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MIDDLE EAST TECHNICAL UNIVERSITY

EE463 — Static Power Conversion - I

Hardware Project Report

Happy EE Friends

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Contents

1 Introduction

In this report, the design process of the AC-DC converter is analyzed. The simulations and the data obtained while implementing and demonstrating the hardware project are shown in the report with explanations on the component selection are included. In the project, we have used rectifiers, buck converter, gate drivers, capacitances, and isolators. The problems encountered in the demonstration of the project are discussed and possible explanations for the failures of the hardware project are analyzed.

2 Topology Discussion

2.1 AC/DC Conversion

When all the topologies are compared, 3-phase full-bridge diode rectifier topology is selected. The high output voltage ripple and comparatively lower output voltage value of the single-phase rectifiers are the reasons why single phase rectifiers are not selected. Also, in the single-phase rectifiers there are higher order harmonics and as a result the THD of the rectifier is greater, while the 3-phase rectifiers eliminate the third order harmonics completely and the THD is lower than the single-phase rectifiers. The edge of the 3-phase full-bridge diode rectifier over the thyristor rectifier is simplicity and easier control. Each thyristor would need a gate signal, which would complicate the system by both cabling and control standpoint. The relative simplicity and superior qualities of the 3-phase full-bridge rectifier topology were the main reasons in the selection of it as the AC-DC rectifier topology. To realize this topology, 6 diodes are needed, and these diodes are selected according to the simulations, which will be discussed in the component selections and simulations parts.

Comparison of Rectifiers

Type	Vout	ΔVout	f_{ripple}
Single Phase	$\frac{2\sqrt{2}}{\pi}V_{ph}$ = 207 V	$\sqrt{2}V_{ph} = 325V$	100 Hz
3-phase Half Bridge	$\frac{3\sqrt{2}}{2\pi}V_{l-l}$ = 270 V	$\frac{\sqrt{2}}{2}V_{ph} = 162.5V$	150 Hz
3-phase Full Bridge	$\frac{3\sqrt{2}}{\pi}V_{l-l}$ = 540 V	$(1-\frac{\sqrt{3}}{2})\sqrt{2}V_{l-l} = 75.8V$	300 Hz

Figure 1: Comparison of Rectifiers

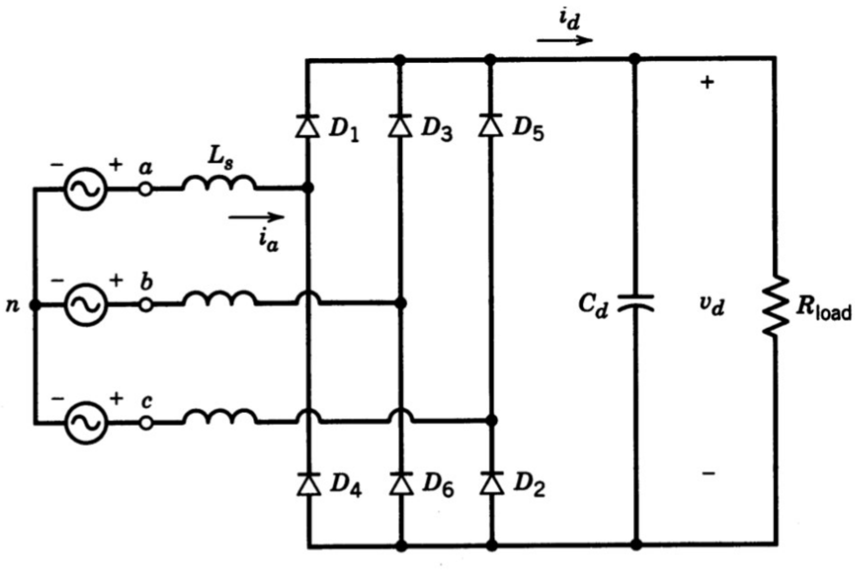

Figure 2: 3 Phase Full Bridge Rectifier

2.2 DC/DC Conversion

After selecting 3-phase full-bridge rectifier topology, a need for DC/DC conversion has come up. As the variac voltage was set to a fixed level, the average DC voltage would be a constant level at the output of the diode rectifier. This meant that achieving a soft-start would be impossible and the converter would blow up immediately when powered up. We have decided to implement a switching mode converter after the rectifier to gain control over the voltage level. We have done this using a buck converter as our DC average voltage could be achieved at a higher level than motor ratings and buck converter would be easy to implement.

