Middle East Technical University
Electrical & Electronics Engineering

EE463 Hardware Project – AC to DC Motor Drive
Final Report
12.01.2020

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Introduction

This final report is presented as a part of the hardware project of EE463 – Static Power Conversion I class of Fall 2019-20. In this hardware project, the team is required to build a DC motor driver. The driver is to be supplied via an AC voltage and should be able to produce an adjustable level DC voltage. As proposed in the simulation report, the Ree-Wired team has chosen a topology that employs a 3-phase rectifier and a buck converter cascaded with it. In the following sections, detailed information on how the design is implemented, thermal design for the components, considerations and decisions taken by the team members, the difficulties the team has gone through the implementation process and are to be mentioned. The performance of the design during the demo day is also presented in the last section.

Design Decisions

Design of the circuitry is kept as simple as possible. The design decisions are discussed in more detail in Simulation report but some important points are also worth mentioning here as well since unexpected problems occurred during the testing of the circuit.

- For 3-phase rectification, a rectifier module is employed. It consists of six diodes connected properly in a casing. Considering the risk of failure by using seperate diodes and and also the increasiing cost that may be introduced by them, it is decided to use a module for this part of the project.
- The DC-Link capacitor is chosen primarily based on the voltage rating. Since the output voltage is limited to 200 V, voltage rating of the capacitor should be at least 400 V. This was the most important factor for the DC-Link capacitor.
- An IGBT is used as the switching element since it can withstand higher currents compared to a MOSFET. It is also placed in the low-voltage side to make the implementation of gate driver circuitry simpler.
- The switching frequency was not one of the main concerns since the size of the driver circuit was not that much important. Also, the load was a motor. Since a motor is basically a big inductance in series with a resistance, the load itself was a high frequency filter in our case. Therefore, the switching frequency is chosen to be low as possible to keep the switching losses minimal.
- Since the gate driver for the switching device should be electrically isolated from the high voltage part of the circuitry, a gate driver circuit with an embedded optocoupler is used. This made the usage of two seperate DC power supplies unavoidable.

Simulation Results

Although the simulation results are presented in the Simulation Report, they are also included in Final Report. Also, thermal design for semiconductor parts is made based on them.

Duty cycle is adjusted to 0.7 in these simulations.

