MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE463: STATIC POWER CONVERSION I
HARDWARE PROJECT
FINAL REPORT

by GET REKTIFIED

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1. Introduction

A DC motor is a commonly used electrical machine in industry. However, they are not always intended to be used in rated conditions. Therefore, controlling them is a serious problem. This report focuses on a hardware system, which drives a 180V DC motor. It consists of simulational results, design and discrepancies in practice. Finally, it includes, thermal and electrical simulations, design units and parameters, pcb layouts of the units and deviations in practice.

2. Design

a. Topology

To design this hardware system, the problem should be defined properly at the very beginning of the procedure. The problem is driving a 180V DC motor at rated speed and constant AC signal (three or single phase). The motor is an highly inductive and resistive system, which makes the system more sensitive to the voltage ripples. To meet these specifications, an AC/DC converter is utilized. However, the output of the rectifier should be controlled as it produces output with relatively high voltage ripple and constant DC average. To control the output of the rectifier in terms of average and ripple, a DC/DC

converter is utilized. By adjusting the duty cycle with the switch, the control of the driver would be achieved. Figure i shows the overall circuitry of the driver.

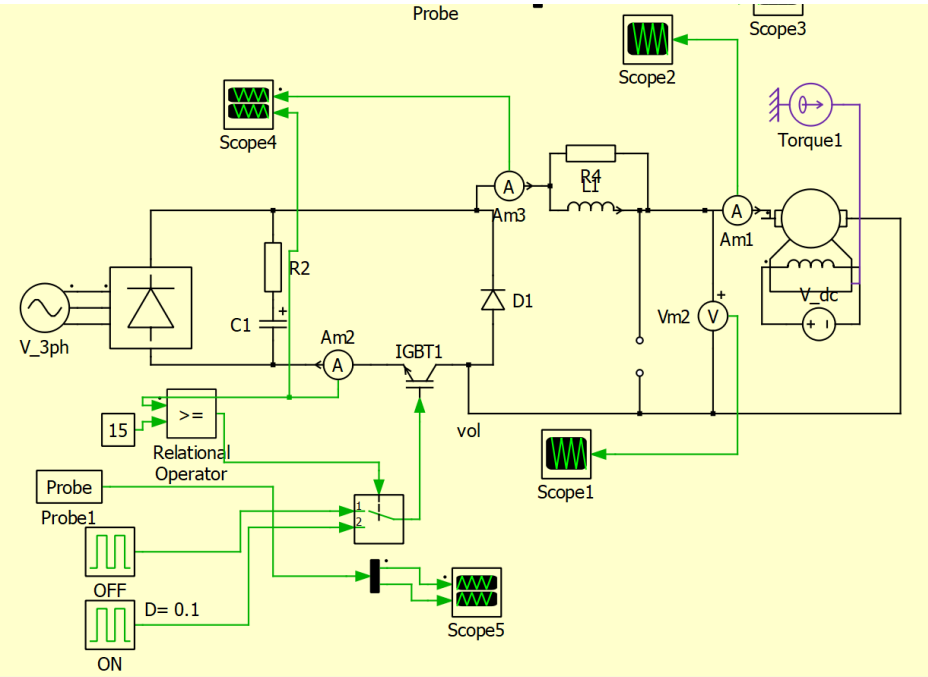


Figure 1: *The overall circuit diagram of the driver used in simulations.*

b. Units

i. Rectification Unit

It is needed to produce up to 180 V_{DC} output at the final stage. In this range, a three phase diode rectifier meets the system needs in an optimum way. By employing three phase full bridge rectifier, the buck converter will have 2.34*V_{ph} as input voltage. However, by nature of the full-bridge, there will be a ripple with magnitude 0.32*V_{ph}. This ripple will be significant as the system is highly inductive. Thus, an addition of a parallel capacitor would be a simple and great solution for the ripple problem. As a result, the three phase AC signals are rectified and the rectified signal with negligible ripple is given to the buck converter as input.

ii. Conversion Unit

The conversion unit is a buck converter. This unit takes the output voltage of the rectifier as input, adjusts it and gives it to the load. The load is a DC machine. An IGBT, placed at the low-side of the buck converter to prevent the use of an isolated voltage source is decided as the switch. The IGBT will be driven by the control signals produced by the Arduino and.

iii. Control Unit

To achieve a successful operation, there should not be an overvoltage and overcurrent. The control unit consists of a current controller. The current is aimed to be controlled by an on-off controller, turning the IGBT off whenever the current threshold has

been reached and turned on with the desired duty cycle, when the current is less than the threshold current.

c. Component Selection

As stated before, 180 V_{DC} is required to drive the motor at the final stage. When 90 V_{AC} is given, 210 V_{av} is provided at the output of the rectifier. At this level with 0.85 duty cycle, desired output voltage is obtained. At rated voltage to provide 2 kW for tea bonus, average 11A is drawn by the motor. So, the system should be able to fit in these conditions.

i. 36MT160 Three-Phase Bridge Rectifier (1600V 35A)

Instead of using single diodes for rectifying, a 3-phase full bridge rectifier is used in order to save board space and ease of controllability.

ii. ACS712-30A Current Sensor

To prevent overcurrent situations, an analog current sensor which is suitable to use with Arduino is used.

iii. IXGH24N60C4D1 IGBT (600V 24A)

It is used to perform the switching work in the buck converter.. It was chosen because it is a component available in the inventory of our lab and allows us to save design time and cost since it already satisfies the needs of the driver. We've also added a 10R resistor to the gate of the IGBT to reduce ringing and a diode to allow the IGBT to discharge easily without the resistance

iv. DSEI30-06A Fast Recovery Diode (600V 30A)

It will be used as the freewheeling diode in the buck converter. The current rating is chosen high in order to withstand the fluctuations that may occur in the current and since it is a fast recovery diode, the switching losses will be relatively low, allowing us to operate at higher frequencies.