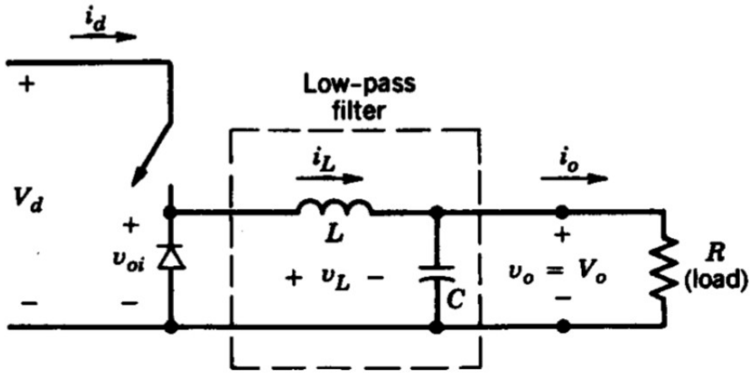

Figure 3: Buck Converter

3 Design

3.1 Pre-Design Considerations

After finalizing our choices we started our design based as a 3-phase full-bridge diode rectifier + buck converter. We also discussed about the extra features we were planning to implement for bonuses and took according design steps. These extra features were

- Tea Bonus
- PCB Bonus
- Industrial Design Bonus
- Single Supply Bonus
- Closed-loop Current Control Bonus (EE407)
- Closed-loop Speed Control Bonus (EE407)

We decided to use an Arduino for our logical operations therefore there was a need to implement an extra conversion to lower voltage levels around 9V to power it up so that we could operate with single AC supply. Also, we have drawn a PCB layout to provide a neat design. Component selections was done considering 2kW rated load conditions.

3.2 Design Approach

Our motor is rated at 220V average, which must be divided by our steady state duty cycle so that we can find the maximum voltage that the components will be exposed to. Considering a general case for D = 0.5, we limited our search within voltages higher than 440v. Our current rating will be around 12A considering tea bonus and losses.

We started our design from 3-phase full-bridge diode rectifier where we initially searched for single diodes whose ratings are within our operating point. It was revealed shortly after that purchasing a package which has all 6 diodes would be both cheaper and more efficient.

During the design of buck converter, we decided to omit the inductor; as the motor itself acts as a high inductive load. Also, we stayed within limits while picking components, except for one (unfortunately revealed during demonstration), and finalized our selection.

After the components were chosen, we started drawing it on PCB immediately; without any prototype attempts. This was due to lack of time, and also due to our trust at PCB being more stable than any other prototyping methods.

3.3 Arduino Supply Circuitry

We have designed another AC/DC converter circuitry for Ardiuno voltage supply with a transformer and linear regulator. The transformer had a 230/12 turns ratio which lowered a grid level AC voltage to 12V RMS. A single phase full-bridge diode rectifier was connected at the secondary side of the transformer to rectify the AC voltage to DC. This voltage then filtered with a $1000\mu F$ capacitor and supplied to a linear dropout (LDO) regulator with a fixed 9V output voltage rating with up to 1.5A current rating. The current rating was selected as high as possible in order to supply the gate driver with the output of LDO as well.

3.4 PCB Design

We have prepared schematics and layout using KiCad as the software offered a fast learning curve thanks to its simple interface. KiCad also offers a considerably large library for components together with baselines for almost all IC packages which can be easily adapted for any component.

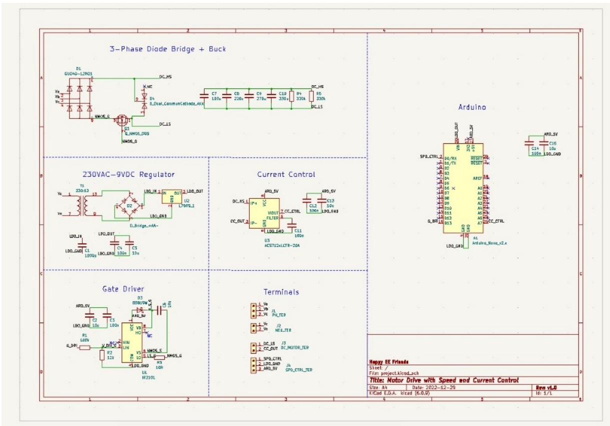

Figure 4: PCB Layout.

