MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE463 – Hardware Project
AC-DC Motor Drive Simulation Report
NAM-I POWER

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TABLE OF CONTENTS

I. ABSTRACT

This report includes thorough details of our hardware project for EE463: Static Power Conversion-I course. The aim of this project is to design and implement an AC/DC converter to drive a DC motor where the input is taken from the grid. This process will be explained under various steps which are topology selection, computer simulations, component selection, test results, thermal analysis and cost. As the tool for simulations, Simulink has been used.

II. INTRODUCTION

The main objective of power electronics branch is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads. In order to substantiate this objective, a hardware project that requires a design of an AC to DC converter to be used for driving purposes of a DC motor was assigned as a part of EE463: Static Power Conversion course.

In this project, the aim is to design and implement an AC/DC converter to drive our DC motor. The mentioned AC to DC converter is required to convert the 3 phase AC input coming from an autotransformer (i.e. Variac) to a adjustable DC output that can drive a specified DC motor. This objective requires a multiple-step process to result in successful implementation. First of all, one of the options among all available topologies must be chosen considering the trade-off with other topologies. For that purpose, a diode rectifier and buck converter has been chosen considering its advantages such as easy switching control, simple speed control and gate drive, ripple control and high efficiency. Next, various simulations have been done on computer environment so that critical parameters such as startup currents and voltages, steady-state currents and voltages, peak reverse currents and voltages and rated component values can be determined. This process made it possible to choose proper components for the converter. Afterwards, real-time tests have been done to observe system performance and temperature variance.

All of these steps will be explained thoroughly in corresponding subsections. Main challenges and cost analysis will also be mentioned.

An image of the designed AC-DC converter can be seen at Figure 2.1 as a final product.

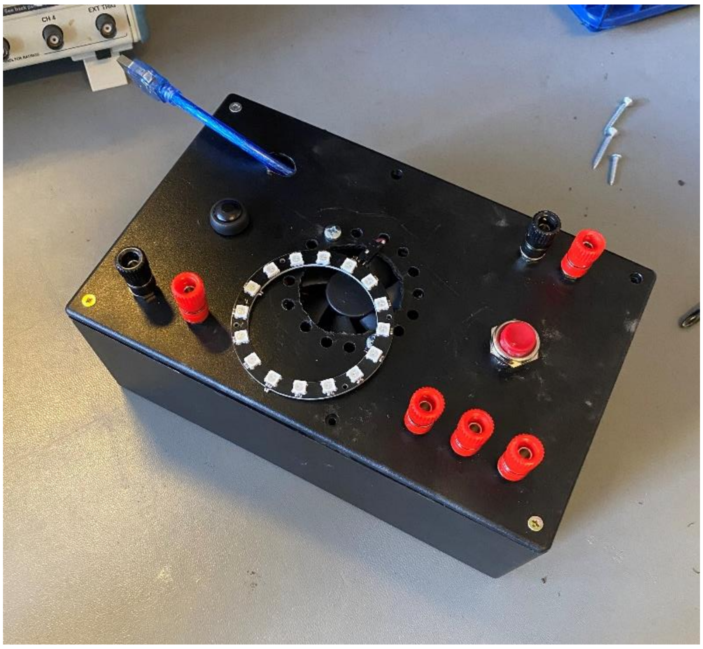

Figure 2.1: Image of the final product AC-DC Converter

III. POSSIBLE SOLUTION APPROACHES

Before diving into the implementation processes of the main solution approach, one should compare the advantages and the disadvantages of different possible solution methodologies in order to make a better decision on both the economical aspect and the efficiency, complexity, etc. In the case of this pre-defined project, there are many possible topologies that can be used as a solution approach, but when it is thought by means of the components' availabilities, circuits' complexities, additional costs, sub-systems, etc. the total number of the possible solution approaches decrease to four which are listed as,

1. Three-Phase Full-Bridge Diode Rectifier
2. Three-Phase Fully Controlled Thyristor Rectifier
3. Single-Phase Fully Controlled Thyristor Rectifier
4. Dimmer

Those four topologies listed above are the most widely used designs in power conversion applications and their selection carries vital importance in the design procedure of the defined project's solution. In order to give a slight insight to the reader, the operational principles of the given four topologies are going to be briefly explained in this part.

In the topology of "Three-Phase Full-Bridge Diode Rectifier" there should be six diodes or one three phase diode rectifier IC at the input stage of the circuit which are used in the rectification process of the AC input signal. By the gate drive of a switch with a generated PWM, this input signal is transmitted to the output stage as ripple-free as possible by the virtue of L-C filter connected at the output stage of the circuit. If one changes the duty cycle of the generated PWM, the switching is changed accordingly and therefore the output voltage is controlled.

The solution approach of "Three-Phase Fully Controlled Thyristor Rectifier", needs six thyristors which should be implemented and the drive operation of the gates of each thyristor by impulse gate currents supplied from a generated PWM with 120 degrees phase difference between each of the gate currents of each phase. The output signal can be changed according to the firing angle of the thyristor which can supply a user the necessary output voltage.

When "Single-Phase Fully Controlled Thyristor Rectifier" is taken into consideration, the same principles of Three-Phase Fully Controlled Thyristor Rectifier shall be applied. The only difference is the thyristor numbers which is four and the gate drives of the thyristors which should have 180 degrees phase difference between each phase.

"Dimmer Circuit" is a topology which has diac, triac, capacitor and two resistors where one of the resistors are a POT to change the time constant of the capacitor to supply the desired output voltage to the load.

1) Three-Phase Full-Bridge Diode Rectifier and Buck Converter (Selected)

This topology is composed of a "Three-Phase Full-Bridge Diode Rectifier" integrated circuit in order to take a DC kind of output at the output stage while a three-phase AC signal is applied to its input, a DC-Link capacitor to decrease the ripple at the output stage of the rectifier as much as possible and a buck converter topology which is used in order to decrease the input DC signal to lower levels by an internal switching components like IGBT or MOSFET, a freewheeling diode and an L-C configuration at the output stage of the converter.

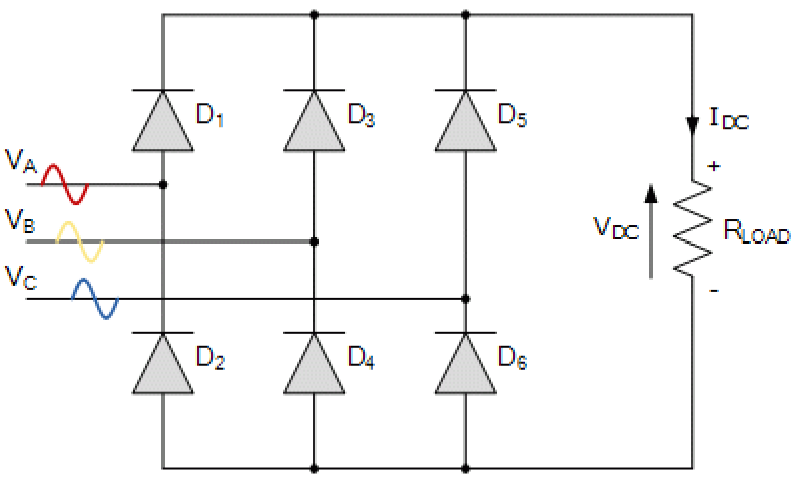

Figure 3.1: Circuit schematic of 3-Phase full-bridge diode rectifier

In order to control the switching frequency and switching period (conduct and cut-off period) of the switching component (an IGBT or a MOSFET) a PWM signal should be applied to the switching component's gate from an analog controller or a microcontroller at the desired frequency. Besides, since the generated PWM is a very small voltage -like 5 Volts- and this small voltage circuitry should be isolated from the high voltage side from where the main power flows. In order to isolate the low-voltage circuit from the high-voltage side, an optocoupler or an isolation component shall be used in the design. As it can be clearly observed, there are several components that should be included in the designed solution.

From the point of view of the above information, the advantages and the disadvantages of the "Three-Phase Full-Bridge Diode Rectifier and Buck Converter" topology can be listed as,

1. **Advantages**
   a. *Easy controllable switching frequency to control the output ripples*
   b. *Simple speed control with only one switching device and an analog PWM generator or a controller*
   c. *The freedom of the design of output L-C filter by which the output ripples are controlled*
   d. *Relatively higher efficiency up to 94% according to the desired output voltage*

2. **Disadvantages**
   a. *The number of the components are relatively higher when compared to other design alternatives*
   b. *Due to higher components number, it results in relatively higher costs*
   c. *Any mistake in the design procedure or the operation may blow all the components of DC-DC converter which might yield to a higher cost and longer implementation processes*
   d. *It has high switching losses if a high kHz switching frequency is used*
   e. *If the inductance value of the converter is chosen as a large value to decrease the output ripples, the converter gets into discontinuous conduction mode easier which yields to higher output voltages which may harm the DC motor being driven.*

2) Three-Phase Fully Controlled Thyristor Rectifier

The circuit schematic of three-phase fully controlled thyristor rectifier can be seen in Figure 3.2. This topology is composed of six thyristors utilized for 3 phase rectification purposes. A control circuit is required to feed current pulses to the gates of each thyristor with specified firing angle. Average output voltage can be controlled by means of firing angle of current pulse to the thyristors.

Thus, this topology provides a simple controllable operation without the need of a buck or boost converter to regulate the output. Also compared to other topologies, a larger output voltage with a small voltage ripple can be achieved even without DC side capacitor thanks to the controllable operation. Two quadrant operation is possible in this topology thanks to the inverter mode of thyristors. For achieving four quadrant operation, two parallel three phase thyristor rectifier can be used.

The biggest drawback of this topology is the synchronization problem. Basically, the control circuit that generates current pulses should be in synch with the 50 Hz 3 phase AC input in order to provide desired operation. This results in a relatively complicated control circuit design. Furthermore, in terms of power considerations, the delay caused by firing angle results in lower power factor (PF) and discrete power factor (DPF) for smaller output voltage levels compared to diode rectifiers. Thus, reactive power effects should be considered carefully for this topology.