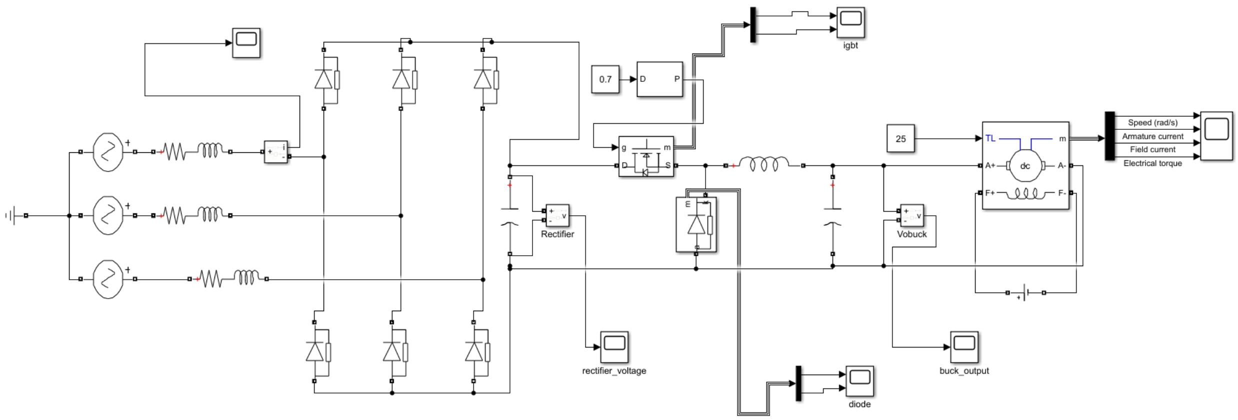

Figure 1. Model for simulations in SIMULINK

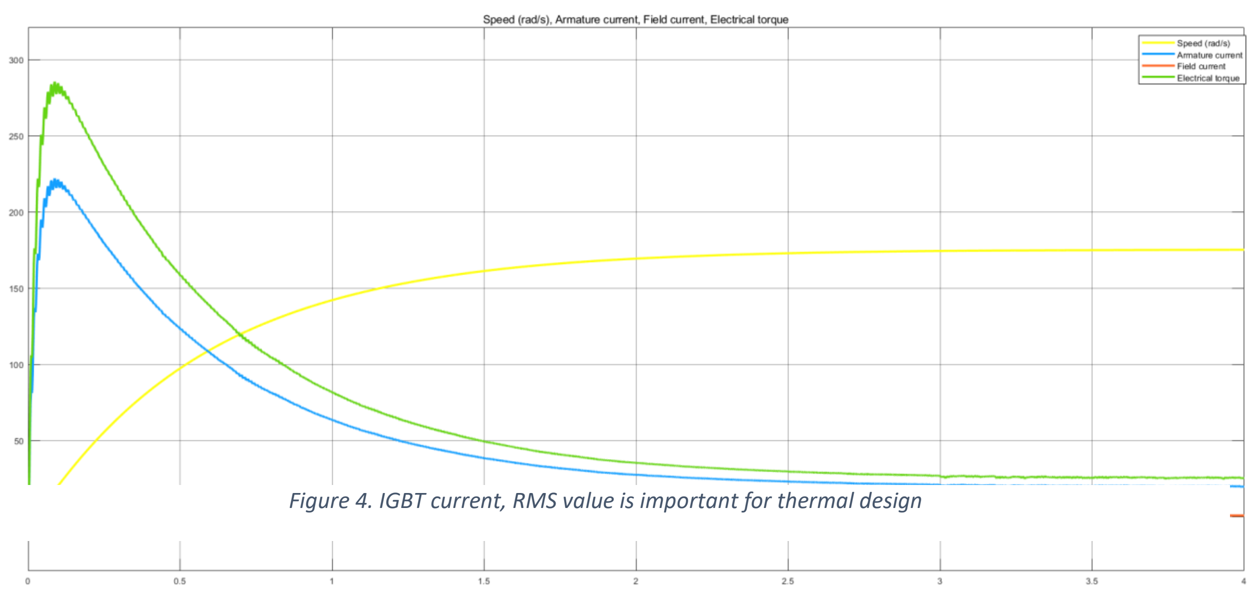

Figure 4. IGBT current, RMS value is important for thermal design

Figure 2. Motor parameters for D=0.7

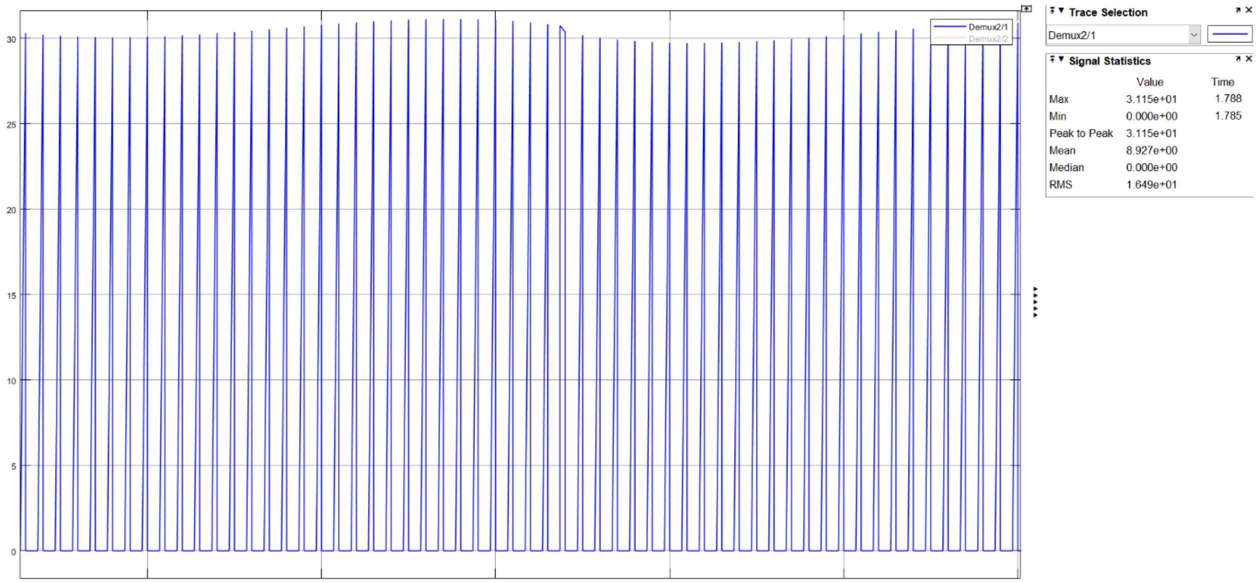

Figure 3. Diode current, RMS value is important for thermal design

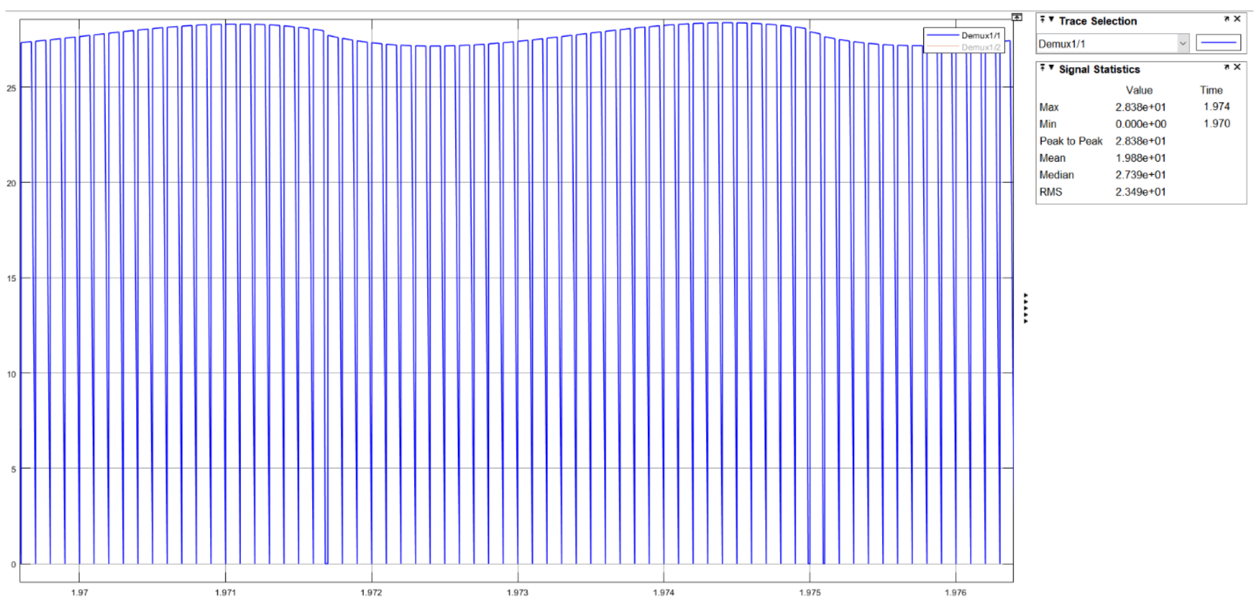

Figure 4. IGBT current, RMS value is important for thermal design

