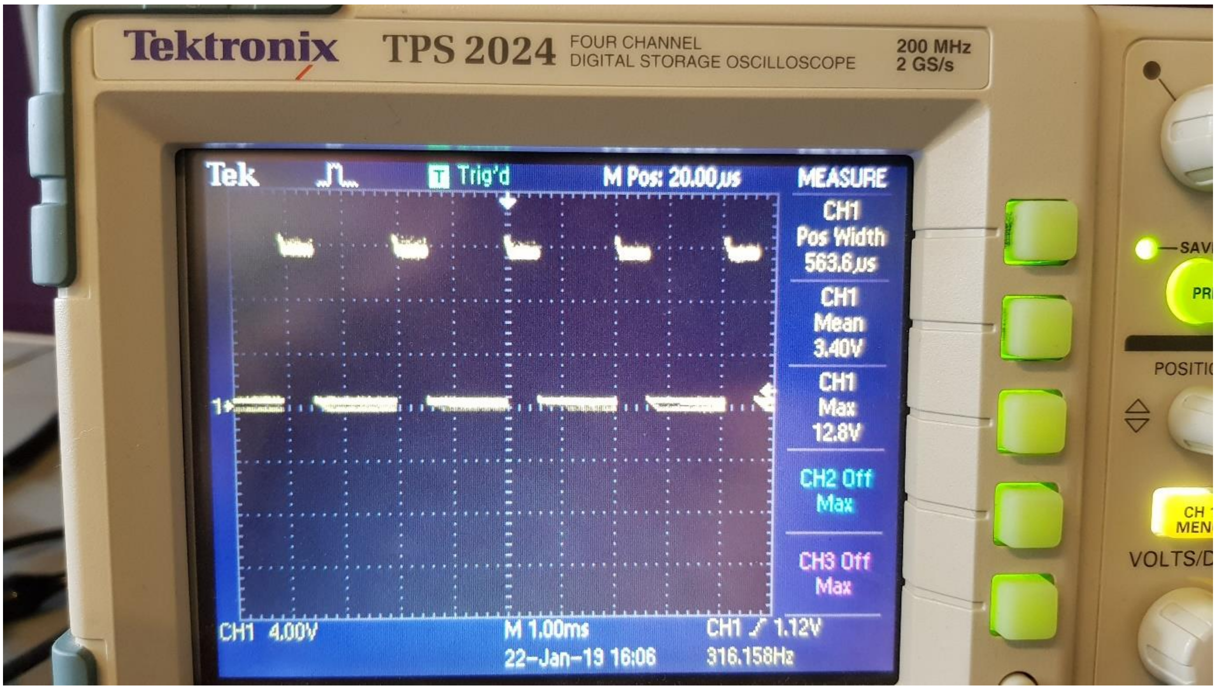


*Figure 16: PWM output of the optocoupler (28% duty cycle)*

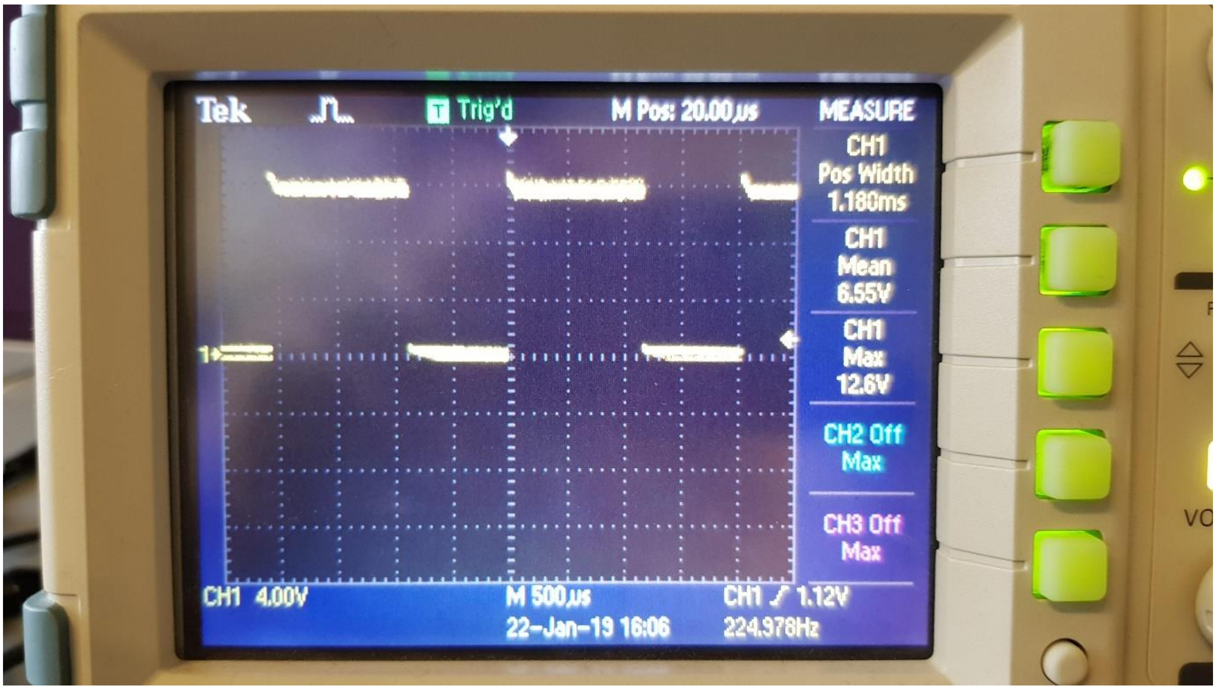


*Figure 17: PWM output of the optocoupler (59% duty cycle)*

Output voltage waveform of the overall circuit is also tested for different input voltage (until the15074$V_{(l-l)}$ AC input) and different duty cycles. Following figüre-18 shows the output voltage waveform of the buck converter at 74$V_{(l-l)}$ AC input with 92% duty cycle.