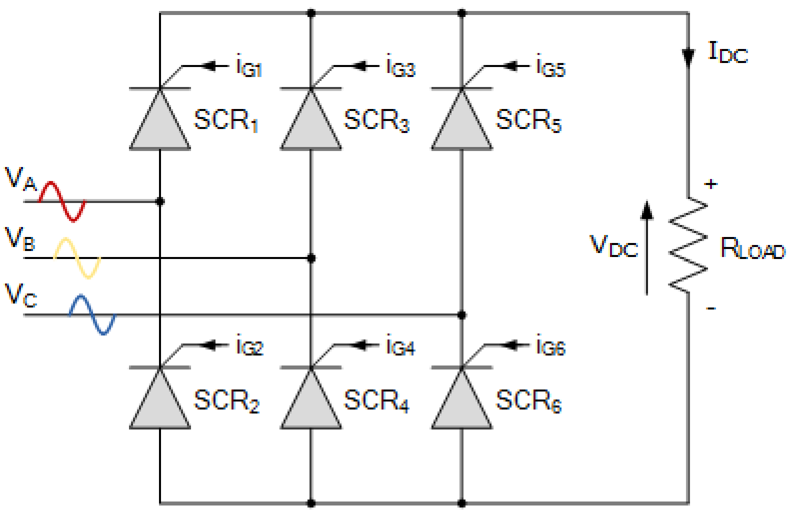

Figure 3.2: Circuit Schematic of 3-phase full-bridge thyristor rectifier

From the point of view of the above information the advantages and the disadvantages of the "Three-Phase Fully Controlled Thyristor Rectifier" topology can be listed as,

1. **Advantages**
    a. *Higher output voltage thanks to three phase input*
    b. *Lower output voltage ripple is achieved so that filtering is not necessary at the output*
    c. *The efficiency is higher compared to the other rectifiers*
    d. *Two quadrant operation, inverter mode, is already possible without the need of a parallel circuit.*

2. **Disadvantages**
    a. *A relatively complicated control circuit is required to achieve synchronization with AC input*
    b. *Lower power factor (PF) and discrete power factor (DPF) for smaller output voltage levels*

3) Single-Phase Fully Controlled Thyristor Rectifier

The circuit schematic of single-phase fully controlled thyristor rectifier can be seen in Figure 3.3. This topology is composed of 4 thyristors utilized for single phase full wave rectification purposes. A control circuit is required to feed current pulses to the gates of each thyristor with specified firing angle. Similar to three phase fully controlled thyristor rectifier, average output voltage can be controlled by means of firing angle of current pulse to the thyristors.

However, for this topology output voltage level is lower than the three-phase case, therefore a boost converter might be needed in order to drive the DC motor properly in preferable levels. Also output voltage ripple is higher due to single phase source in this topology. Thus, three phase fully controlled thyristor rectifier is more preferable over single phase fully controlled thyristor rectifier.

The major drawback of this topology is that the gate signals of thyristors used in the circuit need to be controlled properly as it was the case with three phase fully controlled thyristors rectifier topology. However, control circuit is relatively simpler than the control circuit in three phase fully controlled thyristor rectifier topology due to the fact that less pulses are needed in a cycle. Furthermore, it should be noted that large harmonics are present in the input current in this topology type.

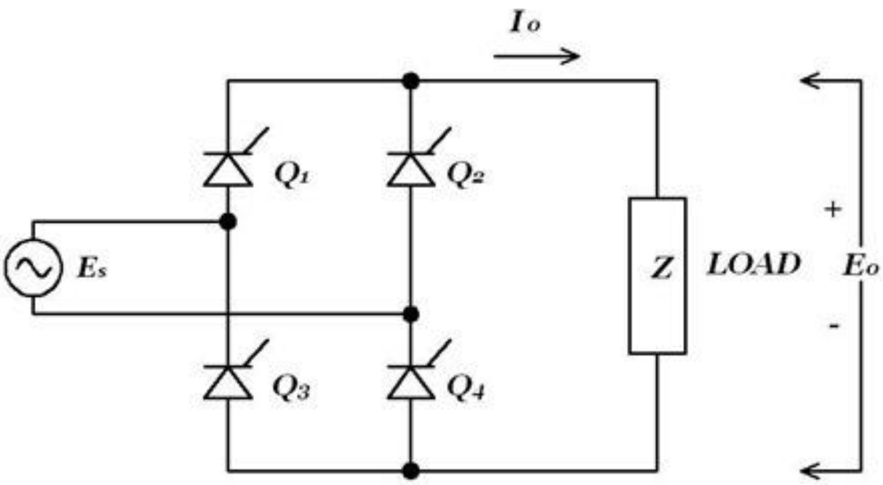

Figure 3.3: Circuit schematic of single-phase full-bridge thyristor rectifier

1. **Advantages**
    a. *Simpler control circuit compared to three phase fully controlled thyristor rectifier*
    b. *A cheaper solution relative to others*
    c. *Two quadrant operation, inverter mode, is already possible without the need of a parallel circuit.*

2. **Disadvantages**
    a. *Still a complicated control circuit is required to achieve synchronization with AC input*
    b. *Lower power factor (PF) and discrete power factor (DPF) for smaller output voltage levels*

4) Dimmer

One of the options that is taken into consideration is the Dimmer topology. It is not an option provided in the project definition, but due to its simplicity, that topology is selected as a possible solution approach. After conducted researches, it is understood that the dimmer circuit comes with some benefits when compared to its alternatives. As it was explained in Chapter-I, the circuitry has diac, triac, capacitor and two resistors where one of the resistors are a POT to change the time constant of the capacitor to supply the desired output voltage to the load. In order to provide clearer information to the reader, the operational principle of the circuit will be analyzed. Figure 3.4 shows the circuit diagram of the Dimmer circuit. In the application, light bulb will be implemented as the load which is the DC motor in the project. BTB12 represents the TRIAC and DB3 is represents the DIAC. As it can be interpreted from the graph, it is a compact design with fewer components. In this part, TRIAC and DIAC will be explained briefly. Then; the roles of resistor, capacitor and potentiometer will be explained.

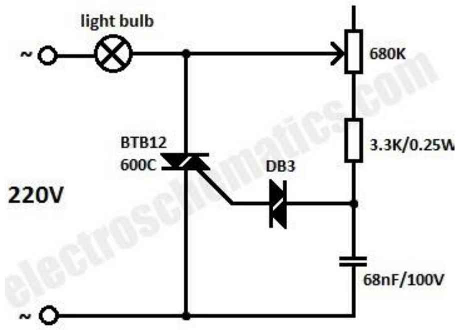

Figure 3.4: The Schematic of the Dimmer

"Figure 4" shows the I-V characteristics of TRIAC. It is as if an I-V graph of a thyristor where 1st quadrant is reflected to 3rd quadrant symmetrically. Indeed, it is true. A TRIAC is composed of simply two thyristors connected back to back and they are fed from the same gate connection. As the graph suggests, TRIAC is a 1st and 3rd quadrant device. This means that it can be opened with a negative current as well in which case it will conduct in reverse direction due to symmetry. Hence, there is no anode or cathode in TRIAC.

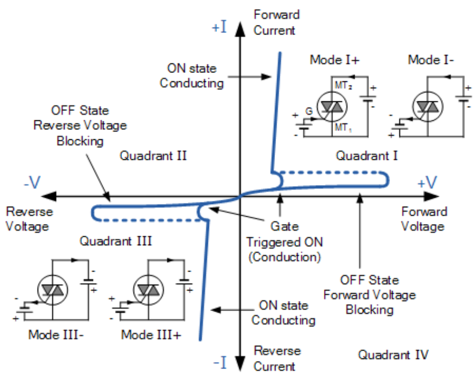

Figure 3.5: The I-V Graph of the TRIAC

Figure 3.6 shows I-V graph of a DIAC. As in previous case where TRIAC has been likened to a symmetrical thyristor, DIAC looks quite like a symmetrical diode. Actually, it is a double diode connected back to back. This gives an I-V graph symmetric with respect to origin. Only difference is there is a pulse in I_{BO}-V_{BO} point unlike a diode. Advantage of this characteristic is that it opens up at a relatively high voltage whereas a diode opens up at 0.7V. This can help with stability as the component does not open and close in an unstable way. Break-over voltage (V_{BO}) is usually in an amount of 30V. Since both TRIAC and DIAC are 2-quadrant components, they are used together in this topology to exploit the advantages of 2-quadrant operation.

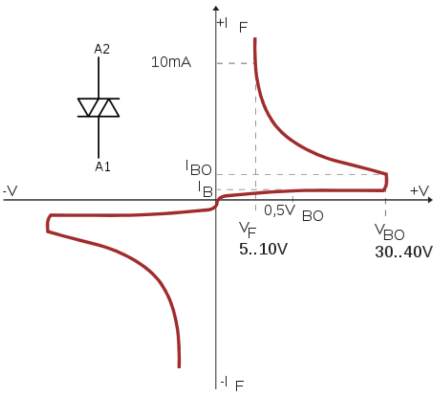

Figure 6: The I-V Graph of the DIAC

Apart from TRIAC and DIAC, there is also an R-C branch in dimmer. Main role of this branch is to adjust time constant. Capacitor is placed between one end of DIAC and the ground to facilitate voltage variation to be continuous and smooth. The embedded resistance plays a role to prevent time constant to go to “0”. If that resistor wasn’t placed, time constant would be varying in the range of zero to maximum value of R_P*C. With this resistor, it will vary in the range of $R.C$ to $(R + R_P).C$. Eventually, TRIAC will not open at “0” degree as there is always a time constant bigger than “0”. The advantages and the disadvantages of the Dimmer can be listed as,

1. Advantages
    a. Relatively small number of components
    b. Lower cost
    c. Compact design availability
    d. Lower Frequency drive availability

2. Disadvantages
    a. Higher Output Ripples

IV. DESIGN CONSIDERATIONS

While coming up with a decision to make, N.A.M.-I Power decided on 3-phase full-bridge rectifier with buck converter. Underneath that decision lies a couple reasons.

- Buck converter offers a wide range of switching frequency choice. This gives more precision on controlling as well as adjusting output ripple.

- 3-phase full-bridge rectifier with buck converter provides a wide range of component selection. After determining the power demand, one can decide on components to use.

- While designing a buck converter, one has the ability to adjust the ripple of output. This offers a trade-off between performance and cost. While designing this converter, it is possible to decide on a low ripple to care for performance and buy more expensive components or decide on a higher ripple to save from component expenses, or a middle point somewhere in-between. Buck converter provides this flexibility.

- Buck converter is more efficient than its alternatives for higher duty cycle values.

V. SIMULATION RESULTS

As a prospective Power Electronics Engineer, all of the design procedures should be implemented through the simulation software programs in order to observe whether the theoretical analyses are correct or not. Since there are many interpretations to the designed circuitry like the in-rush currents, peak reverse voltages, start-up conditions, etc. one should implement the design with a complete understanding to check the calculated results so that the pre-decided components can be ordered without any doubt about the operational limits. In order to observe those possible discrepancies, the whole circuit is designed on Simulink to conduct the simulation analyses. After the implementation of the design, the constructed circuit is given below in the Figure 4.1.