v. TLP250 Optocoupler Gate Driver

This component is chosen in order to provide the isolation between the signal and power elements.It is also a required choice because it includes a totem pole gate driving circuit which is necessary in order to safely turn the IGBT. It was also available in the inventory of our lab which allowed us to save design time and cost.

vi. Arduino Nano

An Arduino Nano was chosen because we were familiar with the Arduino language and we wanted to use a digital control algorithm for ease of use. An arduino also allowed us to work on frequencies higher than 1kHz.

vii. Capacitors

The ripple level of the 3 phase rectifier is relatively high. Therefore, in order to prevent ripple, using the data of the teams from the past year and since we are operating at 5kHz, it was decided to use a 330µF 400V capacitor. To prevent ripple at the output of the buck converter 100µF 400V capacitor was decided to be used.(However after our first demo, we've decided to remove this capacitor because it caused voltage ripple at the output).In order to filter the lower frequency noises 4.7µF capacitors were used after the power supplying elements. Similarly, 0.1nF capacitors are used to filter the high frequency noise in the circuit and placed in required places.

d. Bill of Materials (BOM)

Table 1: *The components used in the driver and their prices*

Components	Description	Price(₺)	Amount
36MT120	3 Phase Full-Bridge Diode Rectifier	Sponsor	1
ACS712	Current Sensor	Sponsor	1
TO247	Heatsink	22.5	2
Fan	10V DC Fan	Inventory	2
DSEI30-06A	600V 37A Diode	65.63	1
IXGH24N60C4D1	600V 30A IGBT	Lab Inventory	1
TLP250	Optocoupler Gate Driver	Lab Inventory	1
-	36Ω Resistor	Lab Inventory	1
-	560Ω Resistor	Lab Inventory	1
-	15kΩ Resistor	Lab Inventory	1
-	330µF 400V Capacitor	29.06	1
-	100µF 400V Capacitor	22.5	1
-	4.7µF 400V Capacitor	4.45	3
-	0.1nF 1000V Capacitor	0.27	3
Arduino Nano	Single-board Controller	110	1
-	Female Pin Header	3.5	1
3D Printing		50	1
Total : 307.91 + 191.9 (Sponsor) +126.61 (Lab Inventory)=576.42 ₺=33.32 $			

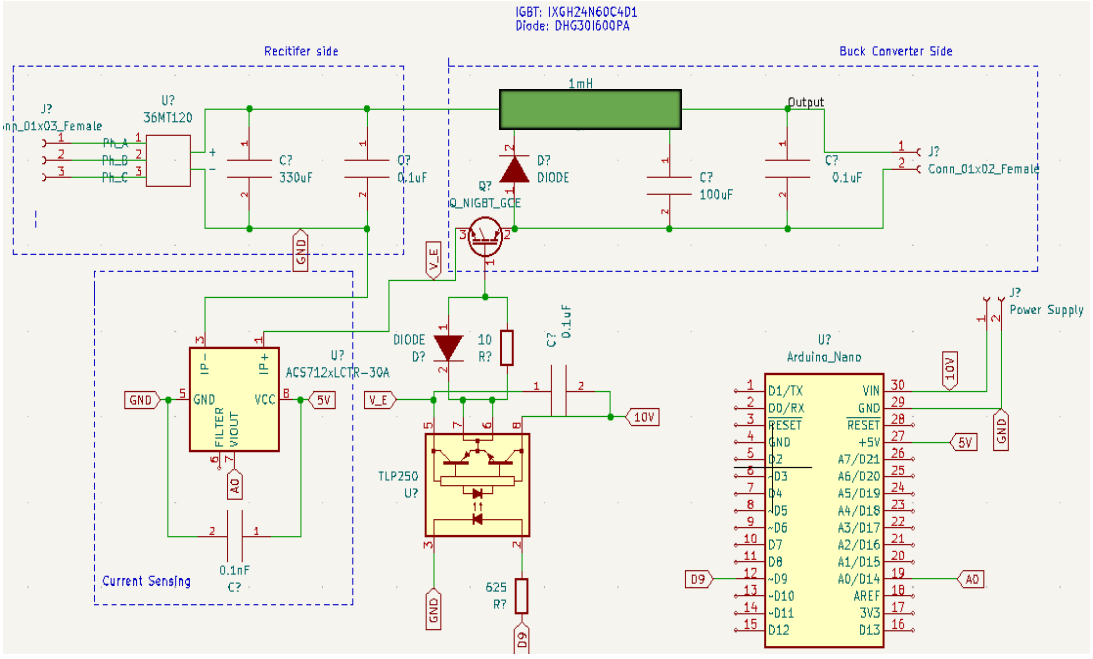


Figure 2: *The overall circuitry after deciding the components*

e. PCB Layouts

In order to reduce the cable inductances and more neat operation, we've opted to design a PCB and implement a LPKF board to our circuit.

