Z-Source Inverter for Fuel Cell application

A Dissertation submitted in partial fulfillment of the requirements for the award of degree
Of

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In

Power Systems

Submitted by

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DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, **"Z-Source Inverter for Fuel Cell application"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in **Power Systems** submitted to Electrical and Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Santosh Sonar, Assistant Professor, EIED. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

14/7/15

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It is certified that the above statement made by the candidate is true to the best of my knowledge and belief.

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ABSTRACT

The thesis presents the analysis of a single phase and three phase Z-source inverter used for fuel cell applications and its control methods for implementation in dc-to-ac power conversion system is presented.

This thesis brings together the problems in the use of fuel cell as a power source. The basic problem is with the fuel cell is that it give a fixed DC output. So this can't be used for various function like in HEV or other applications. So to overcome this problem Z-source is connected to the full cell. The design of Z-network, single phase and three phase full bridge inverter mathematical modeling is done .The simulation work is carried in MATLAB-Simulink. A fixed DC input voltage (V) is applied across the inverter and a controlled AC output voltage (V) is obtained by varying the duty cycle of the inverter. The duty cycle variation is be achieved by using pulse Width modulation (PWM) control methods. In control strategies Sinusoidal carrier-based PWM and Simple Boost Control method is used. These methods are described in detail and simulation work is presented in support of that. The output voltage and current ripples are controlled by varying the modulation index and switching frequency. The effect of short switched state on the traditional inverter is eliminated in the Z-source inverter. The traditional inverters can be used either as buck or boost converter .This limitation is sorted by the use Z-source inverter. Z-source buck-boost capabilities are verified analytically and simulation results are presented. Different applications are presented for the verification of the modeling and simulated system along with two control strategies. One of the strategies is based on performance and simulation analysis of fuel cell (FC) system. Second application is based on modeling and simulation of Z-source inverter for single phase and three phases to control the speed of Induction Motor.

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LIST OF ABBREVIATIONS

SCR	Silicon Controlled Rectifier
GTO	Gate Turn Off Thyristor
IGBT	Insulated Gate Bipolar Transistor
VSI	Voltage Source Inverter
CSI	Current Source Inverter
ZSI	Impedance Source Inverter
BJT	Bipolar Junction Transistor
ZSC	Impedance Source Converter
IM	Induction Motor
UPS	Uninterruptible Power Supply
NPC	Neutral Point Clamped
SVM	Space Vector Modulation
D	Duty Cycle
THD	Total Harmonic Distortion
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation

CHAPTER 1

INTRODUCTION

1.1 RESEARCH MOTIVATION

The power electronics literature has focused the level and characteristics of the source voltage have been changed using different converter topologies. Each converter topology has its own advantages and disadvantages regarding different aspects like stress on semiconductor switches, number of components used and converter efficiency. Some of these converters have been used in industry for a variety of applications. Today, efficient power conversion is more important than earlier because of the alternative energy sources as fuel cells, ocean wave and wind energy that requires proper power conditioning to adapt to different loads. As hybrid vehicles are very promising new applications of power converters. Also, the area of electrical drives is demanding for new topologies in order to be more efficient and cheaper for converting the form of energy from electrical to mechanical or vice versa. Since reliable, clean and high quality energy is today’s one of the main concerns in the world, power electronics is definitely playing an important role in filling this gap.

As Power electronics is used widely in various applications in the industry. The single / three phase inverter, that converts dc current and dc voltage into single and three phase ac current or voltage. It is used widely in uninterruptible power supplies (UPS), used in ac machine control, grid connected photo voltaic (PV) system, etc. There are two types of traditional inverters, namely voltage source inverter (VSI) and current source inverter (CSI). However, both of these inverters have some conceptual barriers, which are discussed in detail later. So to overcome some of the limitation of the traditional voltage source (VSI) and current source inverters (CSI) a newly Z-source inverter is presented. The purpose of this work is to Model and Simulation of a single/three phase Z-source inverter and its control strategy in implementation dc to ac conversion.

The research motivation for this thesis has also come from the necessity of maximum power point tracking MPPT, for the fuel cell. The Z-source inverter and its control system should be capable of deal with variable load.

So for this power electronics combines digital systems, control theory, semiconductor devices and power systems. Due to this fact any innovation in one of these fields also affects power electronics and opens for new research opportunity. Among all of these fields, control theory is in a close relationship with power electronics. This is because power converters are "variable structure periodic systems" whose states are determined by control signals. In most of applications, converter voltages and currents are to be limited by the maximum values specified by component vendors and to be controlled around a steady state values defined. So this can be done by designing controllers based on true mathematical models. As discussed in the literature many times, power converters can be modeled based on averaging state variables over a switching cycle; hence they are suitably conformed for the application of existing control theories.

1.2 BRIEF LITERATURE REVIEW

1.2.1 LITERATURE REVIEW OF Z-SOURCE

[3] This paper provides the z source converter and the control method for conversions like ac to ac, dc to ac, dc to dc and ac to dc. This converter provides a unique feature that is not in traditional converters. It also overcomes the limitations and problems of other converters. Z-Network is used along with Fuel cell to give the desired output voltage. It reduces the losses and cost and increases the efficiency and reliability of the system.

[4]This paper presents the two technique for the maximum constant boost for the ZSI to get maximum voltage gain for any duty cycle without producing any output ripple. In this paper the relationship between modulation index and voltage gain is explained. Also different control method are compared.

[5]This paper tells about the conventional ZSI connected to resistive load supplied by PV cells. Further, in this paper different type of modulation technique are compared like maximum boost, maximum constant boost and simple boost. Then a control strategy is given like MPPT. The output of MPPT varies the duty cycle of inverter to control the output.

[7]In this paper, a detailed working of ZSI is given. Then a 50 kW fuel cell is connected with ZSI so to demonstrate the validity of design. So to study the eff. Of the network and also thermal and 3-d design is given

[10]This paper presents the study of five different type of modulation control technique. For the study of these technique a ZSI network is connected to resistive load. By comparing all these five techniques a better and effective dc boost with lower ripple can be achieved. By comparing there it is observed that modified space vector modulation gives better results.

[12]This paper offerings the study about the fuel cell connected to micro grid with use of inverter. So that it can be integrated to large power grids. Here controllers are being used to gives a stable supply to the grid.

[13]In this paper a new type of filter are introduced, which can improved the performance of fuel cell (PEM) stack when it is under sudden loads. Because under sudden loads there are transients in the fuel cell output so eff. Of fuel cell will be less. In future different type of electrical motors can be connected to the fuel cell using this technology.

[14]This paper introduced an algorithm based on dc link for effective energy management. In this paper a PMSG based wind energy is converted and then connected to battery or dump loads. A concept a given that maintaining the dc link constant and controlling the duty cycle of PWM inverter. The output voltage can be controlled even when the loads is changed.

[15]This paper tells about ZSI for vehicles. In this paper there are three application of ZSI network for HEV, PHEV and FCHEV. This study of application is done to improve the vehicle efficiency and also to reduce the cost.

[16]This paper states about the methodology for proper model of fuel cell stack with the static and dynamic behavior. It also gives the possible topologies for the dc to dc conversion and control methods for the simulation of fuel cell. This study is done to reduce the losses and increase the efficiency.

[17]This paper presents the study of PEM fuel cell. It show the structure of single cell and also gives the advantages and disadvantages of PEM fuel cell. In this paper the modelling and simulation of a single fuel cell is done to study the efficiency and characteristics of fuel cell.

[18]This paper introduces the modelling and Simulink of ZSI. In this paper it tell the unique feature of ZSI to buck and boost. This feature is unique in ZSI which is not seen in other traditional inverters. It gives a detailed information about the design of ZSI network and the control method of PWM techniques.

[20]This paper offers the study for the fuel cell power plant. In this FCPP fuel cells, dc to dc converters, inverters and load or grid is connected. This paper gives the flow limits for alone or distributed grid environment. For the control methods PI controllers are used. Duty cycle is changed to control and supply a constant voltage.

[22]This paper tells about a simple boost control for the ZSI. In this paper the relation between modified simple boost and modulation index is given for the ZSI network. Here maximum boost control and maximum boost control uses high modulation index to get a required voltage.

[24]This paper gives the study about analysis and enhance the transient stability of the grid connected to the fuel cell. The aim of this study is to make a model of fuel cell and analysis the faults. This study can be used to compare various renewable and alternating sources connected to grid.

[26]As the paper introduce, the behavior of fuel cell with the change in the flow rate of oxygen is studied. This study is done to get the better efficiency of fuel cell. A no. of flow rate of oxygen is taken to study. And we came to know that with the increase in flow rate to oxygen the voltage of fuel cell get increased.

[27]This paper presents the study about the boost converter for PEM fuel cell. In this paper the converter is used to boost the PEM output voltage. For this a fuel cell model is done in simulation and the behavior is studied. After that a control system is presented to control the output with use of PID controllers.

[29]This paper gives the ZSI converter and the control method for implementing dc to dc, ac to ac, dc to ac and ac to dc conversions. This converter provides a unique feature that is not in traditional converters. It also compare the VSI and CSI with Z-source. It also overcomes the limitations and problems of other converters. In this paper fuel cell is connected to ZSI so to increase the eff. and to reduce the cost.

[34]This paper offerings a ZSI based on DC to DC converter for fuel cell supplied system. Here it is used to buck and boost functions in a single converter. So that to reduce the additional switching methods. Due to this we can maintain a constant voltage and current magnitude to the grid. Further LC filter is introduced to reduce the THD of the system.

[35]This papers aims to find the maximum efficiency point tracking for the fuel cell. This study is done for the maximum efficiency of fuel cell. This paper provide an algorithm to find the maximum efficiency point. By this performance of fuel cell can be improved.

[37]This paper, the carrying out of fuel cells with low voltage range providing the high voltage loads. Here it gives a theoretical background to the topology that can be used for impedance source inverter in the input stage to the converter.

1.2.2 LITERATURE REVIEW ON APPLICATION OF SINGLE PHASE Z –SOURCE

[9]This paper states a new modified technique is introduced. The aim of this study is to reduce the no. of switches in a single phase inverter. As for a single phase full bridge converter to two switches only. This MZS single phase inverter with only two switches is connected to single phase PMSM.

[19]In this paper simulation and execution of control strategy for the ZSI to control the speed of machine is done. In this paper micro controllers are used to sense the motor speed and to send the feedback signal to inverter to change the voltage output w.r.t speed of motor. In this paper simple boost control is used.

[21]This paper presents analysis and simulation of ZSI network connected to the single phase motor drive. The output of ZSI is used for the control of speed of induction motor. A feedback loop signal is taken from the speed of motor. PID controllers are used to feedback loop. So the change in the voltage is done change in the duty cycle and this required voltage is used to control the speed of motor.

[23]This paper introduces the ZSI network. In this paper the study and analysis of single phase ZSI network is done. It tells about the unique features if ZSI network which are not seen in the other VSIs and CSIs. In this paper z network is connected to the resistive load.

[30]In this paper the simulation of control strategy for the Z-source inverter is offered. So the single phase induction machine with the control of the single phase Z-source using the Simple boost controller is done .The controller will sense the speed of motor and gives the PWM signal that will change the voltage and due to which speed will also change and can be controlled.

[33]This paper introduces the analysis of single phase induction motor with fuel cell based multilevel dc to dc boost.in this paper single phase motor is connected to single phase supply of ZSI. The speed of motor is controlled with the change in voltage.

1.2.3 LITERATURE REVIEW ON APPLICATION OF THREE PHASE Z-SOURCE

[6]This paper presents the ZSI and control for motor drives. So by controlling the short switched state with duty cycle, the required output can generated which will be greater than the line voltage. So z-source is used to improve the efficiency and reliability also to reduce the harmonics.

[28]This paper proposed ZSI simple boost inverter to control the speed to locomotive drive. The control strategy for this ZSI network is simple boost control. The speed control technique for motors is variable voltage at variable frequency with the constant torque mode.

[36]This Paper presents the hybrid modulation technique containing of the single reference six pulse modulation (SRSPM) for the front end dc to dc converter and 33% modulation for the 3 phase inverter. This technique is used to control the fronted dc to dc converter which produces the high frequency (HF) pulsating dc voltage waveform. This Paper explains operation and analysis of the HF two stage inverter with SRSPM technique.

1.2.4 CONTROL METHODS

[2]This paper proposed the control of the sensor-less PMSM drives and presents the design of the 3-phase PMSM sensor-less Vector Control drive without position encoder coupled to the motor shaft. The speed control of a sensor-less non-salient PMSM which uses the estimated rotor flux instead of transformation angle is designed. This paper introduces a new sequential switching control strategy in the current control of the three phase inverter. This design is applied to the control of a three phase PMSM. Its operation at low speed is improved by reducing the disturbance impact.

[8]This paper introduces the modelling and modified space vector PWM execution (MSVPWM), and the control system design of the Z-source inverter. For the analysis of the fuel cell system is modelled with an R and C circuit including its current and voltage polarization characteristics. In this paper a discrete-time state space equation is given to digital control and the space vector pulse-width modulation technique is modified to realize the shoot-through zero vectors that boost the dc-link voltage.