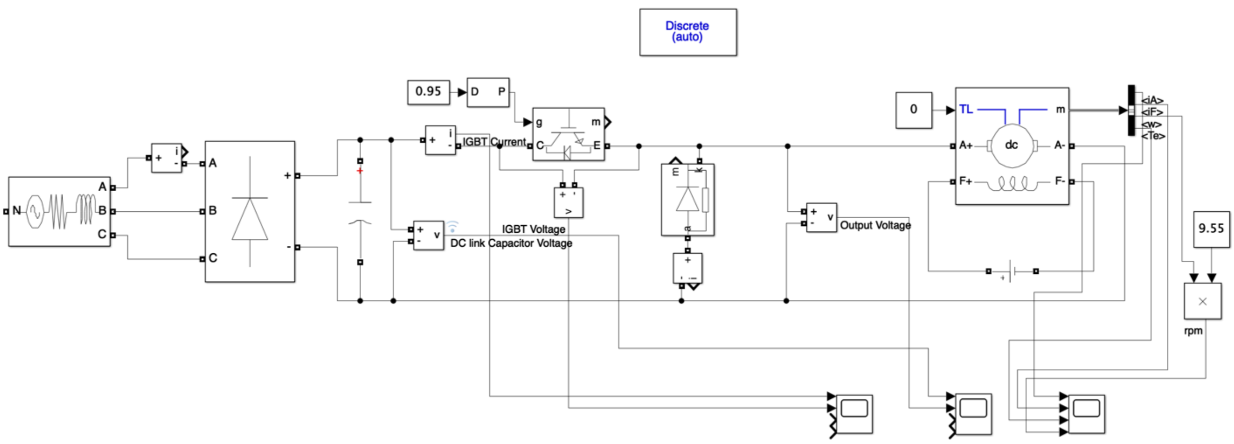

Figure 4.1: Three Phase Diode Bridge Rectifier and Buck Converter Schematic

As one can clearly observe from the figure, there is a Three-Phase AC voltage source which represents the voltage of the Variac to feed our circuitry. A Three-Phase Full Bridge Diode Rectifier is connected to that input voltage in order to rectify it into a DC one so that the DC-DC Buck Converter can be operated accordingly. A DC link capacitor is connected at the output side of the Three-Phase Full Bridge Diode Rectifier as a smoothing capacitor i.e. the rectified signal converted to a more ripple-free one to increase the efficiency of the operation. That DC signal is given to the collector of an IGBT which is used as a switching component in the circuitry. The gate of the IGBT is fed with a PWM signal which is generated from the analog controller or microcontroller. The IGBT conducts and cuts-off according to the PWM signal's period (which is chosen as 1kHz) to make the operator able to supply the desired voltage at the output. The diode connected to the emitter of the IGBT is used as a freewheeling diode to complete the current path being conducted because of the internal inductance of the DC motor when the IGBT is off.

By the usage of the same operational principle at each cycle, the input voltage is converted to the necessary output voltage through the Buck Converter.

1) 5% Duty cycle Results of the Circuit

The start-up of the operation carries vital importance since there would be very high starting currents and voltages for each of the component used in the circuit. In order to analyze the starting process, 5% duty cycle is selected in order to observe the results. According to the simulation results of the circuit the current and voltage of the IGBT is given in the figure.

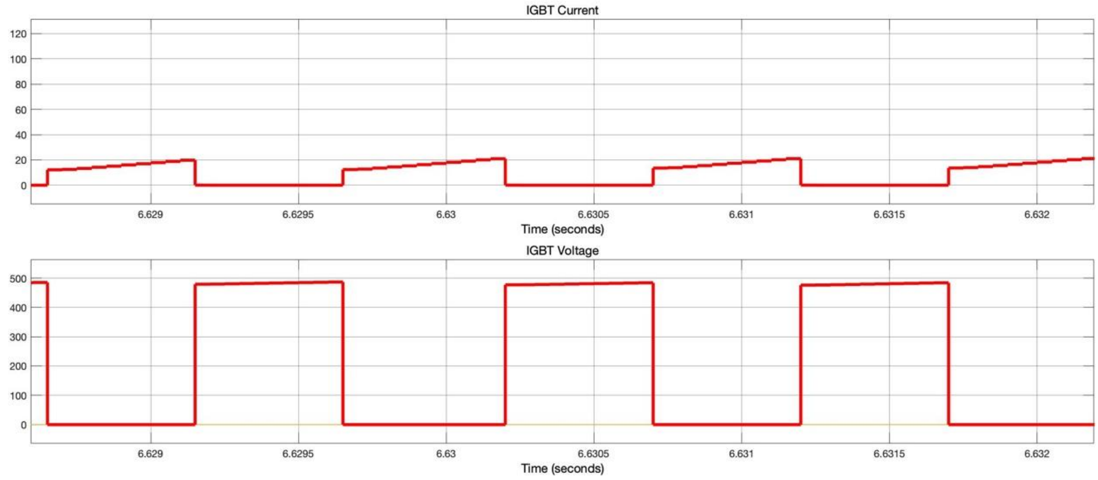

Figure 4.2: The IGBT Current (up) and Voltage (down) for 5% Duty Cycle

As it is seen from the figure above, the IGBT is drawing 3A during the steady state operation and the voltage across it is 550V. During the start-up, those values are increase to 35A and 685Volts. The maximum ratings are so important to conduct the component selection. After the analysis of IGBT voltage and current, the DC-Link capacitor and output voltage waveforms are given in the following figure. The mean output voltage is 25V for 5% duty cycle.

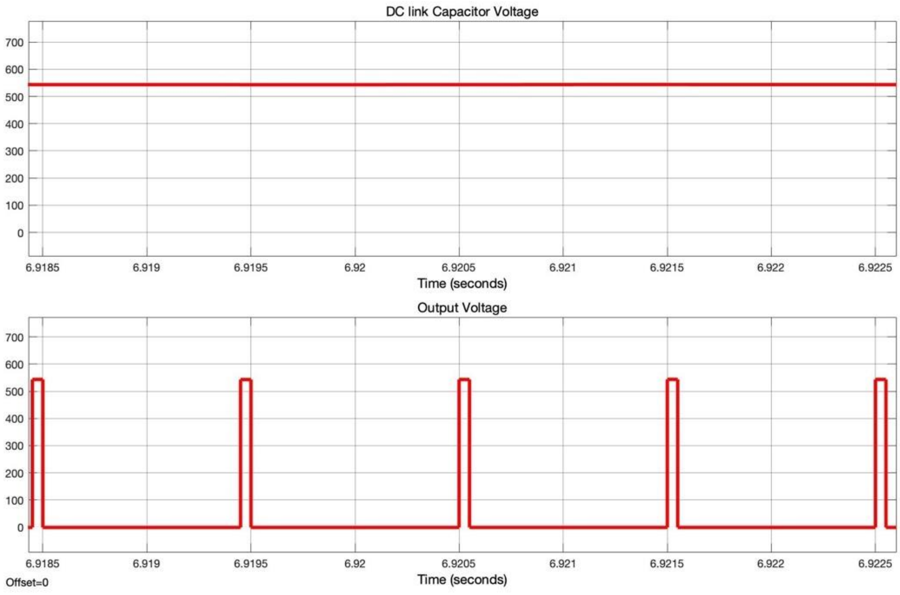

Figure 4.3: The DC-Link Capacitor (up) and Output (down) Voltage for 5% Duty Cycle

After the observations are made on the rectifier output and converter output voltages, the armature current, field current electrical torque and RPM of the DC motor is observed as follows. The RPM of the motor is 200 in this case.

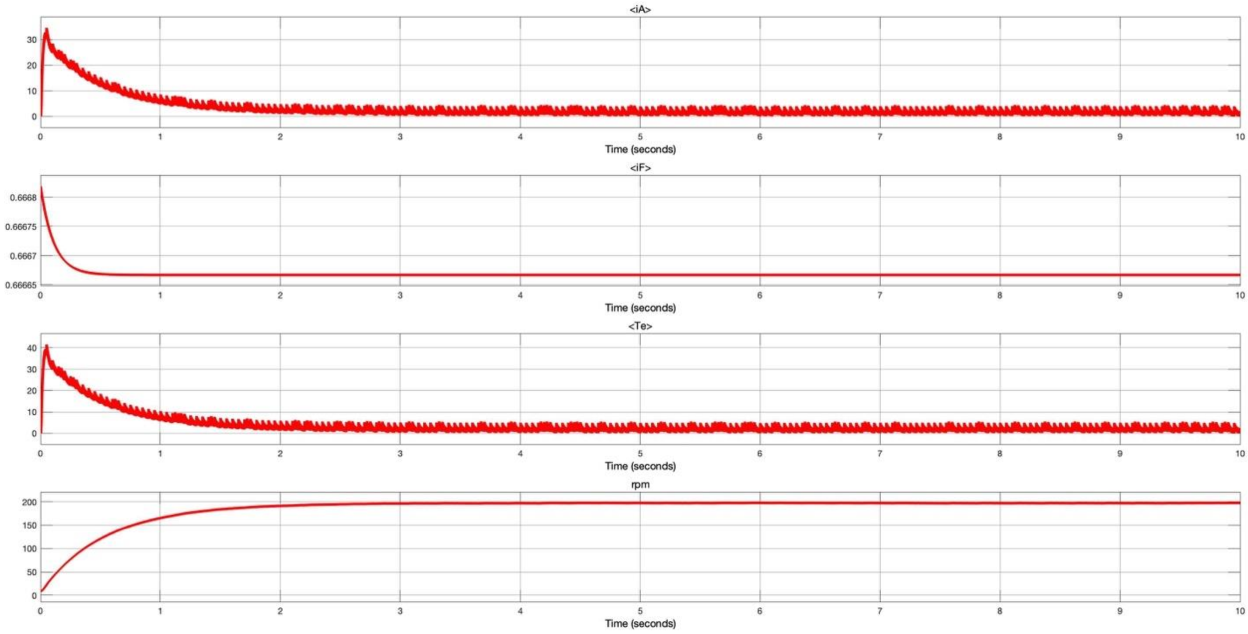

Figure 4.4: The Ia, If, Te and RPM Values of the DC Motor for 5% Duty Cycle

The output voltage waveforms are like a square wave shaped since there is no inductance and capacitance connected at the output stage of the converter since the corner frequency synchronization of the L-C filter needs a deep analysis.

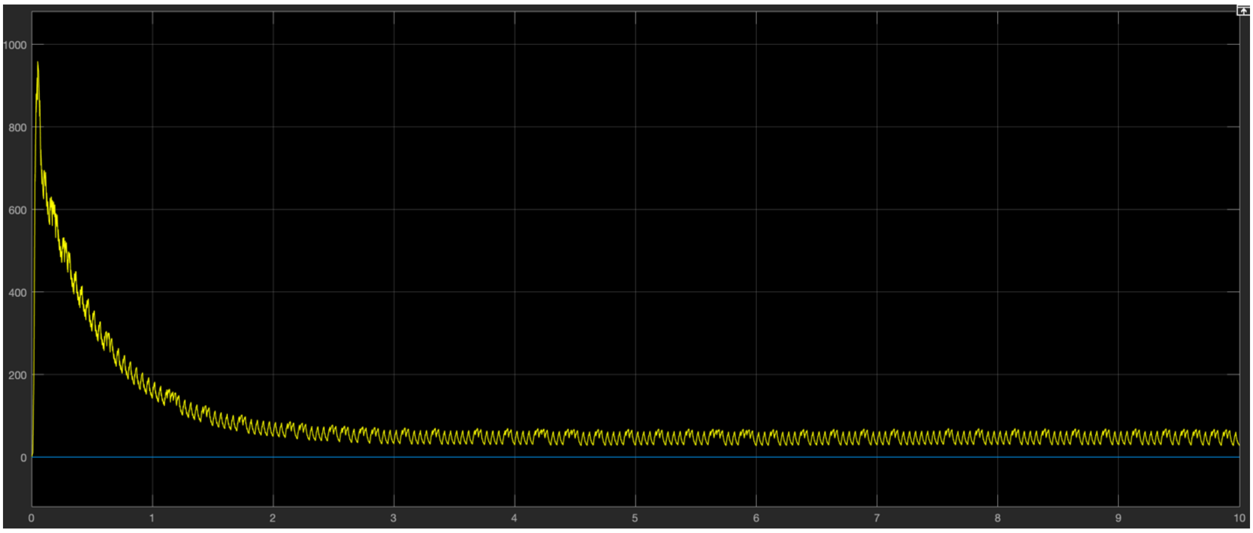

Figure 4.5: The Power Output of the DC-DC Converter for 5% Duty Cycle

2) 25% Duty Cycle Results of the Circuit

Since the circuit will reach up to steady state when the duty cycle is increased incrementally to 25%, the simulation results give the results for IGBT voltage and current as in the figure.