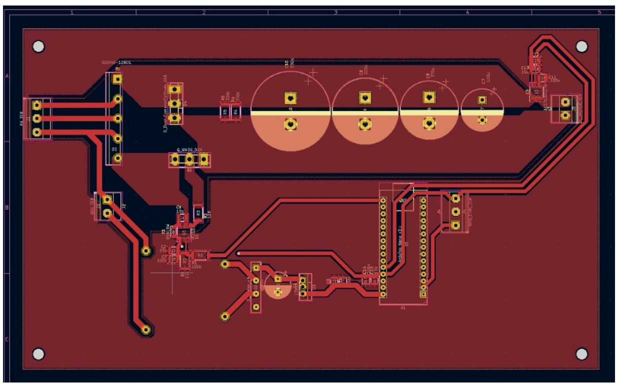

Figure 5: PCB Layout.

3.5 Design Errors

3.5.1 PCB Clearance

When the circuit was given input voltage for the first time, current has jumped and exploded two of the input paths of the 3-phase full-bridge rectifier. After the malfunction, it is analyzed that either the lack of clearance of those paths provided a jumping opportunity for the current, or the soldering was not done properly such that current has jumped between the paths. This meant high amounts of voltage difference between two points, which almost don't have any resistance. This high current exploded two of the input paths of the rectifier.

3.5.2 Arduino Supply Circuitry

Although the circuitry worked as intended, there was a fundamental error with the design that it required 100% variac voltage to operate. Firstly, 100% variac voltage would end up around 540V at the output of the diode bridge, leading a very difficult operation of buck converter. Secondly, in order to control the gate signal of the buck converter we needed to power up Arduino first. However; as both the main converter and low voltage converter operated simultaneously, there was a need to provide AC voltage to both of them at the same time. It was reveal experimentally that, the voltage that could power up the Arduino was around 130VAC. Therefore the circuit wouldn't operate below 130V, and wouldn't operate as intended around 130V as the LDO couldn't supply 9V at those levels. This led to us giving up on single supply bonus.

3.5.3 MOSFET PCB Footprint

There was a minor error in the MOSFET footprint where we had drawn it as D-G-S configuration. The correct order was G-D-S and we fixed this by cutting the drain pin and soldered it to its correct position with a cable. We connected the gate pin with a slight bent to achieve a lower parasitic inductance compared to connecting with a cable.

3.6 Failures at Implementation

Throughout the implementation of the project, several different errors were encountered. Although most of them were identified and corrected, at both project demonstrations some new problems have occurred which resulted in the failure of the hardware project. Regardless, in this report these new errors have been analyzed and possible solutions to them are proposed.

3.6.1 Misplaced Components

Freewheeling Diode

While soldering the components on PCB, the freewheeling diode was soldered in the opposite direction. This would cause short circuit on the circuit when the switch was turned on, so X volts of potential would flow on a path with minimum resistance. This high amount of current would be too much for the components of the system and the path of current on the PCB would explode, together with the MOSFET and freewheeling diode. After PCB was severely damaged, the decision to transfer the project to soldering board was taken.

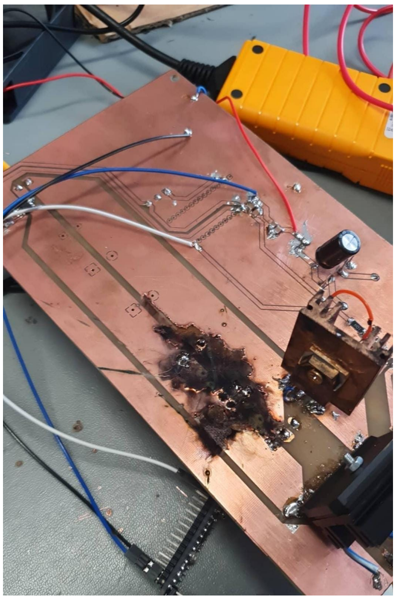

Figure 6: Exploded PCB.