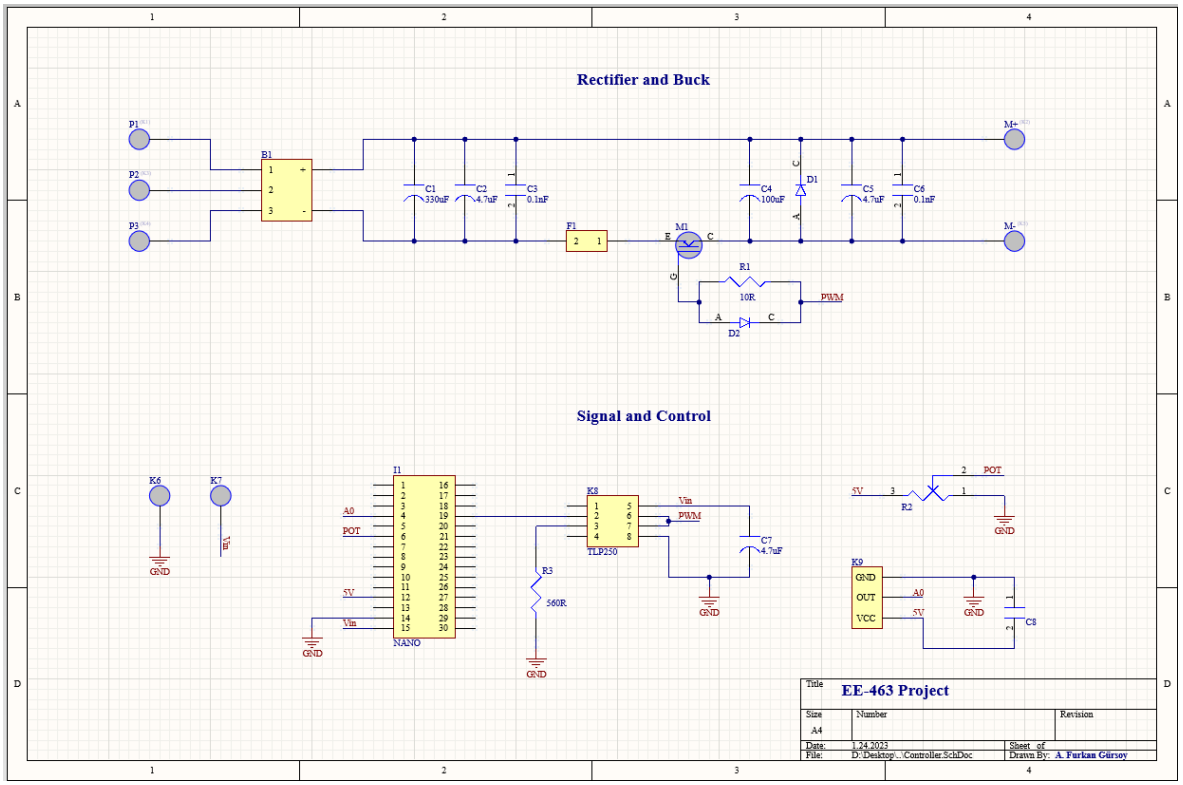


Figure 3: *The Schematic of the PCB*

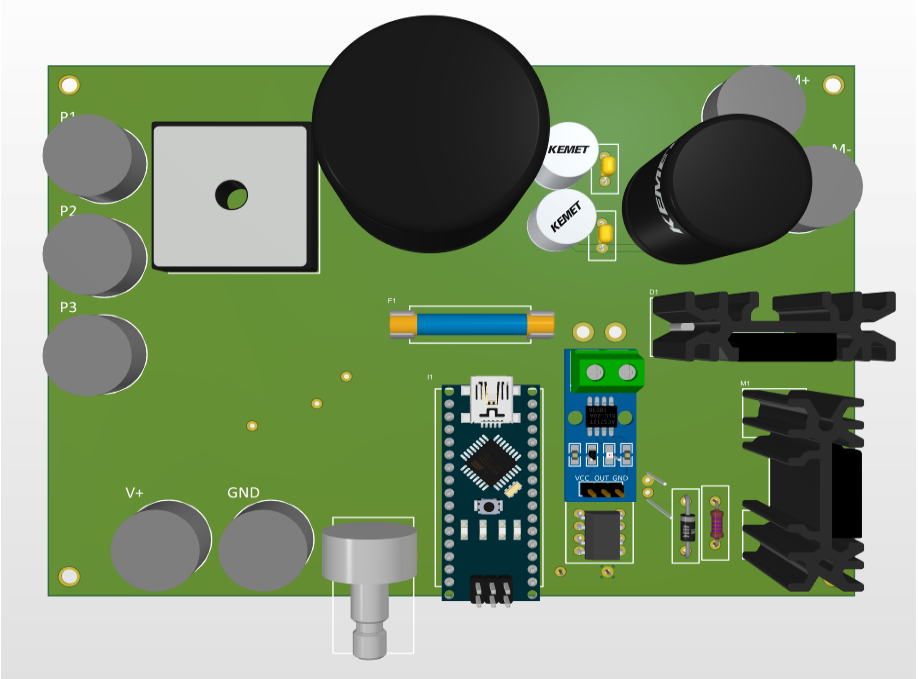


Figure 4: *Top View of the Board*

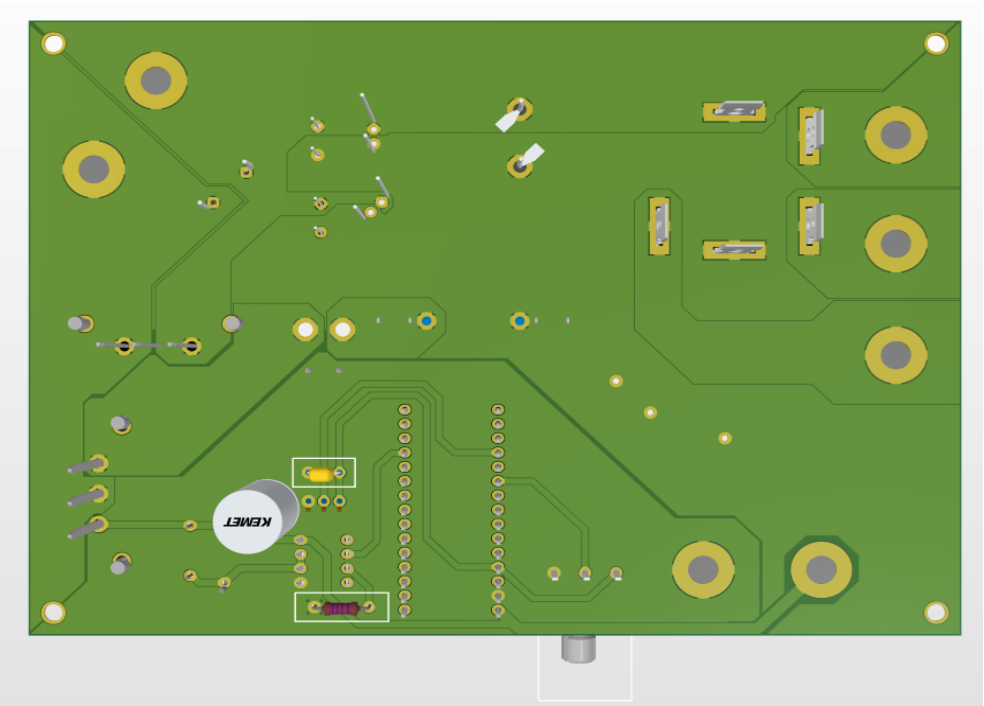


Figure 5: *Bottom View of the Board*

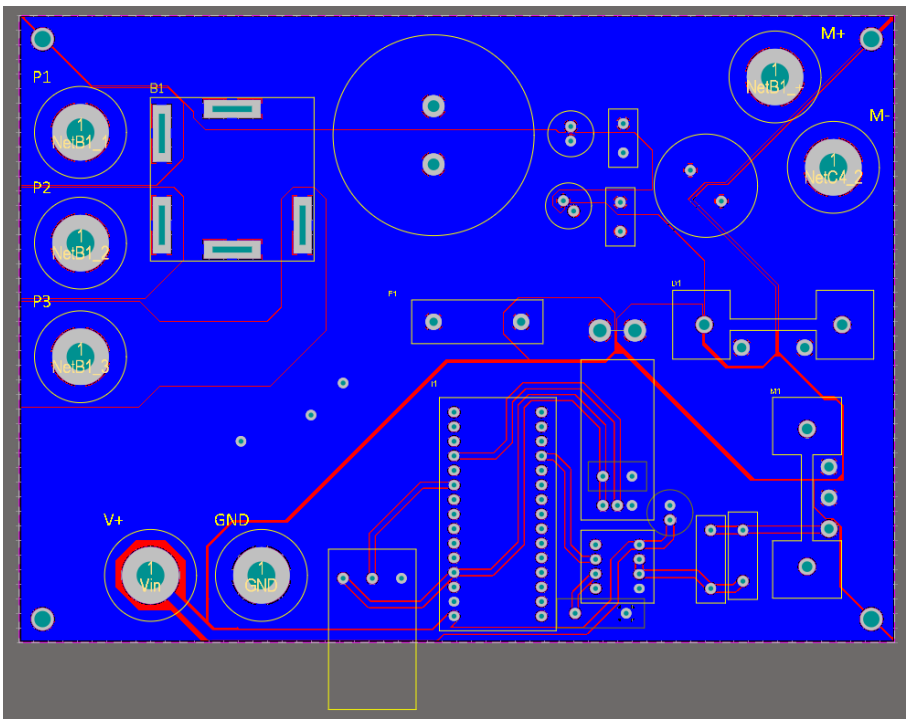


Figure 6: *Copper Paths of the Circuit*