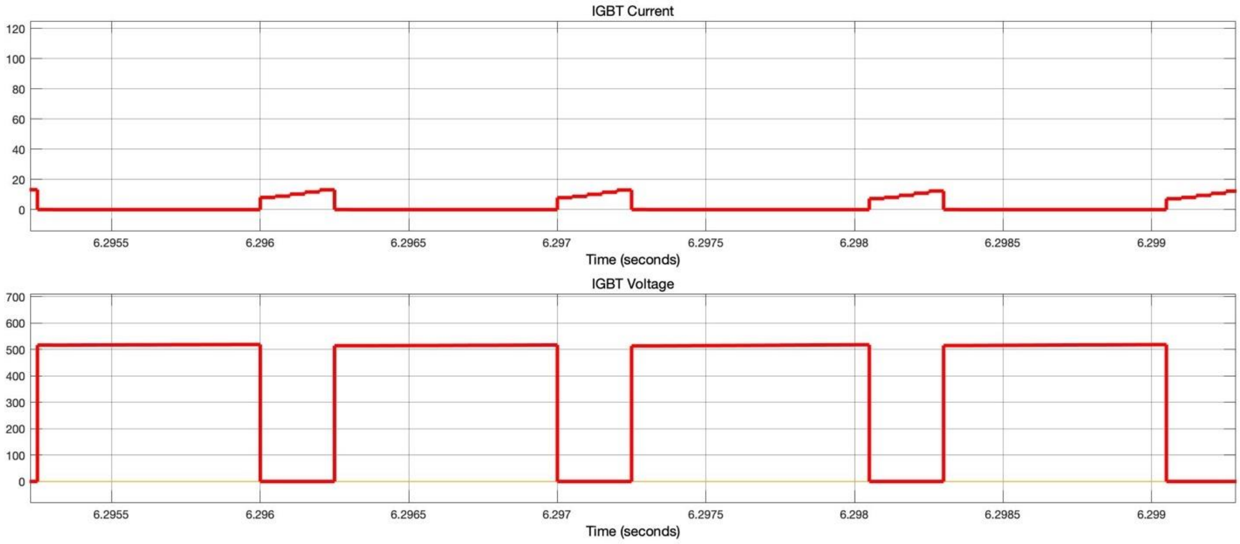

Figure 4.6: The IGBT Current (up) and Voltage (down) for 25% Duty Cycle

As it is seen from the figure above, the IGBT is drawing 18A during the steady state operation and the voltage across it is 520V. The result is a meaningful one since the conduction period is increased. The DC-Link capacitor and output voltage waveforms are given in the following figure. The mean output voltage is 128V for 25% duty cycle.

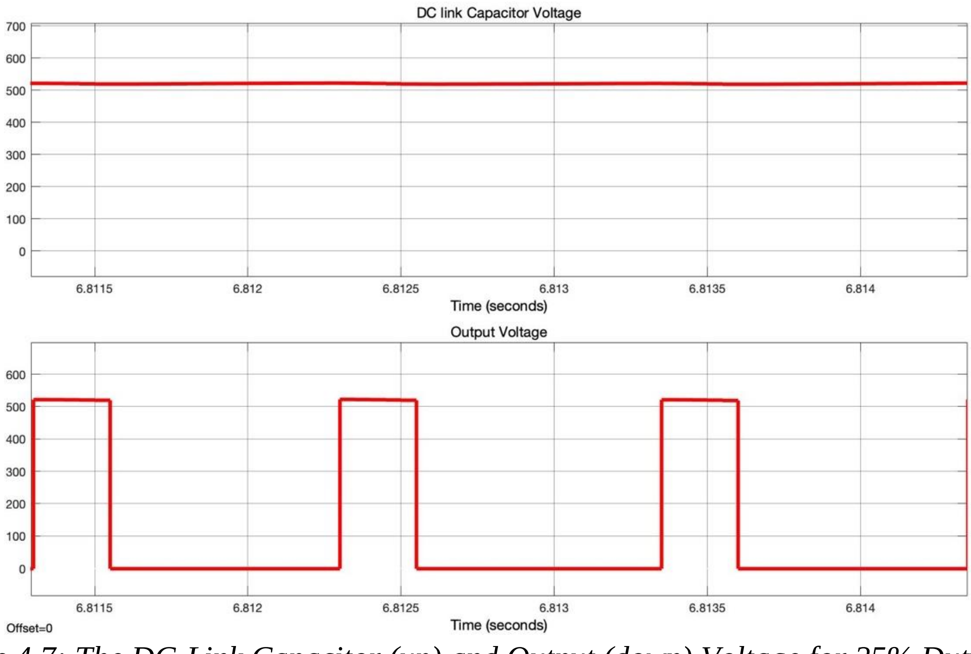

Figure 4.7: The DC-Link Capacitor (up) and Output (down) Voltage for 25% Duty Cycle

After the observations are made on the rectifier output and converter output voltages, the armature current, field current electrical torque and RPM of the DC motor is observed as follows for 25% Duty Cycle. The RPM of the motor is 880 in this case.

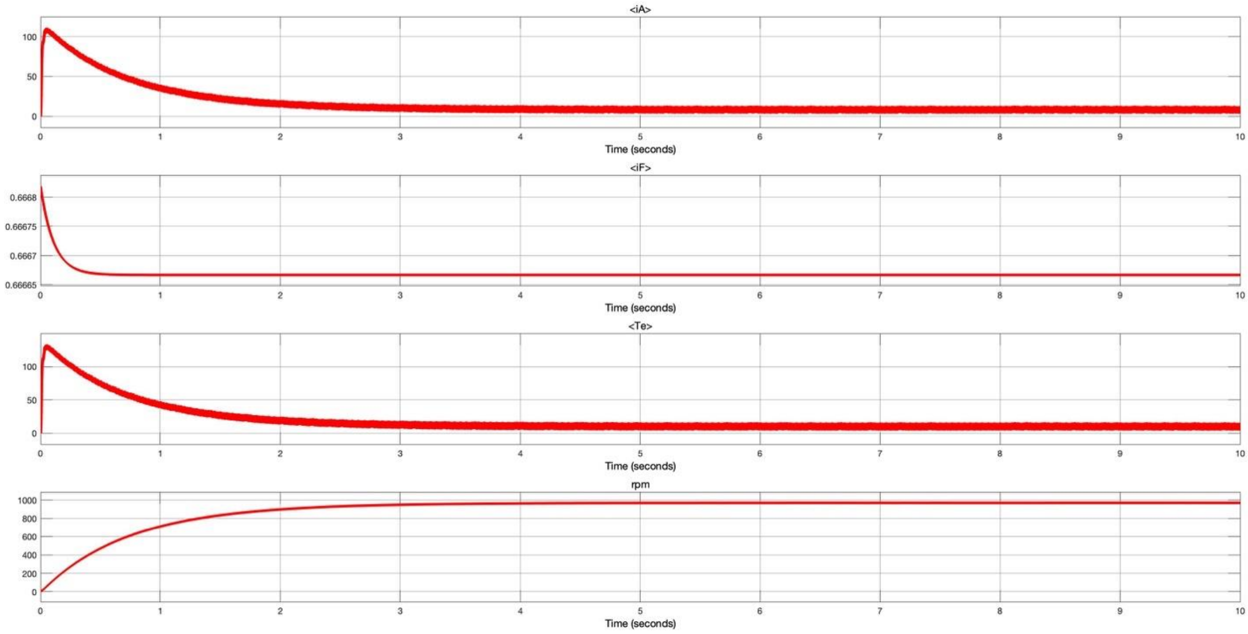

Figure 4.8: The Ia, If, Te and RPM Values of the DC Motor for 25% Duty Cycle

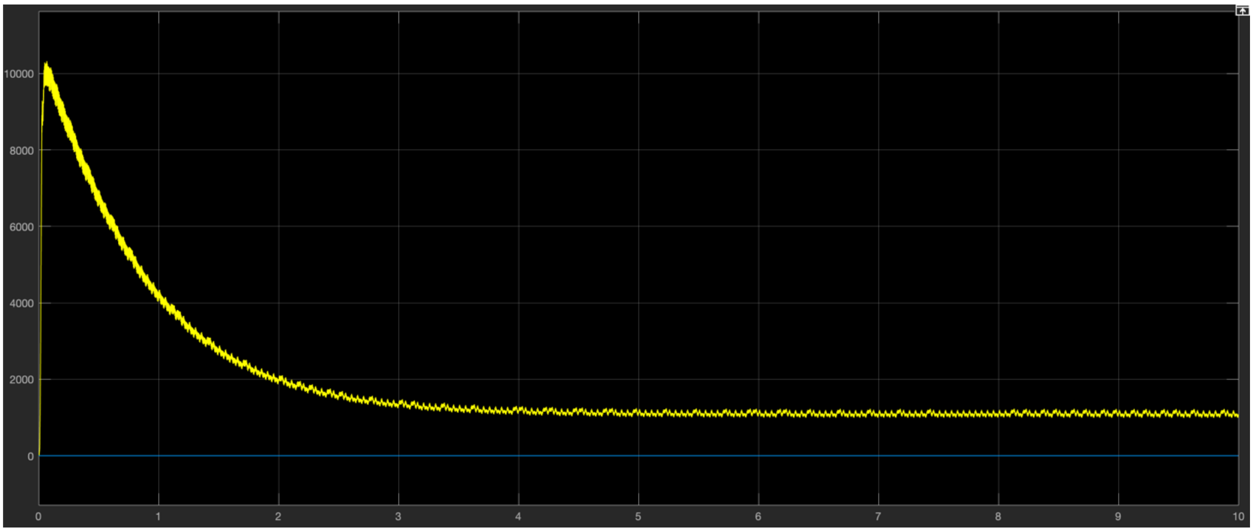

Figure 4.9: The Power Output of the DC-DC Converter for 25% Duty Cycle

3) 50% Duty Cycle Results of the Circuit

During the operation at 50% Duty cycle, the IGBT voltage and current is represented in the figure.