[25]This paper introduced a modified and improved of ZSI. This improved model is used for the control the speed of the induction motor. The ZSI is a inverter with a buck and boost feature and this proposed topology also increases the efficiency of circuit by reducing the voltage stress through the capacitors. A speed sensor is connected to the induction motor to sense the speed of motor, which is then compared with the reference speed. The PI controllers are designed to which will helps the motor to run at the reference speed. The proposed topology that can be applied to improve the inverter efficiency.

[31]In this paper a new dynamic model is developed to connect the PEM Fuel Cell (PEMFC) to a Z-source inverter. A model is used to analyze the behavior of the fuel cell by providing the polarization curve. A controller is designed based on an interpolation to spot the parameters of PEMFC such as temperature (or anode and cathode pressure). A current feedback is gained to regulate the output voltage through determination of the physical parameters. The ZSI is used in the proposed model to generate the AC power. In this research, to compensate the voltage drop of fuel cell the capacitor voltage of the Z-network is controlled using the state space averaging method to stabilize the AC output voltage of the ZSI.

[32]In this paper, a new converter without using the chemical storage elements for the purpose of the photovoltaic water pumping or the treatment system is presented. The converter is fed to drive a three phase Induction motor directly from the solar energy. The experimental result proves that a peak efficiency of 91 % at rated power of 210 W, also the proposed system is expected to have high lifespan due to the inexistence of electrolytic capacitors so that the total cost of the converter is very low.

1.2.5 LITERATURE REVIEW ON DESIGN OF LC FILTER

[1]In this paper, the analysis and design methods of the LC filter of single phase PWM inverter are presented. The obtained closed form expressions of the inductance and capacitance of the LC filter eliminate the time consuming conventional Fourier series method. This LC filter is used to reduce the harmonics. So the value of LC is calculated form the no. of equation in this paper.

[11]In this paper a new design of output LC filter of single phase inverter is presented. The aim to this paper is to meet the IEEE STD. 1547 required to reduce the harmonics of output. In this paper the simulation is done for 220 V, 5 KVA inverter.

1.3 PROBLEM DEFINITION

To obtain the desired output AC voltage in a Z-source inverter, there are basically two parameters which can be varied. One is the modulation index (M), which also exists in traditional VSIs. The second one is the boosting factor (B_{bf}), which depends on the shoot-through time of the inverter. Theoretically, the modulation index can take values from zero to one (0 < M <1), while the boosting factor can take values from one to infinity ($1<B_{bf}<\infty$). So all levels of desired voltages at the output by their multiplication. These two parameters are considered while designing of single/three phase Z-source inverter and their control strategies.

1.4 RESEARCH OBJECTIVES

This thesis presents the solution of problems in the use of fuel cell as a power source. The problem is with fuel cell is that it give a fixed DC output. So that’s why fuel cells can’t be used for various function like in HEV or other application. Therefore to overcome this problem Z-source network is connected to the full cell. The design of Z-network network, single phase and three phase full bridge inverter and their mathematical modeling is done. The simulation work is carried in MATLAB/Simulink. A fixed DC input voltage (V) is applied to the inverter and a controlled AC output voltage (V) can obtained by varying the duty cycle of inverter. The duty cycle variation can be achieved by using different modulation (PWM) control methods. In control strategies Sinusoidal carrier-based PWM and Simple Boost Control method are used. These methods are described in detail and simulation is presented in support of that. The output voltage and current ripples can be controlled by varying the modulation index and switching frequency. The problem of short switched state in the traditional inverter is eliminated in Z-source inverter. The traditional inverters can be used just either as buck or boost converter. This limitation is also sorted by the use Z-source inverter. The Z-source buck-boost capabilities are verified analytically and simulation results are presented. So different applications are presented for the verification of the modeling and simulated system along with two control strategies. One of these strategies is based on performance and simulation analysis of the fuel cell (FC) system. Second application is based on modeling and simulation of the Z-source inverter for single phase and three phases to control the speed of Induction Motor.

1.5 MATERIAL AND METHODS

In this thesis we have used MATLAB/ Simulink 2014. In this we have simulated models to analyze the behavior of fuel cell for various applications. First to study the behavior and construction of fuel cell is done [16, 17, 20, 26 and34]. Further the study of Z-source network for single phase and three phase for different applications [3, 4, 18, 29 and 37]. Then to control the speed to motor different techniques are studied. In this thesis we can used abc to αβ transformation is done [2, 8, 25, 31 and 32]. So to reduce the harmonics LC filter is designed [1 and 11].

1.6 THESIS ORGANIZATION

Chapter 1 gives a general introduction and the purpose of the thesis.

Chapter 2 deals with theory and calculations of fuel, need to fuel cell, fuel cell architecture, different of fuel cell and modelling and working principle of fuel cell, the classification of converter, different types of power converter topologies of inverter like voltage source (VSI) and current source converter (CSI), the Z-network and full wave bridge inverter design and operation strategy, comparison between voltage sources (VSI), current source (CSI) and Z-source (ZSI),

Chapter 3 deals with mathematical modeling of Z-source, closed loop for speed control, design procedure of single phase LC filter

Chapter 4 is based on results and simulations design verification of Z-source inverter system in chapter 3 with the Modeling and Simulation of Z-Source Inverter carried in MATLAB/-Simulink environment.

Chapter 5 deals conclusions and future work.

CHAPTER 2

THEORY AND CALCULATIONS

2.1. FUNDAMENTALS OF FUEL CELL

As the demand of energy is increasing due to rising population and the improvement in standard of living, particularly in the developing countries like India. Still a very large population which is living in remote areas has no access to electricity. In the year 2012 around 1.3 billion people around the world did not had any access to electricity. As 2/3 of this population was living in rural areas of Africa and Asia. The dependence on technology in everyday life is increasing the power consumption in urban areas. This is a main reason as increase in power generation will result in rise in the fossil fuel consumption and also pollution. Also fossil fuels are depleting, so there is urgent need for the world to move to renewable sources of energy like fuel cell, solar energy and wind energy which can be used again and again.

Besides the advantage of being non- polluting energy, renewable sources can also be used as distributed sources of energy as they can be installed anywhere according to the availability of renewable energy. The distributed energy resources (DER) which includes wind energy, solar energy, biomass, geothermal, fuel cell etc. out of all of these, fuel cells have the advantage like they can be installed in the remote areas also inside residential and commercial buildings. As their only requirement is the constant supply of hydrogen (H_2 gas) as a fuel. Earth receives solar energy from the sun. Around 3.78×1024 joule of energy which is received by earth every year is equal to energy from 1.3× billion ton of standard coal. So the use of renewable energy resources like wind, geothermal, tidal etc. are subjected to their availability. As fuel cells have very higher potential in terms of efficiency and also can transfer higher amount of power as compared with batteries.

The distributed energy resources (DER) are seen as possible solution to the increasing demand of electricity and also for sustainable development of the power generation. Although the problem with the use of solar energy, wind and geo thermal energy for power generation is the changing weather conditions and also high installation cost. Many innovations are going on to improve this technology for commercial power generation. This also includes the use of fuel cells along with the other energy resources like battery bank, super-capacitors as hybrid power generation.

2.2. FUEL CELL ARCHITECTURE

There are many types of Fuel cells like MCFC, PEMFC, SOFC and AFC. But there is problem that is only PEMFC can be operated at normal air temperature. PEMFC is quite light weighted so it can be easily transported and used for distribution power generation. There are a large number of fuel cells from which it can be chosen according to the power rating or according to power demand. 1kW FC has the output voltage range of about 25-50V and 5kW and above fuel cells have output voltage of about 200-400V. A fuel cell systems have five basic sub systems which includes fuel processor, air management, water management, thermal management, and power conditioning sub systems. All of these are briefly discussed one by one in the following subsections:

2.2.1 FUEL PROCESSOR

As hydrogen gas (H_2) is the most preferred fuel for fuel cells, so a fuelprocessor is needed to produce hydrogen from various sources like hydrocarbons. But transportation and storing of high pressure hydrogen remains the issues in implementation of fuel cell technology. Also the nature of fuel processor depends on the type of fuel cell used. As mentioned PEMFC is a low temperature fuel cell, so a relatively complex fuel processor is used which will include de-sulfurize and a gas clean-up system for removal of CO gas (carbon monoxide). For those fuel cells which operates at higher temperature like MCFC and SOFC preheating of fuel is required before it will be injected into the fuel cell. Therefore fuel processor for such types of fuel cells contains de-sulfurize as well as pre heater.

2.2.2 AIR MANAGEMENT

For oxidation of fuel, the fuel cell requires air as an oxidant. So air management is very important aspect of the fuel cell system. Either air compressor or blower is used for the providing air to the fuel cell. The choice of either blower or air compressor to be used depends on whether to give a high pressure air or low pressure air to the fuel cell. The advantage of giving high pressure air to the fuel cell is that it increases that stack efficiency and also improves the electrochemical reactions kinetics. In some cases an ultra-high speed compressor was used for better air management of the fuel cell. The centrifugal compressors are quite compact in size and have advantage of less noise pollution. However increasing the air pressure has also some disadvantages like it decreases the capacity of air to hold water so that affects the humidification processes of the fuel cell. As the power required for the compressing air to high pressure is derived from the fuel cell. Thus power required for air compressor is more than any of the other devices that are connected with fuel cell.

2.2.3 WATER MANAGEMENT

As mentioned, the removal of water from cathode of the lower operating temperature fuel cell like PEMFC is a challenge. The common practice for this is to purge the cathode flow fields. A tapered flow field channel is presented which separates water produced from the air flow that is needed for the fuel oxidation. Water is produced as a by-product of the electrochemical reactions that takes place inside the fuel cell. This means even where large amount of water is produced, the air management of the fuel cell does not get affected. As water is required for a variety of applications in fuel cell. In fuel processor water is required to react with hydrocarbons for steam reforming reactions. Moreover in PEMFC pre humidification of reactant gases are required to prevent the drying of the fuel cell membrane. For automotive applications it is very important that water produced in fuel cells are sufficient for humidification of reactants. If water produced is not sufficient then it has to be externally added for the reactant humidification.

2.2.4 THERMAL MANAGEMENT

As thermal energy is released by the fuel cell depends upon the output power of the fuel cell. This thermal energy can be used for a variety of applications like cogeneration. Low temperature fuel cells requires air to be flown through cathode to drive out excess heat. In high temperature fuel cells like SOFC and MCFC the excess heat is removed by the liquid coolant. However in these cases the thermal energy generated by fuel cell is used to pre heat the reactant gases and fuel reforming in fuel processor. Extra heat generated by fuel cell can be used for cogeneration. The fuel cells must be properly integrated for optimal use of thermal energy of fuel cell.

2.2.5 POWER MANAGEMENT

The output of fuel cell is dc. The direct current produced by fuel cell at a voltage VARIOUS with the change in the load. Therefore a dc-dc or dc-ac converter is required for the protection of fuel cell from overvoltage and over current originating with load variations. For the AC load an inverter is required for DC output of fuel cell to AC. As the response of fuel cell is slow to the load variations so a super capacitor or battery is required for supplying the initial power to the load. As mentioned as the load changes, there is an increase in the inrush current to the super capacitor or battery. Therefore for the protection of the storage device it is important to use a bi-directional converter. The bi-directional converter protects the storage device by controlling charge and discharge of current.

2.3. TYPES OF FUEL CELLS

Following are some of the popular fuel cells and their characteristics are listed in Table 1 [34].

Table 1 Types of Fuel cells

Fuel cell type	Electrolyte	Charge carrier	Operating temperature	Fuel	Electric efficiency	Application
Alkaline FC	KOH OH−	OH^-	60^0- 120^0◦C	Pure H_2	35-55%	<5kW, military
Proton exchange membrane FC	Solid polymer	H^+	50^0- 100^0C	Pure H_2, tolerates CO_2	35-45%	5-250kW automotive, portable CHP
Phosphoric acid FC	Phosphoric acid	H^+	~220◦C	Pure H_2, tolerates CO_2	40%	200kW CHP
Molten carbonate FC	Lithium and potassium carbonate	CO_3^{2-}	∼ 650◦C	H_2, CO, CH_4, tolerates CO_2	>50%	200kW-MW CHP and standalone
Solid oxide FC	Yttria, Zirconia	O_2^-	~1000◦C	H_2, CO, CH_4, tolerates CO_2	>50%	2kW-MW CHP and standalone

2.4. WORKING EQUATIONS OF FUEL CELL

A Fuel cell uses the hydrogen gas as a fuel. This fuel is used to produce electrons, protons, heat and also water. The Fuel cell combustion reaction is given below

$$H_2 + O_2 = 2H_2O \tag{2.1}$$

The electrons can be attached to produce the electricity in a replaceable form through a simple circuit connected with load. Now Problems stand up when a simple fuel cell is built as simple fuel cell has a very small areas of the contact between the gas fuel, electrodes and electrolyte. Because of this fuel cell offer very high resistivity. So, due to this limitation, the fuel cells are built to avoid these problems. A very porous electrode with a sphere-shaped thin structure is best so that penetration by the gases and electrolyte can happen. Therefore because the area of contact is increased similarly the efficiency will also increase [17].