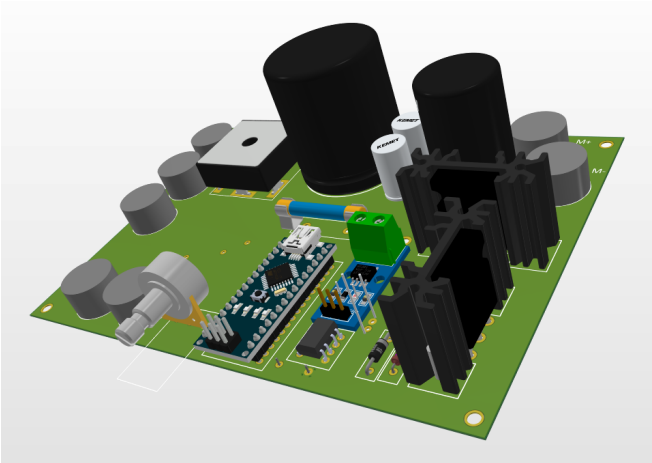


Figure 7.a: *3D view of the system*

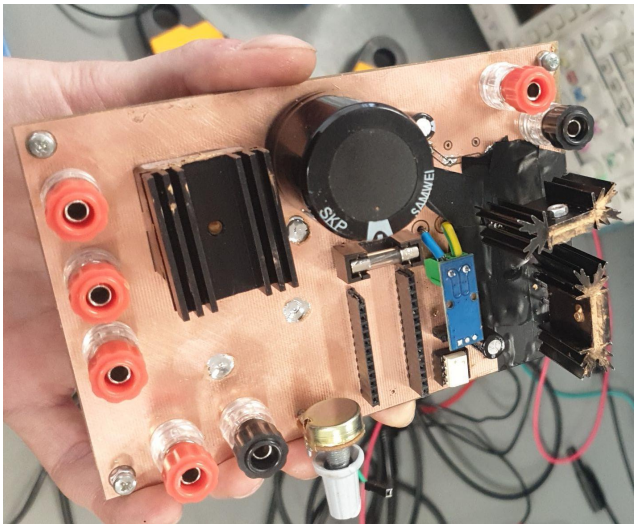


Figure 8.b: *Constructed Circuit*

f. 3D Casing

To make our circuit more customer friendly, we've designed a box in Shapr3D program and used a 3D printer to have a solid enclosure. The casing size is 160mm-110mm-60mm(L-W-H)