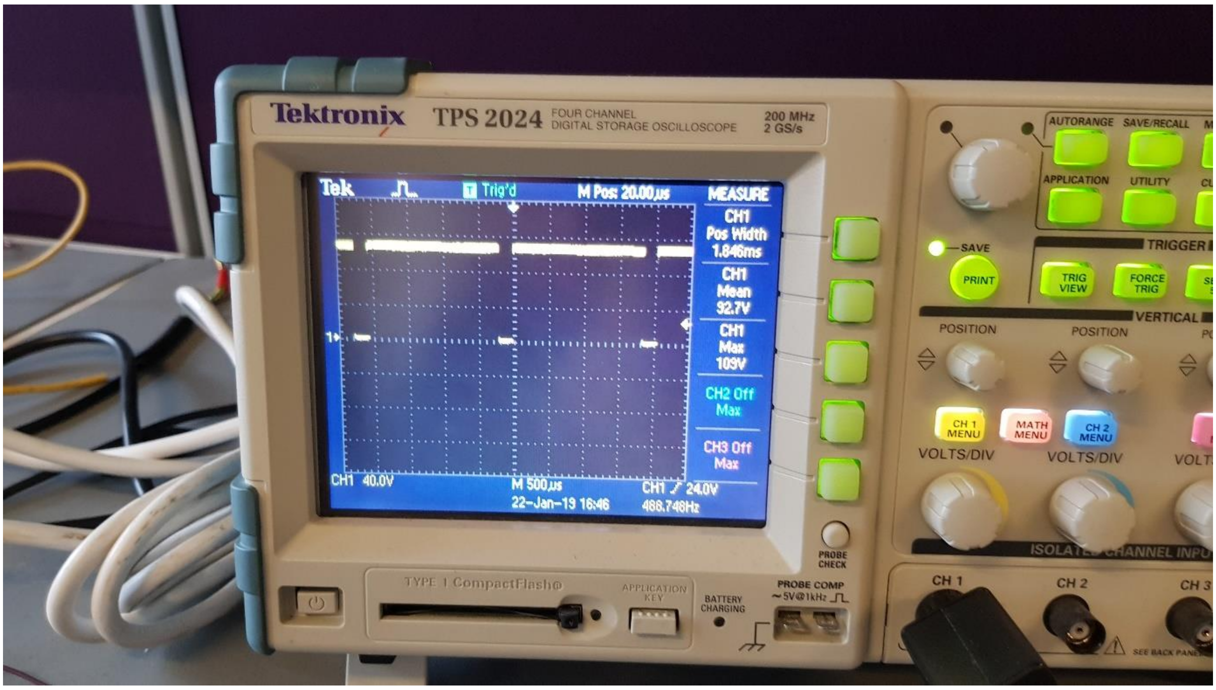


*Figure 18: Output voltage waveform of the buck converter ($74V_{(l\text{-}l)}$ AC input with 92% duty cycle)*

## 2) Motor-Load Test

After completing the resistive load tests successfully, we connected our circuit to DC motor. Test is done with 2 kW-load. Armature voltage and armature current waveforms of the motor is shown in figure-19 (yellow line is the armature voltage and green line is the armature current). As in seen in the figure-19, buck converter works in continuous conduction mode. However, when decreasing the PWM, buck converter works in discontinuous conduction mode which is shown in figure-20 (yellow line is the armature voltage and green line is the armature current). This mode changes occurs because inductance of the motor cannot meet the current needs of the motor for closed switching time and inductor becomes charge empty. As a result of that two-step armature voltage formed (second one is back-emf of the motor) which is shown in figure-20.