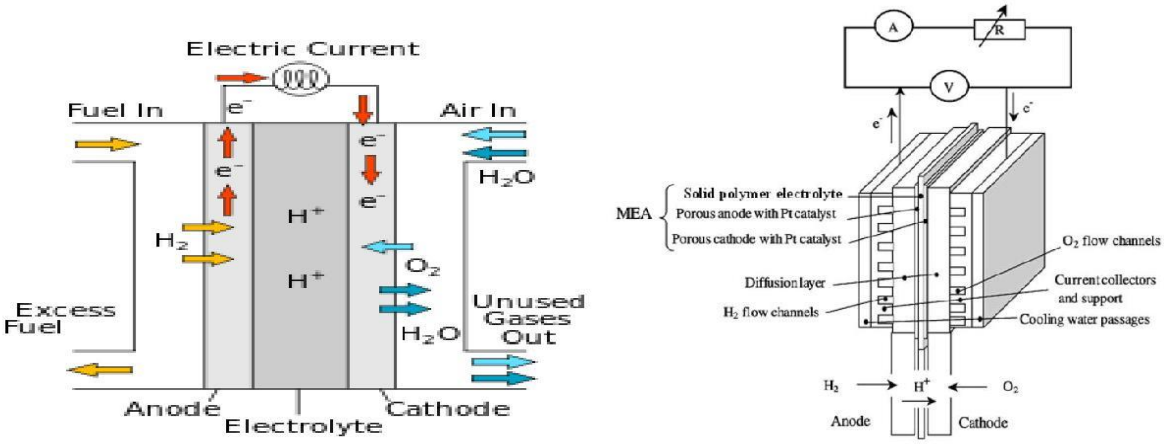

Figure 1 . Basic Fuel cell component

A basic structure of fuel cell has two (cathode and anode) electrodes parted by solid membrane acts as an electrolyte. The H_2 gas flows through the passages to the anode, where it divides into protons these protons flow through the electrolyte to the cathode and electrons which are composed as electrical current by an external circuit joins the two electrodes. Similarly the O_2 gas flows through the passages to the cathode where O_2 gas combines with the electrons collected by electrical current by the external circuit and proton flows through the membrane, which produces H_2O. The chemical reaction happens cathode and the anode of fuel cell are shown follow [16, 20 and 34], This fuel cell is based on the simple chemical reaction as:

$2H_2 + O_2 == 2H_2 0$ + electricity + heat (2.2)

The electro-chemical reactions has two parts as given below:

Anode: H_2 - 2e == 2H+ (2.3)

Cathode: O_2 + 4H+ == 2 $H_2 0$ (2.4)

The protons will pass the membrane but cannot pass the electronics. So if the load is connected to the electrodes and the reaction will be in progress, then electrons produced by the anode reaction (2.3) will create electricity. The O_2 gas is used up with electrons and protons and with remaining heat and water.

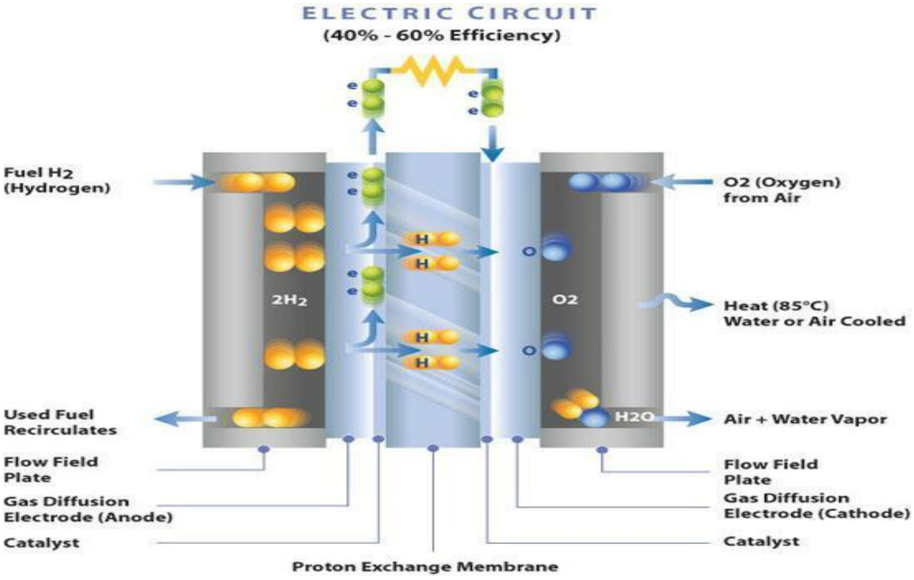

Figure 2 Basic reaction process

2.4.1 STATIC EQUATIONS

Output voltage of a single cell

$$V_{FC} = E_{Nerst} - V_{act} - V_{Ohmic} - V_{con} \qquad (2.5)$$

Thermodynamic potential

$$E_{Nerst} = 1.229 - 0.85 \times 10^{-3} \times (T - 298.1) + 4.31 \times 10^{-5} \times T \left[\ln P_{H2} + \frac{1}{2} \ln P_{O2} \right] \quad (2.6)$$

Activation over potential

$$V_{act} = -\varepsilon 1 + \varepsilon 2 \times T + \varepsilon 3 \times T \ln(CO_2) + \varepsilon 4 \times T \times \ln(i_{FC}) \qquad (2.7)$$

Ohmic over potential

$$\mathrm{V_{Ohmic}} = \mathrm{i_{FC}}(\mathrm{R_M} \times \mathrm{R_c}) \qquad (2.8)$$

Concentration over potential

$$\mathrm{V_{con}} = -\mathrm{B} \times \ln\left(1 - \frac{\mathrm{J}}{\mathrm{J_{max}}}\right) \qquad (2.9)$$

Output voltage of stack

$$\mathrm{V_s} = \mathrm{n} \times \mathrm{V_{FC}} \qquad (2.10)$$

2.4.2 DYNAMIC EQUATION

Dynamical voltage across the capacitor

$$\frac{dV_d}{dt} = \left(\frac{1}{c} \times i_{FC}\right) - \left(\frac{1}{\tau} \times V_d\right) \qquad (2.11)$$

Electrical time constant

$$\tau = C \times R_a = C \times (R_{act} + R_{con}) \qquad (2.12)$$

2.4.3 PERFORMANCE

Electrical power

$$\mathrm{P_{FC}} = \mathrm{i_{fc}} \times \mathrm{V_{FC}} \qquad (2.13)$$

Efficiency

$$\mathrm{n_{el}} = \mu_\mathrm{f} \times \left(\frac{\mathrm{V_{FC}}}{1.48}\right) \times 100\% \qquad (2.14)$$

2.5 CONVERTER REQUIREMENT OF AC AND DC LOAD

In the electrical engineering, power conversion has a specific meaning, namely converting the electric power from one form to another from. Power conversion systems has often incorporate redundancy and voltage regulation.

One way of classifying the power conversion systems is according to whether the input and the output are direct current (DC) or alternating current (AC) thus:

DC to DC conversion

- DC to DC converter
- Linear regulator
- Voltage stabilizer

DC to AC conversion

- Inverter

AC to AC conversion

- Voltage regulator
- Voltage converter
- Transformer/autotransformer
- Cyclo-converter
- Variable frequency transformer

AC to DC conversion

- Rectifier
- Switched-mode power supply
- Mains power supply unit (PSU)

There are also some devices and methods to convert between power systems designed for single and three-phase operation

The increased power capability, ease of controls, and reduced cost of the modern power semi-conductor devices have made converters more affordable in a large number of applications and have opened a new conversion topologies for the power electronics application. Power inverters are the electrical devices that convert direct current (DC) or DC power to alternating current (AC) or AC power. The converted alternating current (AC) can be at any required frequency and voltage with the use of appropriate switching, transformers and control circuits. An inverter (power inverter) allows to run emergency equipment uninterruptible power supplies (UPS) in medical facilities, life supporting systems, electrical equipment computers, telecommunications, data centers, industrial processing, online management systems automobile applications, adjustable-speed AC drives and in AC appliances for houses. When it is used as UPS, providing reliable, uninterruptible, and high quality power for the vital loads becomes critical. Moreover they add an extra layer of protection for the essential loads against power outage, over-voltage, and over-current conditions.

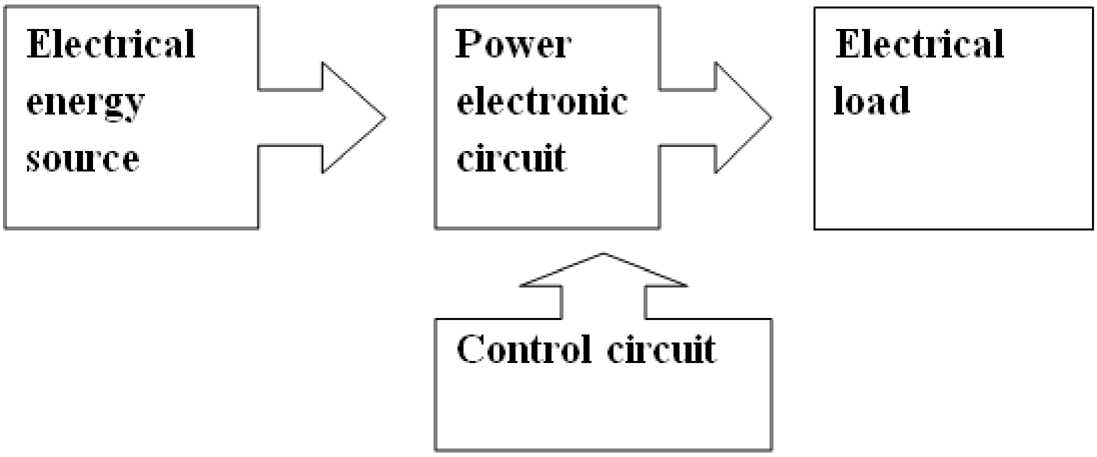

Figure 3 A basic power electronic circuit

The complete concept of a basic power electronic circuit is shown in figure 3. Such a system consists of an energy source, a power electronic circuit, an electrical load, and control functions. Power electronic circuit contains switches, magnetic transformers, and lossless energy storage elements. The control circuit take information from the source, the load, and designer and then determine the switches operation to achieve the desired output conversion. The control circuits are normally built up with the conventional low-power analog and digital electronics. For a sinusoidal ac output, frequency, phase, and magnitude should be controllable. One of the most important thing is the selection of power electronics circuit topology. To achieve the optimal performance, it needs to seriously consider the suitability of associated power electronic converter since it is power electronic technology that enables various applications.

A typical DC/AC converter system is shown below in figure 4. Here input is from DC source (current or voltage) and the output is designed to be sinusoidal current or voltage with a zero DC components. The load can be a passive R-L-C network load, an AC current sink, or an AC voltage sink. Control parameter can be an angle, a pulse width, a current or voltage signal.

Figure 4 dc/ ac converter block

For the simplest form of a DC/AC converter is shown in figure 5(a), which shows a single phase bridge. Single phase DC/AC conversion can be obtained by the alternately opening and closing diagonal switch pairs of the bridge, i.e. S1 - S4 and S2 - S3, receptively. Figure 5(b) shows the waveform of output voltage, where either the input voltage or the negative counterpart is seen at the output depending on switch states. The parameters of the AC voltage (the amplitude of its fundamental component or its RMS value) are constant here.

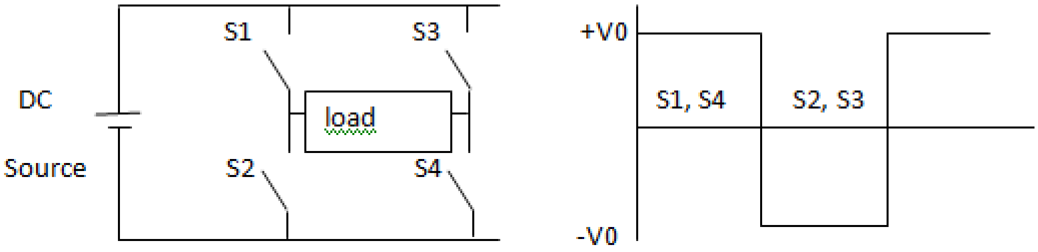

Figure 5 (a) single phase bridge inerter and (b) output ac voltage

The common way of varying the AC voltage parameters is to introduce a third state which is called a zero state. A zero state can be obtained by closing either upper leg switches (S1 and S3) or lower leg switches (S2 and S4). Figure 6 (a) shows output AC voltage of a single phase inverter in figure 5 (a) when a zero state is used to change the AC voltage parameters. Different methods of the harmonic cancellation at the output by introducing a zero state are explained.

Pulse Width Modulation (PWM) technique is also a very common in DC/AC conversion. Using this high frequency switching technique, as it is possible to eliminate the undesirable low and high frequency switching harmonics are easy to filter. The output waveform of a single phase inverter in figure 5 (a) is shown in figure 6 (b) when the PWM technique is used. As two of the four switches (S1 and S2) are switched at the high frequency and the other two (S3 and S4) are switched at the low frequency. The low frequency variation of the fundamental component can be observed after a proper filtering.