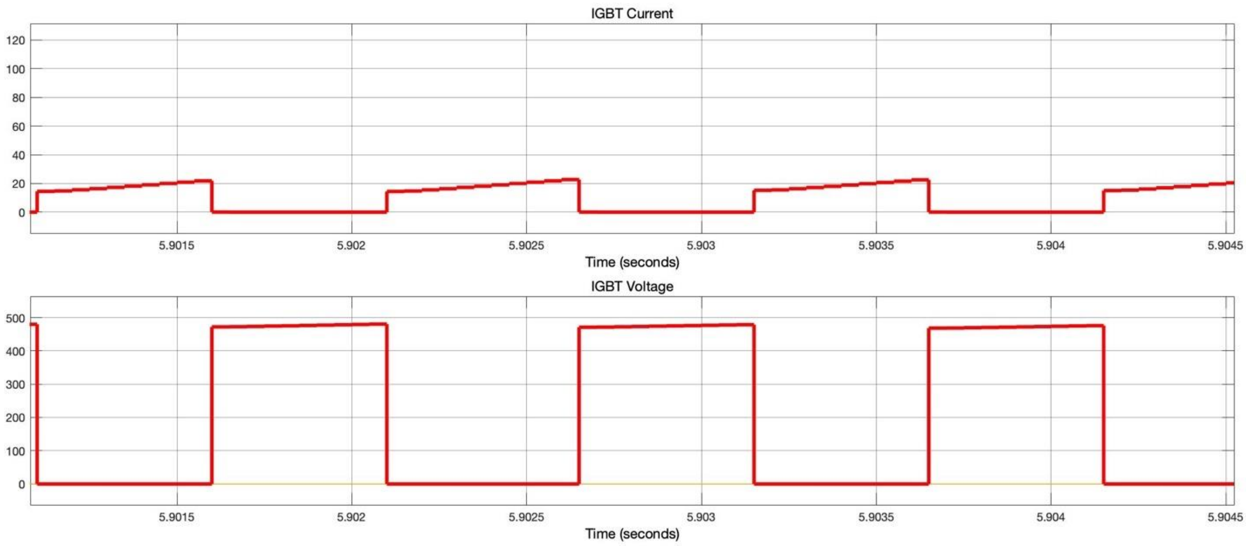

Figure 4.10: The IGBT Current (up) and Voltage (down) for 50% Duty Cycle

During the operation the voltage across the IGBT is 486V and the current is 22A. Since the on period of the Duty Cycle is increased, the current flowing through the IGBT has increased and the mean output voltage is increased accordingly to 243V at 50% Duty Cycle.

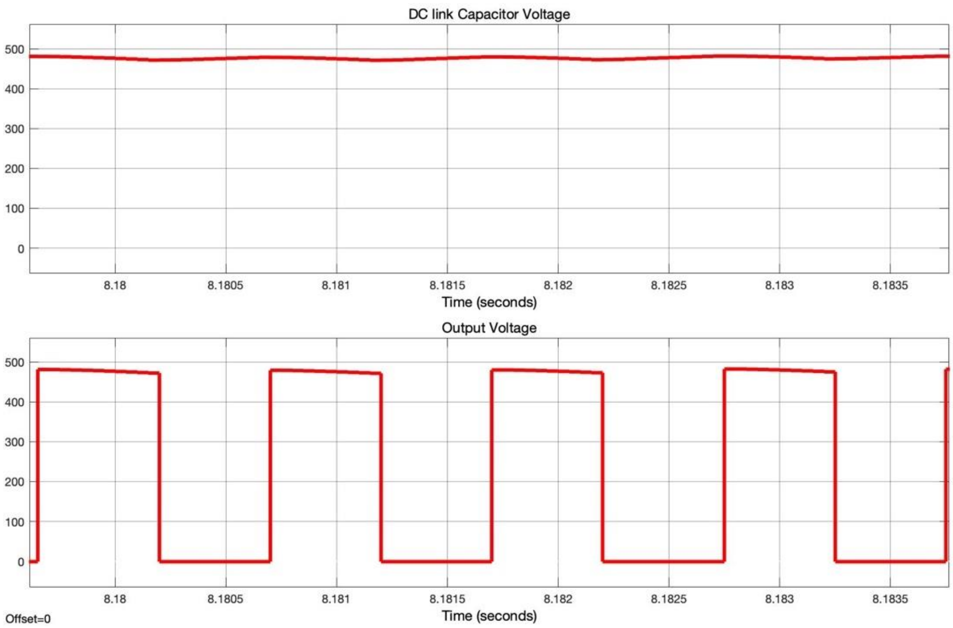

Figure 4.11: The DC-Link Capacitor (up) and Output (down) Voltage for 50% Duty Cycle

After the observations are made on the rectifier output and converter output voltages, the armature current, field current electrical torque and RPM of the DC motor is observed as follows for 50% Duty Cycle. The RPM of the motor is 1750 in this case.

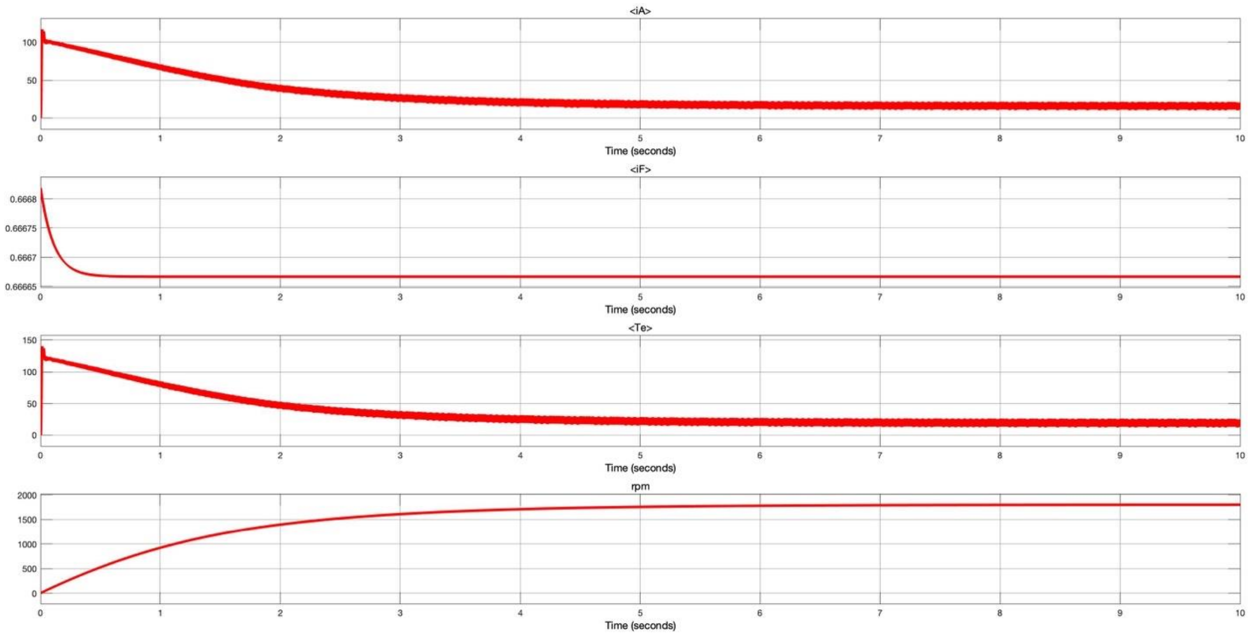

Figure 4.12: The Ia, If, Te and RPM Values of the DC Motor for 50% Duty Cycle

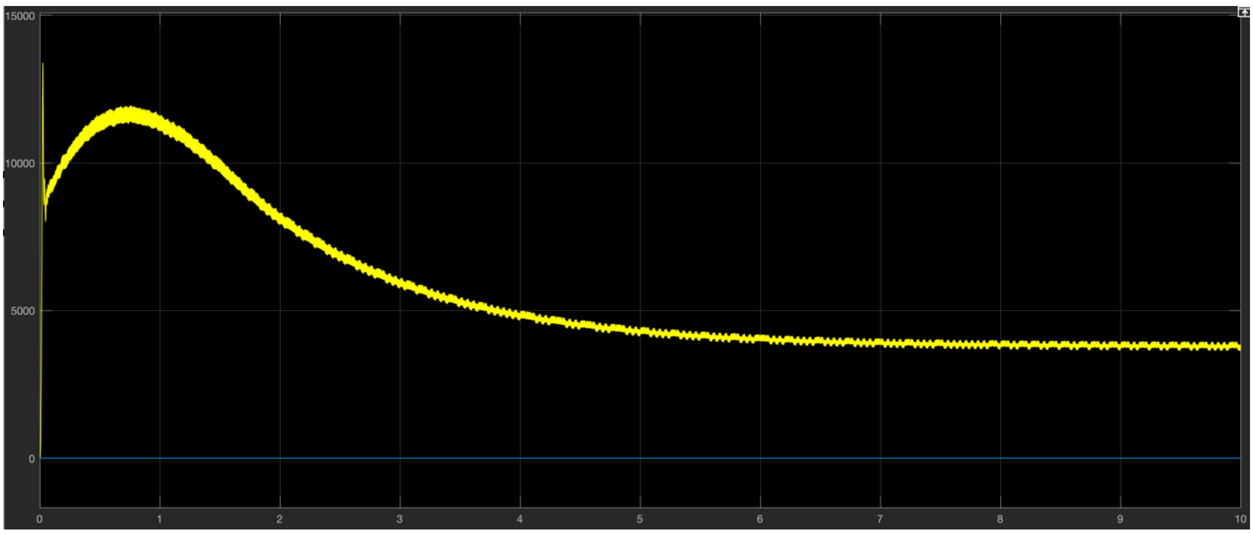

Figure 4.13: The Power Output of the DC-DC Converter for 50% Duty Cycle

4) 75% Duty Cycle Results for the Circuit

The IGBT voltage and current is observed from the simulation as in the figure below. The IGBT carries 26A at 440V during the operation of 75% Duty Cycle.

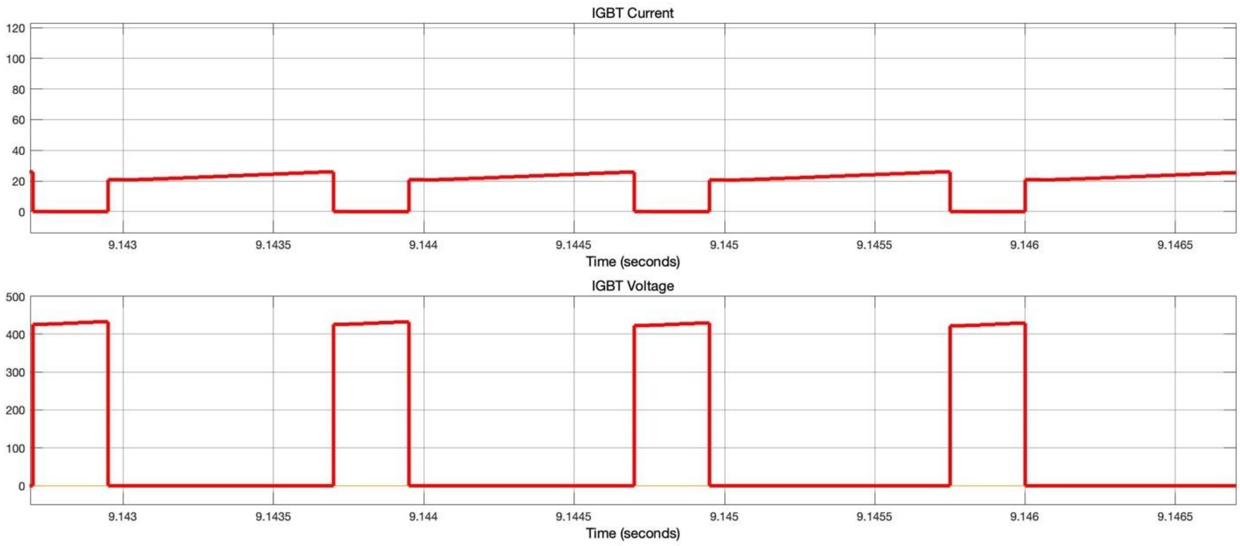

Figure 4.14: The IGBT Current (up) and Voltage (down) for 75% Duty Cycle

During the operation the voltage across the IGBT is 486V and the current is 22A. Since the on period of the Duty Cycle is increased, the current flowing through the IGBT has increased and the mean output voltage is increased accordingly to 325V at 75% Duty Cycle.