Capacitor

The DC motor we were aiming to drive can be modelled as a high inductive load. In the first proposed topology, the capacitor was placed after the buck converter as parallel to the DC motor. However, this would not be meaningful because the aim of putting a capacitor in the system was to increase the output voltage characteristics and make it smoother. This output voltage would then be transmitted to the buck converter and this steady voltage would be critical to eliminate voltage differences between each switch, which would amount to high current values at each switching. For this purpose, the capacitor was moved to the output of the rectifier such that the output voltage would be smoother, and ripple would be minimal.

3.6.2 Soft Start Problem

At first demonstration, the soft starting was aimed to be done by adjusting a pot by hand. However, this method proved to be unhealthy, as trying to soft start the DC motor manually is prone to human error. In the demonstration, pot was adjusted faster than it's optimum rate, so a huge inrush current traversed the system and as a result two of the three fuses and MOSFET blew up. After the identification of this problem, a soft starting code was implemented into the Arduino such that there would be no human element in the soft starting. An optimal soft starting would mean no inrush current to disrupt the system. Indeed, in the final demonstration soft starting would not be a problem as the DC motor would start to run without any problem at low voltages.

3.6.3 Wrong Component Selection

The trials of the system were made at low voltage to understand whether the system would work at low voltages or not. It was concluded that with R load and RL load the system would work however high voltage was never tested. When high voltage was applied in the demonstration, the diode exploded and the system stopped working. Analysis of the system after the demonstration proved that 300V rating of the freewheeling diode was not sufficient for the operation and thus the system malfunctioned. This was the final error. Given that the system would manage to start the motor and run at low voltages without any problem, it is concluded that the voltage rating of the freewheeling diode was the only error remaining in the system and only possible future malfunction could be caused by thermal properties.

3.6.4 Control Loops

Due to insufficient time, we failed to implement the control loops to the system before the demonstration day. If we were able to implement them on time, the spark during the demonstration would not occur as we would have a current limiter integrated.

4 Simulation Results

The computer simulation results are done using the following simulation setups.

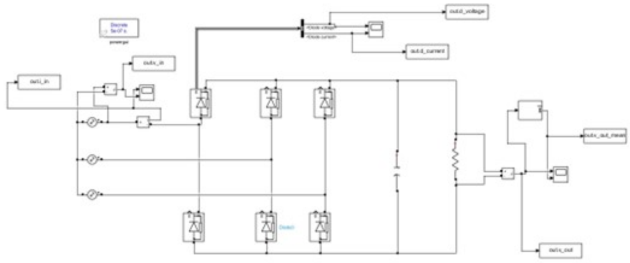

Figure 7: Simulation Setup for the Full Bridge Rectifier.

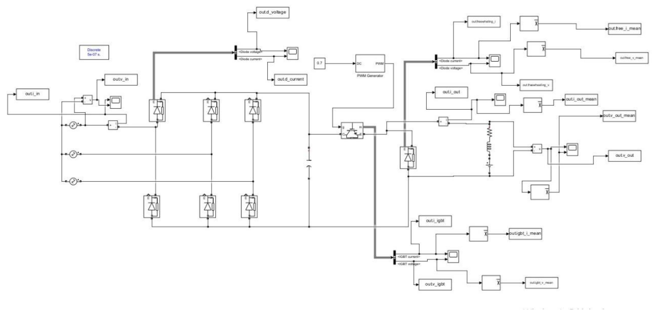

Figure 8: Simulation Setup for the Full Bridge Rectifier + Buck Converter.

The simulations were done for an average output current of $15A$ since we tried to design our driver for the tea bonus. The rectifier output voltage waveform is given in figure 9 below.

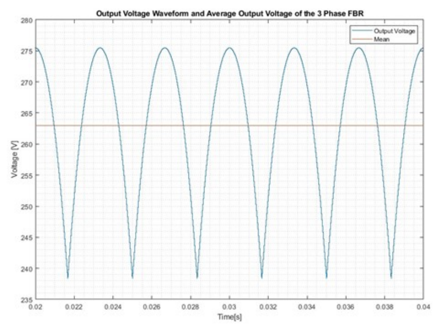

Figure 9: FBR Output Voltage Waveform.