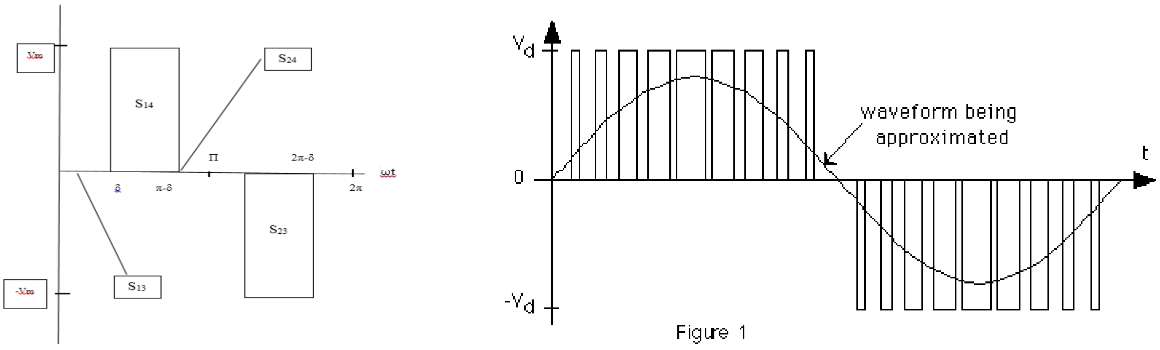

Figure 6: Output AC voltages (a) with zero state (b) with PWM control

Conventional Voltage Source Inverter (VSI) (figure. 2.5) and Current Source Inverter (CSI) (figure. 2.6) can be the power electronic circuits. However, a conventional Voltage Source Inverter (VSI) is a DC-AC buck inverter (AC-DC boost rectifier). It means the AC output voltage is restricted below and not to surpass the DC bus voltage. On the other hand, in a conventional Current Source Inverter (CSI) is a DC-AC boost inverter (AC-DC buck rectifier). The AC output voltage of CSI will be greater than the original DC voltage of the inductor.

2.5.1 BASICS OF VSI

Figure 7 shows a traditional single phase voltage source converter construction. A dc voltage source is maintained by a comparatively large capacitor that feeds the main converter circuit in a single phase bridge. The dc source can be fuel-cell stack, capacitor, and/or diode rectifier. Four switches are used in the single phase main circuit; each is traditionally collected of a power transistor and an anti-parallel (freewheeling) diode to deliver the bidirectional current flow and the unidirectional voltage blocking capability [3 and 18].

However, it has the following conceptual and theoretical barrier.

- Ac output voltage is restricted below and cannot surpass the dc-rail voltage. Hence, the VSI is a buck converter for the dc-to-ac power conversion and the voltage source converter is a boost rectifier for the ac-to-dc power conversion. The additional power converter stage rises system cost and lowers effectiveness.

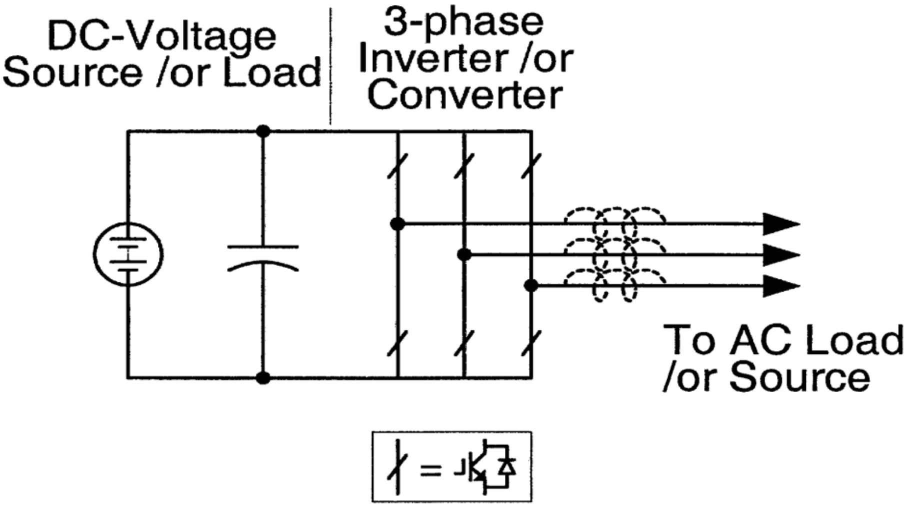

Figure 7: Traditional VSI

- The upper and lower devices for each phase leg cannot be gated on at the same time either by determination or by the EMI noise. Or else, a short switched state would happen and extinguish the circuit. The short switched state problem by the electro-magnetic interference (EMI) noise's mis gating-on is the main destroyer to converter's steadfastness.
- An *LC* output filter is required for a sinusoidal voltage related with the CSI, which reasons extra control and power loss difficulty.

2.5.2 BASICS OF CSI

Figure 8 shows a traditional single-phase current-source converter (I-source converter) construction. A dc current source feeds a single-phase bridge. The dc current source can be the relatively large dc inductor which is fed by a voltage source such as a fuel-cell stack, battery, diode rectifier or thyristors converters. Four switches are used in the single phase bridge; each of them is traditionally made of a semiconductor switching device with the reverse block capability such as a Silicon Control. Rectifier (SCR) or gate turn-off thyristor (GTO) and a power transistor with a series diode to provide the unidirectional current flow and the bidirectional voltage blocking [3, 18].

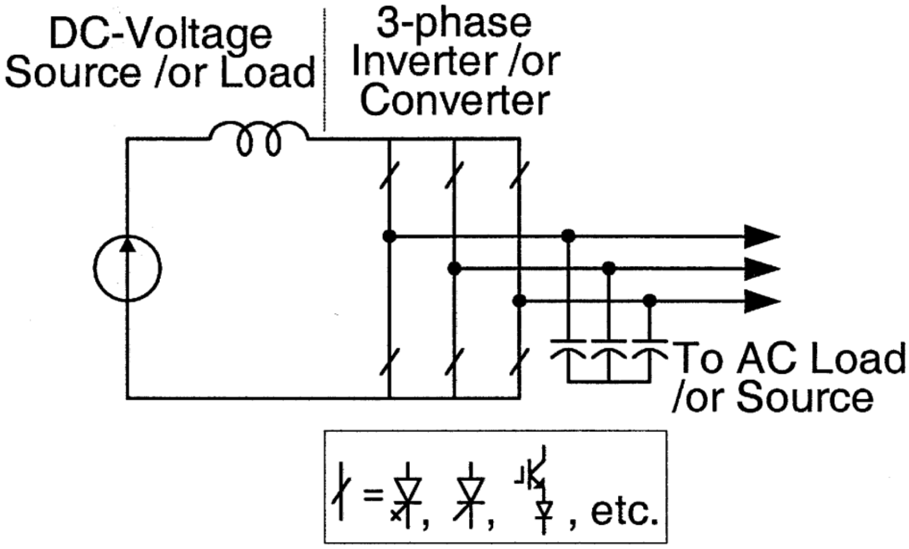

Figure 8: Traditional CSI

Though, the Current source converter have the following theoretical barriers, conceptual and limits.

- AC output voltage is to be greater than dc voltage input that is fed to the DC inductor. Hence, the CSI is a boost inverter for the dc-to-ac power conversion and current source converter is a buck converter (or buck rectifier) for the ac to dc power conversion. For the applications where a large voltage range is required, an additional dc-dc buck (or boost) converter is desired.
- One of the lower and one of the upper devices have to be gated on and kept on at any time. The open circuit problem by the EMI noise's mis gating off is a main worry of the converters.
- This series diode is to be used in combination with the high-performance and high-speed transistors such as insulated gate bipolar transistor (IGBT). This avoids the direct use of high-performance and low-cost IGBT module and intelligent power module (IPM).

In addition to that both voltage source converter and current source converter has following common problems.

- They are either a buck or a boost converter and but cannot be a buck-boost converter. So, their obtainable output voltage range is limited either greater or smaller than the input voltage.

- The VSI is a down (buck) inverter where the AC output voltage cannot exceed the DC input voltage. The CSI is an up (boost) inverter where the AC output voltage is always greater than the DC voltage feeding to the inductor. For the applications more than available voltage range an additional buck (or boost) DC/DC converter is needed. This increases the system price and decreases the effectiveness.
- As their main circuits is not interchangeable. In other words, neither the current source converter main circuit can be used for the voltage source converter, or vice versa.
- They are susceptible to EMI noise in terms of reliability.
- For a VSI, the upper and the lower switches cannot be on at the same time which can cause a short circuit. On the other hand for a CSI one of the upper switches and one of the lower switches have to be on at the same time to provide a path for continuous input current. The CSI (VSI) requires overlap time to provide safe commutation which causes waveform distortion.
- In a CSI, switch implementation needs diodes in series with the switches. This averts the use of low cost switches which come with anti-parallel diodes implementation.

2.6 BASICS Z-SOURCE INVERTERS

A new kind of converter in power conversion, Z-source converter (ZSC) was presented in 2002, which has unique feature that can overcome the limits of CSI and VSI, This chapter gives the introduction about Z-Source Inverter or impedance-fed or impedance-source power converters and its control method for the implementation of dc-to-dc , ac-to-ac , dc-to-ac and ac-to-dc power conversion. The AC voltage from ZSI can be controlled to between zero and infinity. Figure 6 shows the general arrangement of the Z-source converter [3, 4 and 18].

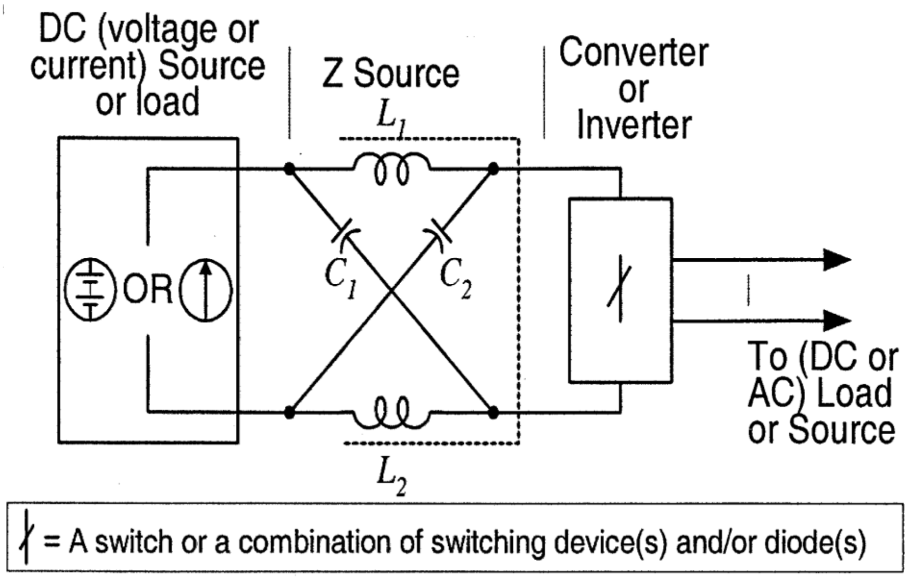

Figure 6 A general arrangement of a ZSI

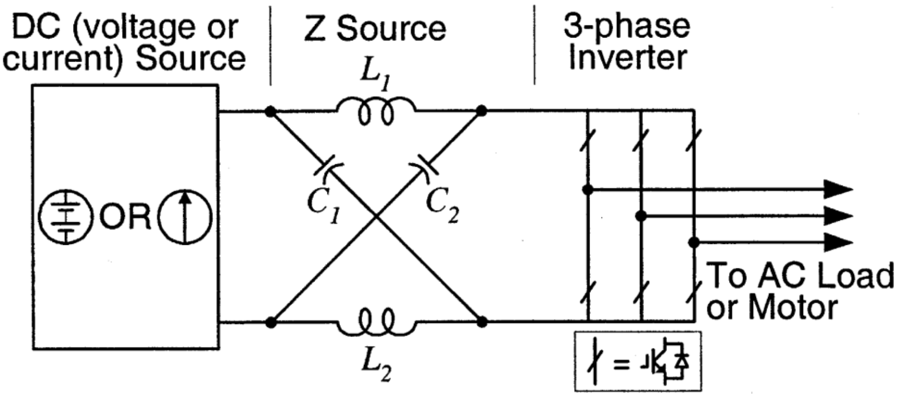

Figure 7 ZSI structure with the antiparallel combination of diode and switching.

Figure 7 shows the simplified equivalent circuit for the voltage source based Z-source converters (ZSC). In the simplified circuit, the Voltage source inverters (VSI) inverter bridge is observed as an equivalent current source or drain in parallel with an active switches.