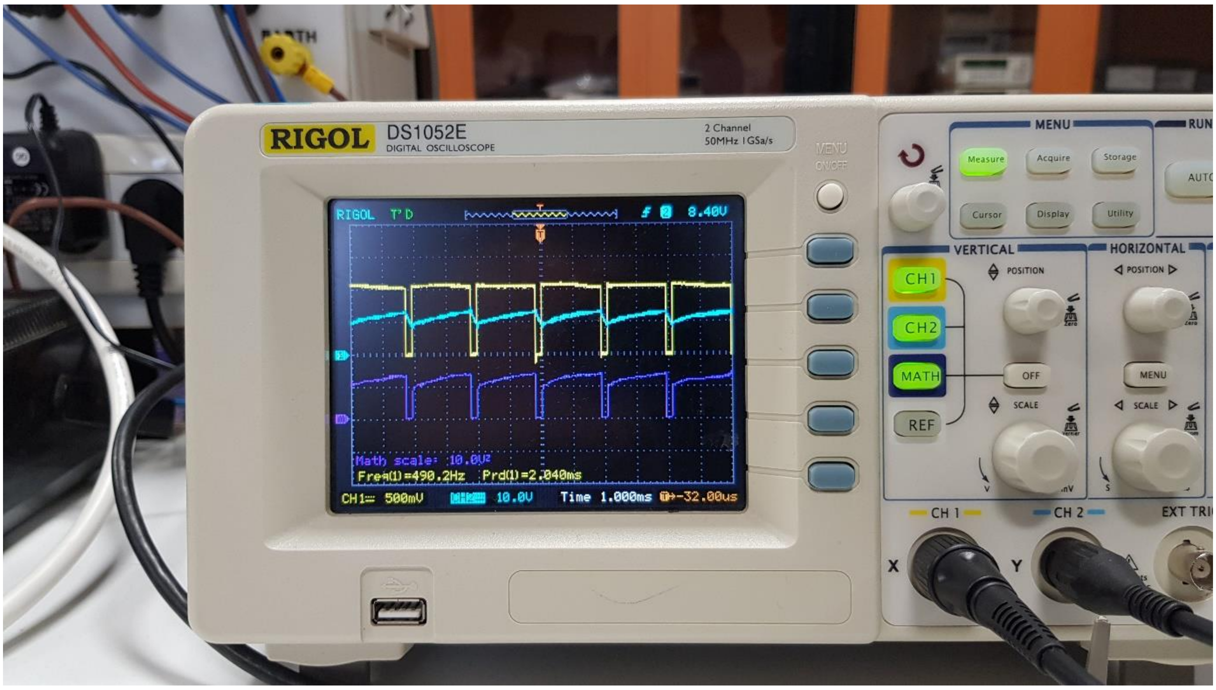


*Figure 19: 2 kW-load motor test armatüre current & voltage waveforms in ccm (yellow line is the armature voltage and green line is the armature current)*

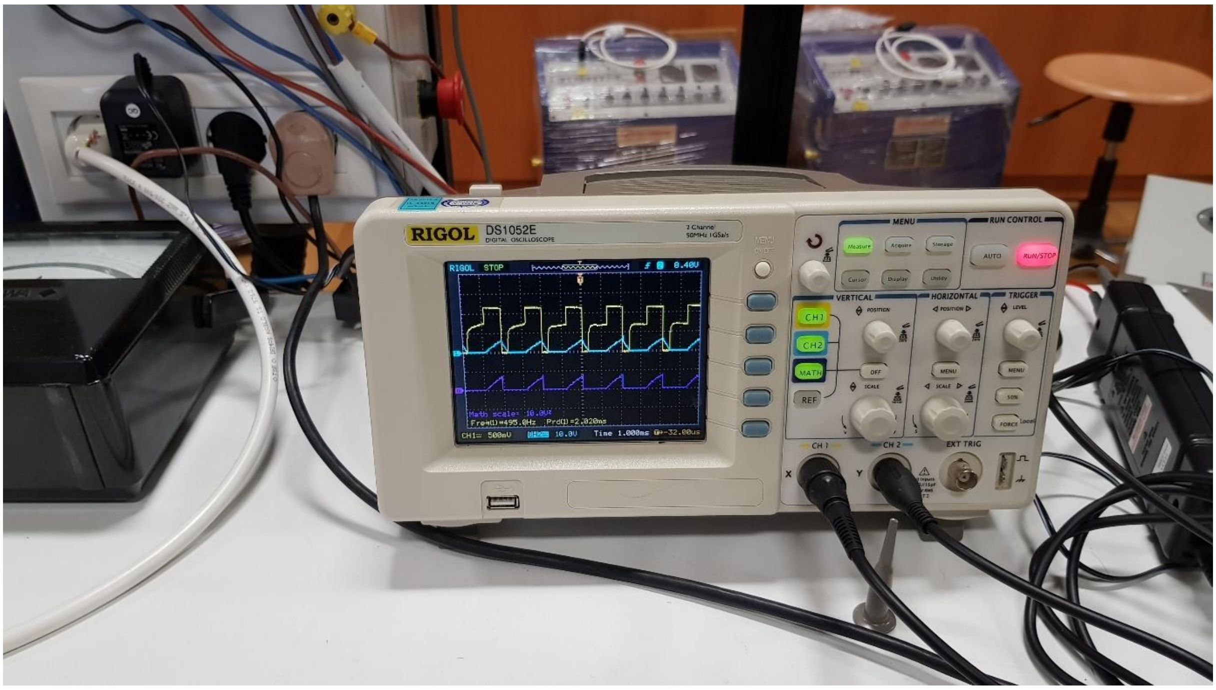


*Figure 20: When decreasing the PWM armatüre current & voltage waveforms in dcm (yellow line is the armature voltage and green line is the armature current)*

Temperature of the circuit is observed at 2 kW-load with thermal camera which is shown in figüre-22. Figure-21 shows camera angle on the circuit. After 5 minutes, IGBT reaches to 65ºC.