Starting the simulations, it is decided that the duty cycle of the buck converter would be at most 0.7 because at higher values of duty cycle, the non-idealities become more dominant. Considering the output of the buck converter should be at most 180V (input to the DC motor) we have decided to equate the output of the three-phase rectifier to be 180/0.7=257.1 V. In Figure 2, this DC output voltage of the rectifier can be seen. Also to reduce the output voltage ripple of the rectifier, 47 uF of capacitance is placed at the output, however, the dominant filtering effect comes from the motor itself when the DC motor is connected to the rectifier. Since the DC motor is not currently connected to the rectifier, the filtering is not sufficient with a 14.4% ripple.
The FBR diode voltage and current are given in figure 10 below.

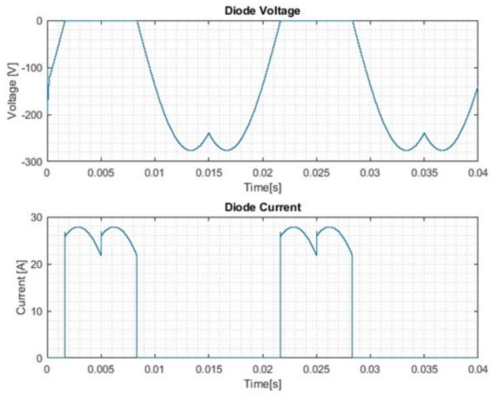

Figure 10: FBR Diode Voltages and Currents.

From the simulations, the selected diodes for the FBR rectifier should have a current rating of at least $I_{ave} = 10.5A$ and $V_{RRM} = 300V$.

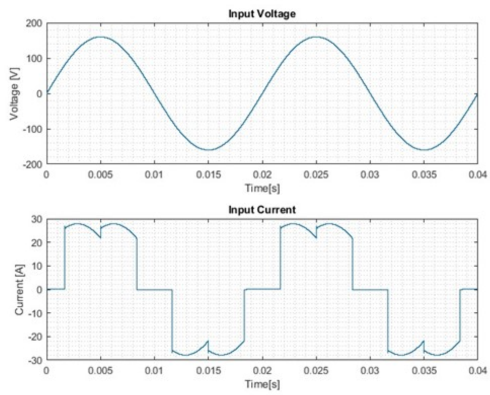

Figure 11: FBR Input Voltage and Currents.

From figure 11, the converter current has a high harmonics component but it is not an issue for this project.

The output voltage and current of the buck converter are given in figures 12 and 13 for $D = 0.05$ and $D = 0.7$, respectively.

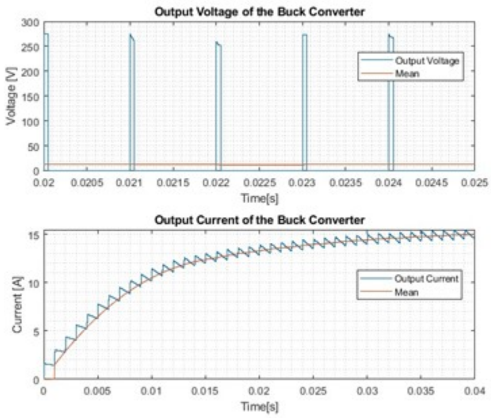

Figure 12: Buck Converter Output Voltage and Current for D = 0.05

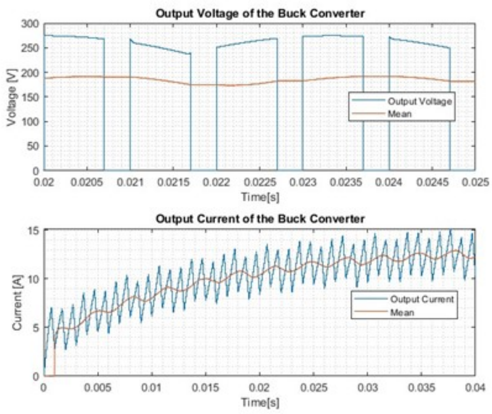

Figure 13: Buck Converter Output Voltage and Current for D = 0.7

From the simulations, the output voltage of the converter is a square-like wave since the filtering is not applied to the converter. However, the square wave is sufficient to drive the DC motor, so it is not an issue. Also, it is seen that the current ripple increases with an increasing duty cycle, so it must be considered during the component selection.

