A Project Report on

A WIDE INPUT-VOLTAGE RANGE QUASI-Z-SOURCE BOOST DC-DC CONVERTER WITH HIGH- VOLTAGE GAIN FOR FUEL CELL VEHICLES

Submitted in partial fulfilment of the requirements for the degree of

MASTER OF ENGINEERING

in

ELECTRICAL ENGINEERING

(Specialization: Power Electronic Systems)

by

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CERTIFICATE

This is to certify that the project work titled **"A Wide Input-Voltage Range Quasi-Z-Source Boost DC-DC Converter With High-Voltage Gain for Fuel Cell Vehicles"** submitted by **K. LAXMI MAANASA,** Roll No.1005-16-743-304, a student of Department of Electrical Engineering, University College of Engineering in partial fulfilment of the requirement for the award of the degree of **Master of Engineering** in **Electrical Engineering**, with Power Electronic Systems as specialization, is a record of the bonafide work carried out by her under my guidance and supervision during the academic year 2017-2019.

This project report has not been submitted to any other university or institute for the award of any degree.

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DECLARATION

I declare that the work reported in the thesis entitled **“A Wide Input-Voltage Range Quasi-Z-Source Boost DC-DC Converter with High-Voltage Gain for Fuel Cell Vehicles”** is a record of the work done by me in the Department of Electrical Engineering, University College of Engineering, Osmania University.

No part of the thesis is copied from books / journals / Internet and wherever referred, the same has been duly acknowledged in the text. The reported data are based on the project work done entirely by me and not copied from any other source. Further, I declare that the report has not been submitted to any other university/institute for the award of any degree.

Signature of student

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ABSTRACT

A quasi-Z-source boost dc–dc converter, which uses a switched capacitor, is proposed for fuel cell vehicles. The converter obtains a high -voltage gain with a wide input voltage and requires only a low voltage stress across each of the components. The drawbacks of other converters are explained. A scaled down 400V/ 4 kW prototype is developed to validate the proposed technology. When there is a wide variation in the input voltage, the respective variation in the output voltage is avoided by proportional integral controller in the voltage loop. A supercapacitor used in parallel to the fuel cell network through bi-directional converter in order to supply instantaneous power to the high voltage DC link bus.

CHAPTER 1

INTRODUCTION

Clean energy technologies have to be developed for improving the environment and addressing the challenges to energy usage due to the increasing penetration and the need to reduce fossil fuel consumption. Increasing number of automobiles across worldwide is becoming a great problematic which results in raising air pollution. Recently, the development of vehicles powered by clean energies has been increasing and their numbers are growing as a percentage of total transportation.

Fuel cell vehicles are an important contributor to these clean energy vehicles and have been applied widely, as they have high-density current output, clean electricity generation, and high-efficiency operating characteristics.

However, unlike batteries that have a fairly constant output voltage, the fuel cell output voltage drops quickly with an increase of output current. Therefore, it has to be interfaced to the high-voltage dc-link bus of the inverter through a step-up dc–dc converter with a wide range of voltage gain. We have two types of dc-dc converter namely, isolated and non-isolated.

The isolated step-up dc–dc converter can achieve a high-voltage gain easily. However, the energy of the transformer leakage inductance may produce high-voltage stress, increase the switching losses, and cause serious electromagnetic interference. Therefore, a non-isolated step-up dc–dc converter is often more desirable to reduce the cost, reduce the volume of the converter, and improve the conversion efficiency. The commonest non isolated step-up dc–dc converter is the conventional boost dc–dc converter.

However, due to the presence of parasitic elements in the circuit, the voltage gain is limited. In addition, the voltage stress of the power switch is as large as the output voltage, and this demands a high-voltage-rated power switch when the output voltage is high.

In view of the problems described, a quasi-Z-source boost dc-dc converter with a switched capacitor is proposed for improving the voltage gain and reducing the voltage stress across the components.

1.1 OBJECTIVE: The aim of the project is to develop a Quasi-Z-source Boost DC-DC converter with wide input voltage range is used to run a motor with high voltage gain.

1.2 LITERATURE SURVEY:

Emadi and Williamson, focussed on fuel cell applications and their opportunities and challenges. They also explained the working principle of fuel cell. Schematic diagram of a basic vehiclular fuel cell electric power system with an on-board fuel cell processor is shown. He stated that there are three major steps involved in the generation of power from a fuel cell. The first step is to achieve purity of a fuel processor. This is done with the help of a fuel processor where hydrogen is produced from hydrocarbon fuel. The generation of the DC voltage via the fuel cell makes up the second step. Tn third step, the power output needs to b properly treated.

Chiru and Len, explained how bidirectional DC-DC converter is used in fuel cell electric vehicle driving system. Bidirectional DC-DC converter is placed between the storage device and DC link. It is used to supply power to the dc link from the storage device when the voltage across the dc link is insufficient. And it also used to charge the storage device when there is excess of power at dc ink. Finally, it is said that it helps in maintaining the constant voltage across the dc link.

Pera and Candusso, explained about the generation of power from fuel cell. The electricity is generated from the reaction of hydrogen and oxygen to form water in a process called reverse of electrolysis. Fuel cell has two electrodes called the anode and cathode. The reactions that produce electricity take place at the electrodes. Fuel cell, such as hydrogen, is fed to the anode and air is fed to the cathode. In hydrogen fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity.

Garnier also explained how PEM fuel cell is used in automobile applications. The advantages of a PEM fuel cell is that they have a high power density and are low in weight. The major disadvantage of PEM fuel cell is that they require an expensive catalyst, in this case platinum, which adds to the overall unit cost.

1.3 ORGANISATION OF THESIS:

In chapter1, a brief introduction on converter, fuel cell is given. The objective of the project is stated. The literature survey has been discussed. Organization of thesis is also explained for each chapter.

Chapter2 consists of brief introduction about fuel cell operation, its equations and advantages. It also includes the operation of buck converter, PWM technique and PI controller. It also includes the super capacitor operation.

Chapter3 consists of the operation of converter and the voltages across the diodes, capacitors and the currents through the inductors.

In chapter 4, simulation and results of open loop control of converter and closed loop control of the converter is shown. Th voltages across diodes, capacitors and currents through inductors are shown. It also includes how the converter and supercapacitor are used in fuel cell applications.

Chapter5 concludes the project.

CHAPTER 2

FUEL CELL AND CONVERTER

2.1 FUEL CELL:

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions.

Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. Fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. They are also used to power fuel cell vehicles, including forklifts, automobiles, buses, boats, motorcycles and submarines.

There are many types of fuel cells, but they all consist of an anode, a cathode, and an electrolyte that allows ions, often positively charged hydrogen ions (protons), to move between the two sides of the fuel cell. At the anode a catalyst causes the fuel to undergo oxidation reactions that generate ions (often positively charged hydrogen ions) and electrons. The ions move from the anode to the cathode through the electrolyte. At the same time, electrons flow from the anode to the cathode through an external circuit, producing direct current electricity. At the cathode, another catalyst causes ions, electrons, and oxygen to react, forming water and possibly other products.

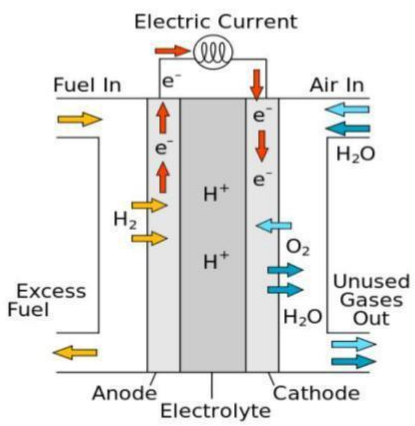


Fig: 2.1 Fuel Cell

Individual fuel cells produce relatively small electrical potentials, about 0.7 volts, so cells are "stacked", or placed in series, to create sufficient voltage to meet an application's requirements. In addition to electricity, fuel cells produce water, heat and, depending on the fuel source, very small amounts of nitrogen dioxide and other emissions. The energy efficiency of a fuel cell is generally between 40–60%;

Anode Reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^{-}$

Cathode Reaction: $O_2 + 4e^{-} \rightarrow 2O^{2-}$

Overall Cell Reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Advantages:

- ➢ So long as fuel provided, the cells can provide constant power in remote locations.
- ➢ Fuel cell power is usually proposed as the green, alternative to the internal combustion engine, fuelled only hydrogen and leaving no pollutants other than water.

2.2 BOOST CONVERTER:

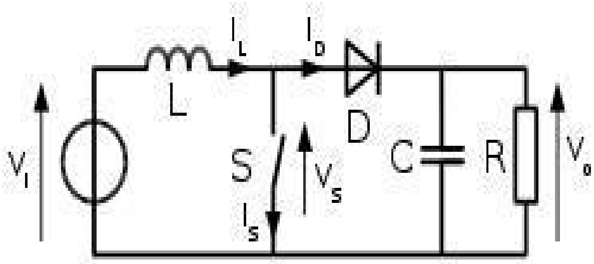


Fig 2.2 Boost converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

Operation:

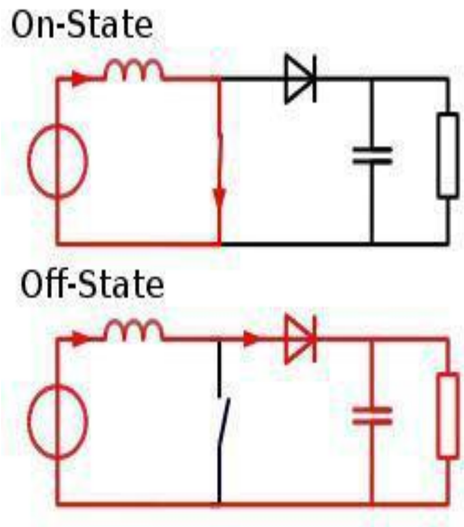


Fig 2.3: Operating states of boost converter

❖ When the switch is closed, current flows through the inductor in the clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.

❖ When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (meaning the left side of the inductor will become negative). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

❖ If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.

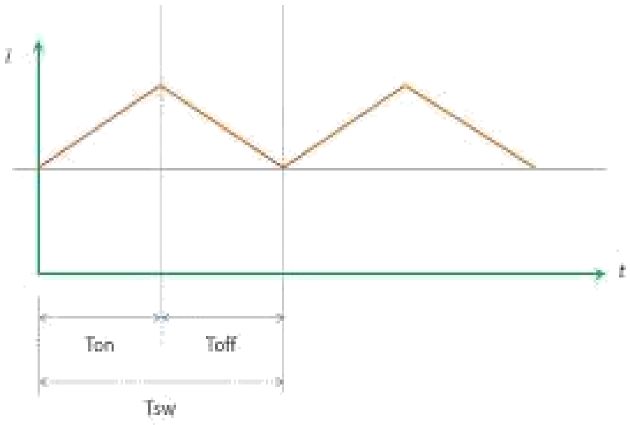


Fig 2.4 Inductor current of the boost converter.

The basic principle of a Boost converter consists of 2 distinct states

- In the On-state, the switch S is closed, resulting in an increase in the inductor current;
- In the Off-state, the switch is open and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure 2. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.

2.3 PULSE WIDTH MODULATION TECHNIQUE:

The purpose of pulse width modulation is

- ➢ Control of ac-side fundamental voltage (dc bus voltage being fixed and possibly neglected).
- ➢ Mitigation of harmonic voltages and their harmful effects (harmonic currents, increased losses in the ac-side elements, pulsating torque in case of motor drives).

The popular real time PWM technique is Sinusoidal PWM (SPWM).

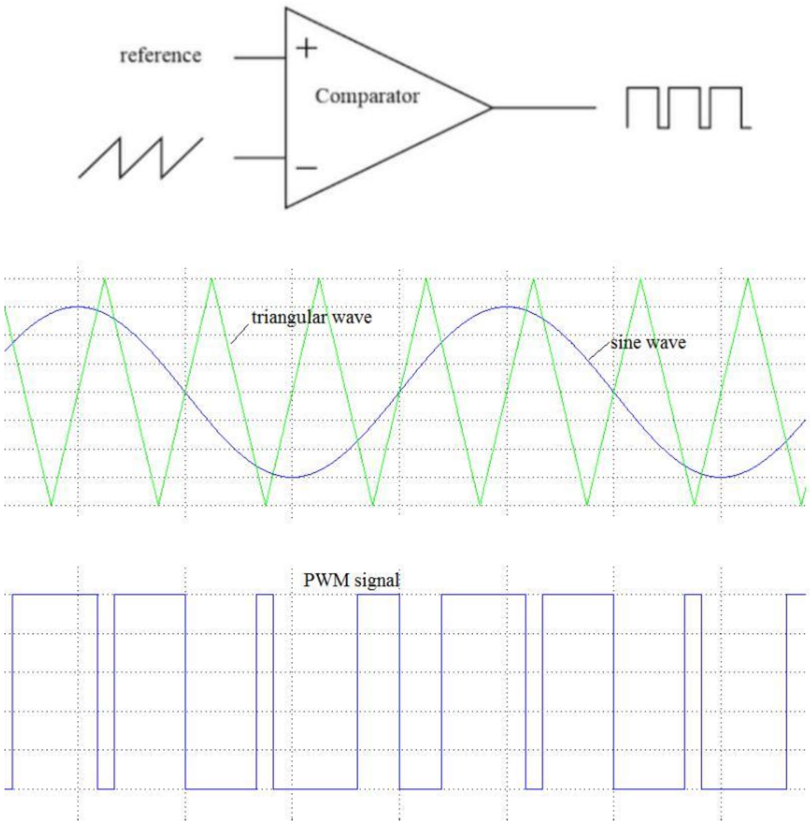


Fig 2.5 PWM technique

To generate the PWM pulse train corresponding to a given signal is the interceptive PWM : the sine wave is compared with a triangular wave, when the latter is less than the former , the PWM signal is in high state(1), otherwise it is in the low state (0).

2.4 PROPORTIONAL INTEGRAL (PI) CONTROLLER:

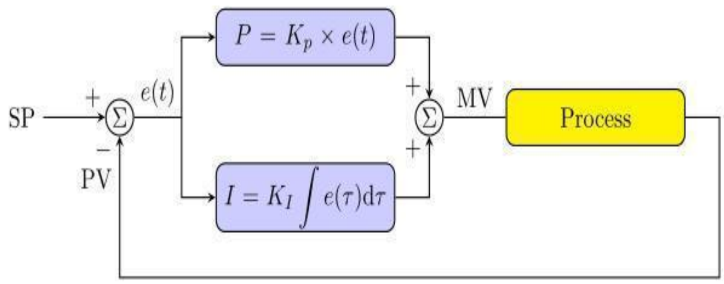


Fig: 2.6 PI controller block diagram

Proportional integral control is a type of linear feedback control system in which a correction is applied to the controlled variable which is proportional and integral to the difference between the desired value and the measured value.

The output of a proportional controller is given as

$$P_{out} = K_p\, e(t) + K_I \int e(t)dt$$

Advantages:

- Desired value can be achieved accurately.
- Ease to apply for fast response process as well as process in which load change is large and frequent.
- Removes steady state error.

Disadvantages:

- The speed of response of system becomes sluggish due to the additional of integral term.
- During start-up of a batch process, the integral action causes an overshoot.
- Since PI controller doesn't have the ability to predict the future errors of the system, therefore it cannot eliminate steady state oscillations and reduces settling time. Hence, overall stability system is comparatively low.