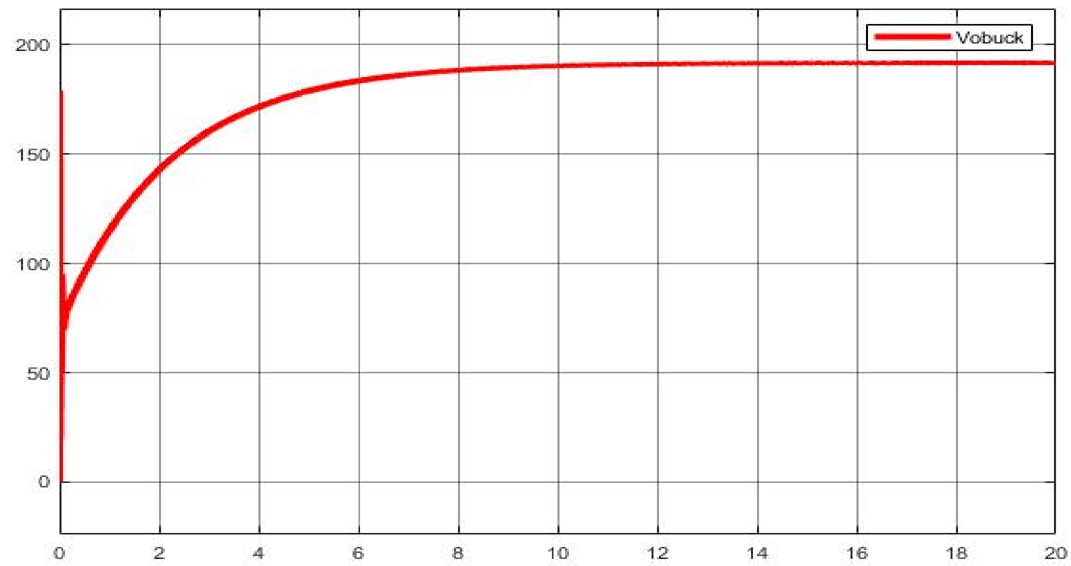

Figure 5. Buck converter output voltage for D=0.7

Sub-blocks & Component Selection

In this section, the sub-blocks of the design are examined in detail and the component selection for each of them are discussed. A rectifier block, DC-link capacitor, free-wheeling diode and the switching circuitry with the IGBT as switching element can be counted as the sub-blocks for the design.