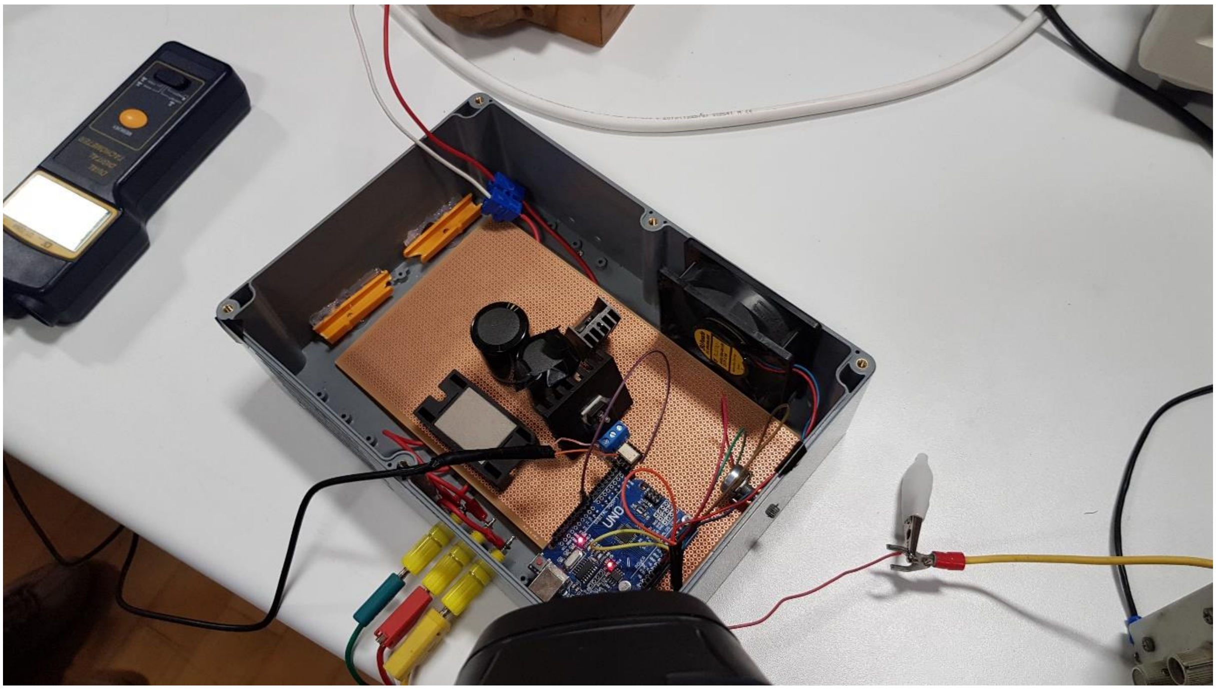

*Figure 21: Thermal camera angle*

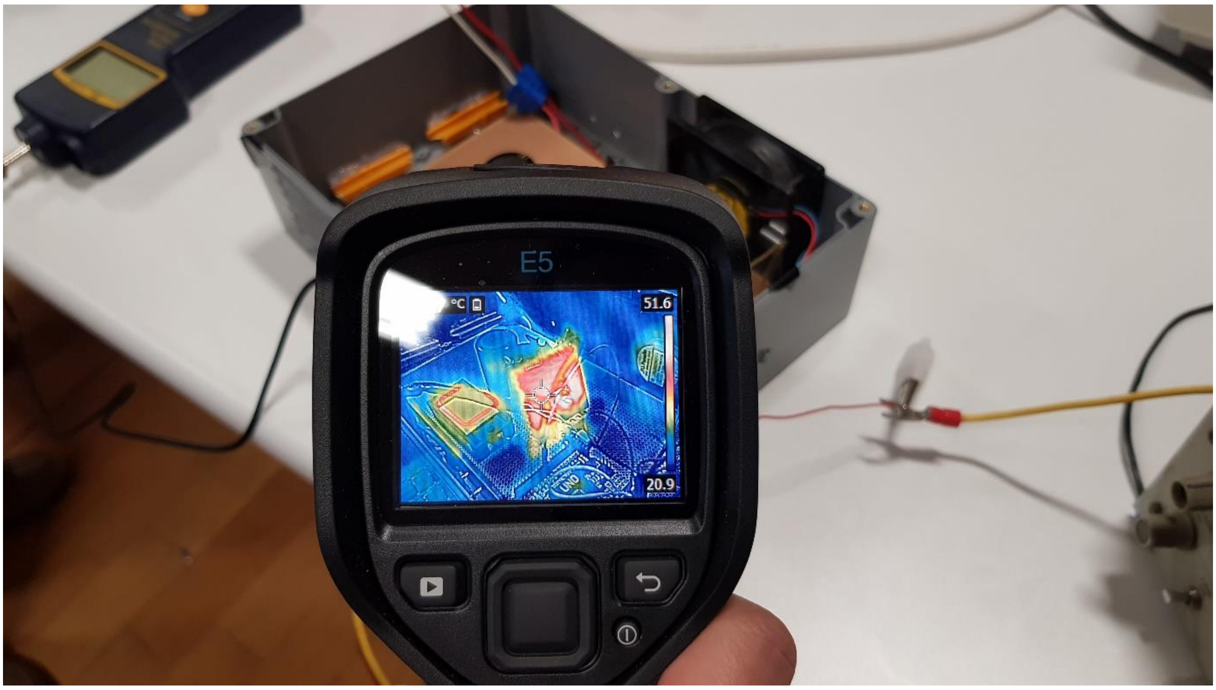


*Figure 22: Thermal results*

# Cost Analysis

Cost analysis of the project is shown in the following table-2.

*Table 2: Cost analysis table*

| Component | Cost |
|---|---|
| Three-Phase Rectifier | 10.2 $ |
| Capacitor | 2 x 5.2 $ |
| Diode | 1.73 $ |
| TLP250 | 1.3 $ |
| Arduino | 4 $ |
| IGBT | 5 $ |
| Heat Sinks | 3 $ |
| Other Equipment | 15 $ |
| Total | 50.63 $ |

# Conclusion

In this project, firstly, the PWM generation by using Arduino and a POT is studied. Then the combination of the Arduino and TLP250 is done and the input signal of the gate of the IGBT is obtained. Secondly, converting three-phase AC input into a DC output is done by using a three-phase diode rectifier and DC link capacitors. The capacitor values are set in order to decrease the ripples at the DC voltage. Thirdly, the switching element is implemented in order to adjust the output voltage based on the duty cycle of the PWM signal. Lastly, a freewheeling diode is connected at the output terminals. This diode creates a path for current to flow when the switch is off.

After implementing all components into the stripboard, test procedures started. From the beginning to the end, all components and the output waveforms are tested. Then, the motor tests started. By taking data from the tests, improvements are done in the design. At the end of the project, the demo procedure is completed correctly.