2.5 SUPER CAPACITOR:

A supercapacitor is a high capacity capacitor with a capacitance value much higher than other capacitors, but with lower voltage limits, that bridges the gap between electrolytic capacitors and rechargeable batteries. It typically stores 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerates many more charge and discharge cycles than rechargeable batteries.

Supercapacitors are used in applications requiring many rapid charge/discharge cycles, rather than long term compact energy storage in automobiles, buses, trains, cranes and elevators, where they are used for regenerative braking.

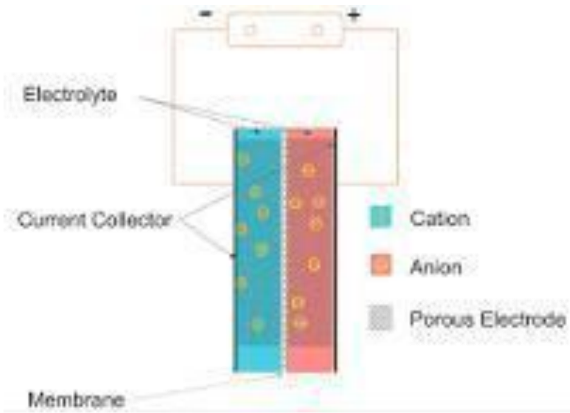


Fig: 2.7 Supercapacitor

Supercapacitor consists of two electrodes separated by an ion-permeable membrane and an electrolyte ionically connecting both electrodes. When the electrodes are polarized by an applied voltage, ions in the electrolyte from electric double layers of opposite polarity to the electrode's polarity. For example, positively polarized electrodes will have a layer of negative ions at the electrode/electrolyte interface along with a charge-balancing layer of positive ions absorbing on to the negative layer. The opposite is true for the negatively polarized electrode.

CHAPTER 3

CONTROL METHODOLOGY OF DC-DC CONVERTER

Boost converter structure is simple: only one power switch. The theoretical duty cycle of the power switch can be adjusted from 0 to 1, so the voltage gain can be infinite. However, due to the presence of parasitic elements in the circuit, the voltage gain is limited. In addition, the voltage stress of the power switch is as large as the output voltage, and this demands a high-voltage-rated power switch when the output voltage is high.

In view of the problems described, many solutions have been presented to this challenge:

A hybrid boost three-level dc–dc converter with a high-voltage gain was proposed as a power interface between the low-voltage photovoltaic (PV) arrays and the high-voltage dc bus for the PV generation system to reduce the voltage stress and match the voltage levels. Although the desirable voltage stress and the voltage gain are obtained, the noncommon grounds appear between the input and output sides, which may limit its applications.

A dc–dc converter with a high-voltage gain and reduced switch stress was proposed for fuel system in, but a complex three-winding coupled inductor is needed, and the switch surge voltage may be caused due to the leakage inductor.

Based on diode–capacitor voltage multipliers, a dc–dc converter can obtain a high-voltage gain and reduced voltage stress. However, a decrease in the output voltage will be caused due to the presence of the internal voltage drop, when the number of the multipliers increases.

In another way, Z-source and quasi-Z-source networks have been employed with the boost dc–dc converters, and the voltage gain of these converters can be increased up to $1/(1 - 2d)$, where d is the duty cycle of the power switch. However, a limitation in the voltage gain of these converters with Z-source and quasi-Z-source networks has been found in high-voltage-gain applications.

In order to improve the voltage gain and reduce the voltage stress across the power semiconductors for the step-up dc–dc converter, two quasi-Z-source converters are combined with the structure of input-parallel and output-series and simplified as shown in figure.

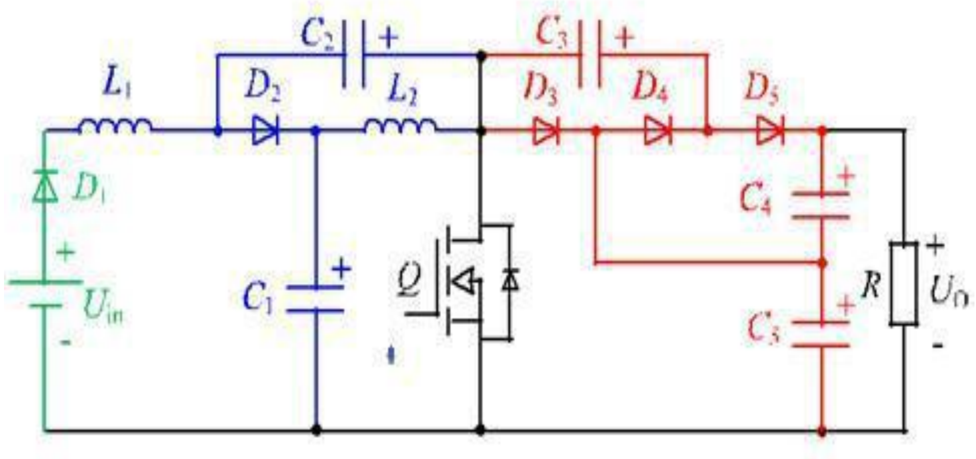


Fig.3.1: Proposed converter

The input voltage source of the converter is comprised of the fuel cell voltage source U_{in} and the reversed blocking diode D_1. The quasi-Z-source network is comprised of "$L_1 - D_2 - L_2 - C_1 - C_2$," and the switched-capacitor network is comprised of $C_3 - D_4$, $C_4 - D_5$, and $C_5 - D_3$.

According to the switching states of the power switch Q, there are two states for the proposed converter: $S = 1$ and $S = 0$ (assuming that T is the switching period, d is the duty cycle of the power switch Q, and $d \times T$ is the interval of $S = 1$). The following figure shows the current flow of the proposed converter in the two switching states.

3.1 ANALYSIS OF OPERATING STATES:

1) When switch is ON (S = 1):

The equivalent circuit of the proposed converter in the switching state $S = 1$ is shown in Fig. 3.2(a). According to the key operating waveforms of the proposed converter shown in Fig. 3.3, Q is turned ON, while diodes D_2, D_3, and D_5 are turned OFF. The input voltage source U_{in} and the capacitor C_2 transfer energy to the inductor L_1 through the diode D_1 and the power switch Q. C_1 transfers the energy to L_2 through Q. Capacitor C_5 transfers energy to C_3 through D_4 and Q, meanwhile C_5 and C_4 in series provide the energy for the load.

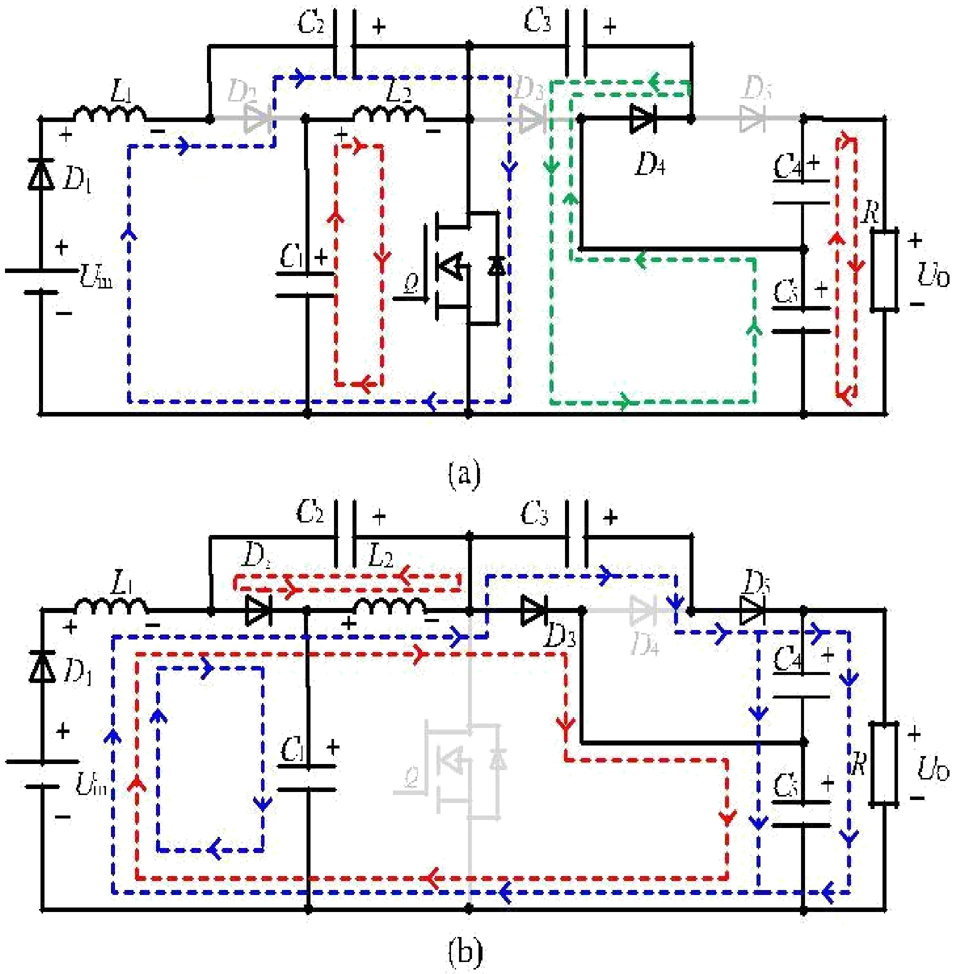


Fig: .3.2. Two operating states of the proposed converter. (a) S=1, (b) S=0.

2) When switch is OFF (S = 0):

The equivalent circuit of the proposed converter in the switching state $S = 0$ is shown in Fig. 3.2(b). According to the key operating waveforms of the proposed converter shown in Fig. 3.3, Q is turned OFF, while D_2, D_3, and D_5 are turned ON. U_{in} and L_1 transfer energy to C_1 through D_1 and D_2. L_2 transfers energy to C_2 through D_2. U_{in}, L_1, and L_2 transfer energy to C_5 through D_1, D_2, and D_3. At the same time, U_{in}, L_1, L_2, and C_3 in series transfer energy to C_4 and C_5 in series and the load, through D_1, D_2, and D_5.

The operating waveforms of the proposed converter over a switching period are shown below

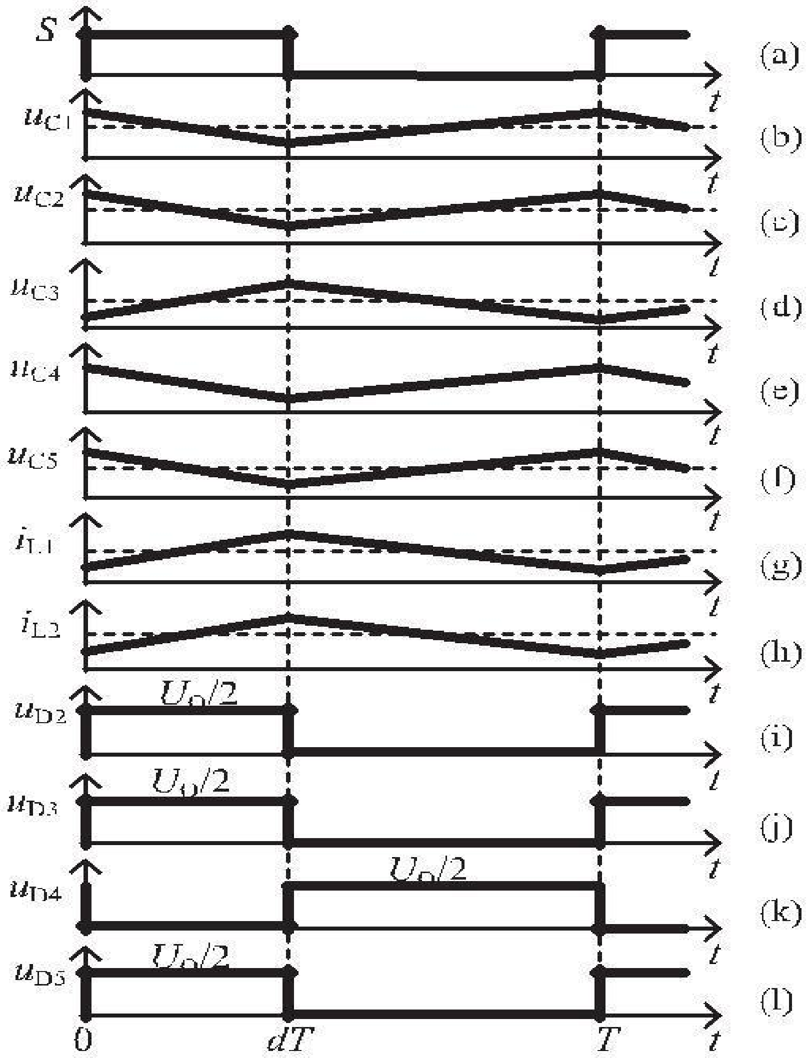


Fig: 3.3 Waveforms of various components of the converter

3.2 VOLTAGE GAIN:

It is assumed that the forward voltage drops and the on-state resistance of all power semiconductors and the parasitic parameters is ignored, and the capacitance of capacitors and the inductance of inductors in the topology are large enough. The capacitor voltages across C_1, C_2, C_3, C_4, and C_5 are U_{C1}, U_{C2}, U_{C3}, U_{C4}, and U_{C5}, respectively, the inductor voltages across L_1 and L_2 are U_{L1on} and U_{L2on} when the power switch Q is turned ON, and the inductor voltages across L_1 and L2 are U_{L1off} and U_{L2off} when Q is turned OFF.

By applying Kirchhoff's voltage laws to Fig. 3.2(a) and (b), the following equations can be derived for $S = 1$ and $S = 0$, respectively.

S=1:

$$\begin{aligned} U_{L1on} &= U_{in} + U_{C2} \\ U_{L2on} &= U_{C2} \\ U_{C3} &= U_{C5} \\ U_{0} &= U_{C4} + U_{C5} \end{aligned} \tag{1}$$

S=0:

$$\begin{aligned} U_{L1off} &= U_{in} - U_{C1} \\ U_{L1off} &= U_{in} - U_{0} + U_{C2} + U_{C3} \\ U_{L2off} &= -U_{C2} \\ U_{C3} &= U_{C4} \end{aligned} \tag{2}$$

By applying the voltage-second balance principle to the inductors L_1 and L_2 in the current continuous mode

$$\begin{aligned} U_{L1on} \times d\,T + U_{L1off} \times (1-d)\,T = 0 \\ U_{L2on} \times d\,T + U_{L2off} \times (1-d)\,T = 0. \end{aligned} \tag{3}$$

From (1) – (3), (4) can be obtained as

$$\begin{aligned} U_{C1} &= \frac{1-d}{1-2d} U_{in} \\ U_{C2} &= \frac{d}{1-2d} U_{in} \\ U_{C3} &= U_{C4} = U_{C5} = U_o/2 \\ U_{0} &= \frac{2}{1-2d} U_{in} \end{aligned} \tag{4}$$

Thus, the voltage gain M of the proposed converter can be expressed as

$$\mathbf{M=\frac{2}{(1-2d)}}$$

Where 0<d<0.5

3.3 ANALYSIS OF VOLTAGE STRESS:

3.3.1 Voltage Stress Across Capacitors:

The capacitor voltages can be expressed as (6) in terms of (4):

$$U_{C1} = \frac{1-d}{2} U_o$$
$$U_{C2} = \frac{d}{2} U_o \qquad (6)$$
$$U_{C3} = U_{C4} = U_{C5} = U_0/2$$

In terms of (6) , the sum of the voltage stresses across C_1 and C_2 is $U_0/2$, and the voltage C_2 stresses across $C_3 – C_5$ are all $U_0/2$.