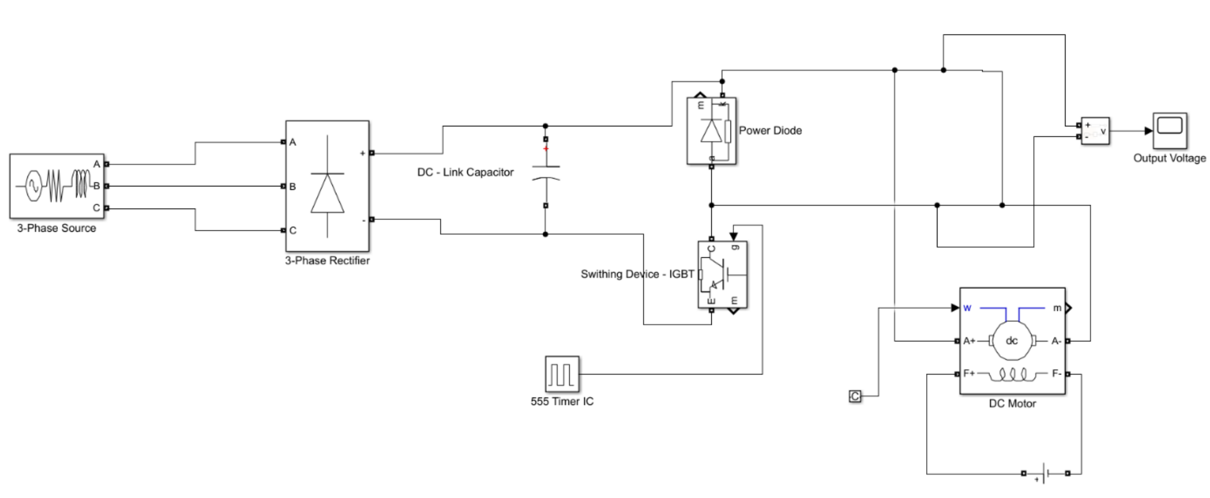

Figure 6. Overall block diagram for the design

Let us start with the rectifier block.

AC to DC Rectifier Block

As mentioned earlier, a 3-phase bridge-diode module is used for the rectification of the AC input voltage. The IXYS VUO34-18NO1 model is chosen.

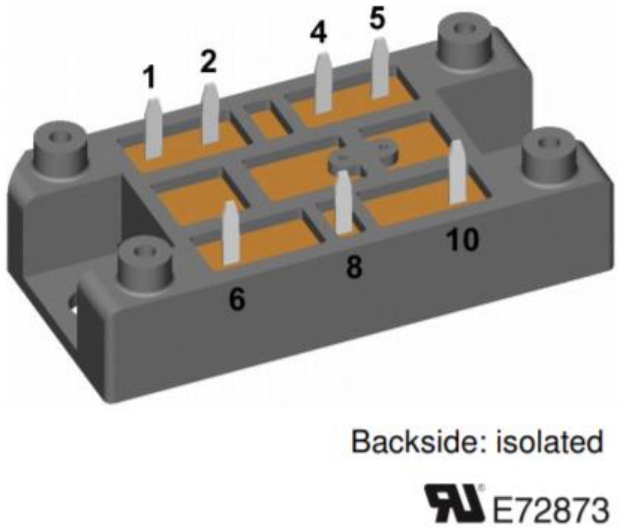

Figure 7. IXYS VUO34-18NO1 module

Reverse blocking voltage value of the block is 1800 V and it can withstand up to 45 A, so both of these specifications were way beyond our needs. But not a redundant number of choices were available, and the cost considerations made this block suitable for us.

DC-Link Capacitor

To keep the ripple content low of the rectified signal, a DC-Link capacitor was more then necessary in this application. Buck converter needs a DC input and the 300 Hz harmonic component in the rectified signal is something that should be avoided. In order to eliminate this signal, a high capacitance value was needed. Simulation results yielded a value around 0.1 percent for the ripple and it was more tha enough for our application.

ESR value of that capactior was also not that much important in our application since it is used as a DC-Link capacitor.

Pulse Generator Circuitry for IGBT

As it is known theoretically, the duty cycle of the switch in the buck converter adjusts the output voltage level. IGBT is opened by applying a gate voltage signal. To produce a square wave with adjustable duty cycle, a 555 timer IC is used in astable mode. By changing the potentiometer, the duty cycle can be adjusted in the circuitry given in Figure 3.