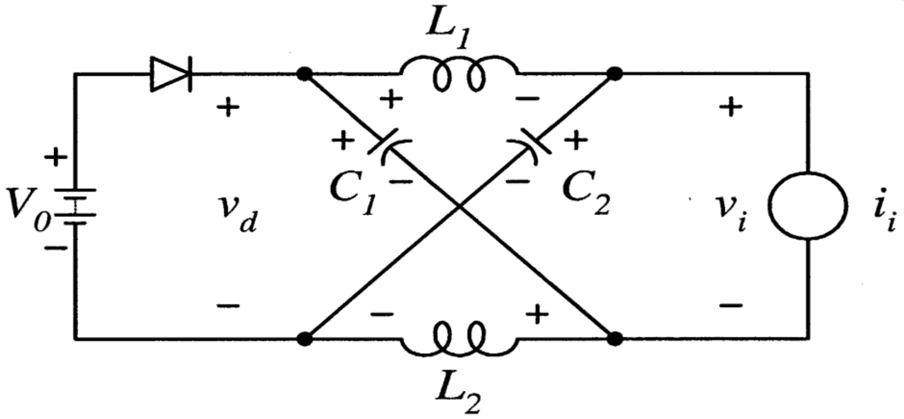

Figure 8 Equivalent circuit of a voltage source based Z-source converter

Not like a conventional Voltage source inverters (VSI), the short switched state is not destructive and it has been used in Z-source inverter. The study tells how the short switched state over non-shoot-through state controls buck-boost factor of the systems. As the boost factor in blend with modulation index M of VSI, the DC-AC buck/boost factor is shown in figure 9.

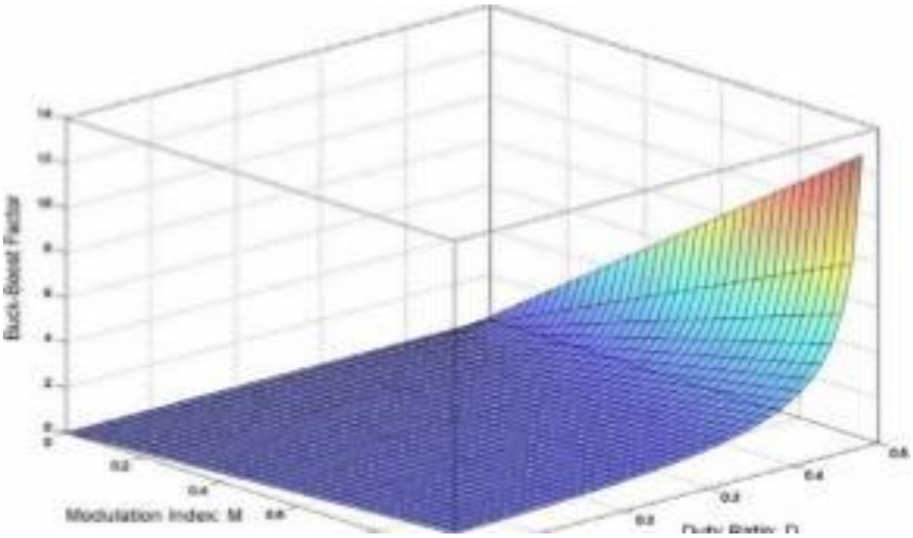

Figure 9 : Buck-boost factor of ZSI

It is vital to note that the process of the energy transfer between AC and DC overlaps the process of the energy transfer from the DC source to the Z-source network. The overlap process looks very demanding on the Switch (S_1). Hence, for both the motoring and the generating operation, S_1 is subjected to the considerable current stresses. In particular, for the high starting current applications, the total current will impose a huge stress on switch S_1. The ripple current through the capacitor C is higher than that through dc bus capacitor used in the conventional VSI. In terms of the voltage, the boosted dc voltage is the voltage across capacitor in the ZSI. Moreover, for the starting and the generating operation, S_1Need to the handle bi-directional current and, so a diode with an anti-parallel transistor have to be used. The selection of the inductors (L) and the capacitors (C) for Z-network is also of great significance. Firstly for the reactive components selection should be assured that no resonance would occur. In addition to that the capacitance (C) and the inductance (L) should be large enough to make the capacitor voltage and the inductor current ripple as small as possible. With shoot-through states evenly distributed between the pulse width modulation (PWM) cycles, the equivalent switching frequency in the Z-network will be several times of that used in the VSI part, implying so that minimization of reactive components is possible.

2.7 COMPARISON BETWEEN VSI, CSI AND ZSI

Table 2 comparison between VSI, CSI and ZSI

Voltage Source Inverter	Current Source Inverter	Impedance source Inverter or Z-Source Inverter
As capacitors are used in the D.C link, they acts as low impedance voltage source.	As inductor is used in the D.C link, the source impedance is high. It acts as a constant current source.	As capacitor and inductor is used in the D.C link, it acts as a constant high impedance voltage source [29].
In situation of the parallel capacitor feeds more power to the faults which makes VSI more dangerous.	A CSI is capable of withstanding short circuit across any two of its output terminals. Hence momentary short circuit on load and mis-firing of switches are acceptable.	In ZSI mis-firing of the switches sometimes are also acceptable [29].
VSI can be only either to boost or to buck operation.	VSI can be only either to boost or to buck operation	ZSI can be used for both the operation of inverter buck and boost.
The VSI's main circuit is not be changeable here also.	The CSI's main circuit is not be changeable here also.	main circuit is be changeable here also.
EMI noise affect this inverter.	EMI noise affect this inverter..	It is less affected by the EMI noise.
There are significant amount of harmonic.	There are significant amount of harmonic.	Harmonics Distortion are less.
Power loss is be high.	Power loss should be high because of filter.	Power loss should be low [29].

2.8 Z-SOURCE INVERTER

The exclusive feature of ZSI is that the ac voltage output can be between zero and infinity irrespective of the D.C source. But traditional I and V-source inverters cannot provide such feature. The ZSI is shown in figure 10; it employs an exclusive impedance circuit to join the converter ZSI to the power source, the load, or to the another converter, for providing the unique features that cannot be witnessed in the traditional I-source and V-source converters where a inductor and a capacitor are used, respectively. The Z-source converter overcomes the above stated Conceptual and the theoretical barriers and the limitations of the traditional I-source converter and the V- source converter and provides a novel power conversion concept [3, 4 and 18].

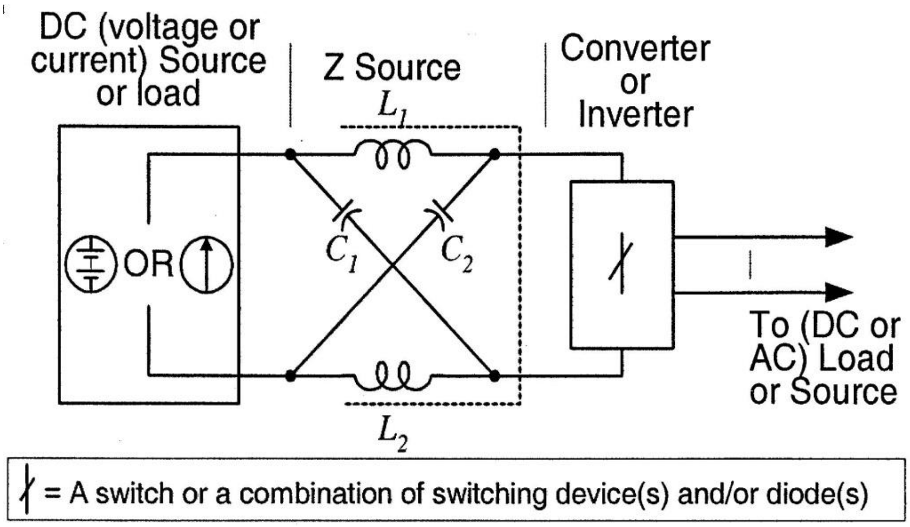

Figure 10 The general formation of a Z source converter

The ZSI has the three operation modes: 1. Normal, 2. Zero-state, and 3. Short switched these are three modes of operation. In the zero state and normal mode, Z network works as the traditional Pulse-width modulation (PWM) inverter. The Z-source inverter advantageously uses the short switched states to boost dc bus voltage by gating on both the upper and the lower switches of a phase leg. So, the ZSI can buck or boost voltage to a desired output voltage which is greater than the existing dc bus voltage. In addition, the reliability of an inverter is greatly improved because the shoot-through state cannot destroy the circuit. Thus it provides a reliable, low-cost and highly efficient single-stage structure for buck or boost power conversion. This chapter gives the detailed design analysis of z network. The designed values of the Z-source inverter is simulated in MATLAB / Simulink environment in order to verify the simulation and the analysis of single phase and three phase Z-source inverter is presented in chapter 5.

The two-port impedance network looks like a symmetrical lattice network most commonly used in the filter and attenuator circuit. The lattice network contains L_1 and L_2 which are the series inductances and C_1 and C_2 which are the diagonal capacitances. Figure 10 shows that the lattice network is connected between dc source (current or voltage) and converter. The dc source can be a fuel cell (PEM FC), battery, Photovoltaic Array (PV), diode rectifier, thyristor converter, a capacitor, an inductor or combination of capacitor and inductor. The full bridge converter made of two legs; each of leg consists of two switches and their antiparallel diodes. The two switches in each of leg are switched like that when one of two switch is in off state, the other switch is in on state. So the output current will flow through load continuously and the output voltage is specially sensed by the switches.

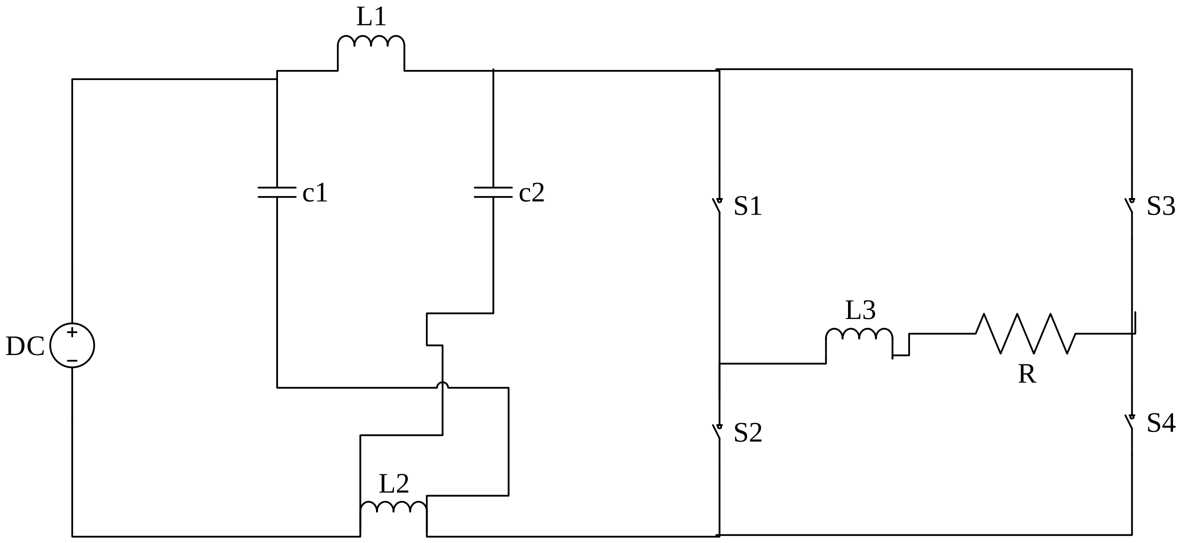

Figure 11 Lattice network and converter switching

To understand the design concept of the symmetrical lattice network it is essential to focus on the operating principle and the control of Z-source network. Figures 10 and 11 show the operating modes of single phase Z-source inverter. It can operate in two modes: 1. Normal 2. Boost mode. The standard operation mode is like a traditional inverter. In boost mode though, the Z-source inverter will boost the voltage across C_1 and C_2 (figures 10 and 11), thus increasing the voltage of the inverter. Table 2 shows, the single phase Z-source inverter’s short switched state. It has five possible switching modes of inverter: two active states with DC source is connected with the load, two zero states with the load terminals are shorted through either the upper or lower two switches and one short switched state with the load terminals are shorted through both lower and upper switches of the inverter of any one leg or two legs. Z-source inverter uses short switched zero states to boost the output voltage.

Table 2 Switching states of a single phase ZSI

Switching states	S1	S2	S3	S4	Output Voltage
Active States	1	0	0	1	Finite voltage
	0	1	1	0	
Zero states	1	0	1	0	Zero
	0	1	0	1	
Short switched state	1	1	S3	S4	Zero
	S1	S2	1	1	

Figure 12 shows the short switched switching state of Z-source inverter where the two switches of one leg or two legs are turned on at the same time. During this state, the diode D on input side is reverse biased and capacitors, C_1 and C_2 charge the inductors, L_1 and L_2 and voltage across the inductors are taken as [5]:

$$V_{L1} = V_{C1} \tag{2.15}$$

$$V_{L2} = V_{C2} \tag{2.16}$$

Taking a symmetrical impedance network (where $\mathrm{C_1 = C_2 = C}$ and $\mathrm{L_1 = L_2 = L}$), we see that

$$\mathrm{V_{L1} = V_{L2} = V_L = V_L \sin(wt\ + \theta_L)} \tag{2.17}$$

$$\mathrm{V_{C1} = V_{C2} = V_C = V_C \sin(wt\ + \theta_C)} \tag{2.18}$$

And output voltage is

$$\mathrm{V_{AC} = V_{DC}} \sin(wt\ + \theta_O) \tag{2.19}$$

Where θ_L, θ_C and θ_O are the phase angles of the Z-source inductor voltage, capacitor voltage and output voltage, correspondingly. Note that $\mathrm{V_L = V_C}$ and $\mathrm{I_{L1} = I_{L2} = I_L}$ the dc-link voltage across inverter bridge during the short switched interval ($\mathrm{T_O}$) is $\mathrm{V_I} = 0$.