3.3.2 Voltage Stress Across Power Semiconductors:

According to Fig. 3.2(a), when Q is turned ON, D_2, D_3, and D_5 are turned OFF. The reverse voltage across D_2 is equal to the sum of the voltages across C_1 and C_2, which is $U_O/2$. The reverse voltage across D_3 is equal to the voltage across C_5, which is also $U_O/2$. The reverse voltage across D_5 is equal to the voltage across C_4, namely $U_O/2$. As seen in Fig. 3.2(b), when the power switch Q is turned OFF, D_4 is turned OFF. The voltage across Q is equal to the voltage across C_5, which is $U_O/2$. The reverse voltage across D_4 is equal to the voltage across C_3, which is $U_O/2$ too. In addition, (7) can be written as

$$U_{C3} = U_{C1} + U_{C2} \qquad (7)$$

By means of (7), the capacitor voltage U_{C5} across C_5 directly depends on the sum of U_{C1} and U_{C2}, which is clamped at $U_O/2$, as well as the capacitor voltages across C_3 and C_4. So, the voltages across the output capacitors C_4 and C_5 have the characteristic of self-balance.

From the analysis above, the voltage stress across all power semiconductors (except D_1, which is still turned ON) in the proposed topology is half the output voltage. This feature is beneficial to reduce the conduction losses by selecting low-rated-voltage power semiconductors, which have lower on-state resistance or lower forward voltage drops.

3.3.3 Analysis of Current stress:

The output load current is I_o, the average inductor currents of the inductors L_1 and L_2, are I_{L1} and I_{L2}, respectively. The average currents through capacitors C_1, C_2, C_3, C_4, and C_5 are I_{C1on}, I_{C2on}, I_{C3on}, I_{C4on} and I_{C5on}, when the power switch Q is turned ON, and I_{C1off}, I_{C2off}, I_{C3off}, I_{C4off} and I_{C5off} respectively, when Q is turned OFF. Then (8) and (9) can be obtained as follows:

S=1:

$$\begin{aligned} I_{C1on} &= -I_{L2} \\ I_{C2on} &= -I_{L1} \\ I_{C4on} &= -I_0 \\ I_{C5on} &= -(-I_{C4on} + I_{C3on}) \end{aligned} \tag{8}$$

S=0:

$$\begin{aligned} I_{C1off} &= I_{C2off} + I_{L1} - I_{L2} \\ I_{C3off} &= -I_{C4off} - I_{out} \\ I_{C5off} &= I_{L1} - I_{out} - I_{C1off} \end{aligned} \tag{9}$$

By applying the ampere–second balance principle to capacitors C1, C2, C3, C4, and C5 in the continuous-current mode, (10) can be obtained as

$$\begin{aligned} I_{C1on} \times dT + I_{C1off} \times (1-d)T = 0 \\ I_{C2on} \times dT + I_{C2off} \times (1-d)T = 0 \\ I_{C3on} \times dT + I_{C3off} \times (1-d)T = 0 \\ I_{C4on} \times dT + I_{C4off} \times (1-d)T = 0 \\ I_{C5on} \times dT + I_{C5off} \times (1-d)T = 0 \end{aligned} \tag{10}$$

Assuming that the input power is equal to the output power, i.e., $U_{in} \times I_{in} = U_O \times I_o$. By means of (5), the relationship between the output load current I_o and the average input current I_{in} can be written as

$$\mathbf{I_{in} = \frac{2}{(1-2d)} I_0} \tag{11}$$

In terms of (8)–(11), the average inductor currents and the average capacitor currents can be derived as

$$\mathbf{I_{L1} = I_{L2} = I_{in} = \frac{2}{(1\text{-}2d)} I_{on}}$$

3.4 COMPONENT PARAMETER DESIGN:

The voltage loop control scheme for the pro-posed converter can be obtained as shown in Fig. 3.5. G_{uod} (s) is the transfer function of the converter, $G_c(s)$ is the voltage controller (i.e., a PI controller) transfer function, shown in below, and $H(s)$ is the feedback transfer function. Therefore, the voltage controller can be designed for the proposed converter to achieve the static and dynamic performances.

$$G_c(s) = K_p + K_i\,(1/s)$$

Where $K_p = 0.0001$, and $K_i = 0.0005$, which are used in the experiments.

Table 1 Parameters of the proposed converter

PARAMETERS	VALUES (units)
Input DC voltage Uin	40-150 V
Output DC voltage Uo	400 V
Inductor L1	323 uH
Inductor L2	318 uH
Capacitor C1	529 uF
Capacitor C2	780 uF
Capacitors C3, C4 and C5	520 uF
Rated power Pn	400 W
Load resistor RL	400 ohms
Switching frequency fs	20kHZ

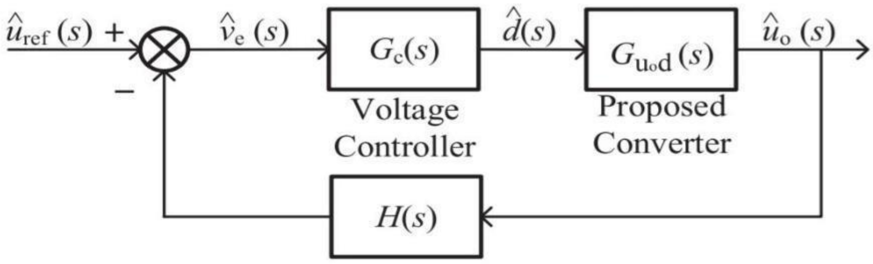


Fig: 3.4. Voltage-loop control scheme of the proposed converter

3.5 APPLICATION OF THE CONVERTER FOR FUEL CELL VEHICLE

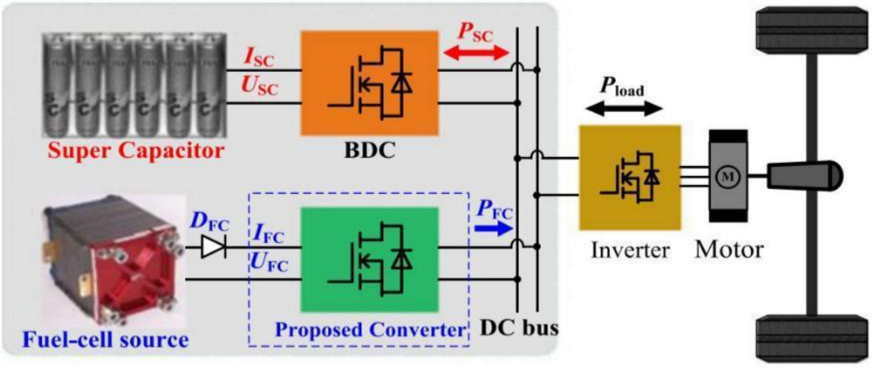


Fig: 3.5 Fuel cell vehicles with the proposed converter.

The energy sources of fuel cell vehicles can be comprised of a fuel cell source and supercapacitor or battery stacks, and the power train of fuel cell vehicles with the proposed converter is shown in Fig. 3.5. In order to decouple the power controls of the hybrid energy sources, dc–dc converters are required for the power interfaces of fuel cell vehicles, as well as the common dc bus, with which the hybrid energy sources can be connected in parallel to provide the proper required powers for the motor, respectively.

As a result, the fuel cell source of the vehicle only needs to provide the average power for the motor without a quick response. The supercapacitor or battery packs can output the required high-frequency power for the motor or absorb the controllable regenerative power from the motor. In addition, the terminal voltage of the fuel cell source varies widely when its output current is within a wide range according to the motor load, and a wide voltage-gain range of a power converter is also required for the fuel cell source.

As shown in Fig.3.5, the proposed dc–dc converter with a high-voltage gain is interfaced between the low-voltage fuel cell source and the high-voltage dc bus. The fuel cell source provides the average power P_{FC} for the dc bus by the proposed converter, boosting the low voltage of fuel cell source to the high dc bus voltage. When the fuel cell vehicle is accelerating, the supercapacitor stacks supply the instantaneous power required from the dc bus by the bidirectional dc–dc converter, due to the slow dynamic response characteristics of the fuel cell source (i.e., the fuel cell output current I_{FC}). Then, I_{FC} increases slowly and the output voltage U_{FC} of the fuel cell source decreases in a wide variation. During this process, the proposed converter steps up the variable fuel cell voltage to the constant high dc bus voltage. When the fuel cell vehicle decelerates or brakes, the regenerative energy is absorbed completely by the supercapacitor stacks, and the fuel cell source decreases its output power, i.e., reducing I_{FC}. At the same time, the proposed converter drops its voltage gain to remain the constant dc bus voltage, according to the increasing U_{FC}. When the fuel cell vehicle runs smoothly, the fuel cell source provides the stable energy for the inverter by the proposed converter with the corresponding voltage gain, and charges the supercapacitor stacks if it is needed.

CHAPTER 4

SIMULATION AND RESULTS

Before the use of converter in fuel cell application, let us have a look about the working of converter with and without control loop. The input dc voltage of the converter is controlled with a timer ranging between 40-150V and the switching frequency of the switch is 2kHZ.

4.1 Open loop control of the converter:

The converter is controlled in open loop control as shown below. The duty cycle of the converter is 0.2.

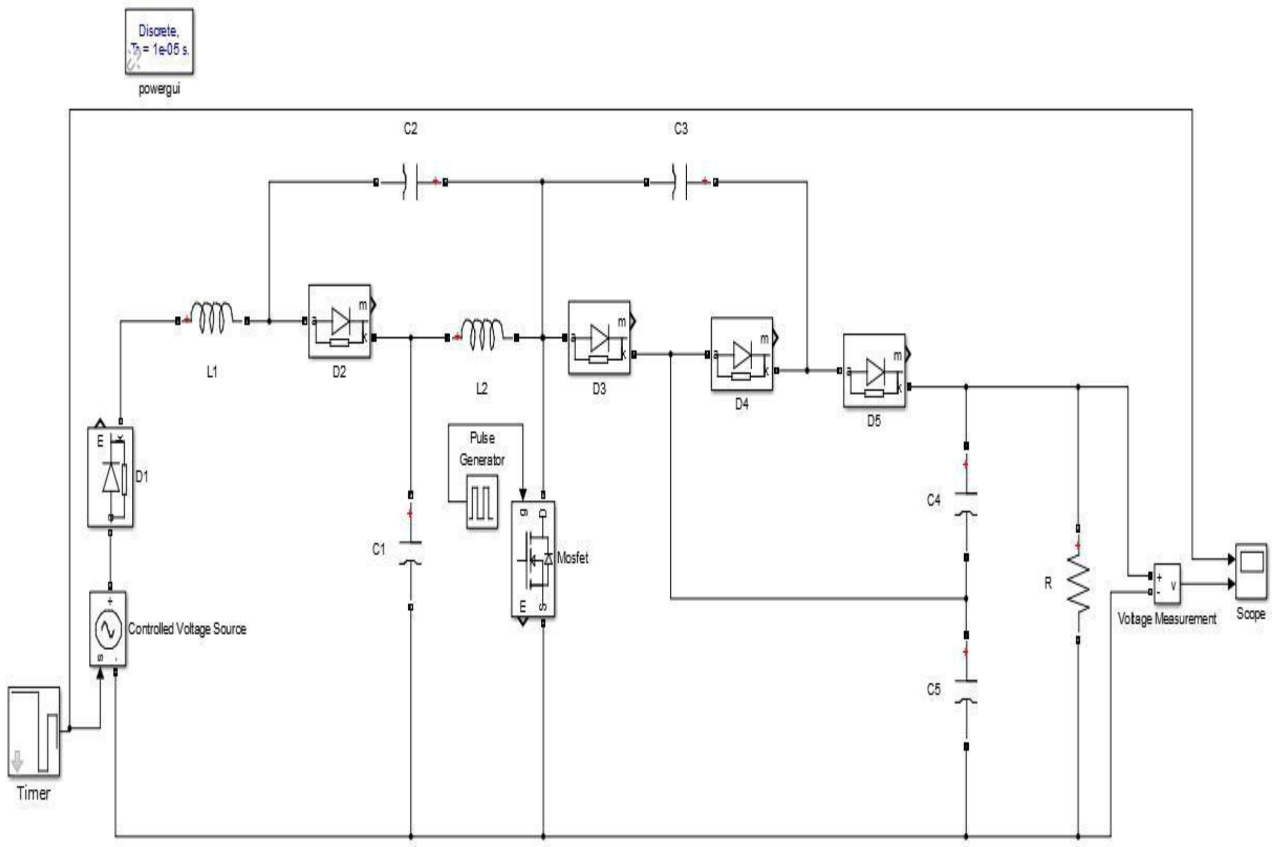


Fig 4.1 Simulation diagram of open loop control of the converter

The simulation results of input and output voltages of the converter are shown below:

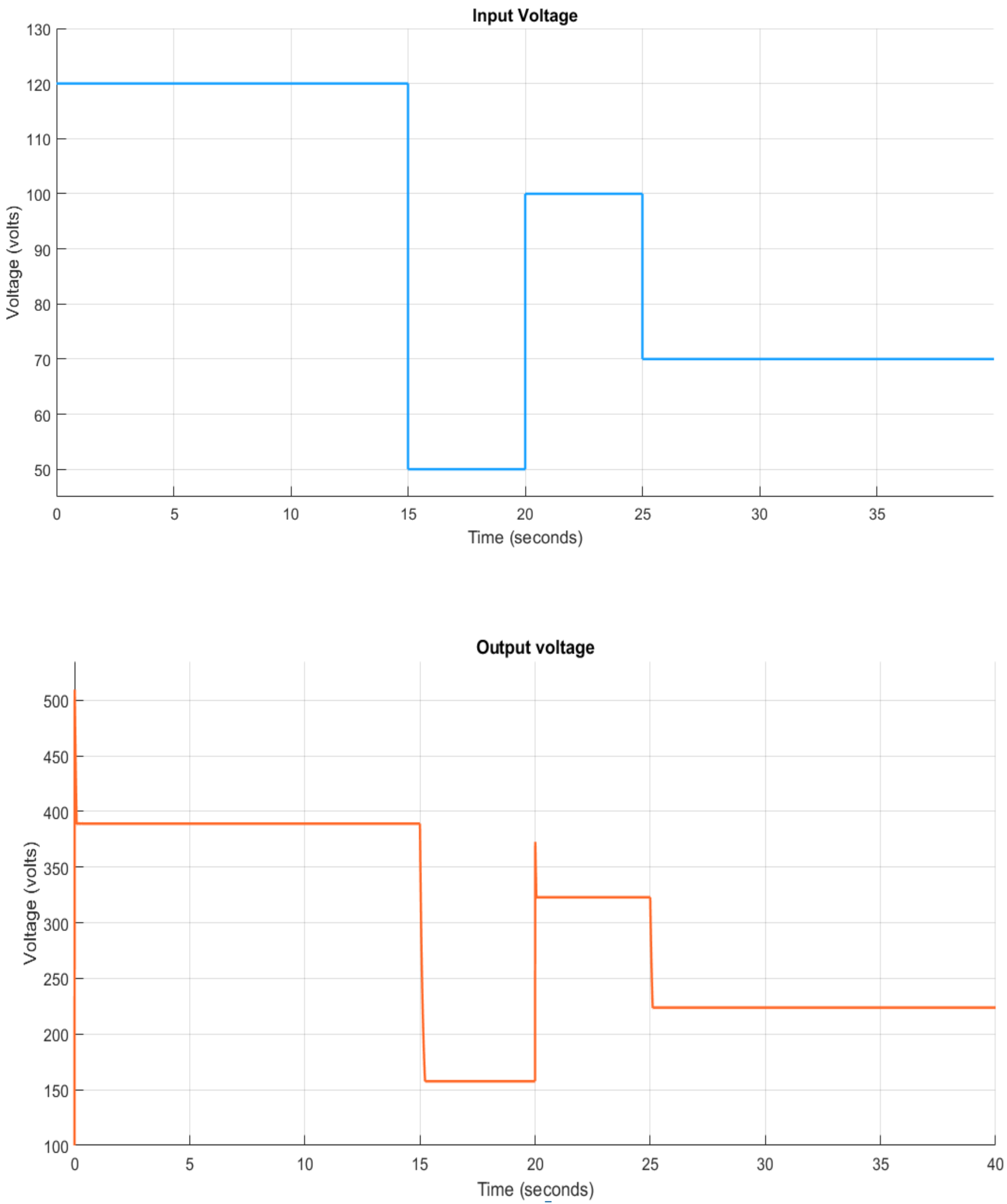


Fig: 4.2 simulation results of input and output voltages of open loop control of the converter

From the above results, it is inferred that the output voltage varies accordingly with the input voltage.