This project gives general information about AC-DC and DC-DC converters. Specifically, buck converter topology is studied. The comparison of simulation results and test data are done.

# Appendices

Arduino code:

```
#define enA 9
int a = 100;
int b = 100;
int finalvalue = 230;
int actualpwm = 0;

void setup() {
  pinMode(enA, OUTPUT);
  Serial.begin(9600);
  TCCR1B = TCCR1B & B11111000 | B00000011; // for PWM frequency of 490.20 Hz
}

void loop() {
  int potValue = analogRead(A0); // Read potentiometer value
  int pwmOutput = map(potValue, 0, 1023, 0 , 255); // Map the potentiometer value from 0 to 255

if (pwmOutput>finalvalue){
    pwmOutput=finalvalue;

     if (1 <= (pwmOutput-actualpwm) ){
     actualpwm = actualpwm + 1;
     analogWrite(enA, actualpwm);
     delay(a);
      }

      else if (-1 >= (pwmOutput-actualpwm)){
      actualpwm = actualpwm - 1;
      analogWrite(enA, actualpwm);
      delay(b);
      }
}

else if (pwmOutput<finalvalue){

      if (1 <= (pwmOutput-actualpwm) ){
      actualpwm = actualpwm + 1;
      analogWrite(enA, actualpwm);
      delay(a);
      }

      else if(-1 >= (pwmOutput-actualpwm)){
           if (15 >actualpwm) {
           actualpwm = 0;
          analogWrite(enA, actualpwm);
          delay(a);
           }

          else if (-1 >= (pwmOutput-actualpwm)){
          actualpwm = actualpwm - 1;
          analogWrite(enA, actualpwm);
          delay(b);
           }
      }
}

else if (-1 < (pwmOutput-actualpwm) <1){
 analogWrite(enA, actualpwm);
 delay(100);
}

delay(100);
}
```