The freewheeling diode voltage and current of the buck converter are given in figures 14 and 15 for $D = 0.05$ and $D = 0.7$, respectively.

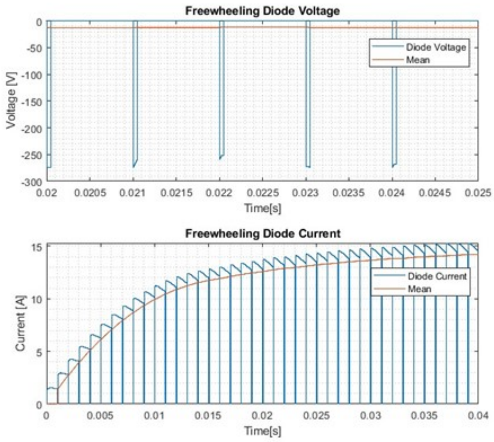

Figure 14: Freewheeling Diode Voltage and Current for D = 0.05

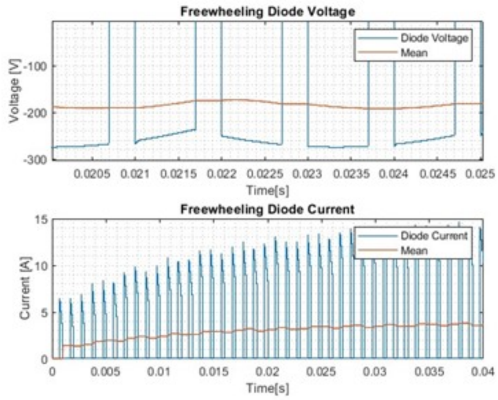

Figure 15: Freewheeling Diode Voltage and Current for D = 0.7

From the simulation results, the selected diode for freewheeling should have a current rating of at least $I_{ave} = 8A$ and $V_{RRM} = 300V$.

The switching IGBT voltage and current of the buck converter are given in figures 16 and 17 for $D = 0.05$ and $D = 0.7$, respectively.

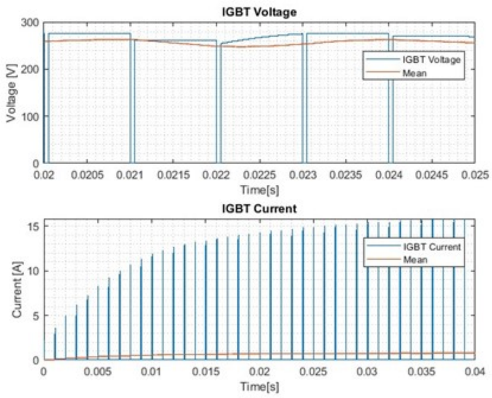

Figure 16: IGBT Voltage and Current for D = 0.05

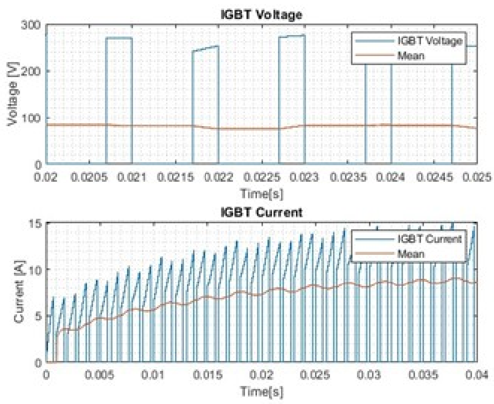

Figure 17: IGBT Voltage and Current for D = 0.7

From the simulation results, the selected switching IGBT should have a current rating of at least $I_d = 5A$ and $V_{DS,max} = 300V$.

5 Component List and Cost Analysis

The components that were mounted on the prototype board with their costs are listed below.