The input voltage is maintained at 120v for 15 seconds and the output voltage is nearly 400v.

<u>Theoretical calculation:</u>

$$\text{Output voltage} = \frac{2}{(1-2d)} U_{in}$$

$$\frac{2}{1-2(0.2)} * 120$$

$$= 400 \text{ V}$$

Later, the voltage is maintained at 50 v and the output voltage is 160 v.

<u>Theoretical calculation:</u>

$$\text{Output voltage} = \frac{2}{(1-2d)} Uin$$

$$\frac{2}{1-2(0.2)} * 50 = 166\text{V}$$

Voltage maintained at 100v gives 333 volts output.

Voltage maintained at 70v gives 233.3 volts output.

4.2 Closed loop control of the converter:

The converter is controlled by closed loop control as shown below. The controller scheme used here is PI controller. The Kp and Ki values of the PI controller are 0.0001 and 0.0005 respectively. The input voltage of the converter is varied between 40 to 150 volts.

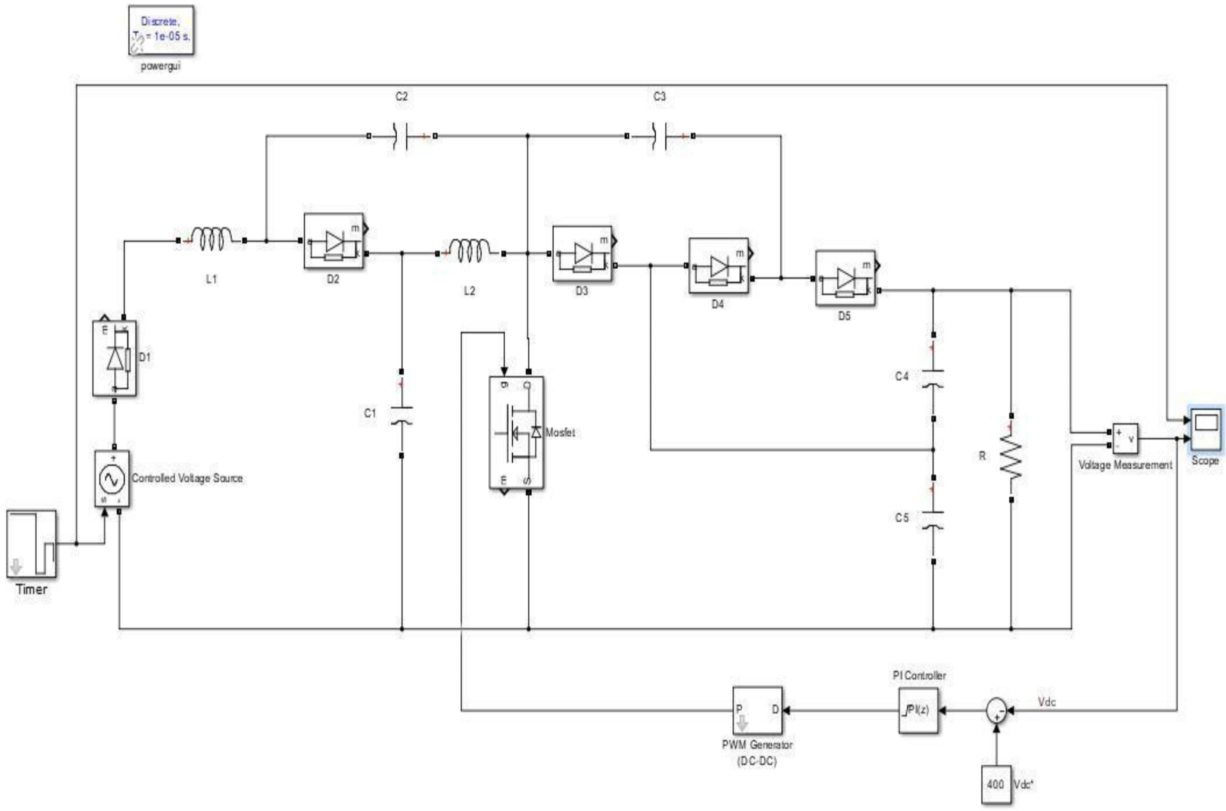
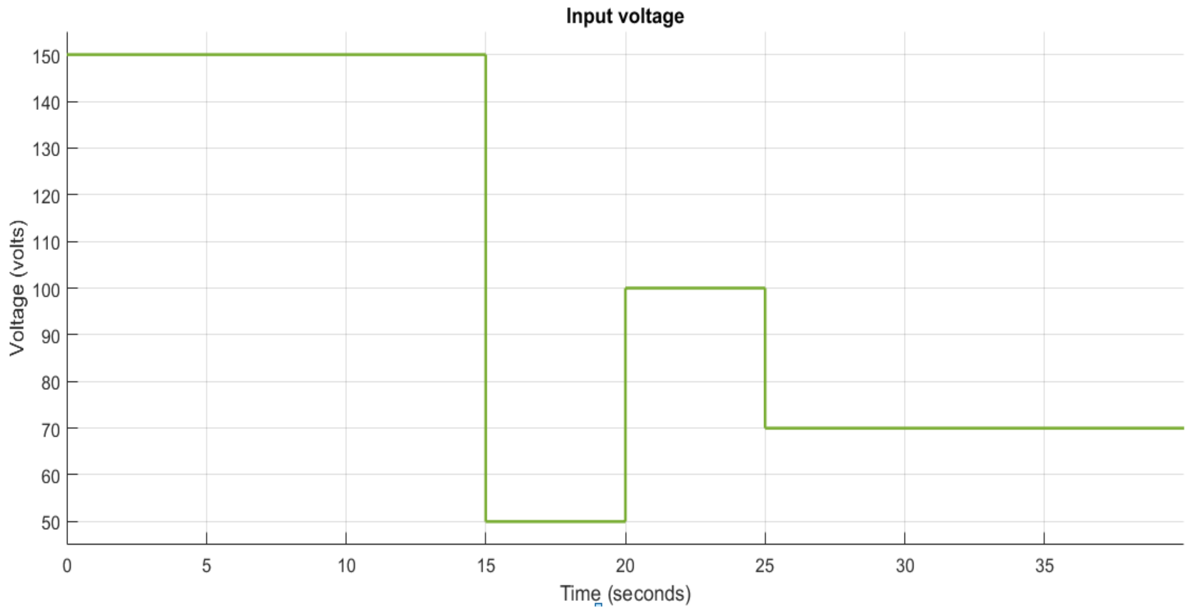


Fig 4.3 Simulation diagram of closed loop control of the converter

Here the output voltage is constantly compared with a constant value 400 and the error is given to the PI controller. And the error is given to switch through PWM generator. In PWM generator, pulses are generated by constantly comparing the error signal with sawtooth signal.

The simulation results of the converter in closed loop control are shown below:



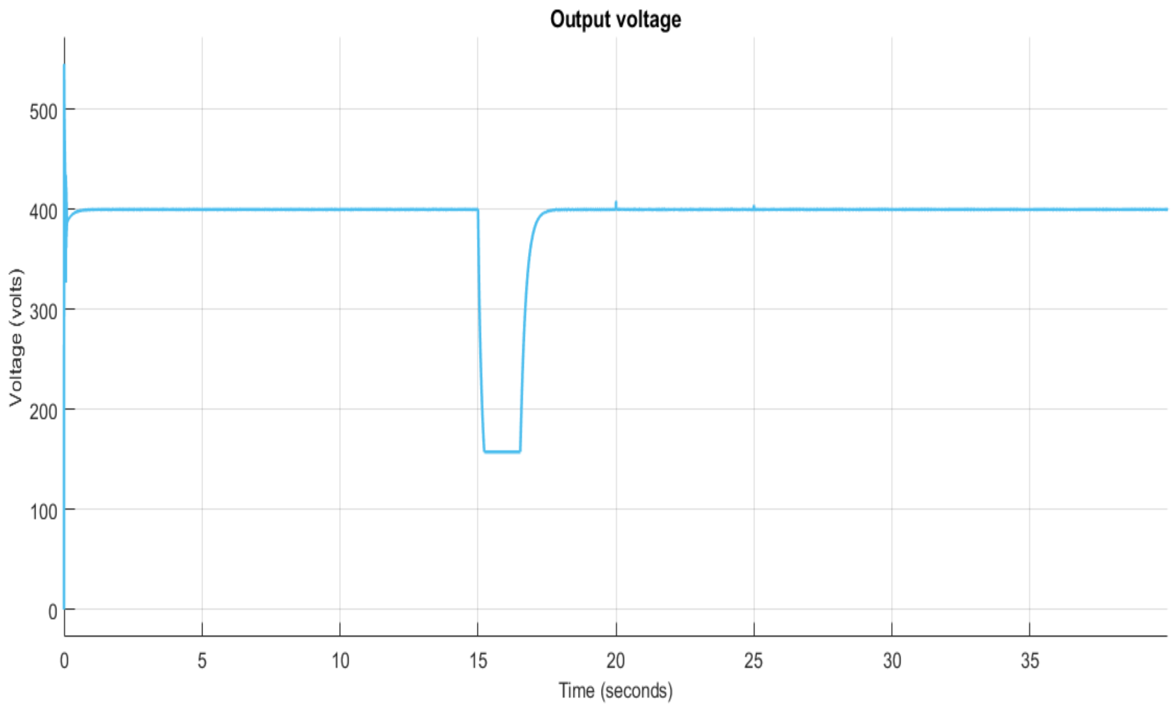


Fig 4.4 Simulation results of input and output voltages of closed loop control of the converter.

From the above results, it is inferred that the output voltage of the converter is constantly maintained at 400V irrespective of the input voltage.

4.3 Theoretical calculations :

The voltage stress of the capacitors and diodes are clamped to half of the output voltage and validated through plots. Here the converter is connected to the input dc voltage of 100V, switching frequency is 2 kHz and the duty cycle of the switch is 0.25.

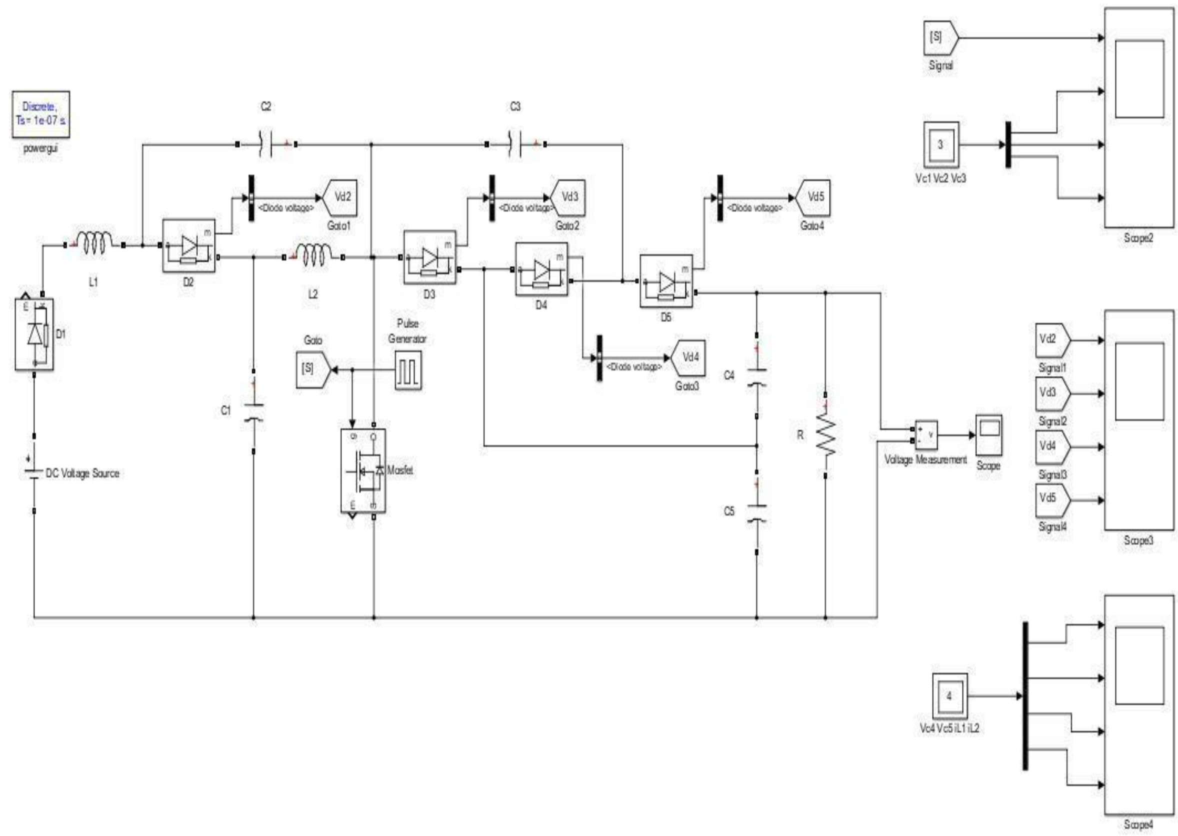
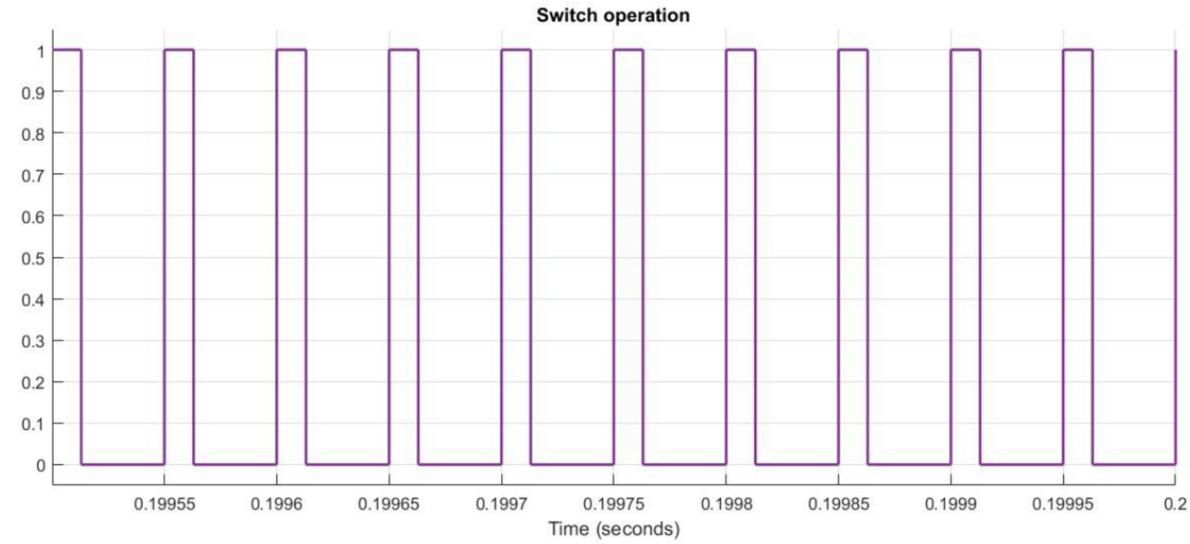
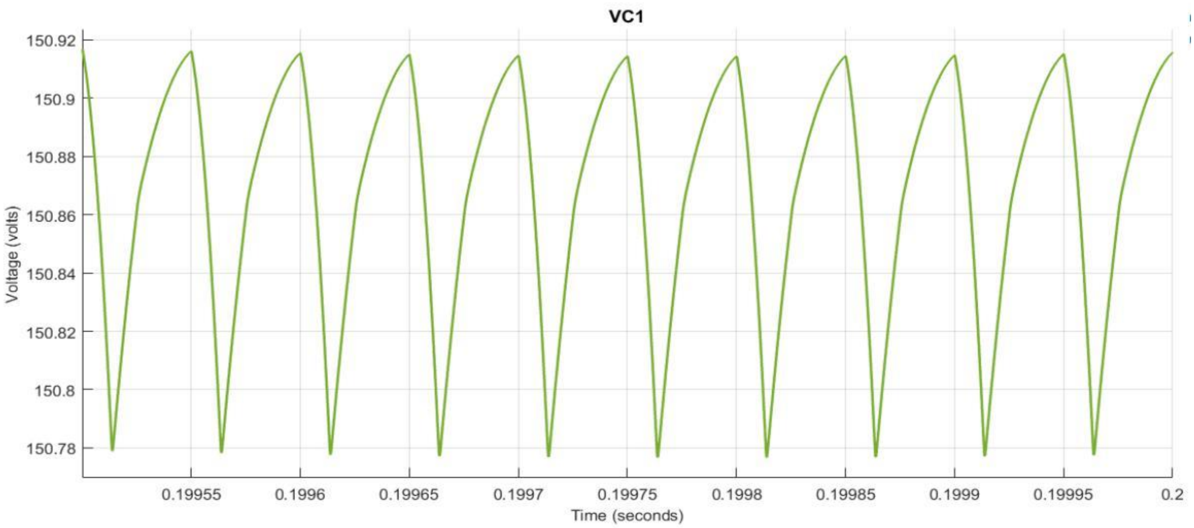