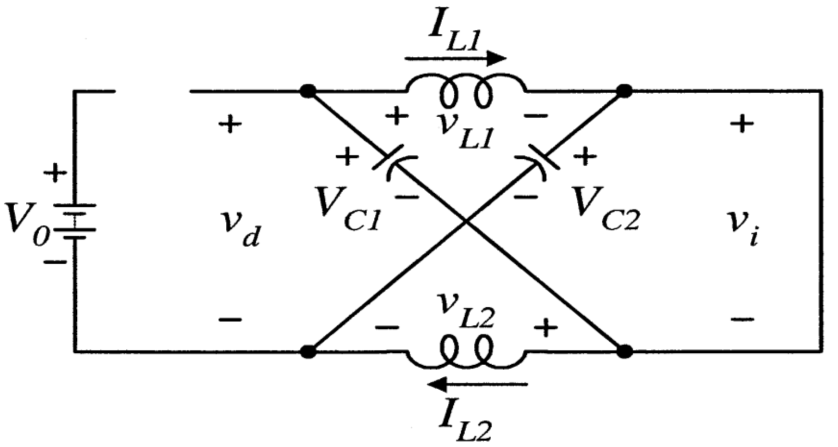

Figure 12 Short switched zero state of a single phase ZSI

Figure 13 shows the non-short switched states of the Z-Source inverter in zero and active states. Due to the symmetrical Z-network, capacitors current (I_{C1} and I_{C2}) and inductors current (I_{L1} and I_{L2}) are equal. The diode, D on the input side conducts and voltage across the inductors is V_d as:

$$V_L = V_{dc} - V_c \qquad (2.20)$$

$$V_c = V_{dc} - V_L \qquad (2.21)$$

$$V_d = V_{dc} \qquad (2.22)$$

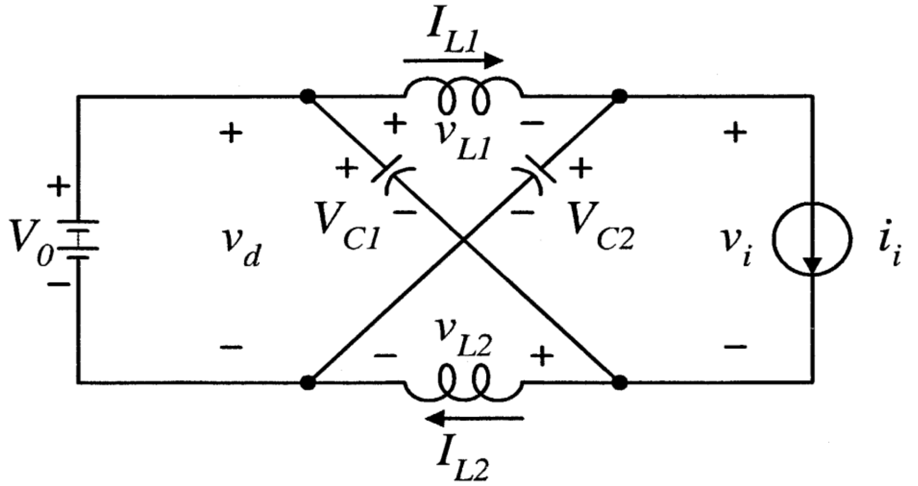

Figure 13 non short switched states of a single phase ZSI

CHAPTER 3

MATHEMATICAL MODELLING OF Z-SOURCE INVERTER

3.1 MATHEMATICS AND CALCULATIONS FOR Z-SOURCE INVERTER

Assuming the capacitors C_1 and C_2 and inductors L_1 and L_2 have the same capacitance and inductance, correspondingly, so Z-source network has becomes symmetrical. Where V_{c1} and V_{c2} voltage across the capacitance similarly V_{l1} and V_{l2} are the voltage across inductance. From an equivalent circuit, we have following equations [3, 4, 7, 18 and 37]:

$$V_{c1} = V_{c2} = V_c V_{l1} = V_{l2} = V_l \tag{3.1}$$

We have an inverter bridge is in shoot-through zero state for an interval of T_{0ff} (off), during the switching cycle, T (time)

$$V_l = V_{cp} V_{do} = 2V_{cp} V_{pk} = 0 \tag{3.2}$$

Consider that the inverter bridge is in one of the eight non-short switched states for an interval of T_1 (conducting period), during switching cycle, T.

$$V_{dc} - V_{cp} V_{do} = V_{dc} V_{pk} = V_{cp} - V_l = 2V_{cp} - V_{dc} \tag{3.3}$$

where the dc source voltage is V_{dc} and T = T_{0ff} +$T_{cond.}$.The average voltage of inductors over one switching period (T) should be zero in the steady state, from (2) and (3), thus, we have

$$V_l = \frac{T_{0ff}.V_{cp} + T_{cond.}.\left(V_{dc} - V_{cp}\right)}{T} \tag{3.4}$$

$$\frac{V_{cp}}{V_{dc}} = \frac{T_1}{T_1 - T_0} \tag{3.5}$$

Similarly, the average dc-link voltage across the inverter bridge can be found as follows:

$$V_{pk} = \frac{T_{0ff}.0 + T_{cond.}.\left(2V_{cp} - V_{dc}\right)}{T} \tag{3.6}$$

$$V_{pk} = \frac{T_1}{T_1 - T_0}.V_{dc} = V_{cp}$$

The peak dc-link voltage across the inverter bridge is expressed in (3) and can be rewritten as

$$V_{pk} = V_{cp} - V_l = 2V_{cp} - V_{dc} = \frac{T}{T - T_{0ff}}.V_{dc} = B.V_{dc} \tag{3.7}$$

Where

$$B = \frac{T}{T - T_{0ff}} = \frac{1}{1 - \frac{2T_{0ff}}{T}} \geq 1; \tag{3.8}$$

B Is the boost factor resulting from the shoot-through zero state. The peak dc-link voltage V_{pk} is the equivalent dc-link voltage of the inverter. The output peak phase voltage from the inverter can be expressed as

$$V_{out} = M_i.\frac{V_{pk}}{2} \tag{3.9}$$

Where M_i is the modulation index Using (7), (9) can be further expressed as

$$V_{out} = M_i.B.\frac{V_{dc}}{2}$$

For the traditional V-source PWM inverter, we have the well-known relationship

$$V_{out} = M_i.\frac{V_{dc}}{2} \tag{3.10}$$

Equation (10) shows that the output voltage can be stepped up and down by choosing an appropriate buck–boost factor B_{bf} ,

$$B_{bf} = M_i.B = (0 \sim \infty) \tag{3.11}$$

From (1), (5) and (8), the capacitor voltage can expressed as

$$V_{c1} = V_{c2} = V_c = \frac{1 - \frac{T_{0ff}}{T}}{1 - \frac{2T_{0ff}}{T}}.V_{dc} \tag{3.12}$$

The buck–boost factor B_{bf} is determined by the modulation index M and boost factor B. The boost factor B as expressed in (8) can be controlled by duty cycle of the shoot-through zero state over the non-short switched states of the inverter PWM.

It is observed that the shoot-through zero state does not affect the PWM control of the inverter, because it equivalently produce the same zero voltage to the load terminal. The available shoot-through period is limited by the zero-state period that is deter-mined by the modulation index.

3.2 CLOSED LOOP CONTROLLER MODELLING

In this section, we have introduced a closed loop for speed control of three phase motor. In the closed loop we have used pi controllers to check the change in speed to motor w.r.t load. We have fixed a constant speed for the motor. Now with the change in load to the motor the speed to motor will various which is detected by pi controllers and compared with fixed constant speed. According to change in the change the speed, the voltage and current to motor must change according to that to make a constant speed at various loads. For that the duty change must be changed. To study the behavior of duty cycle and output voltage (Table no. 2 in chapter 5 is presented which show us that with the change in the duty cycle we can change the output voltage). To control the speed we have used the abc to αβ transformation [2, 8, 13, 25, 27, 31 and 32].

$$U_{alpha} = \frac{2}{3} * (u_a - 0.5 * u_b - 0.5 * u_c) \tag{3.13}$$

$$U_{beta} = \frac{2}{3} * (\frac{\sqrt{3}}{2} * u_b - \frac{\sqrt{3}}{2} * u_c) \tag{3.14}$$

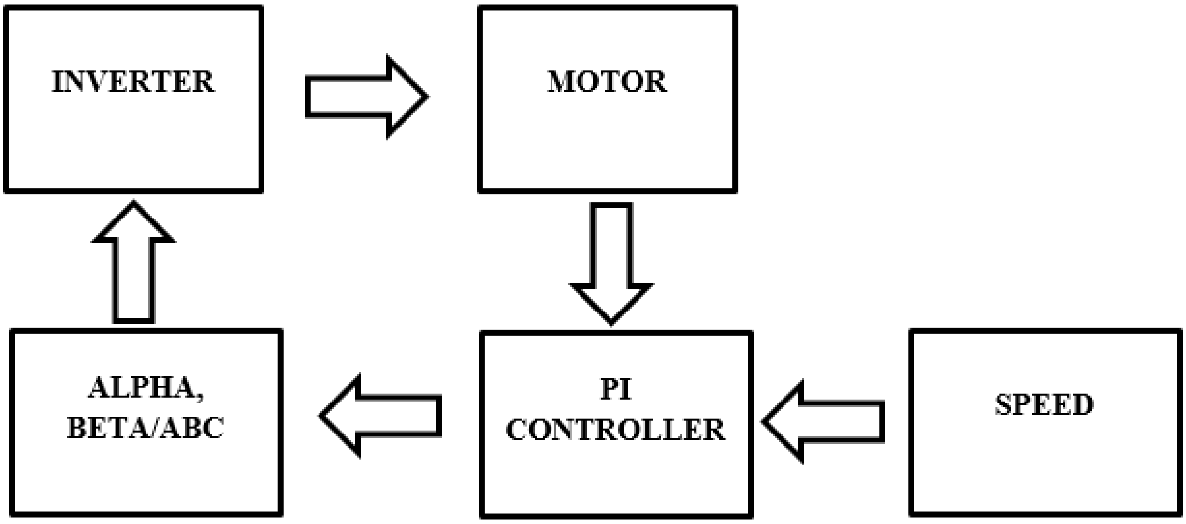

Figure 14 closed speed control for three phase motor

3.3 FILTER DESIGN

The PWM inverter output voltage is then passed through a LC filter network to produce a sine wave with less distortion. Based on the analysis, design procedure of the LC filter is divided into the following steps [1 and 11]:

Based on the nominal dc source voltage Ed and nominal load voltage V_o we can calculate the nominal modulation index. Because the voltage drop across the filter inductor cannot be determined before the parameters of the filters are indicated, the voltage drop is supposed to be negligible. This supposition is justified because this voltage drop at the inductor is compensated in part by the capacitor filter. Therefore to calculate the nominal modulation index, the rms value of the output voltage of the inverter can be supposed equal to rms value of the load voltage,

$$\mathrm{k} = \sqrt{2}\,\frac{\mathrm{V_o}}{\mathrm{E_d}} \qquad (3.15)$$

This factor k is calculated from the result:

$$k = \sqrt{2}\,\frac{v_o}{E_d} \qquad (3.16)$$

$$k = \frac{k^2 - \frac{15}{4}k^4 + \frac{64}{5\pi}k^5 - \frac{5}{4}k^6}{1440} \qquad (3.17)$$

Depending on the normal load current. To switching frequency- fs, fundamental output frequency- fr, and the indicated value of the total harmonic of the load voltage, so the value of inductor is calculated from the equation

$$L_f = \frac{V_o}{10f_s}\left(k\,\frac{E_d}{v_o}\left[1 + 4\pi^2\left(\frac{f_r}{f_s}\right)k\,\frac{E_d}{V_o}\right]\right) \qquad (3.18)$$

Similarly the value of capacitance can be calculated as

$$C_f = k\,\frac{E_d}{L_f {f_s}^2 v_o} \qquad (3.19)$$

In this chapter we have studied Z-source inverter design and its operation strategy. The traditional inverter has dc-link voltage distortion while operating with either the small source inductor or the light-load consequently output voltage of the inverter decreases. The Z-source inverter uses a unique LC impedance network for coupling the converter main circuit to the power source, which provides with a way of boosting the input voltage, a condition that cannot be achieved in the traditional inverters. It allows the use of the shoot-through switching state.