Duty cycle is given by the ratio $D = \frac{R_1}{R_1+R_2}$. The capacitor and resistor values are adjusted to yüeld 1 kHz frequency signal.

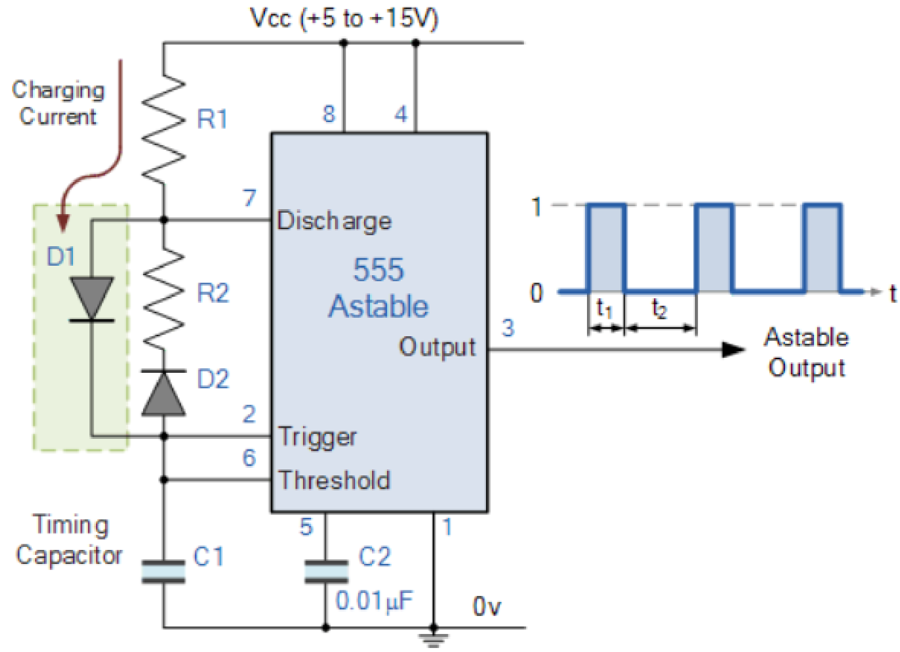

Figure 8. Pulse generator circuitry built by 555 Timer IC

Gate Driver

Gate driver is a need in this application for two main reasons: electrical isolation of low and high voltage sides and the IGBT opening voltage/current values. Since the pulse generator is a simple analog circuitry that work with 10 V DC output, it should be seperated from the high voltage side where motor is driven with currents up to a few amps. The IC can be destroyed by such high voltages and also it is not advised for safety reasons.

To achieve this electrical isolation, a gate driver with optocoupler, TLP-250 is used. The output of the pulse generator part is fed to the TLP250 through a small resistor since the LED inside is driven by current. And the output of the TLP250 is fed to the IGBT.

A better understanding of how TLP250 achieves electrical isolation can be gained by examining the following internal structure schematic.

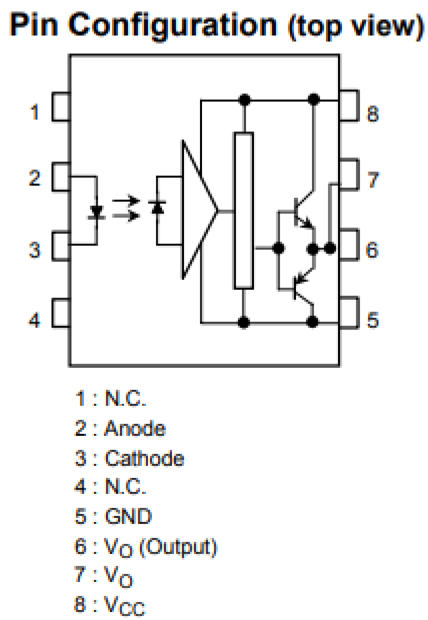

Figure 9. Internal structure of TLP250

Pin 3 represents the signal ground and pin 5 and 8 represents the power inputs for the gate driver circuit. The signal is transferred via light and this makes the left and right hand-side of the optocoupler driver electrically isolated.

The major drawback of this configuration is that its application requires two seperate DC supplies in the overall circuitry. One for the pulse generator and one for the optocoupler.

IGBT

An IGBT is chosen as the switching element in our design. Its model is IXYS IXDP-35N60B and it can carry up to 60 A. It can also withstand 600 V reverse voltage, and those specs are also fittingly well for our application.

Power Diode

The diode is kept on the high-side and connected in series with switching device, as buck converter topology dictates. The motor driven is expected to draw a current up to 15 A at max. Diode chosen in this project is a fast recovery epitaxial diode, IXYS DSEI30-12A. It can withstand up to 1200 V reverse voltage and 26 A of continuous current flow. Hence, its parameters were more than enough for our application.