Fig 4.5 Simulation diagram of open loop control of the converter.

The voltages across the capacitor and the currents through the inductor are shown below and observed that theoretical values and practical values are approximately equal.

The input pulse given to switch is shown below. As the duty cycle is 0.25, only 25% of the pulse is high.



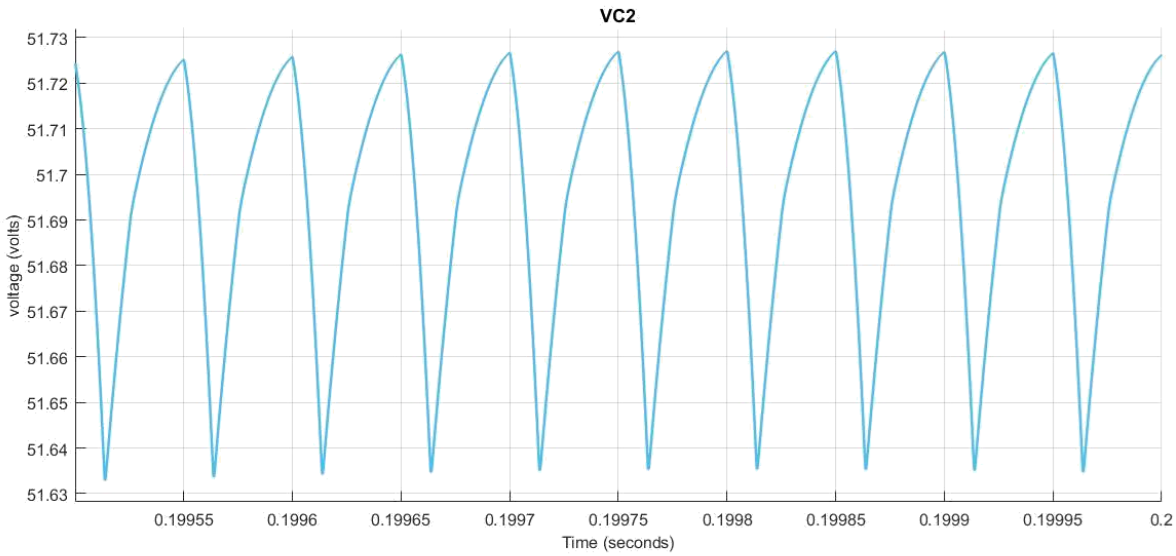


From equation (6)