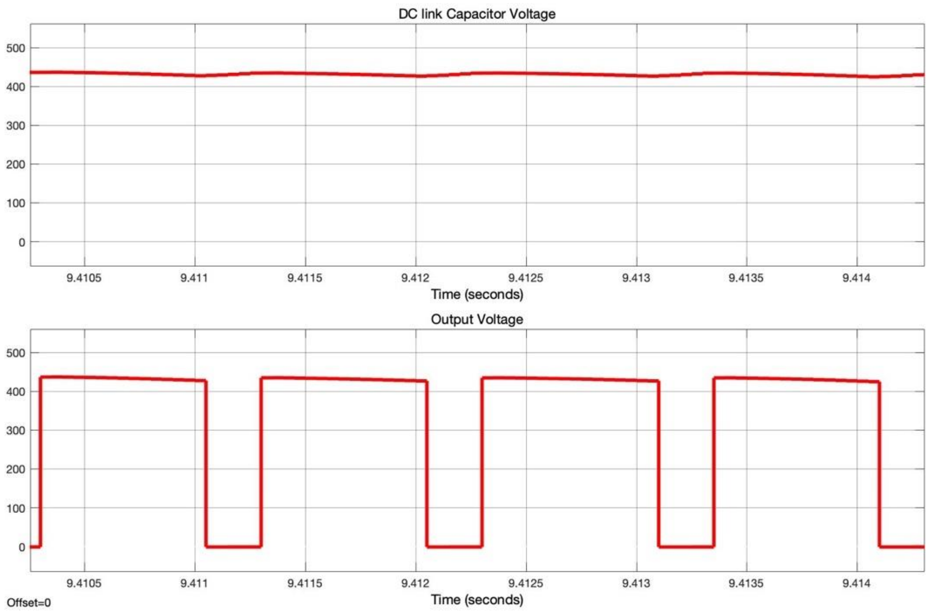

Figure 4.15: The DC-Link Capacitor (up) and Output (down) Voltage for 75% Duty Cycle

After the observations are made on the rectifier output and converter output voltages, the armature current, field current electrical torque and RPM of the DC motor is observed as follows for 75% Duty Cycle and are given in the figure below. The RPM of the motor is 2400 in this case.

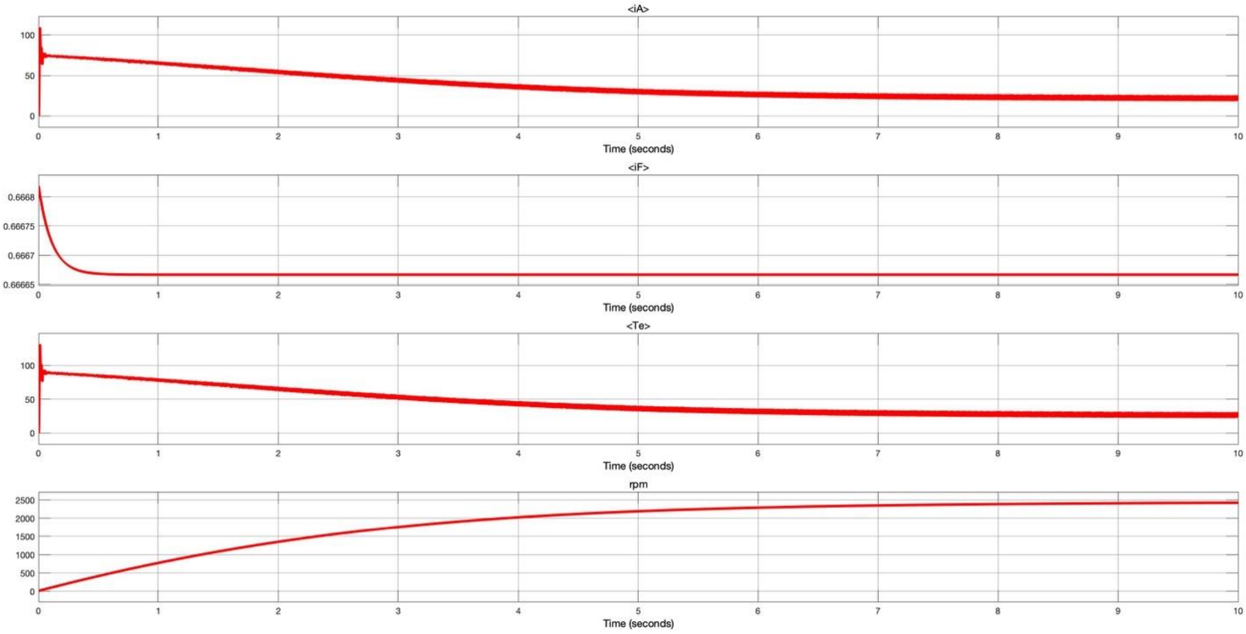

Figure 4.16: The Ia, If, Te and RPM Values of the DC Motor for 75% Duty Cycle

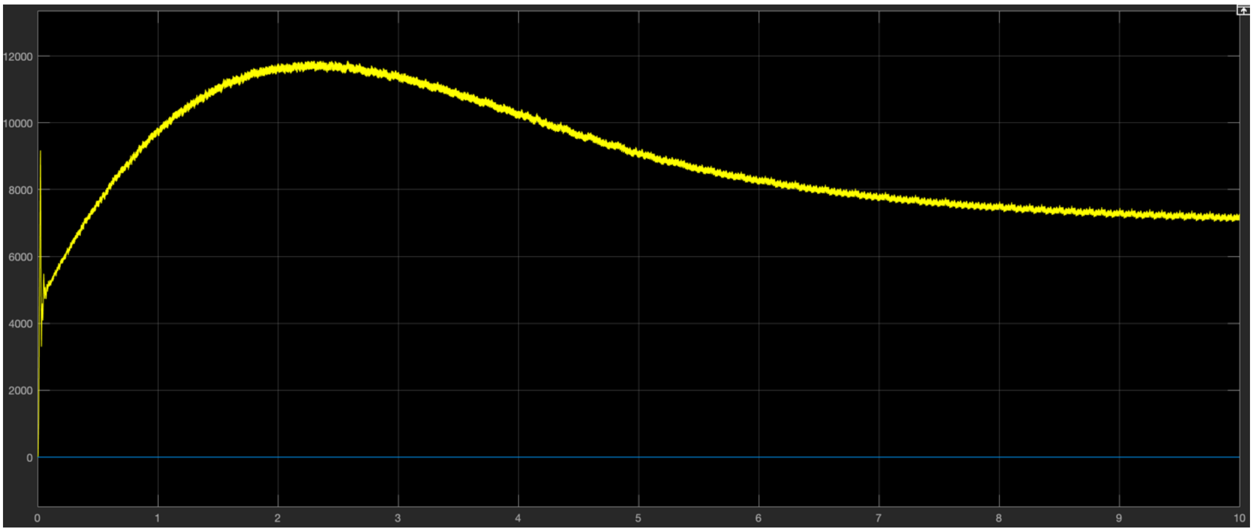

Figure 4.17: The Power Output of the DC-DC Converter for 75% Duty Cycle

5) 95% Duty Cycle Results for the Circuit

The IGBT voltage and current is observed from the simulation as in the figure below.

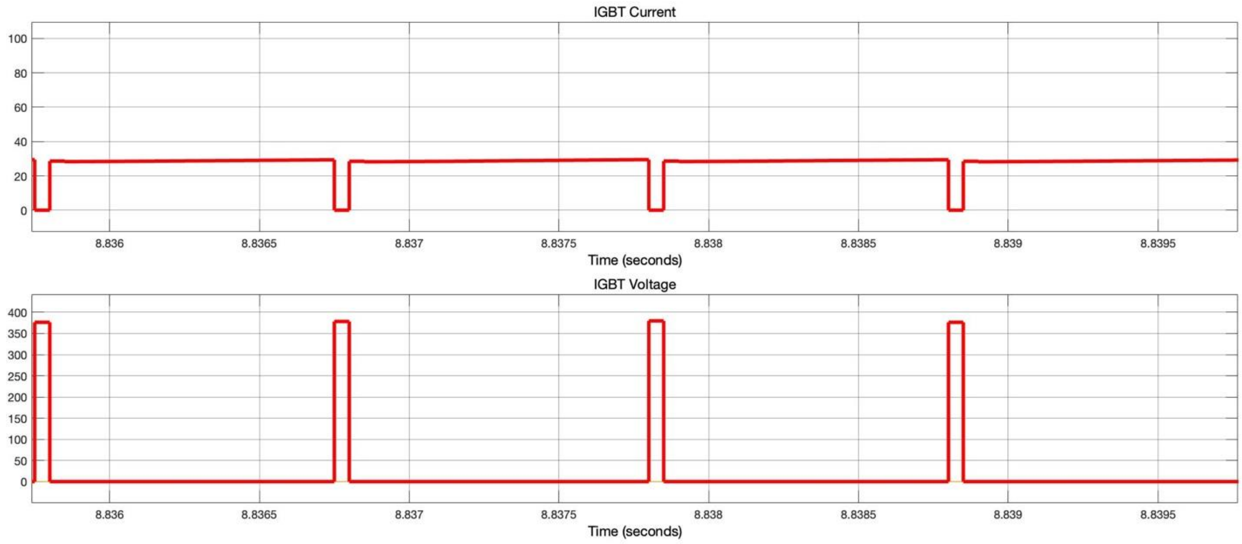

Figure 4.18: The IGBT Current (up) and Voltage (down) for 95% Duty Cycle

During the operation the voltage across the IGBT is 375V and the current is 30A. Since the on period of the Duty Cycle is increased, the current flowing through the IGBT has increased and the mean output voltage is increased accordingly to 375V at 95% Duty Cycle.