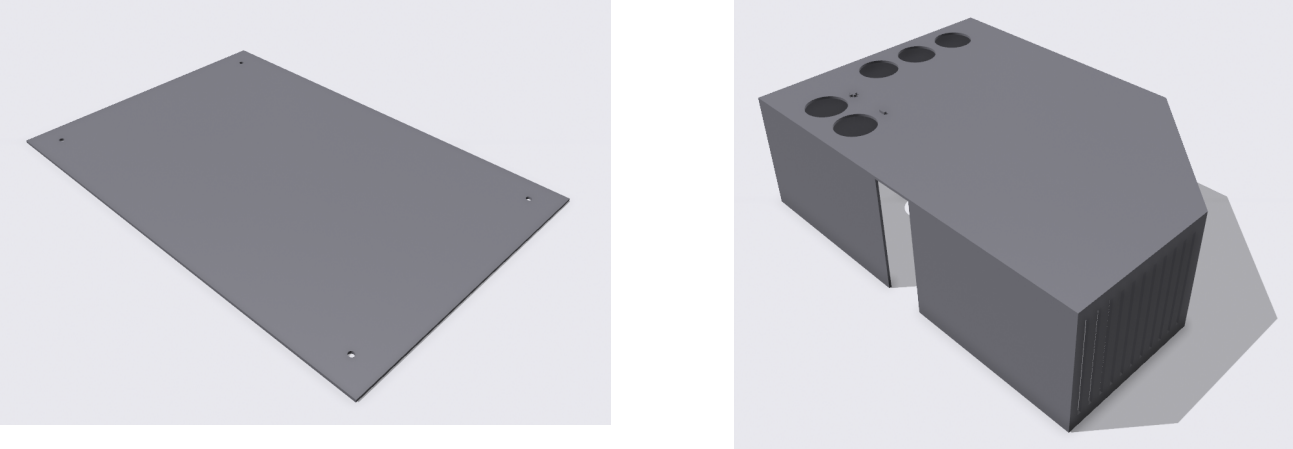


Figure 9.a-b: *3D view of the bottom (a) and top (b) parts of the casing*

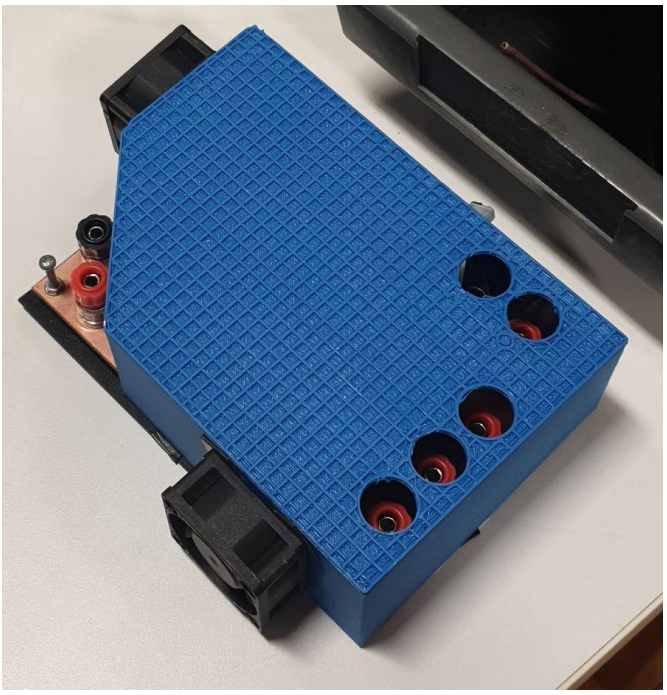


Figure 10: *A photo of the driver on PCB in 3D-printed anclosure*

After implementing the fans to our product, the total size of the circuit was 180mm-130mm-60mm(L-W-H).

3. Simulation & Theoretical Calculations

a. Electrical Simulations

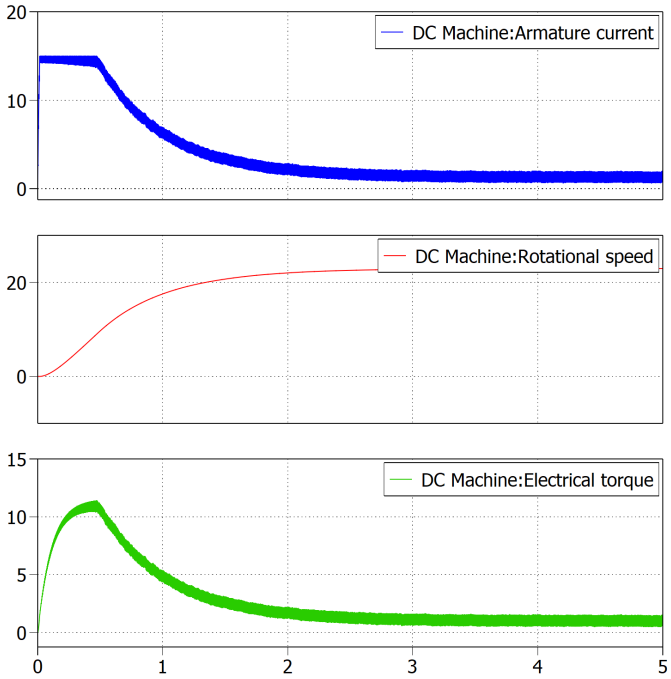


Figure 11: *The DC motor steady-state operation as load of the driver*

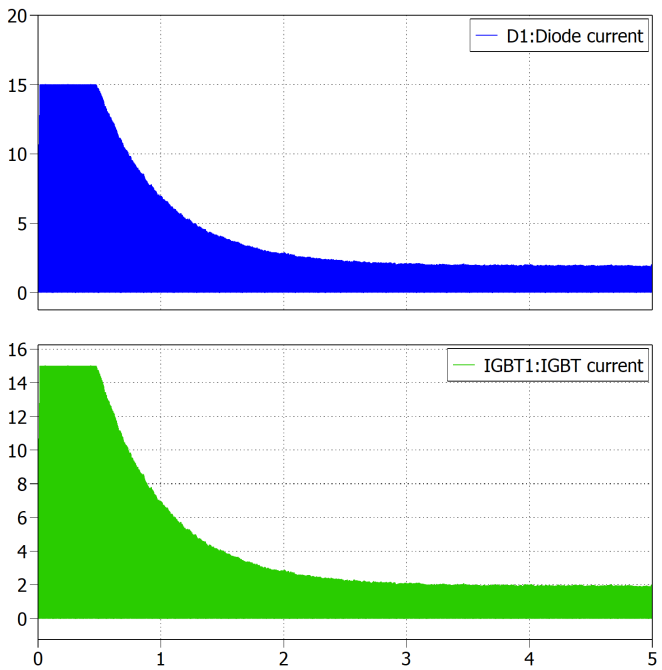


Figure 12: *The diode and IGBT current of the buck converter at steady-state*

In the simulations at 15A threshold current we can see that the circuit is working as desired, limiting the current at 15 A and after the motor reaches its required RPM, the current returns to its normal value.