Component	Description	Ratings	Price ($)
GUO40-12NO1	3-Phase Diode Bridge	1200V-40A	$12.37
IXGH24N60C4D1	IGBT	1200V-40A	$4.17
DSEI30-06A	Diode	1200V-40A	$3.51
$330\mu F$	Capacitor	400V	$2.61
TLP250	Optocoupler	35V-2A	$1.68
IC-7809	LDO	9V-1.5A	$0.32
Arduino Nano	Microcontroller	9V-2A	$9.20
Prototype Board	-	-	$2.38
Heatsink	for Diode Bridge	-	$2.03
Heatsinks	for IGBT and Diode	-	$0.5
Passives	for logic level components	R&C	$1.00
Grand Total:			$39.77

Due to several faults, we have destroyed many components. The costs of those components are given in a separate table.

Component	Description	Fault Reason	Price ($)
ESAF92-03R	Diode	Misplacing	$1.44
PJZ22NA50A	MOSFET	Misplaced Diode	$2.46
PCB	-	Misplaced Diode	$21.27
GUO40-12NO1	3-Phase Diode Bridge	Misplaced Diode	$12.37
ESAF92-03R	Diode	Voltage Rating	$1.44
IXGH24N60C4D1	IGBT	Diode Spark	$2.46
TLP250	Optocoupler	Diode Spark	$1.68
Arduino Nano	Microcontroller	Unknown	$9.20
Arduino Nano	Microcontroller	Unknown	$9.20
Grand Total:			$61.52

6 Test Results

The test results of the motor drive are obtained only for $V_{in,buckconverter} = 114V$ since the converter failed while trying to increase the input voltage of the converter. The oscilloscope images at that operating point are given below.

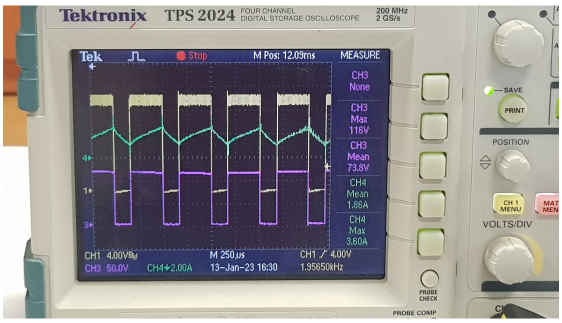

Figure 18: Converter Waveforms

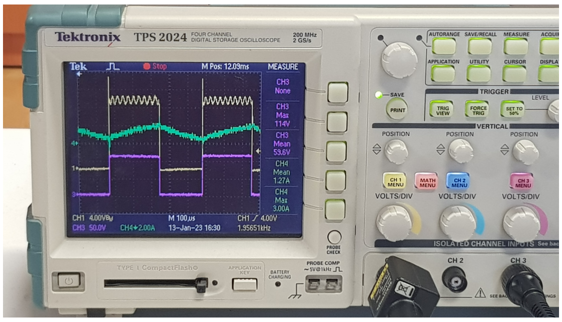

Figure 19: Converter Waveforms - Zoomed

In these results, Channel 1 is the switching node voltage, Channel 3 is the output voltage and Channel 4 is the output current that enters the motor. The data are obtained at $D \approx 0.56$. Also, the switching frequency was determined as $f_s \approx 2kHz$ before and the waveform shows that the switching occurs without any problem. These results are as expected and similar to the simulation results. From these results, we can see the ringing at the switching voltage, which might be the reason for the final fault of the converter (the diode voltage exceeds 300V for an instant and destroys it). The performance metrics at that operating point can be obtained as follows.

$$I_{out} = 1.27A$$

$$\Delta I_{out} = I_{out,ripple} \approx 3A$$

$$V_{out} = D * V_{in} = 59.6V$$

Also, as the output voltage waveform shows, the output voltage is a square wave, which was predicted before in the simulations.