Voltage across C_1 (U_{C1}) = $\frac{(1-d)}{2}$ U_0

$$= \frac{0.75}{2}*400$$

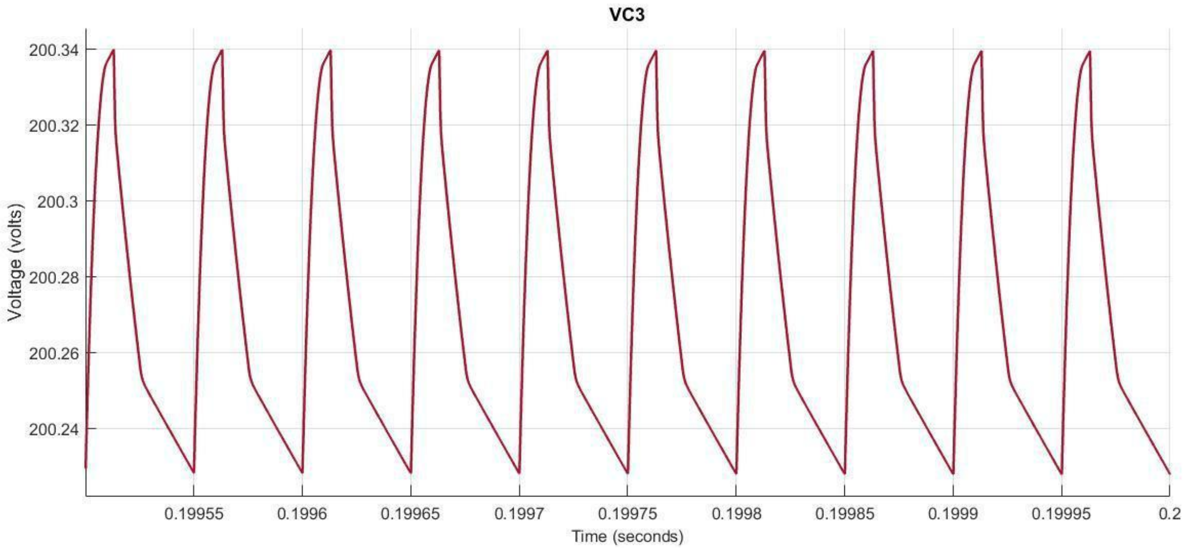
$$= =150V$$



Voltage across C_2 (U_{C2}) $=(d/2) * U_0$

$= (0.25/2) * 400$

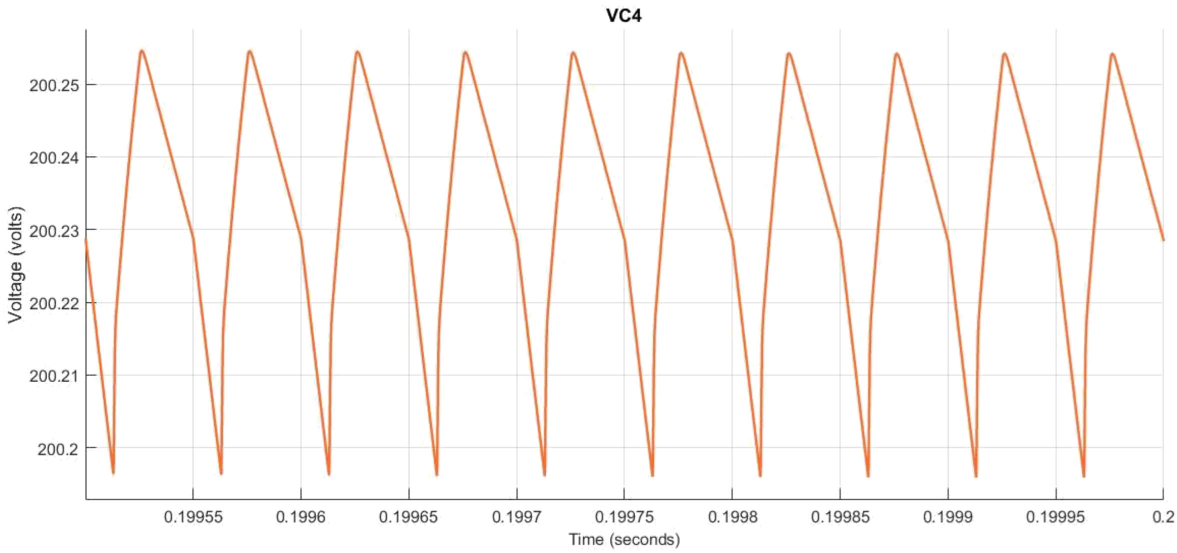
$= 50V$



Voltage across C_3 (U_{C3}) $= U_0 /2$

$= 400/2$

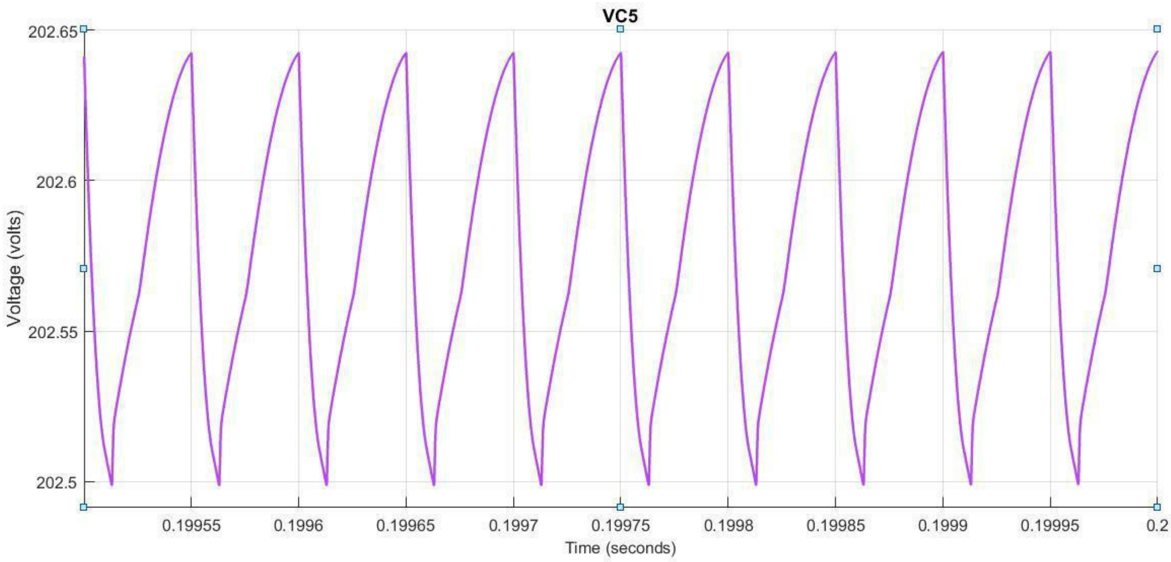
$= 200V$



Voltage across C_4 (U_{C4}) = U_0 /2

= 400/2

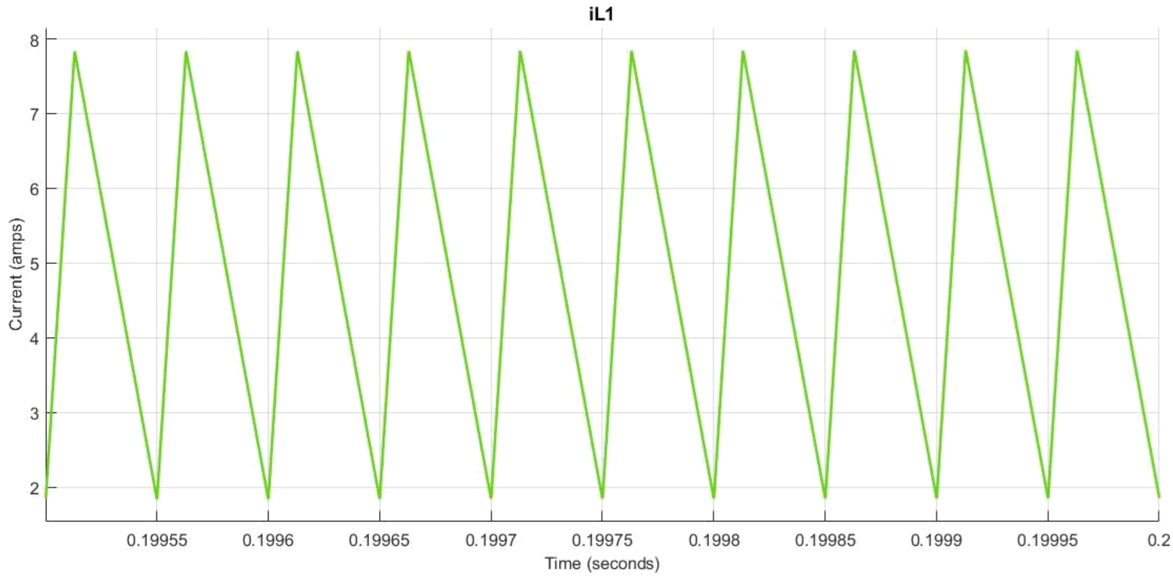
= 200V



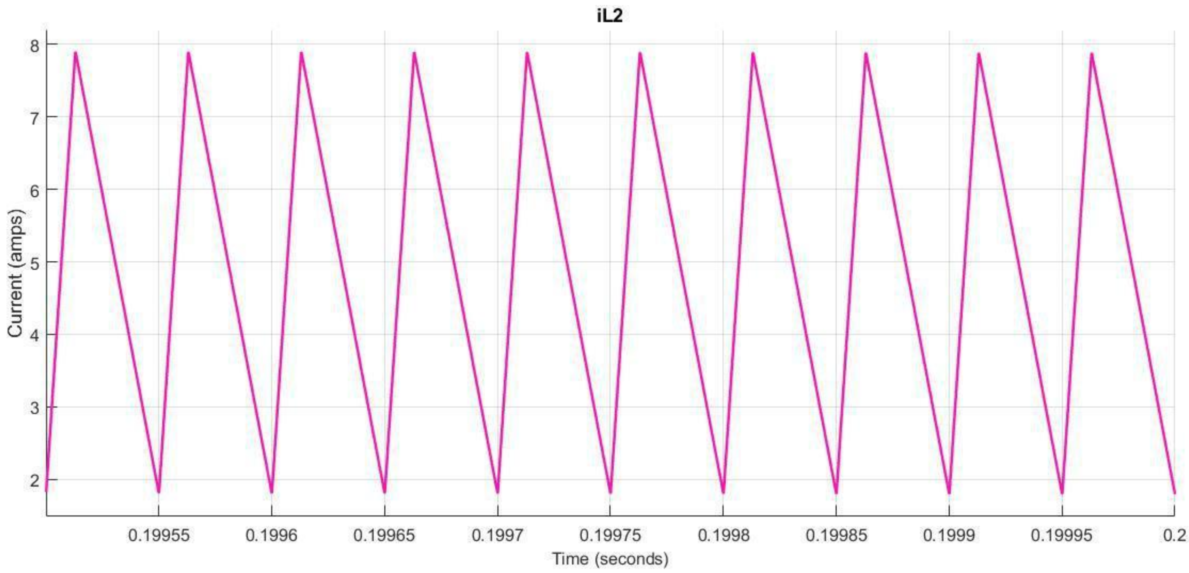
Voltage across C_5 (U_{C5}) = U_0 /2

= 400/2

= 200V



Current through inductor L_1 = 4amps

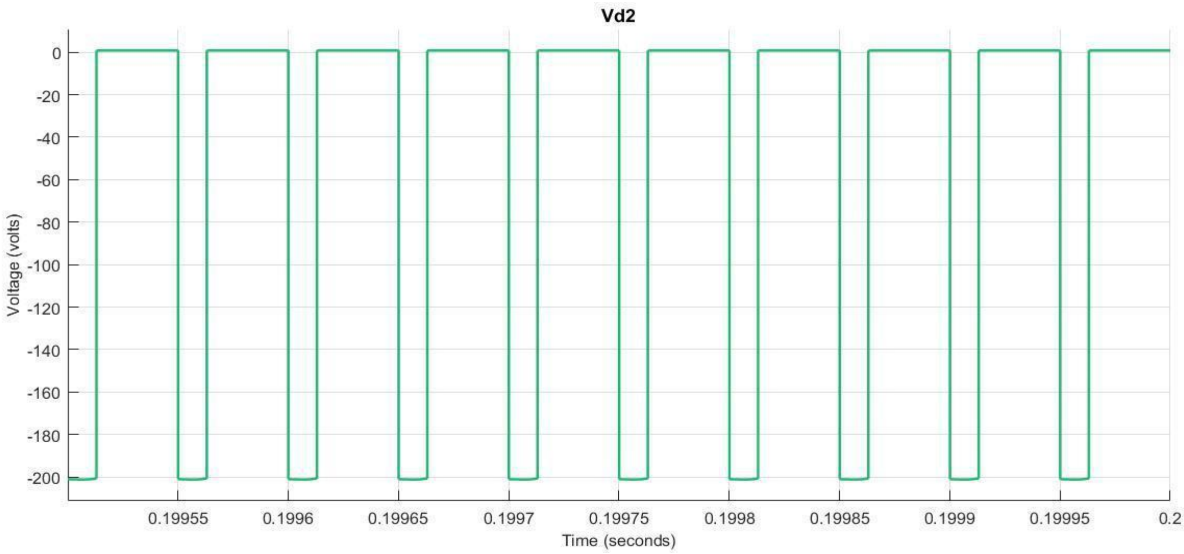


Current through inductor L_2 = 4 amps

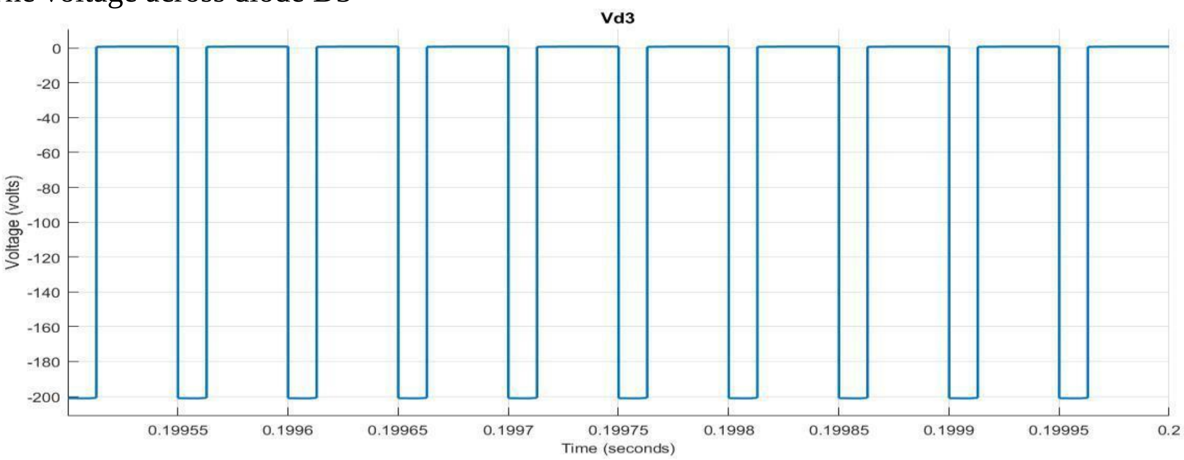
Fig : 4.6 Simulation results of capacitor voltages and inductor currents

The voltages across the diodes are shown below. It is observed that the voltages are clamped to the half of the output voltage (i.e. 200V).

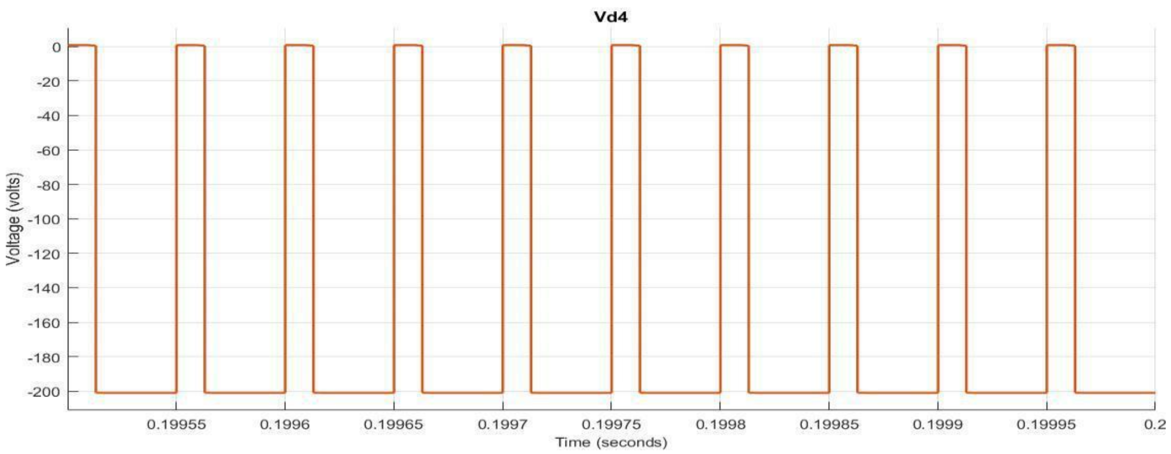
The voltage across diode D2



The voltage across diode D3



The voltage across diode D4



The voltage across diode D5

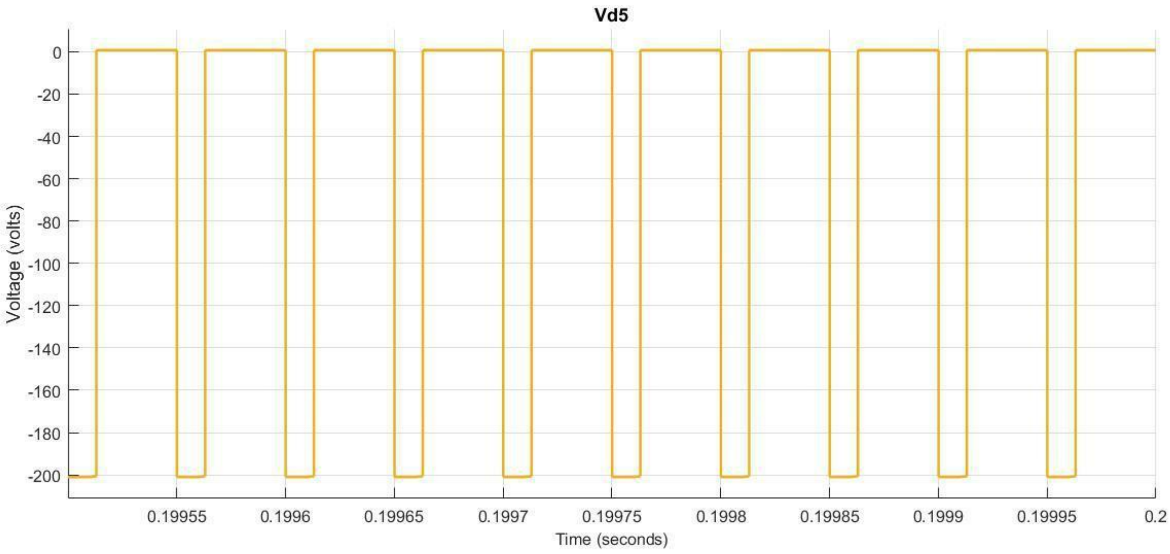


Fig : 4.7 Simulation results of Diode voltages

4.4 Closed loop of the converter used to run an induction motor:

The converter is used in fuel cell applications as shown below. The converter is placed between the low voltage fuel cell and high voltage DC link bus. The closed loop controlled converter is fed to induction motor through inverter. The inverter converts the DC output of converter into AC voltage.

Motor specifications: 400V, 4kW, 1430 rpm, 50 hertz.

Here three phase bridge configured inverter is used. PWM generator is used to give pulses to the switches of inverter.

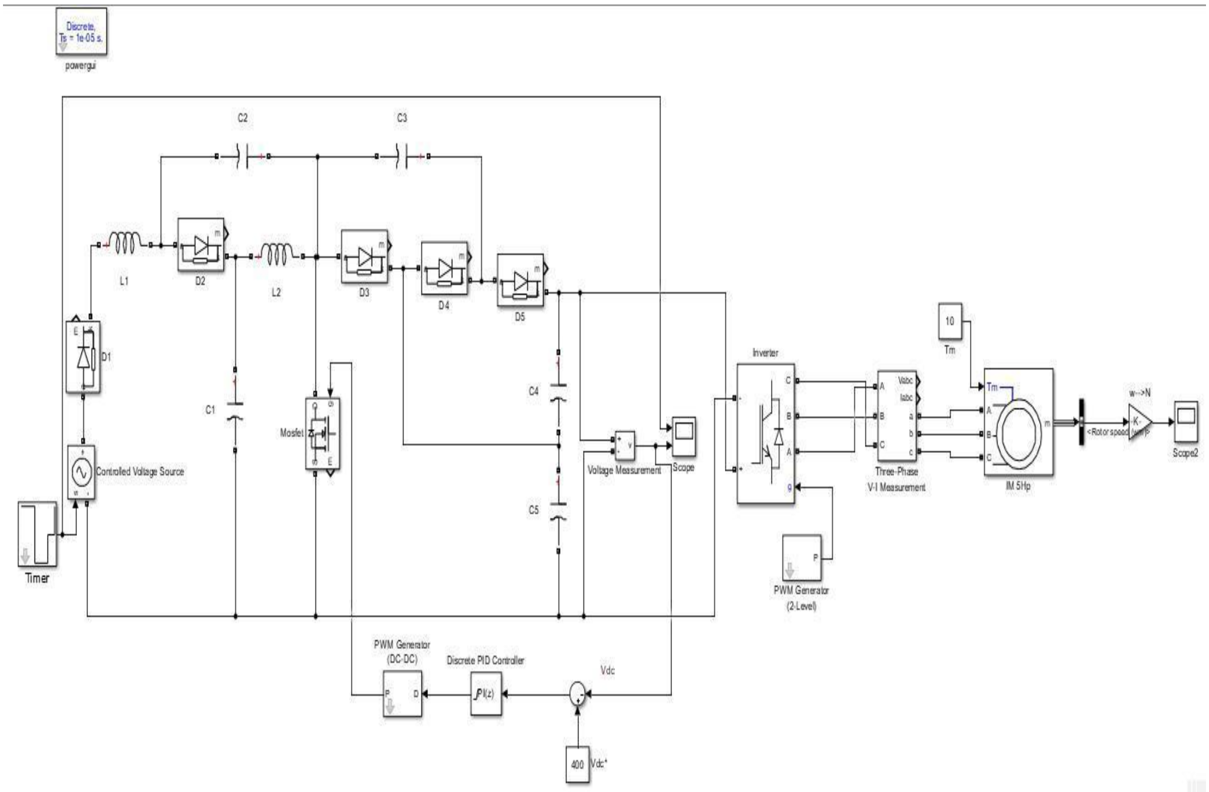
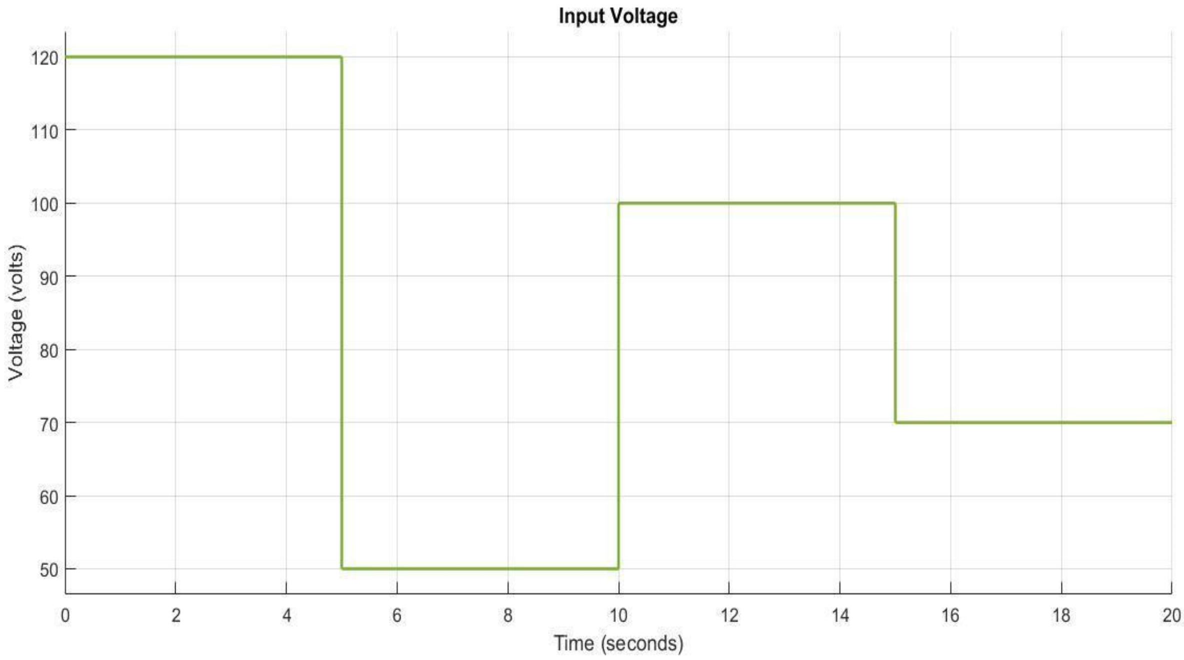


Fig : 4.8 Simulation diagram of converter in fuel cell applications.