b. Thermal Calculations

In thermal calculations, ambient temperature is assumed as 25 ℃. The heatsink of the rectifier has 6 ℃/W and the heatsinks of diode and switch have 9 ℃/W. Thermal grease is assumed as 0.5 ℃/W. For calculations, maximum rated conditions are assumed.

i. Bridge Rectifier(36MT160)

Table 2: *Properties of 36MT160*

$V_{F(max)}$	1.19 V for each diode in rectifier
$R_{\theta JC}$	1.35 ℃/W each diode

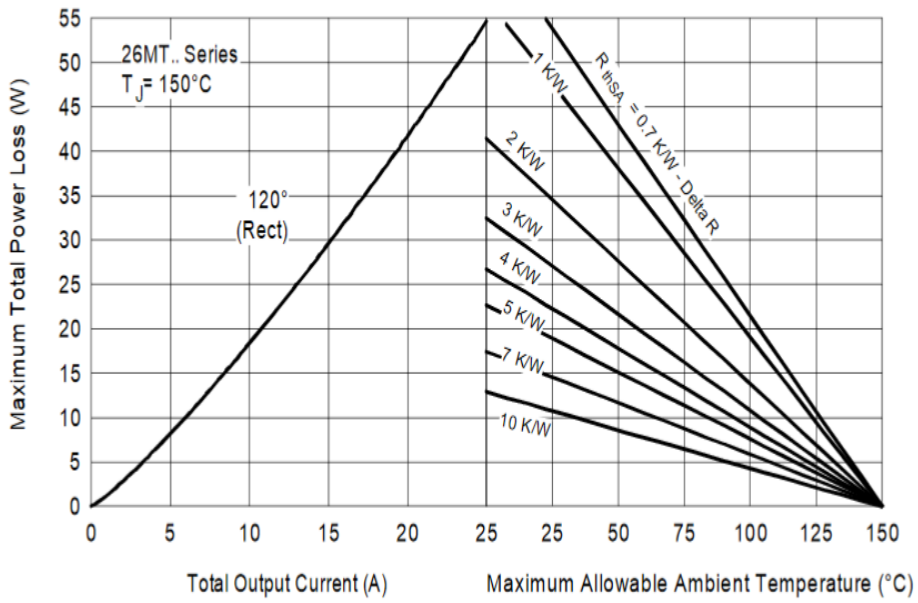


Figure 13: *Power Loss Graph of 36MT160*

$P_{total} \approx 20W$

$T_J = P_{total} * (1.35 + 0.5 + 6) + 25$ ℃ $= 182$ ℃

Which is high, then usage of a fan is compulsory

ii. Switch(IXGH24N60C4D1)

Table 3: *Properties of IXGH24N60C4D1*

$V_{CE(max)}$	1.9 V
$R_{\theta JC}$	0.8 ℃/W
E_{on}	1.0 mJ
E_{off}	1.1 mJ

$P_{loss(con)}$ = 1.9 * 11A * D_{max} = 1.9 * 11 * 0.85 = 17.765W
$P_{loss(sw)}$ = 5kHz * (1+1.1)mJ = 10.5W
P_{total} = 17.765 + 10.5 = 28.265W

T_J = P_{total} * (0.8 + 0.5 + 9) + 25 ℃ = 316,13 ℃

Which is too high, then usage of a fan is compulsory

iii. Freewheeling Diode(DSEI30-06A)

Table 4: *Properties of DSEI30-06A*

$V_{F(max)}$	1.40 V
$R_{\theta JC}$	1 ℃/W
t_{rr}	35ns

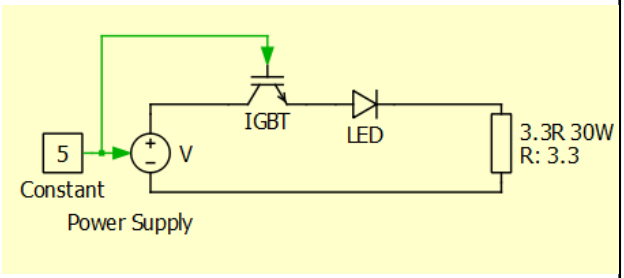
$P_{loss(con)}$ = 1.4 * 11A * (1-D_{max})= 1.4 * 11 * 0.15 = 2.31W
$P_{loss(sw)}$ = 210 * 11 * 5kHz * (1+1.1)mJ = 0.4W
P_{total} = 2.31 + 0.4 = 2.71W

T_J = P_{total} * (1 + 0.5 + 9) + 25 ℃ = 53.5 ℃

4. Tests & Practical Results

a. IGBT Operational Test

In this first test, we wanted to check the threshold voltage of our IGBT and observe the voltage drop between the collector and emitter junctions of the IGBT. A simple circuit illustrated in Fig.14 is constructed and we've seen that the IGBT starts conducting at 5V. In our measurements, we've seen that, the collector emitter voltage of the IGBT is 2.6V, which is close to the typical value of 2.28V in the datasheet of the IGBT



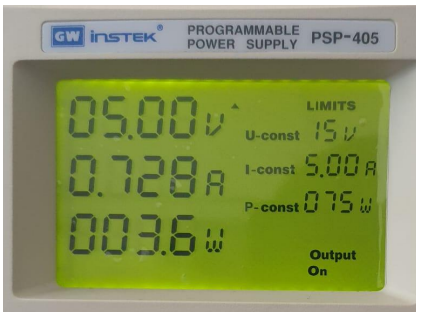


Figure 14: *IGBT Operational Test Circuit and measurement from the power supply*

b. Operation of the On-Off Current Controller Test

The aim of this test was to observe the current characteristics of the on-off controller from the Arduino plotter.The same setup is used with the IGBT replaced with the current sensor and the resistor value has changed with a 25R resistor Initially we observed a more constant current waveform and an average current of 0.4A at 10V which can be seen in Fig 15.