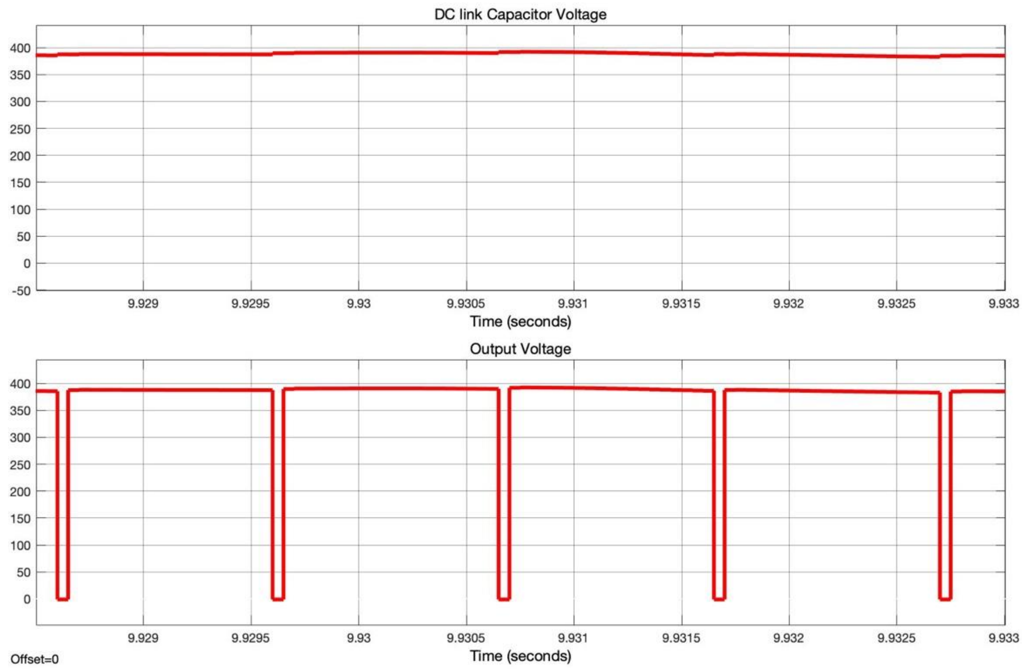

Figure 4.19: The DC-Link Capacitor (up) and Output (down) Voltage for 95% Duty Cycle

After the observations are made on the rectifier output and converter output voltages, the armature current, field current electrical torque and RPM of the DC motor is observed as follows for 95% Duty Cycle and are given in the figure below. The RPM of the motor is 2700 in this case.

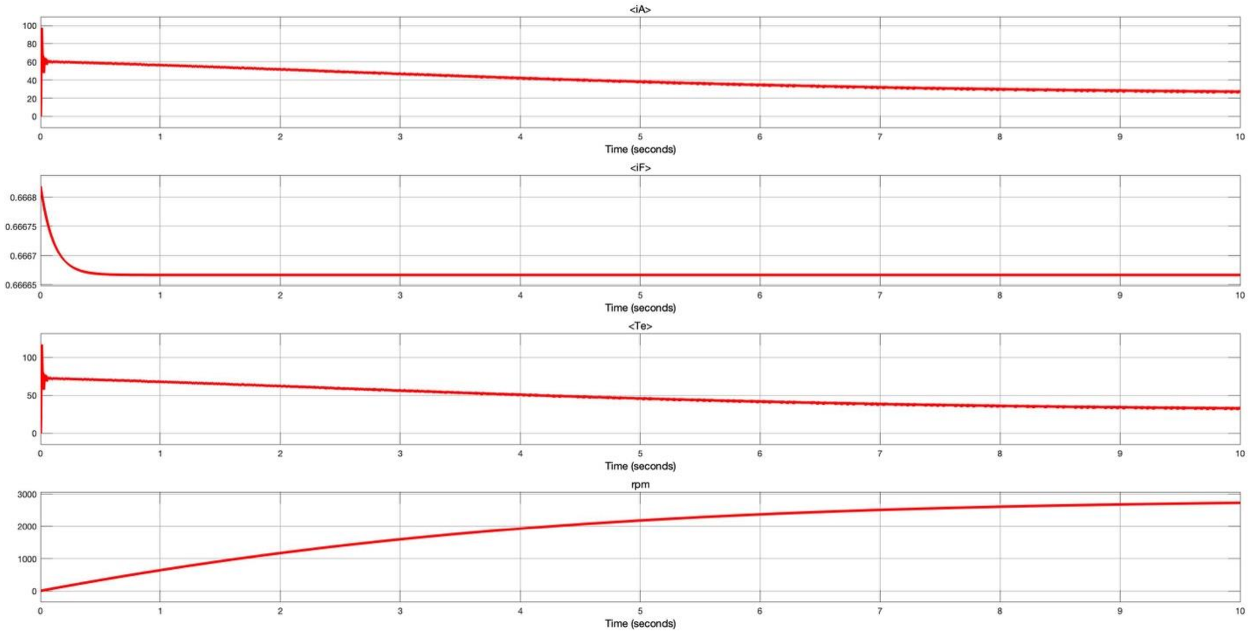

Figure 4.20: The Ia, If, Te and RPM Values of the DC Motor for 95% Duty Cycle

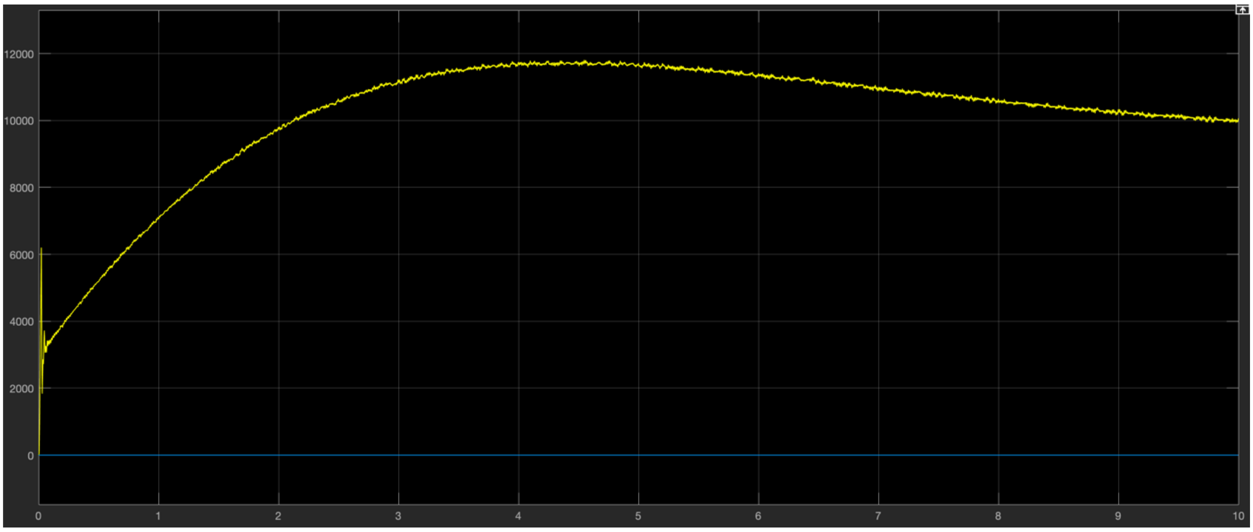

Figure 4.21: The Power Output of the DC-DC Converter for 95% Duty Cycle

VI. COMPONENT SELECTION

After the analyses of the circuit is completed through the simulations, next step was the component selection process according to the results. It should be noted in here that these components were selected with respect to the simulation results and several other considerations. Due to the fact that, during the simulation process the input voltage coming from the variac was chosen as the standard grid voltage (230V line to neutral), maximum potential operating conditions of the AC-DC converter were observed at the simulation results. However for the practical usage, the variac was decided to be set to a value much lower than the standard grid voltage, therefore allowing to select components that have lower ratings compared to the components that could be selected according to the simulation results.

Furthermore an isolation between pulse generator and converter was needed in order to eliminate high voltages to affect the controller circuit. For this purpose, an isolation circuitry using TLP250 optocoupler was utilized in the design

1) Three-Phase Full-Bridge Diode Rectifier

The first necessary component of the circuit is a three-phase full-bridge diode rectifier which will be used as a rectifier component to get a DC from the supplied AC signals. By referencing the simulation results, the input voltage to be used and design considerations, three phase full bridge diode rectifier was selected. The technical specification of the selected three phase full bridge diode rectifier is given below in table 1.

TABLE 1: Three-Phase Full-Bridge Diode Rectifier Parameters

MODEL NAME	*SBR 35 A*
PEAK REVERSE VOLTAGE	*1600V*
DC OUTPUT VOLTAGE	*570V*
DC OUTPUT CURRENT	*8A @ 55 °*
PEAK FULL WAVE ONE CYCLE SURGE CURRENT	*400A*
PEAK FULL WAVE RECURRENT FORWARD CURRENT	*35A*

2) DC-Link Capacitor

There is a three-phase full-bridge diode rectifier at the input stage of the circuit, but still there is a need for a smoothing capacitor. In order to do so, the capacitance value of the DC-Link capacitor is decided to be 470uF at a voltage rating of 630V according to the preliminary simulation results. However, due to the fact that it was decided to work with an input voltage lower than the standard grid voltage, a capacitor with lower rating could be selected. Thus a capacitor w 470uF at a voltage rating of 400V was selected for the AC-DC converter product.

3) IGBT

Since the IGBTs can carry more currents, the selected switching component in the design procedure is decided to be an IGBT instead of MOSFET. By referencing the simulation results, the input voltage to be used and design considerations, IGBT was selected. The technical specification of the IGBT is given below in table 2.

TABLE 2: The Technical Specification of the IGBT

MODEL NAME	IXGH24N60C4D1
COLLECTOR-EMITTER VOLTAGE	*600V*
GATE-EMITTER VOLTAGE	*+/- 20V*
COLLECTOR CURRENT	*24A @ 25°*
PULSED COLLECTOR CURRENT	*130A*
DIODE CONTINIOUS FORWARD CURRENT	*15A @ 100°*
OPERATING TEMPERATURE	*-55°/ +150°*

4) DIODE

In the design, the diode should have an ability of fast recovery and high current carrying capacity in order to withstand high currents during both the start-up and steady state. By referencing the simulation results, the input voltage to be used and design considerations, three phase full bridge diode rectifier was selected. The technical specifications of the selected diode are given in table 3.

TABLE 3: The Technical Specification of the Diode

MODEL NAME	*IXYS DSEI30-12A*
PEAK REPETITIVE REVERSE VOLTAGE	*1200 V*
AVERAGE RECTIFIED FORWARD CURRENT	*26A*
NON-REPETITIVE PEAK SURGE CURRENT	*210A*
FORWARD VOLTAGE	*2.55V*
REVERSE RECOVERY TIME	*60ns*

VII. TEST RESULTS

After completing the product, the constructed AC-DC converter was initially tested with an R-L load that acted as a DC motor load in the laboratory environment. Several important parameters such as Duty cycle at the output of TLP250 optocoupler, IGBT current, IGBT voltage and DC output voltage was carefully investigated and compared with the expected results in order to eliminate any risks before proceeding to connect the converter to the the actual DC motor. Initial test results particularly waveforms showing DC link capacitor voltage and duty cycle at both Arduino and optocoupler output were obtained. These waveforms can be seen at the figures below. The variation of the DC link capacitor voltage with the adjustment of duty cycle can be seen at the figures below. The decrease in the DC link capacitor with increasing duty cycle basically cause the voltage increase in the DC output voltage due to the switching characteristic of the IGBT.