An overall table for the aforementioned components can be found below.

Component Name	Model	Specs
Rectifier Module	IXYS VUO34-18NO1	1800 V, 45 A
Capacitor	-	470 uF
Power Diode	IXYS DSEI30-12A	1200 V, 26 A
IGBT	IXYS IXDP-35N60B	600 V, 60 A
Gate Driver	TLP250	-
Timer IC	555 Family	-

Thermal Considerations

Since we deal with high voltages and currents, power losses will also be high enough to seriously heat up the elements in the circuit. A simple back of the envelope calculation give us the ideas on how to choose the heatsinks in our circuit. Since switching frequency is not chosen to be too high, losses are restricted to acceptable levels and heatsinks can deal with the problems regarding thermal design of the circuit.

The power diode loss calculation is probably the simplest one. Diode current RMS value is found to be around 16 A from the simulation results. Forward voltage drop 2.2 V. The well-known power equation V.I gives us the loss of this component as 35.2 W.

$$P_{loss} = V_f I_{rms} = 2.2\ V\ x\ 16\ A = 35.2\ W$$

Thermal resistance of the device adds up to 0.9 C/W, obtained from datasheet. Again obtained from datasheet, device can work properly up to 150 C. Chosen heatsink has a thermal resistance value 1.1 W. Assuming the room temperature is 20 C, the junction temperature can be calculated as

$$T_{junc} = T_{junc} + P_{loss}\left(R_{j-c} + R_{sink}\right) = 20 + 2.35 = 90\ C$$

90 C for junction temperature poses no threats for safe operation.

Let us continue with IGBT. The power loss can be calculated from the voltage-current waveforms of the device. The triangular area in Figure 7 is lost 1000 per seconds. A body diode is present on the device and its loss corresponds to 15 W. Triangular area is roughly equal to 65 W, therefore the total loss on the device is assumed to be 80 W, total.

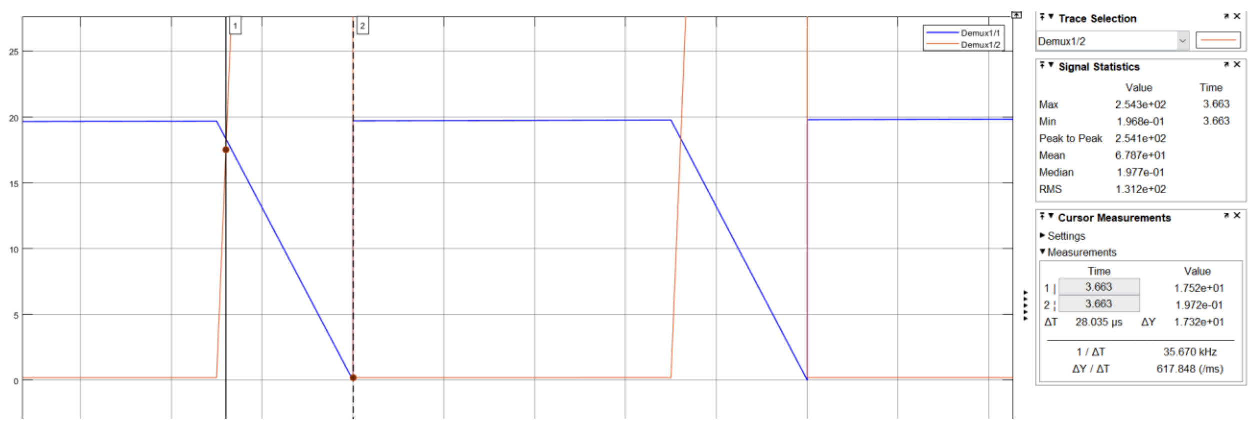

Figure 10. IGBT switching losses calculation

Sink temperature is expected to be around 110 C in this case. Body diode and IGBT junction temperatures are to be calculated seperately assuming that sink temperature is 110 C. Junction to case thermal resistances of both devices are obtained from the datasheet.

$$T_{junc-igbt} = T_{sink} + P_{loss}R_{j-c} = 110 + 0.5\ x\ 65 = 142\ C$$

$$T_{junc-diode} = T_{sink} + P_{loss}R_{j-c} = 110 + 1.5\ x 15 = 117.5\ C$$

Both of the devices can work up to 150 degree celcisus. The IGBT junction temperature is found to be very near to that approximated value. Also, it should be noted that only the switching losses are included in this calculation. It was bound to be a problem for this design, but the most convenient sink available was this one, and the team had to go with it. The design worked properly and steady enough to get the “Robust Design Bonus”, but as expected, IGBT was the problematic component in terms of thermal considerations. It heated up to degrees above a 100 degrees and we had to force cool it in order to keep the device working properly.