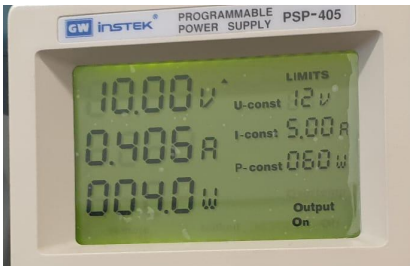
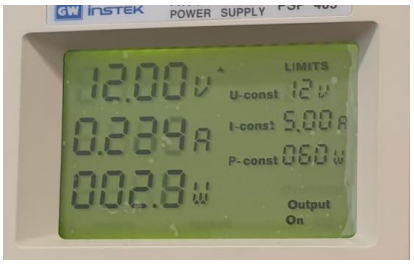


Figure 15: *Current sensor measurements without the on-off controller.*

We can see from Fig16 that the current sensor turns off at currents higher than 0.2A, and the current waveform is rippled as expected, and the average current is 0.23 A at 12V input.



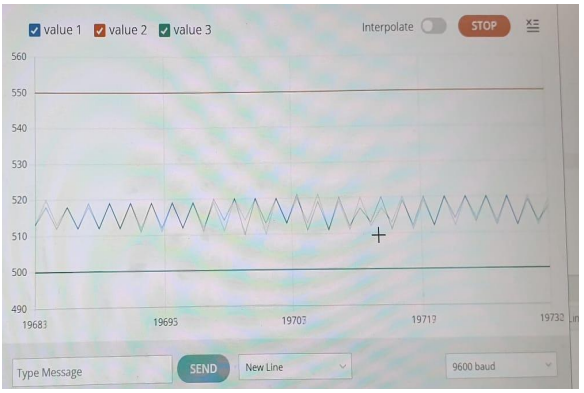


Figure 16: *Current sensor measurements with the on-off controller (0.2A threshold current)*

c. RL Load test (Vin_ph= 22Vac)

In this test, we simulated a DC motor by connecting an RL load to the load side and applied 22Vac input to the circuit. At full duty cycle, we've observed the waveform in Fig. 17. We should have guessed from this waveform that the load side capacitance of 100uF will cause us trouble because this waveform is unexpected for RL load of operation.

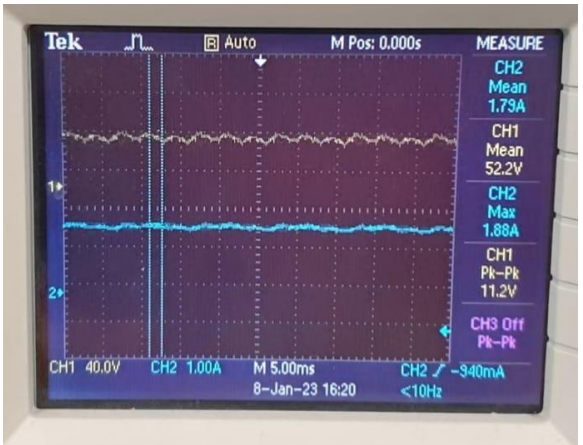


Figure 17: *22Vac 100 Duty RL load after 1st demo modifications*

5. Discrepancies in Practice

On the first day of the demonstrations, when we put out circuit to the test, around 70Vph AC, our circuit failed to operate. After, our first observation, we've decided to remove the 100uF capacitor at the output and add pull down resistors between the gate and the emitter of the IGBT because after some suggestions, we've concluded that the IGBT might have been falsely turned-on and burned. The resulting effect of the input voltage to our circuit can be seen in Fig.18. Luckily, our board was not affected because all the necessary copper roads are under our board.

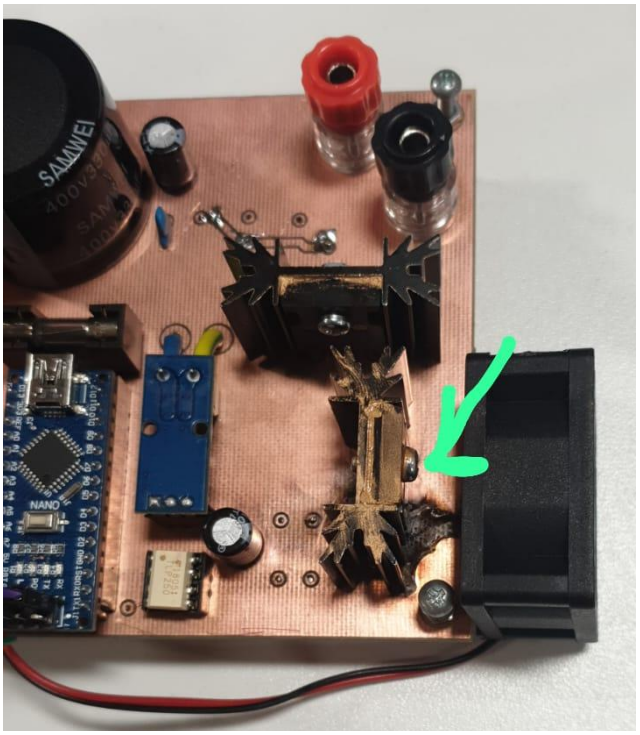


Figure 18. *The board after our first try with the motor on the first day of the demos*

On our second try with the motor, after making the required changes to the board, again after 80Vph AC, our board caught on fire. The degree of the burn to our circuit can be seen in Fig19. Again fortunately, the essential copper roads were under the board and it was still functional besides the IGBT that had burned.