7 Loss Calculation and Thermal Analysis

7.1 Loss Calculation

At the given operating point in Section 6 - Test Results, the IGBT losses can be calculated as,

$$P_{conduction} = V_{CE,sat} * I_{out} * D = 2.70V * 1.27A * 0.56 = 1.92W$$

$$P_{switching} = V_{CE} * I_{out} * f_s * (t_r + t_f)$$

$$= 116V * 1.27A * 2000Hz * (21 + 143)ns = 0.05W$$

For the freewheeling diode,

$$P_{conduction} = V_F * I_{out} * (1 - D) = 1.71V * 1.27A * 0.44 = 0.96W$$

$$P_{switching} = V_{diode} * I_{out} * f_s * t_{rr}$$

$$= 116V * 1.27A * 2000Hz * 150ns = 0.044W$$

For the rectifier,

$$P_{conduction} = 6 * V_F * I_{out} = 6 * 1.28V * 1.27A = 9.75W$$

7.2 Thermal Analysis

For the thermal analysis, it is assumed that there is a heat sink on each of the components with $R_{th,heatsink-to-ambient} = 6^oC/W$ and $T_{amb} = 25^oC$. For the IGBT,

$$P_{loss} = 1.92W + 0.05W = 1.97W$$

$$P_{loss} * R_{th,JA} + T_{amb} = T_{junction}$$

$$P_{loss} * (R_{th,JC} + R_{th,CH} + R_{th,HA} + T_{amb} = T_{junction}$$

$$1.97W * (0.65 + 0.21 + 6)^oC/W + 25^oC = T_{junction}$$

$$T_{junction} = 38.5^oC$$

For the freewheeling diode,

$$P_{loss} = 0.96W + 0.044W = 1.004W$$

$$P_{loss} * R_{th,JA} + T_{amb} = T_{junction}$$

$$P_{loss} * (R_{th,JC} + R_{th,CH} + R_{th,HA} + T_{amb} = T_{junction}$$

$$1.004W * (0.8 + 0.25 + 6)^oC/W + 25^oC = T_{junction}$$

$$T_{junction} = 32.08^oC$$

For the rectifier,

$$P_{loss} = 9.75W$$

$$P_{loss} * R_{th,JA} + T_{amb} = T_{junction}$$

$$P_{loss} * (R_{th,JC} + R_{th,CH} + R_{th,HA} + T_{amb} = T_{junction}$$

$$9.75W * (4.5 + 0.5 + 8)^oC/W + 25^oC = T_{junction}$$

$$T_{junction} = 132.25^oC$$

From the results, all the components are within the allowable temperature limits on this operating point.

8 Conclusions

In this hardware project, an AC-DC converter that can output 180V DC that can drive a DC motor is designed. For that purpose, a rectifier is used to rectify the input AC voltage and a buck converter is designed at the output of the rectifier. In the implementation of the hardware, some problems are encountered, and in dealing with those problems, lots of experience is gained. These can experience can be summarized as follows:

- First, design the circuit at a theoretical level using software such as MATLAB. Then, start simulating the circuit using SPICE software. After that, implement the circuit on a breadboard or a soldering board. Once you are sure that the circuit works, then design the PCB and transfer the circuit to the PCB.
- Nothing works on the first try. Build the system block by block testing it. Then combine all the blocks and build the system. Do the tests in an environment as close as the desired operating environment.
- Parasitic effects are important for this kind of switching circuit. Use snubbers and be aware of the loop inductance created by the paths on the PCB or wires on the breadboard or soldering boards.
- Check twice if the components are placed in the correct direction. Placing diode-like components in a reverse direction might be catastrophic.
- Check if there is any short circuit on the circuit after placing each component.
- Check the thermal conditions of the components. Some components might need active cooling with fans etc.
- Digital controllers are more complex than you think. Use timers to sample and output in order to track the process.
- Digital controllers are also exposed to parasitic effects. They can false switch due to loop inductance or EMI. Keep the controller away from the switching component.
- Don't try to put all the components in a small space than necessary. If possible, build it block by block and put them together.
- Don't put high voltage lines close to each other, especially if the lines are not insulated. If there is not enough clearance between the lines, lines might be shorted due to parasitic capacitances and sparks might occur.

The project was very exciting and educational even if our circuit faulted during the demo. The experiences gained from the project will be useful in our professional life when we are graduated.

9 References

- `https://keysan.me`
- Kim, S. H. (2017). Electric motor control: DC, AC, and BLDC motors. Elsevier.