CHAPTER 4

SIMULATIONS AND RESULTS

4.1 OUTPUT VOLTAGE CONTROL BY CONTROLLING DUTY CYCLE AND FUEL RATE

In the following table we have studied the variation of VARIOUS voltages w.r.t duty cycle at constant fuel rate. In this table we have studied the variation of fuel cell voltage, capacitor voltage, inductor voltage, dc link voltage, ac output voltage and boosted output voltage.

Table 3 Change In Fuel Cell Voltage (V), Cap. Voltage (V), Ind. Voltage (V), Dc Link Voltage (V), Ac Output Voltage (V) and Boosted Output Voltage (V) With Change in Duty Cycle at constant flow rate of 6 kW 45 DC fuel cell

S No.	Duty Cycle	Cap. Voltage(V)	Ind. Voltage(V)	DC Link Voltage(V)	AC Output Voltage(V)	Boosted o/p Voltage(V)
1	0.10	40.64	40.32	57.83	57.82	599.8
2	0.15	40.64	40.320	57.83	57.82	599.8
3	0.20	37.84	37.7	53.81	53.8	512
4	0.25	30.05	30.02	42.54	42.53	366.8
5	0.30	30.05	30.02	42.54	42.53	366.8
6	0.35	30.05	30.02	42.54	42.53	366.8
7	0.40	25.38	25.49	35.87	35.87	286.3
8	0.45	19.67	19.96	27.78	27.78	179.9
9	0.50	19.67	19.96	27.78	27.78	179.9
10	0.55	19.67	19.96	27.78	27.78	179.9
11	0.60	16.05	16.53	22.61	22.61	122
12	0.65	9.436	10.17	13.36	13.36	51.83
13	0.70	9.436	10.17	13.36	13.36	51.83
14	0.75	9.436	10.17	13.36	13.36	51.83
15	0.80	5.188	6.384	8.078	8.078	20.72
16	0.85	2.699	4.589	4.589	4.891	1.099

In the following table we have studied the variation of VARIOUS voltages w.r.t fuel rate at constant duty cycle. In this table we have studied the variation of fuel cell voltage, capacitor voltage, inductor voltage, dc link voltage, ac output voltage and boosted output voltage.

Table 4 Change In Fuel Cell Voltage (V), Cap. Voltage (V), Ind. Voltage (V), DC Link Voltage (V), AC Output Voltage (V) and Boosted Output Voltage (V) With Change in Fuel Rate at constant duty cycle of 0.18 of 6 kW 45 DC fuel cell

S No.	Fuel Rate	Fuel cell Voltage(V)	Cap. Voltage(V)	Ind. Voltage(V)	DC Link Voltage(V)	AC Voltage(V)	Boosted Voltage(V)
1	10	21.94	29.09	29.03	41.08	41.07	349
2	11	21.95	29.19	29.13	41.22	41.22	350.6
3	12	22.03	29.38	29.32	41.5	41.5	356.2
4	13	22.14	29.68	29.62	41.93	41.93	361.2
5	14	22.15	29.95	29.89	42.32	42.32	361.9
6	15	22.16	30.27	30.20	42.78	42.77	365.5
7	16	22.18	30.26	30.28	42.78	42.77	367.7
8	17	22.36	30.94	30.87	43.73	43.73	374.8
9	18	22.41	31.15	31.08	44.04	44.03	381.2
10	19	22.42	31.31	31.24	44.27	44.26	382.7
11	20	22.49	31.82	31.74	44.99	44.98	387.6
12	21	22.57	32.05	31.98	45.33	45.32	393.2
13	22	22.58	32.35	32.27	45.75	45.74	395.7
14	23	22.62	32.58	32.50	46.08	46.07	397.8
15	24	22.65	32.66	32.58	46.19	46.18	399.1
16	25	22.64	32.70	32.62	46.25	46.25	399.6
17	26	22.64	32.72	32.65	46.29	46.28	399.9
18	27	22.62	32.72	32.65	46.29	46.28	399.7
19	28	22.62	32.73	32.66	46.31	46.3	399.9
20	29	22.64	32.75	32.68	46.33	46.32	400.4
21	30	22.66	32.82	32.74	46.46	46.32	401.1
22	31	22.67	32.85	32.76	46.49	46.45	401.4
23	32	22.67	32.87	32.79	46.51	46.49	402.3
24	33	22.68	32.87	32.79	46.54	46.49	402.4

4.2 SIMULINK MODEL OF BOOST CONVERTER (DC TO DC)

In this section, Simulink model of fuel cell connected to simple boosted inverter is presented. In this model a 6kw (PEM) fuel cell is used connected to fixed RL load. In this we have showed voltage and current in both cases like before boost and after boost.

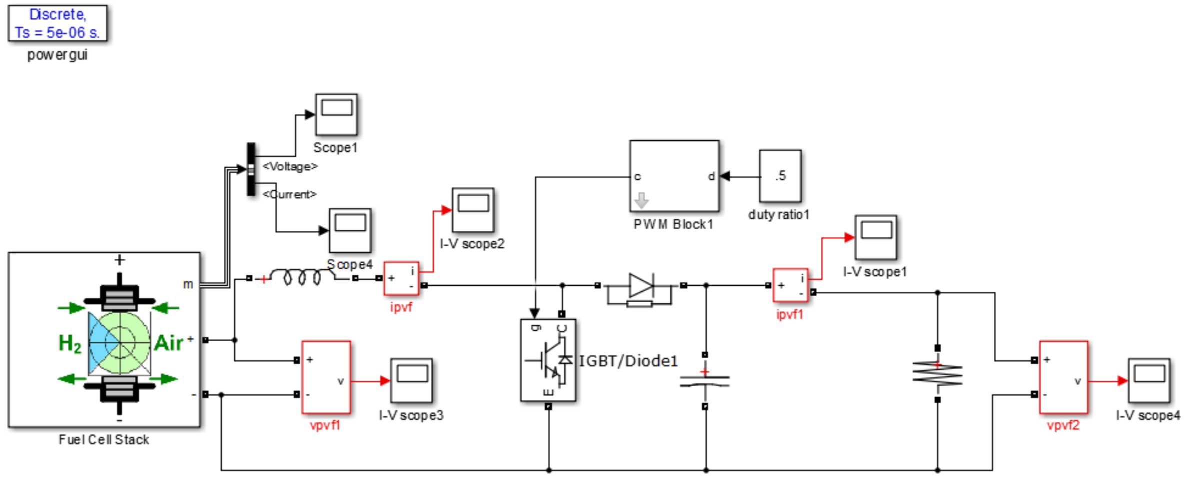

Figure 15 Simulink model of fuel connected to simple boost converter

4.2.1 FUEL CELL OUTPUT VOLTAGE OF BOOST CONVERTER

Following is voltage output of fuel cell before boost. It is a dc output voltage connected to fixed RL load. It is lower as compared with booted output voltage.

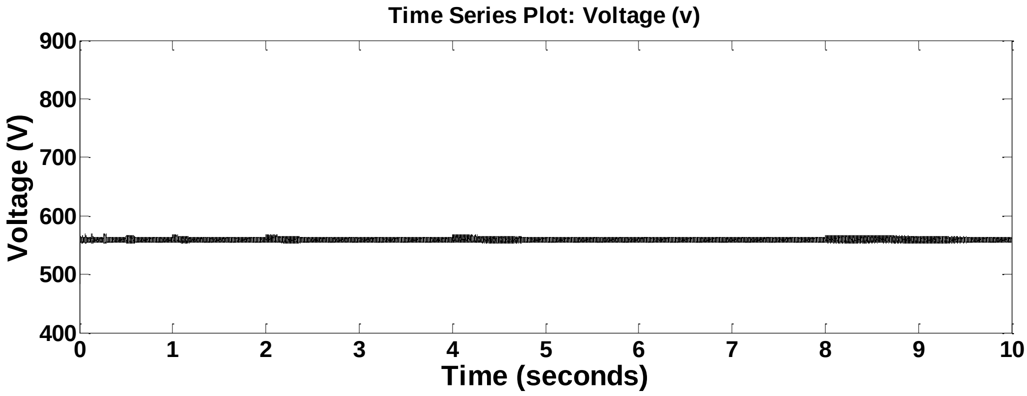

Figure 16 voltage output of fuel cell connected to simple boost inverter before boost

4.2.2 FUEL CELL OUTPUT CURRENT OF BOOST CONVERTER

Following is current output of fuel cell before boost. This current output is higher than the output current after boost of fuel cell. It is a dc output current connected to fixed RL load.

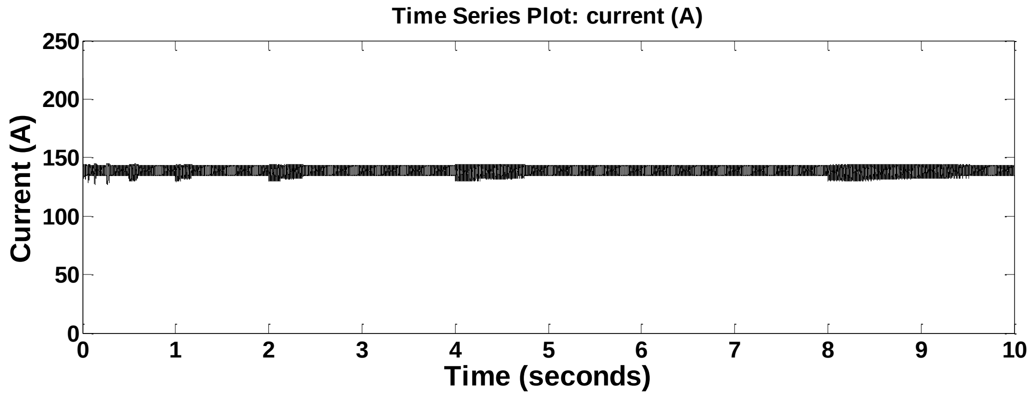

Figure 17 current output of fuel cell connected to simple boost inverter before boost

4.2.3 OUTPUT VOLTAGE OF BOOST CONVERTER

Following is voltage output of fuel cell after boost. This voltage is higher the output voltage of fuel cell. It is a dc output voltage connected to fixed RL load.

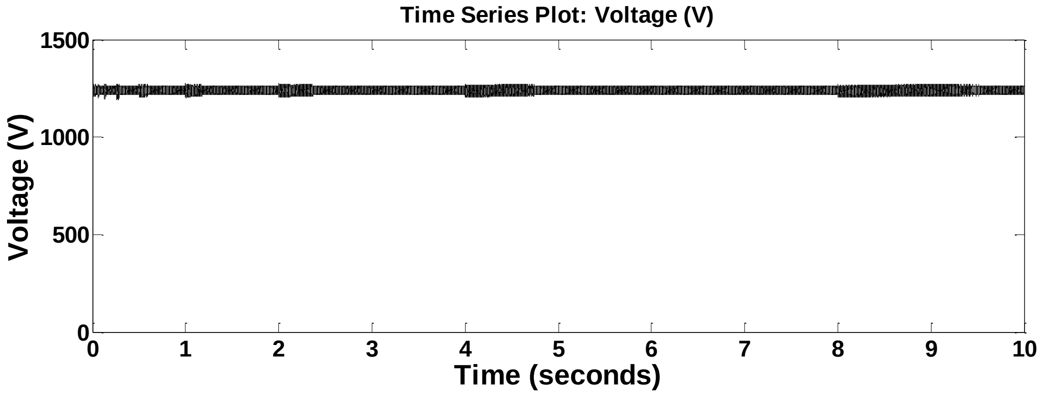

Figure 18 voltage output of fuel cell connected to simple boost inverter after boost

4.2.4 OUTOUT CURRENT OF BOOST CONVERTER

Following is current output of fuel cell after boost. This current output is lower the current output of fuel cell before boost It is a dc output current connected to fixed RL load

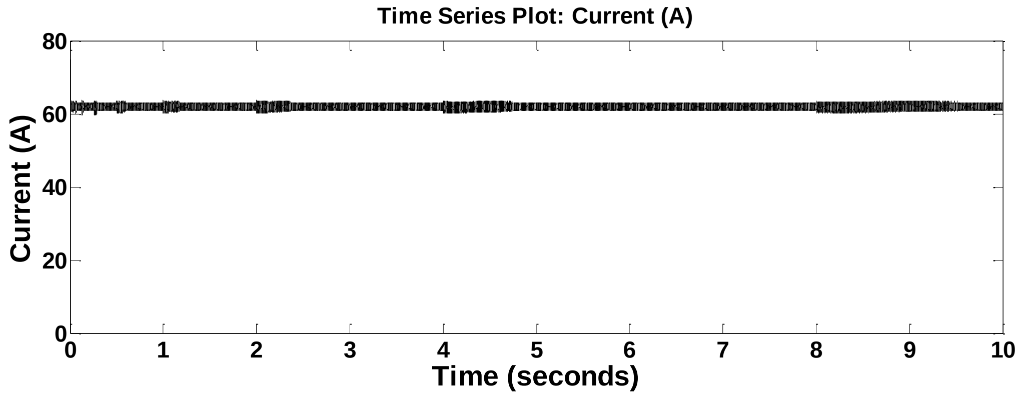

Figure 19 current output of fuel cell connected to simple boost inverter after boost

4.3 SIMULINK MODEL OF Z-SOURCE INVERTERS FOR FUEL CELL APPLICATION (DC TO AC)

In this figure we have deigned Simulink model in this PEMFC6 kW 45V dc fuel cell stack model is connected to Z-Source Inverter which has two inductors and capacitors .There are 4 inverter switches used in the inverter to converter dc to ac.