Figure 7.1: The DC link capacitor voltage and duty cycle of the DC-DC Converter for 5% Duty Cycle

Figure 7.2: The DC link capacitor voltage and duty cycle of the DC-DC Converter for 50% Duty Cycle

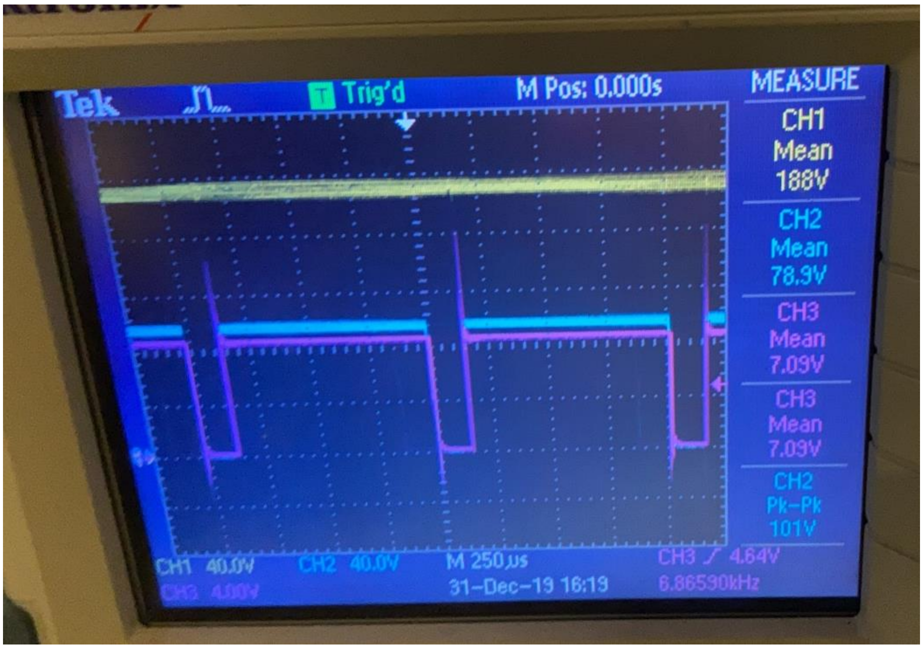

Figure 7.3: The DC link capacitor voltage and duty cycle of the DC-DC Converter for 90% Duty Cycle

After completing initial tests with the R-L load, actual tests with the DC motor were carried on. The speed of the DC motor was successfully controlled with the adjustment of duty cycle. After running the DC motor for around ten minutes, an extra DC load of 1.6 kW (kettle) was connected to the converter output. Our converter managed to successfully drive both of loads for around 5 minutes until the IGBT was burned due to excessive amount of currents. As a result of this the IGBT was quickly replaced and a better heatsink was bought for better heat transfer purposes. At the final demo day our converter operated perfectly for both load conditions for around 10 minutes. The DC output voltage and DC output current at %75 duty cycle with 150V AC line to neutral input for DC motor load and DC motor load-kettle combined can be seen at the figures below. As can be seen from the figure the DC output current increases dramatically as we connect the kettle. A feedback circuitry was planned to be implemented in order to deal with this increase in output current by modifying the duty cycle, however due to lack of time it could not be implemented.

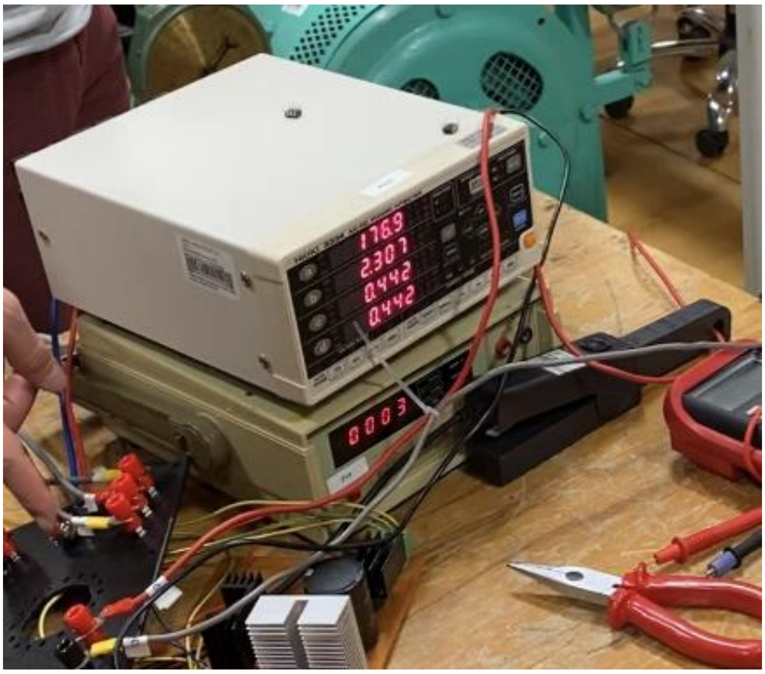

Figure 7.4: The DC output voltage(first line on the multimeter) and DC output current (second line on the multimeter) of the DC-DC Converter feeding just the DC motor for 75% Duty Cycle at 150V AC line to neutral input.

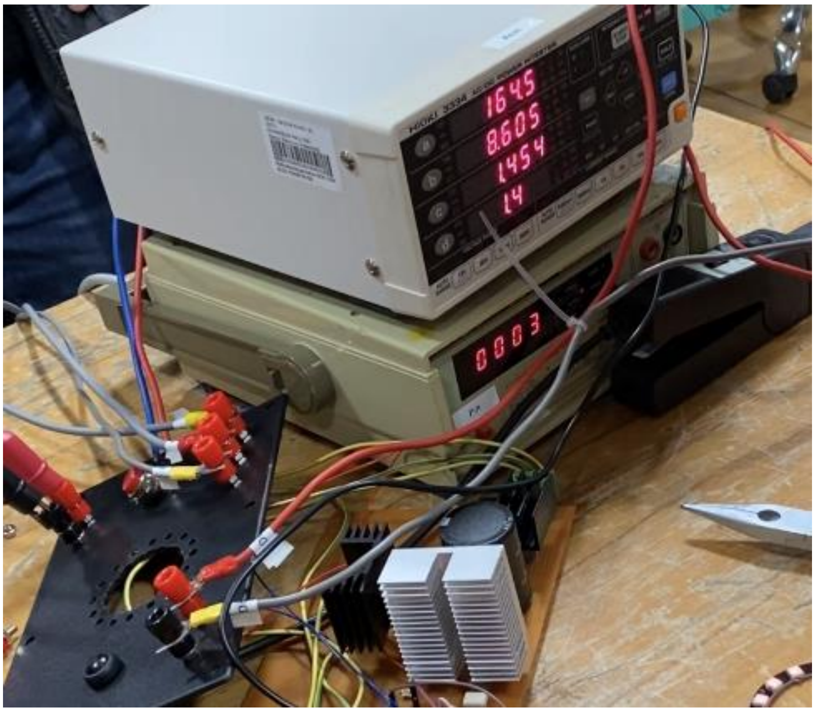

Figure 7.5: The DC output voltage(first line on the multimeter) and DC output current (second line on the multimeter) of the DC-DC Converter feeding the DC motor and kettle combined for 75% Duty Cycle at 150V AC line to neutral input.

Furthermore by measuring the DC output current with an oscilloscope, the buck converter was observed to operate at discontinuous conduction mode as can be seen at Figure 7.5

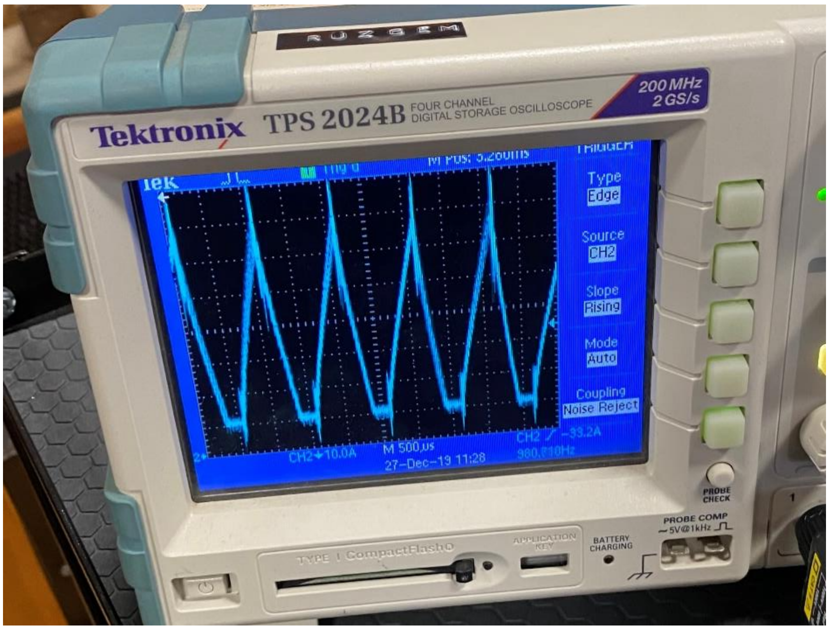

Figure 7.3: The waveform of the DC output current

VIII. COST ANALYSIS

Due to the reason that an economically efficient product is highly sought, a detailed cost analysis were carried out by referencing the requirement analysis of the system. The final product was completed according to the principle of low price-high performance and introduced an compact and efficient product for customers. The cost analysis of the product can be seen at table 4.

It should be noted that, several components were bought in multiple numbers in order to replace components in case of any failure and design modifications. During the testing process of the product, an IGBT and a diode were burned due to excessive currents, luckily they were quickly replaced with the spare products.

TABLE 3: Cost Analysis of the System

COMPONENT LIST	***NUMBER***	***COST(₺)***
IXGH24N60C4D1 *IGBT*	*2*	*45*
IXYS DSEI30-12A Diode	*2*	*20*
SBR 35 A Phase Diode Rectifier	*2*	*35*
470uF 400V DC Link Capacitor	*1*	*40*
Arduino Uno	*1*	*30*
TLP250 OptoCoupler	*1*	*10*
Black Mounting Box	*1*	*35*
12 V Rotary Fan	*1*	*15*
Pertinaks Board	*1*	*35*
Heat Sink	*2*	*20*
Cables	*2(meters)*	*5*
TOTAL		*440*

IX. CONCLUSION

In this project, the aim was to produce an AC/DC converter to drive a DC motor. For that purpose, we have revised course lectures and combined it with more research to propose more solution alternatives. Next we have listed advantages and disadvantages of each option and after considering trade-offs, we have come up with a decision that is buck converter with diode rectifier. Afterwards, various simulations made it possible to decide on proper components. All of them have been tested and the system has been tested as a whole. Hopefully, we have achieved successful implementation. Despite the fact that it sounds relatively easy to design a rectifier, it took a lot of time and effort of us to succeed in this project. There was a lot of workload that this project demanded. Hence, the time that we have spent in laboratory is remarkable. One of the problems we faced was overheating and actually, this happened during demonstration. Hopefully, we have solved this issue afterwards. Another problem is that we couldn’t quite make feedback work. The problem is that we just ran out of time. Although there could have been a little bit more improvement, we have done our best to achieve this operation and unfortunately, time and our efforts run out. Nevertheless, this was quite an achievement for us in the road to become a proper engineer.

Along with its laboratory and homework projects, this hardware project helped us gain a solid experience in AC/DC conversion to achieve learning outcomes of our EE463: Static Power Conversion-I course. Now we have a significant experience with converter design and we also gained knowledge of important factors, simulation usage and process of converter design and these will be important earnings of this course for us as we think about a career on Power Electronics area.