The input voltage of a converter is shown below.



The output voltage of the converter is shown below.

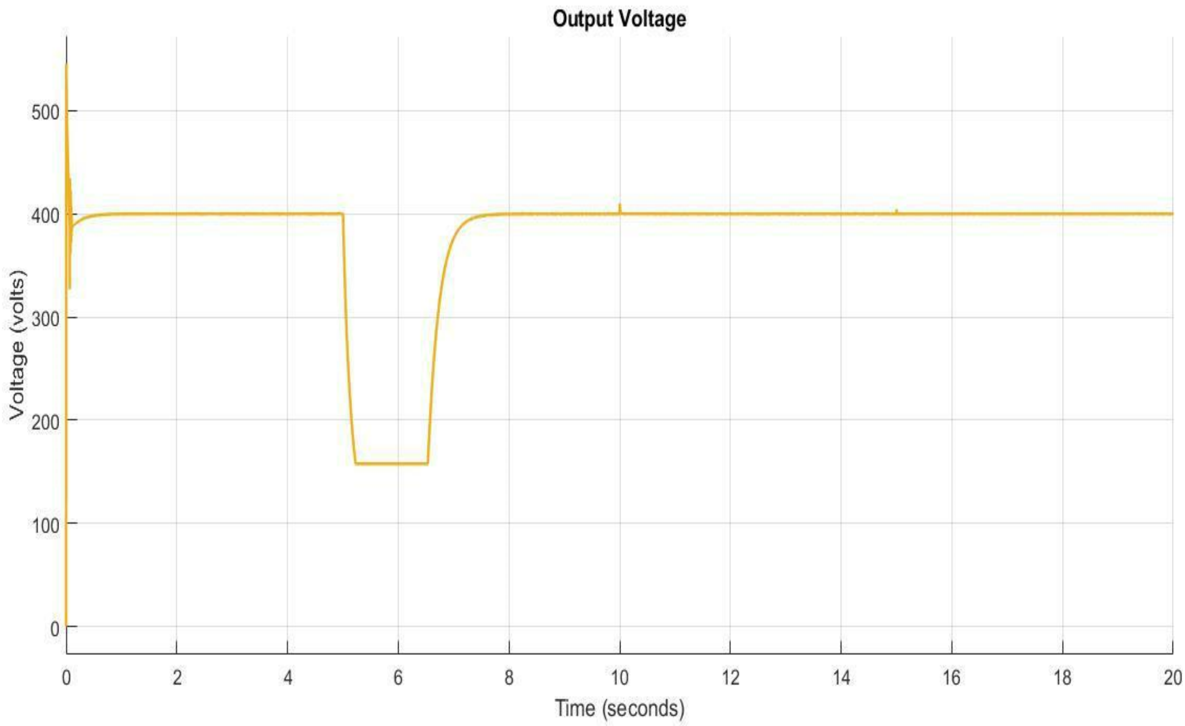


Fig : 4.9 Simulation results of input and output voltages of the converter in fuel cell applications.

We observed that when there is a large voltage difference at the input of converter, there is drop in output voltage of the converter for few seconds.

The speed Vs time characteristics of motor are shown below.

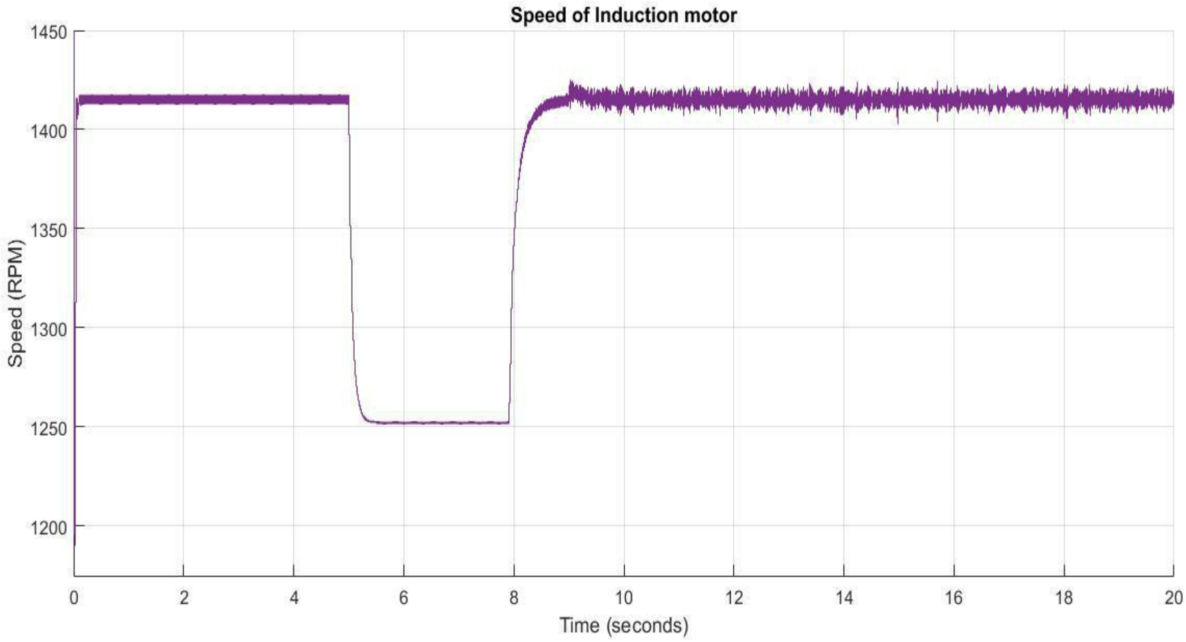


Fig : 4.10 Simulation results of speed of induction motor in fuel cell applications.

It is observed that the voltage is not maintained at 400v for few seconds, and the speed is dropped from rated 1430 rpm to 1420 rpm for a period which is not preferable.

So we have to maintain the output voltage of the converter at 400V. So the additional voltage is to be supplied from a different source. Here Super-capacitor is used.

4.5 Closed loop of the converter to run an induction motor along with Super-Capacitor:

The converter in fuel cell applications is shown below. Converter is placed between low voltage fuel cell source and high voltage DC link bus. Super capacitor is added in parallel to the DC link. It is connected to the DC link bus through a bi-directional dc-dc converter. It is used to supply the power to the DC link when the input voltage is unable to meet the demand.

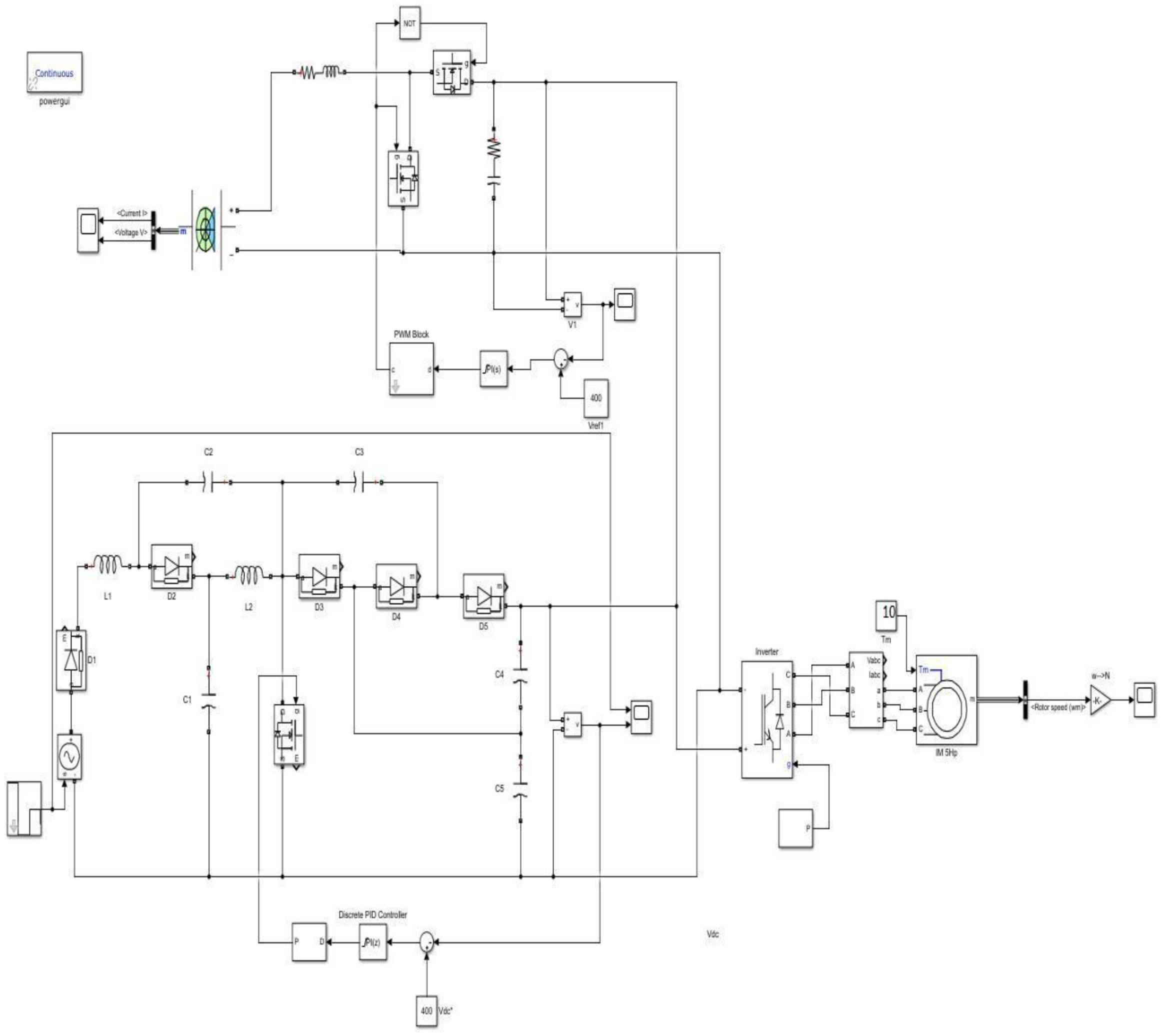


Fig 4.11 Simulation diagram of the converter in fuel cell application along with supercapacitor.

Supercapacitor cannot directly inject the power into the grid so the converter is used to link the DC link. Inductor is connected in series with Supercapacitor to filter current ripples.

The following figure shows the complete circuit diagram of Supercapacitor energy storage system.

In this two IGBT switches are used. The shunt connected IGBT will act as boost mode switch and series connected will act as buck mode switch. This circuit will operate in four modes. When the DC link voltage is above the reference voltage super capacitor will be charged in buck mode and when DC voltage is below the reference voltage Supercapacitor will discharge in boost mode.

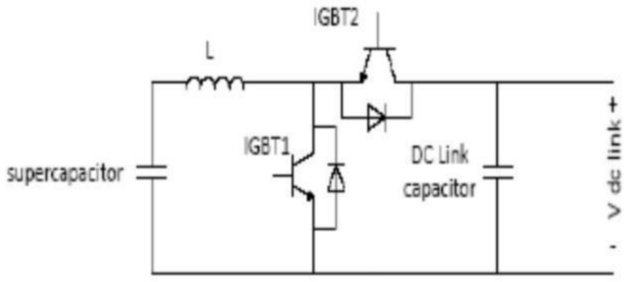
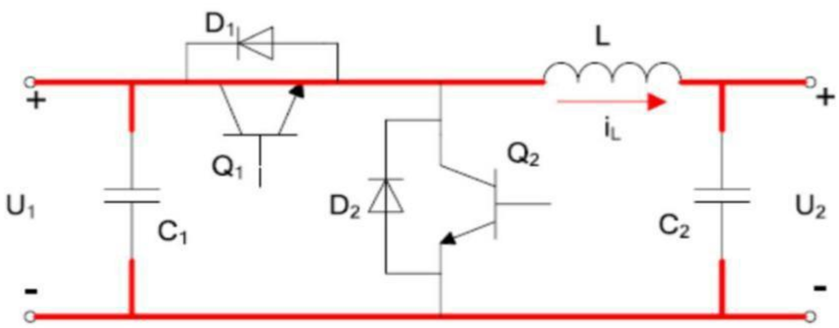


Fig 4.12: Supercapacitor with energy storage system

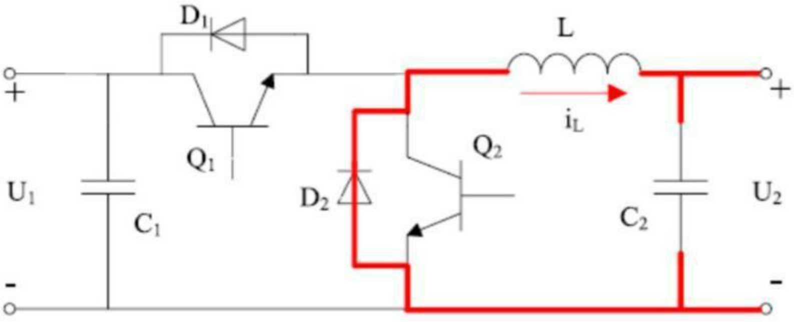
The circuit will operate in four modes:

Mode 1:



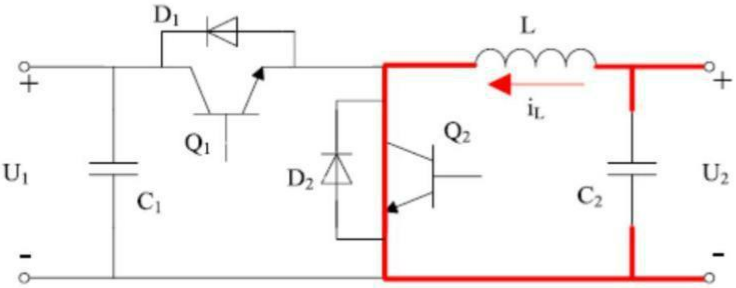
In this mode, Supercapacitor will charge and inductor current increases slowly. Supercapacitor will be charged in buck mode and power flows through Q1.