In Figure 11, a thermal photo from the demo day can be observed. Although it is taken at the early stages, it can be seen that IGBT is way hotter than the other components in the circuit. It suggests that it's temperature was around 63 C at that instant.

Figure 11. Thermal photo from demo day

Experimental Results

The team managed to finish the project one day before the demo. But everything worked as expected. Let us present the material from demo day and observe the similarities with the simulations done previously.

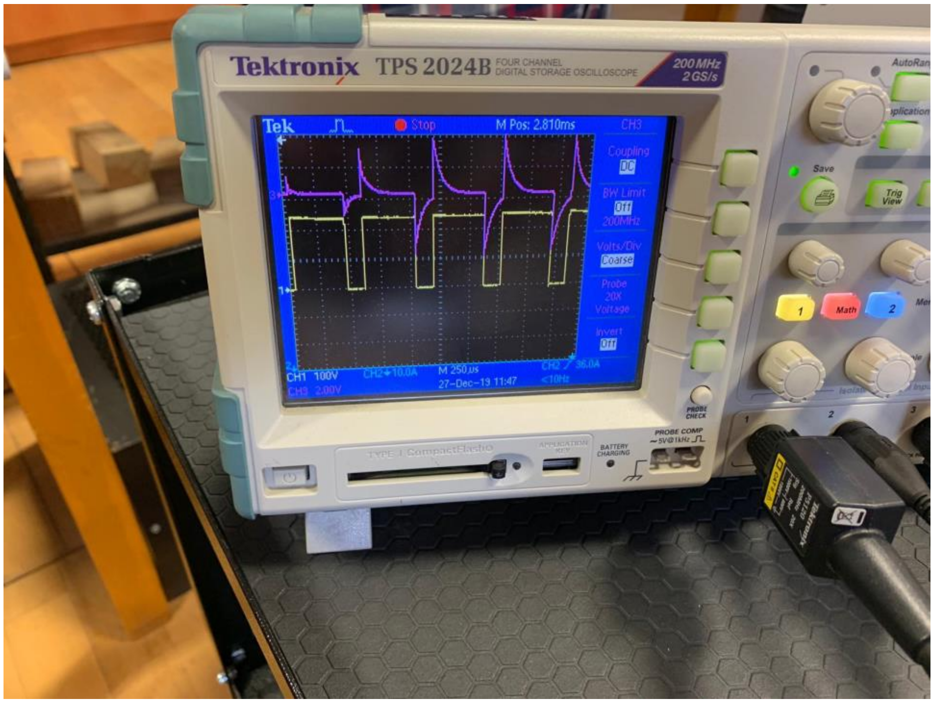

Figure 12. Output Voltage and IGBT C-E voltage

The otutput voltage waveform is similar to the pulse signal and it is expected since no filtering at the output is required. As IGBT opens, voltage across the device increases but then settles.

Under no load conditions, efficiency can be calculated. It is of course higher than the loaded condition.