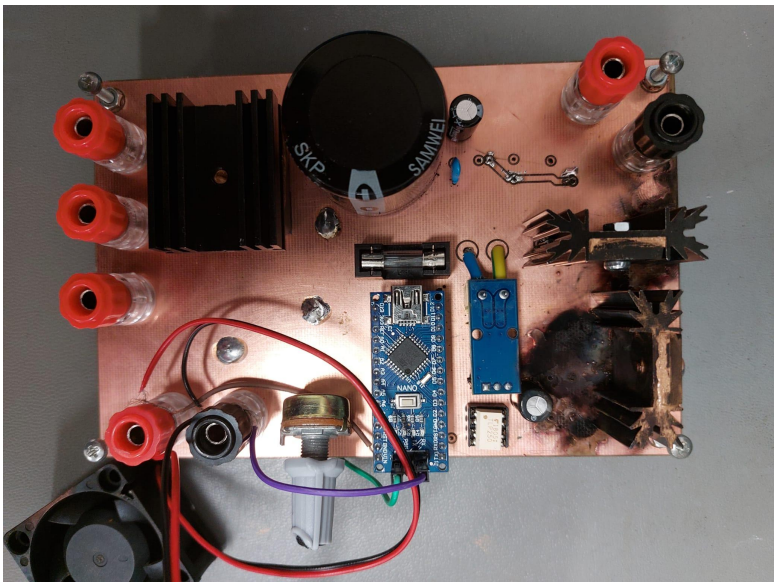


Figure 19. *The board after our second try with the motor on the first day of the demos*

In our last try with the motor, our circuit operated successfully and was able to turn the DC motor with 180V AC input before shutting down after a certain time of operation.

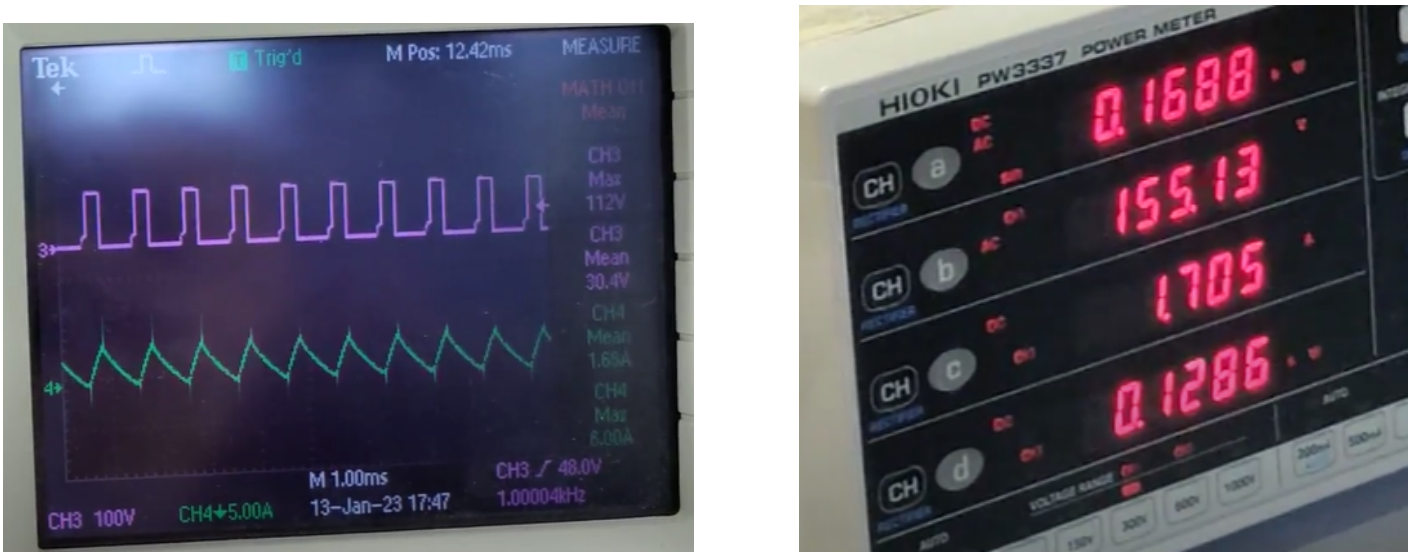


Figure 20. *Voltage and Current waveform when D= 0.15 (left), the readings from the power meter (right)*

Figure 21. *Voltage and Current waveform when D= 0.25*

We can clearly see the DCM mode of operation resulting from the no load operation of the motor in figures 20 and 21. The current is zero after the inductor has discharged and the voltage increases because the load is supplied by the capacitor.

Unfortunately, after working at 0.25 duty cycle for quite some time, our circuit failed to operate and therefore we couldn't get thermal data of our circuit. The circuit failing to operate after some time suggests to us that one of the components may have overheated.After first inspection we saw that the IGBT is not functional. Although we've implemented 2 fans and removed the enclosure to have better air-flow. The peak current of 7A and a mean current of 2A, combined with our switching frequency of 5kHz, might have caused the IGBT to overheat.

6. Conclusion

This paper has been written to guide readers about how to design a DC motor driver. The design specifications and choice of components has been explained. The PCB layout of the driver has been illustrated. Tests and practical results during the procedure have been investigated. Finally, the discrepancies in practice have been investigated.

There are several outcomes of this project for us. Firstly, we were able to see the theoretical concepts (such as rectifiers and buck converters) we've learned in our classes in practice. We were able to see the basics of power circuit design and things to consider when driving switches. This project also allowed us to see a circuit from a manufacturer basis and made us consider things that we usually didn't when designing a circuit in theory (such as a PCB design and an enclosure).

Finally, we'd like to offer our gratitude to Assoc. Prof. Ozan Keysan and to our course assistant Ogün Altun for their guidance and efforts in developing our circuit by giving essential feedback and helping us during the development process of our circuit.