Mode 2:



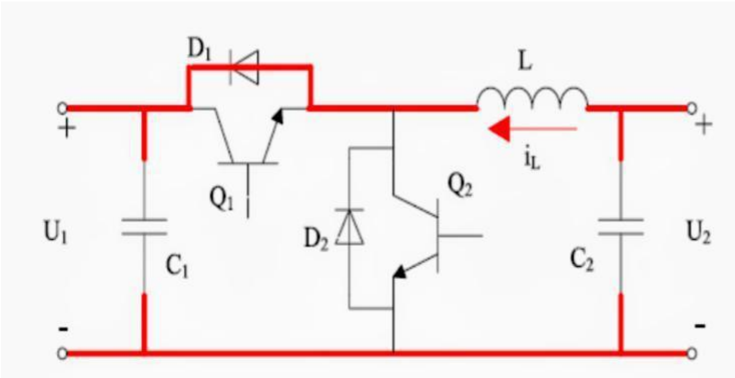
In this mode, inductor current decreases where as Supercapacitor will be getting charged and power flows through D2.

Mode 3:



In this mode, super capacitor will discharge energy to the system in boost mode and power flows through Q2

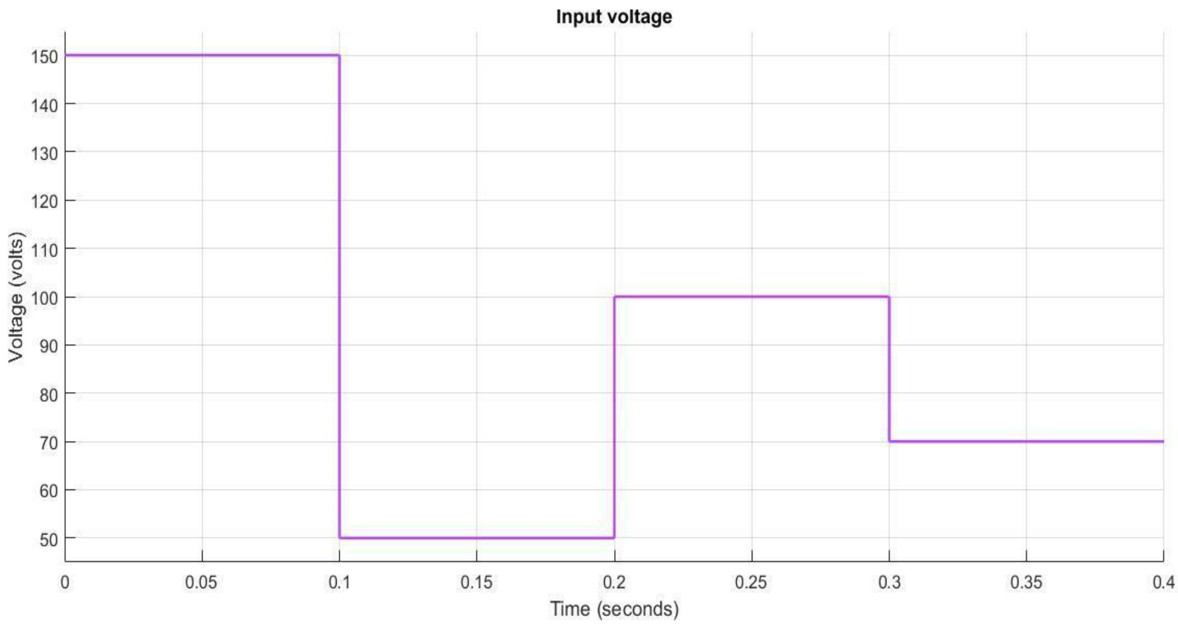
Mode 4:



In this mode, inductor current and Supercapacitor discharge will be delivering to across C1 and power flows through D1.

Fig 4.13: Four modes of supercapacitor energy system storage

The supplied input voltage to the converter is given below



The output voltage at the converter is obtained as below.

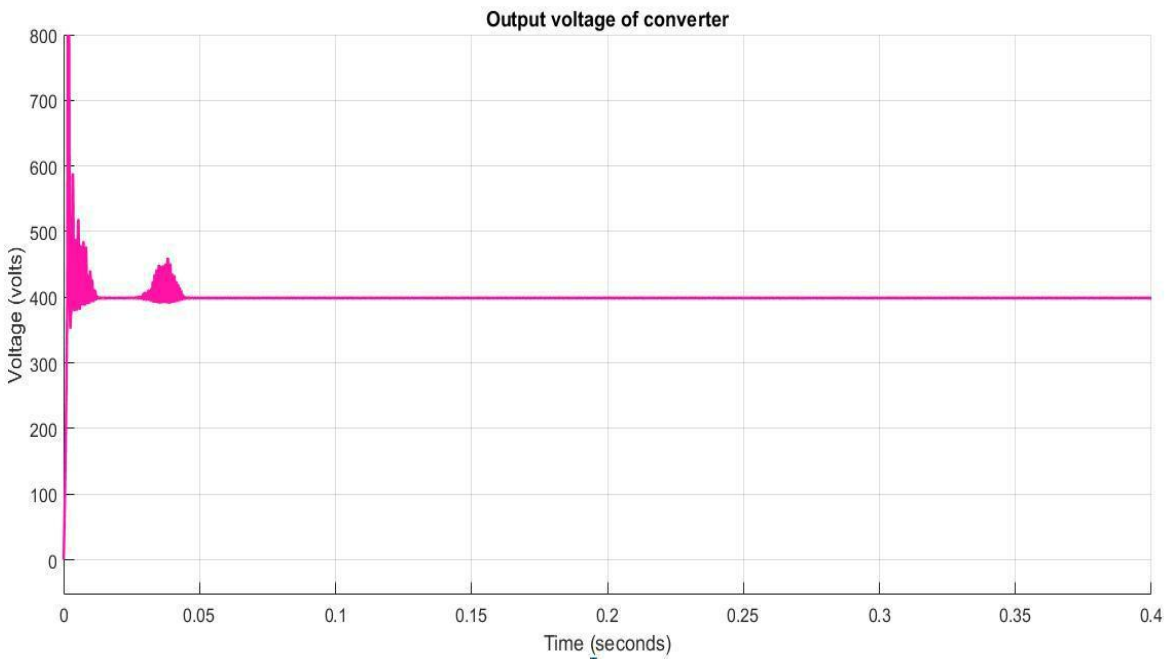


Fig 4.14 Simulation results of input and output voltages of the converter.

And it is clearly observed that the output voltage is maintained at 400V irrespective of change at the input of converter.

The speed of the motor is shown below:

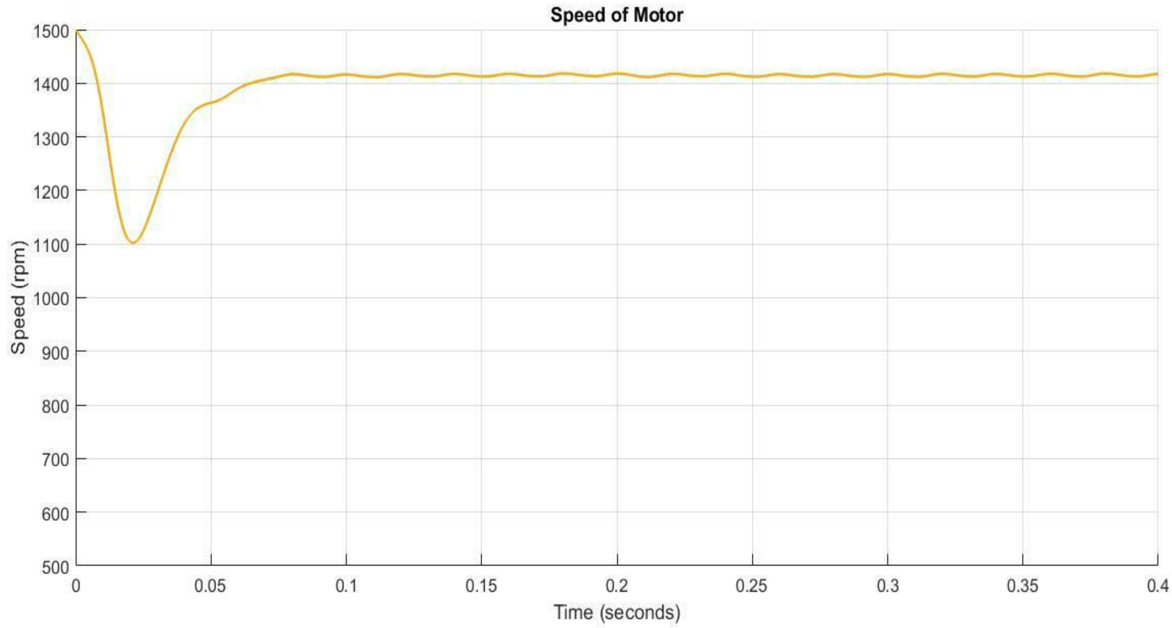
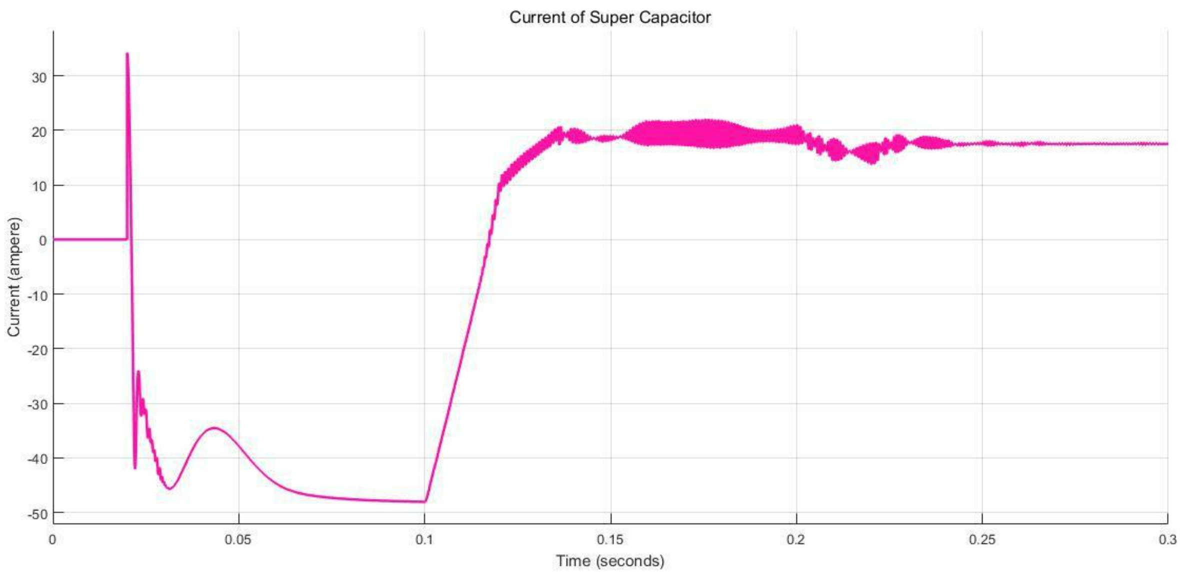


Fig 4.15 Simulation results of speed of induction motor in fuel cell applications.

The speed of the motor is maintained almost near to rated 1430 rpm.

The current, voltage and state of charge of supercapacitor is shown below:



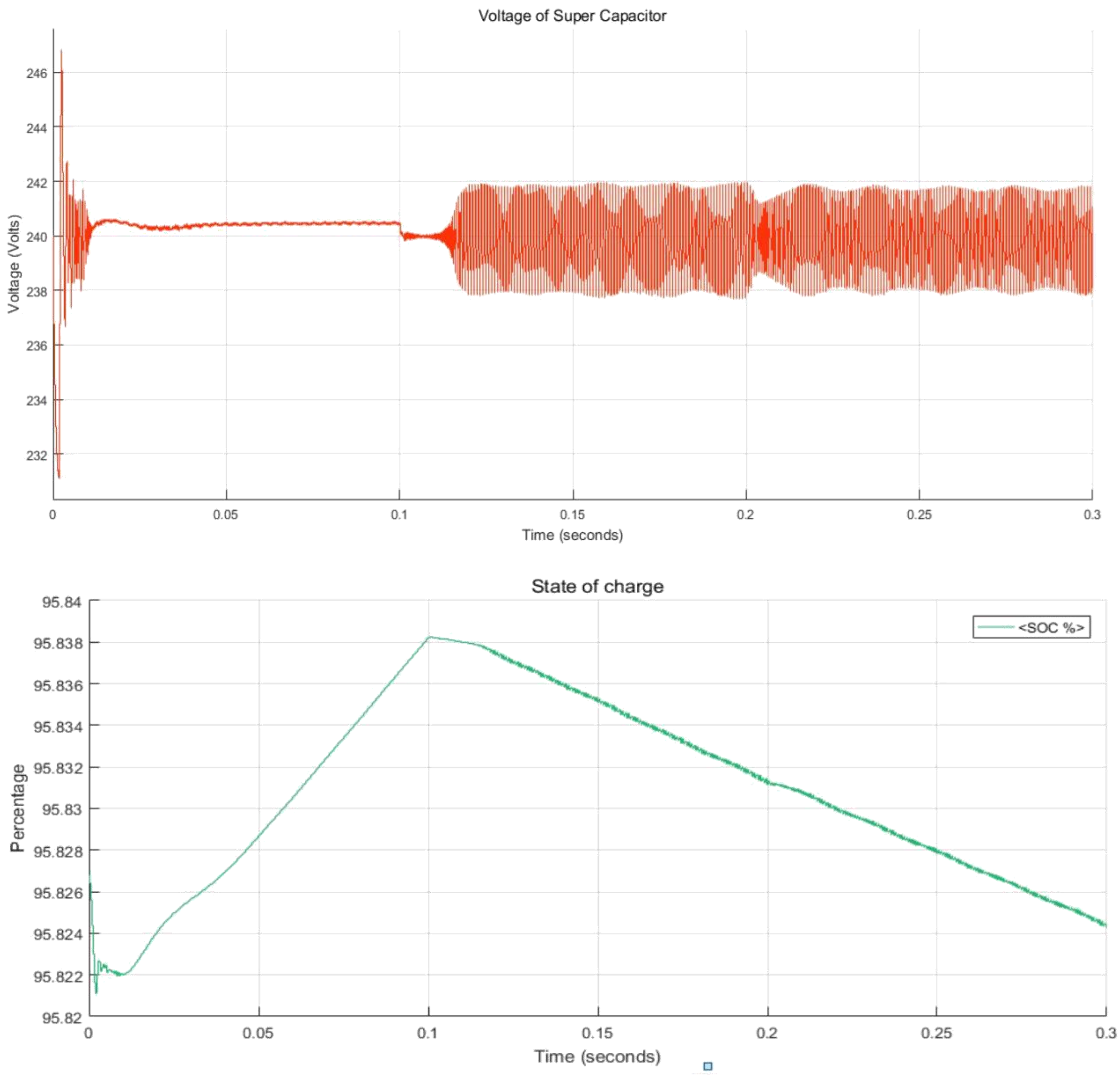


Fig 4.16 Simulation results of current, voltage and SOC of supercapacitor.

CHAPTER 5

CONCLUSIONS

The Quasi-Z-source boost DC-DC converter with a switched capacitor has been developed. The converter has high input voltage range varying 40-150 volts. The voltage stress across the components of Quasi-Z-source boost DC-DC converter is also reduced. Closed loop control is used in order to reduce the output voltage variation with respective to input voltage variation in open loop control. The limitations with PI controller is diminished by Super Capacitor which supplies instantaneous power to the DC link.

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