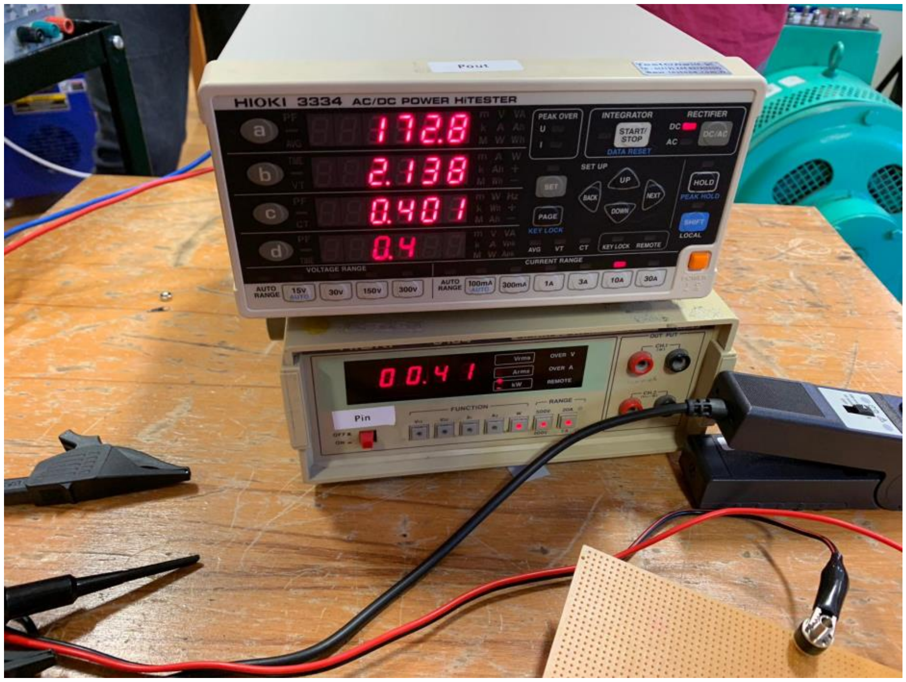

Figure 13. No load condition, input and output powers

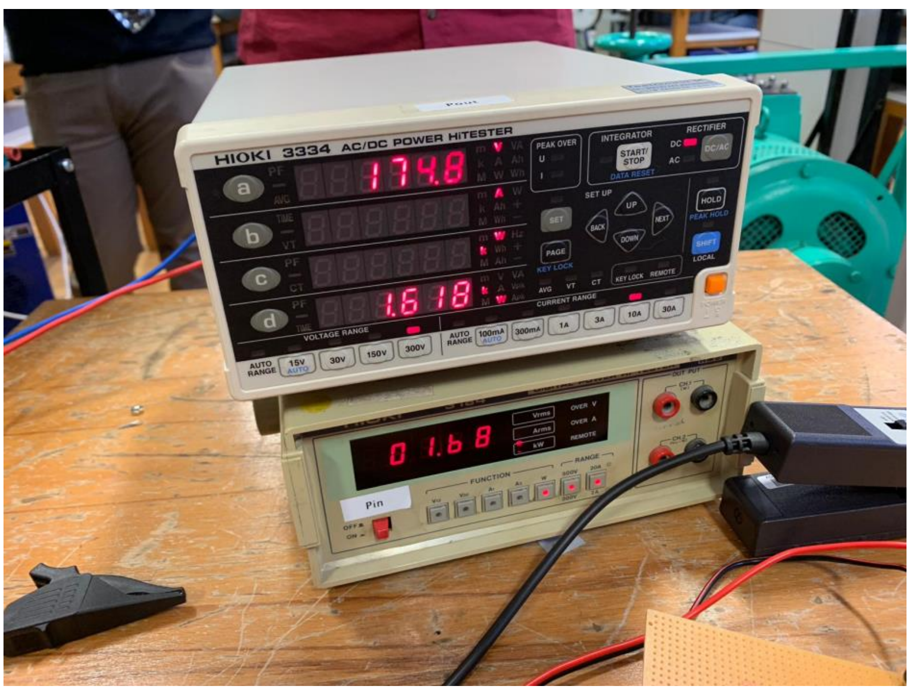

Figure 14. Loaded with kettle, for Robut Design Bonus Attempt

Let us compare no load and load condition efficiencies.

$$\eta_{no-load} = \frac{P_{in}}{P_{out}} = \frac{401\ W}{410\ W} = 97.8\%$$

$$\eta_{loaded} = \frac{P_{in}}{P_{out}} = \frac{1618\ W}{1680\ W} = 96.3\%$$

The power consumption of the motor has significantly increased as can be seen from the numbers. The loss is dissipated mostly on semiconductor devices in the circuit, so we can say thaat the thermal design is made for really high safety margins. The calculation in that section yielded more than 62 W of loss.

Difficulties During Build-Up

There were lots of changes in the design due unexpected problems during the building of the circuit. It is always helpful to learn from mistakes, therefore a seperate section is here for what we have learned during the bilding of the circuit.

- Most important of the skills obtained is soldering. We have never used it that much previously and we are happy to learn how to solder in this project.
- Working on a board with power devices can be tough sometimes. Lots of drilling was also involved in this process.
- Stray inductances create lots of problems such as EMI, increased losses and etc. Keeping the nodes close to switching node is a good idea to get rid of this effect.
- Probably the most problematic component was the gate driver. One should go through the datasheet for the device more than once and properly design how to feed the signal to the device. More the once we have burnt the component down and lost precious minutes re-designing the gate driver part.
- Heatsinks are “must”s.

Conclusion

In this report, the hardware project for EE463 – Class of Fall ’19-’20 is finalized. The design considerations are proposed with simulation results once again. Thermal design for the project is proposed. Then experimental results are presented, efficiency of the ciircuit is calculated for different working profiles. Lastly, discussions on the process itself are made.

The overall project came with valuable experiences to the team. Design and simulation part followed by building up the circuit consist jobs we have never dealt with before. The team worked hard and on demo day, the design worked better than we expected and deserved even a bonus. We are content with what we get.