Positions of the components is shown in figure-23 and final product is shown in figure-24.

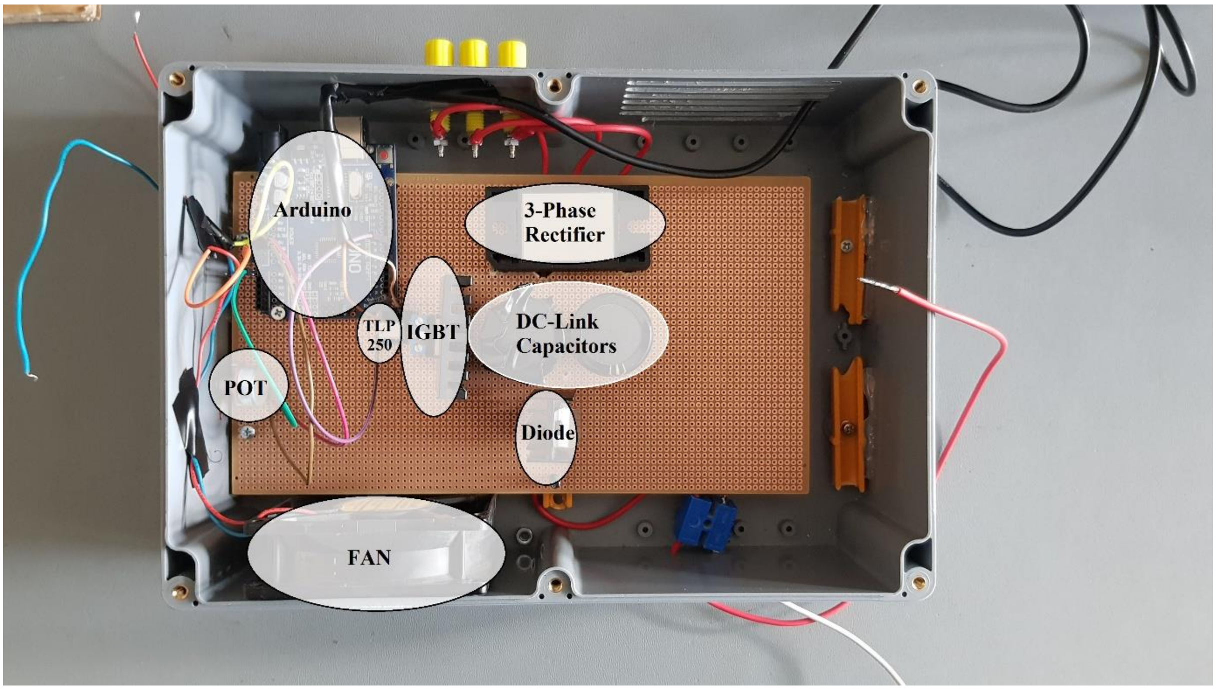


*Figure 23: Positions of components*


*Figure 24: Final product photo*

# References


Diode datasheet: https://media.digikey.com/pdf/Data%20Sheets/IXYS%20PDFs/DSEP30-06CR.pdf

IGBT datasheet: https://img.ozdisan.com/ETicaret_Dosya/344814_2485237.pdf

Rectifier datasheet: http://ixapps.ixys.com/datasheet/vuo34-18no1.pdf