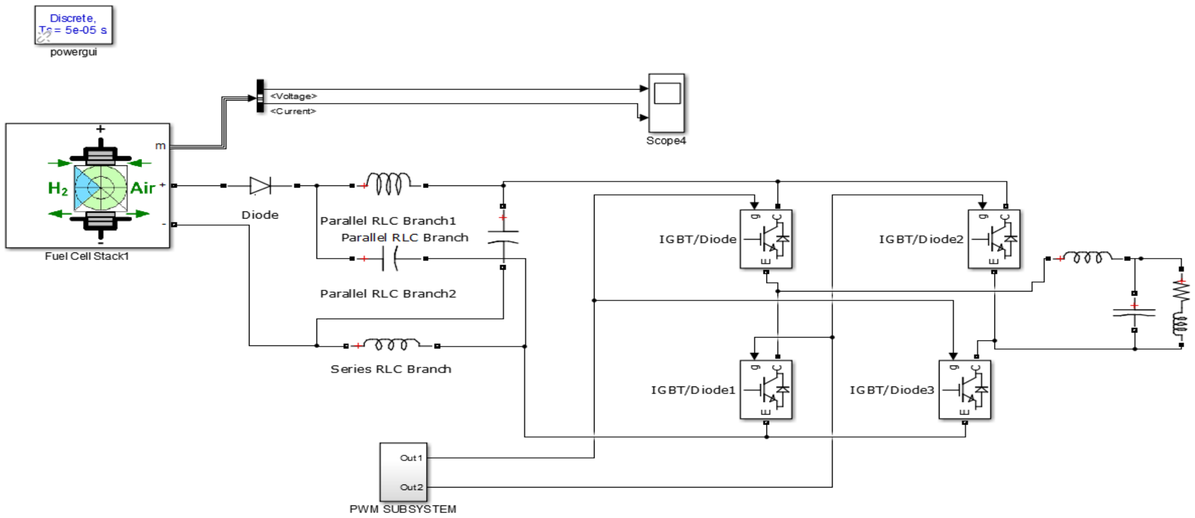

Figure 20: Simulink model of Z-Source Inverters for Fuel Cell application

4.3.1 DC LINK INPUT VOLTAGE OF Z-SOURCE INVERTER

In this we have shown the dc-link voltage of Z-Source Inverter. This voltage is dc output voltage after the Z-Source Inverter .This voltage is the boosted dc output voltage.

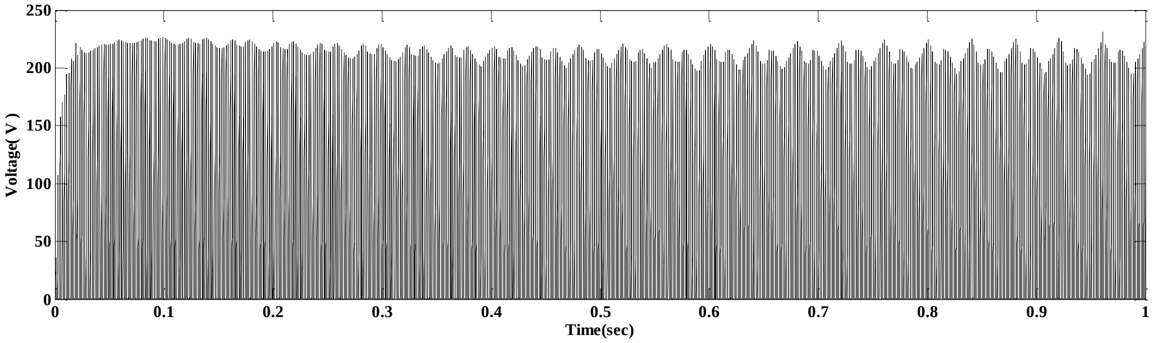

Figure 21: DC link input voltage of Z-Source Inverter

4.3.2 Z-SOURCE INVERTER OUTPUT VOLTAGE (WITHOUT FILTER)

In this figure we have shown alternating output voltage of Z-Source inverter (Without filter) .This voltage is taken after switching

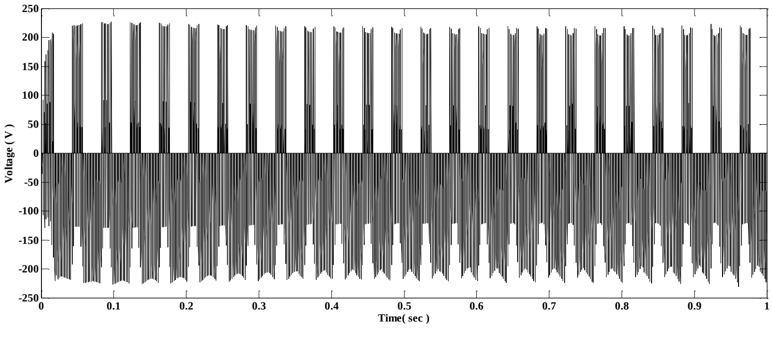

Figure 22: Alternating Output Voltage of Z-Source inverter (Without filter)

4.3.3 FFT ANALYSIS OF THE ZSI OUTPUT VOLTAGE WITHOUT FILTER

In this figure we have shown FFT analysis of the ZSI output voltage without filter .form this figure we can see the THD =287.23% and fundamental (50Hz) = 36.35 .So we can see there a lot of harmonics in this output.

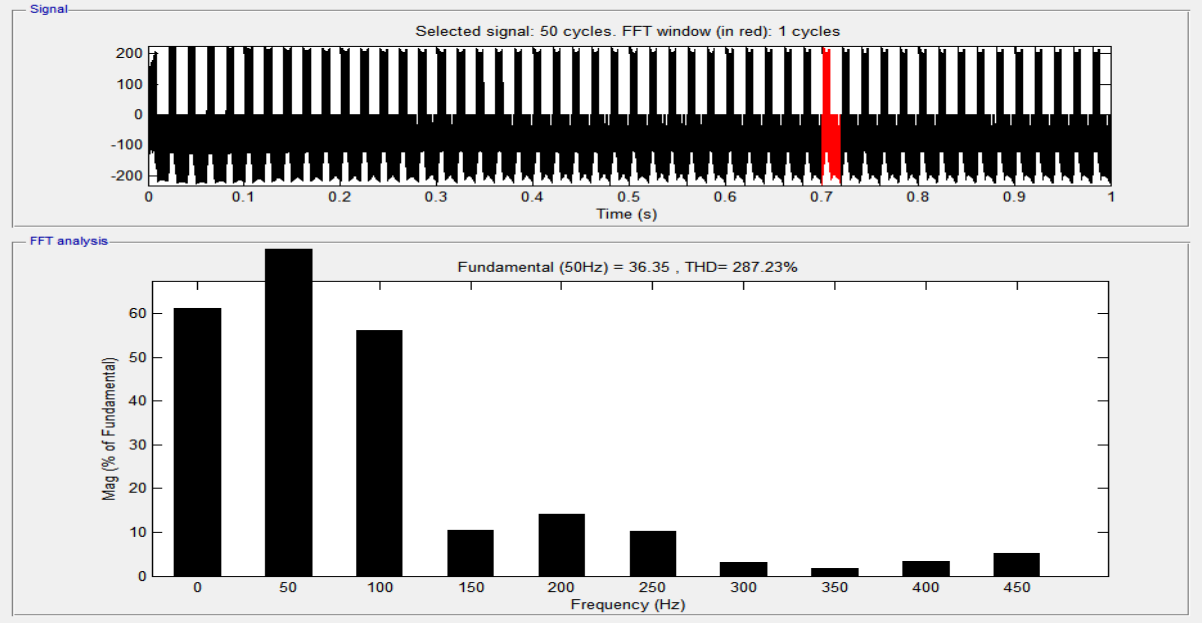

Figure 23 FFT analysis of the ZSI Output voltage without filter

4.3.4 FILTERED OUTPUT VOLTAGE OF Z-SOURCE INVERTER

For this we have used a LC filter .In we have used a series L and parallel C combination.

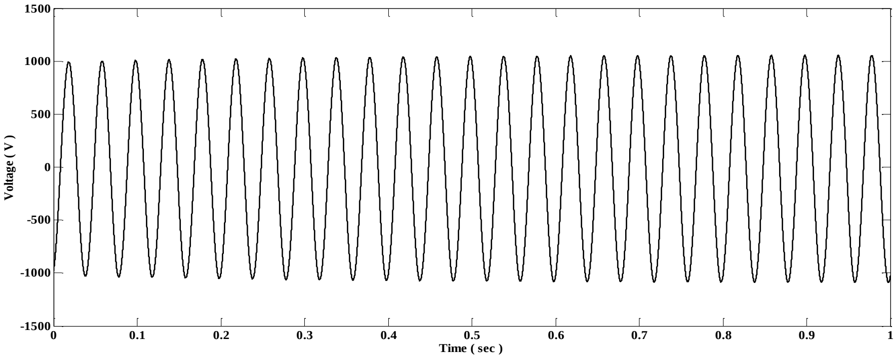

Figure 24: Filtered Output voltage of Z-Source Inverter

4.3.5 FFT ANALYSIS OF THE ZSI FILTERED OUTPUT VOLTAGE

In this figure we have shown FFT analysis of the ZSI output voltage with filter .Form this figure we can see the THD =0.66% and fundamental (50Hz) = 1056 .So we can see that a lot of higher order harmonics are removed in this output.

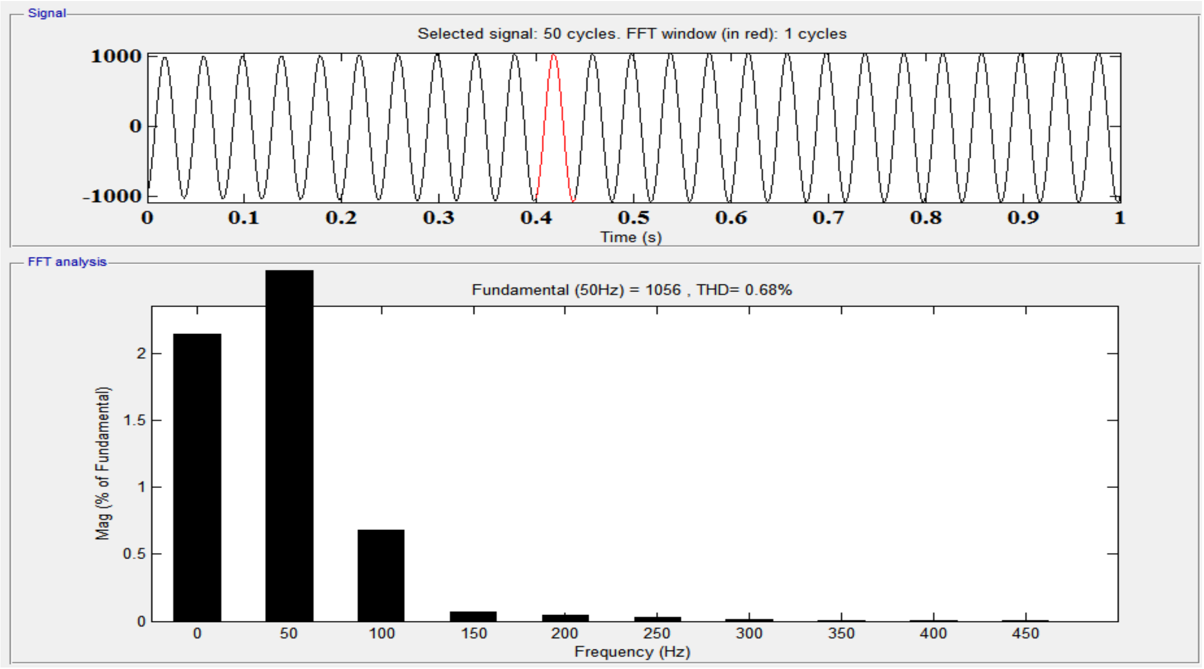

Figure 25 FFT analysis of the ZSI filtered output voltage

4.3.6 INVERTER SWITCHING PULSES

In this figure we can the Inverter Switching pulses used for switching the 4 switches. In this we have used the switching frequency of 10 kHz at a frequency of 50Hz.

Figure 26: Inverter switching pulses

4.4 SIMULINK MODEL OF SINGLE PHASE MOTOR CONNECT TO FUEL CELL

In this figure we have deigned Simulink model in this PEMFC 50 kW 625V dc fuel cell stack model is connected to Z-Source Inverter which has two inductors and capacitors .There are 4 inverter switches used in the inverter to converter dc to ac .Then a single phase motor is connected to that ac supply at various load connected to motor. In this case we have two loads each of time period of 5 sec. Here the load is change from 1 to 5 N-m.

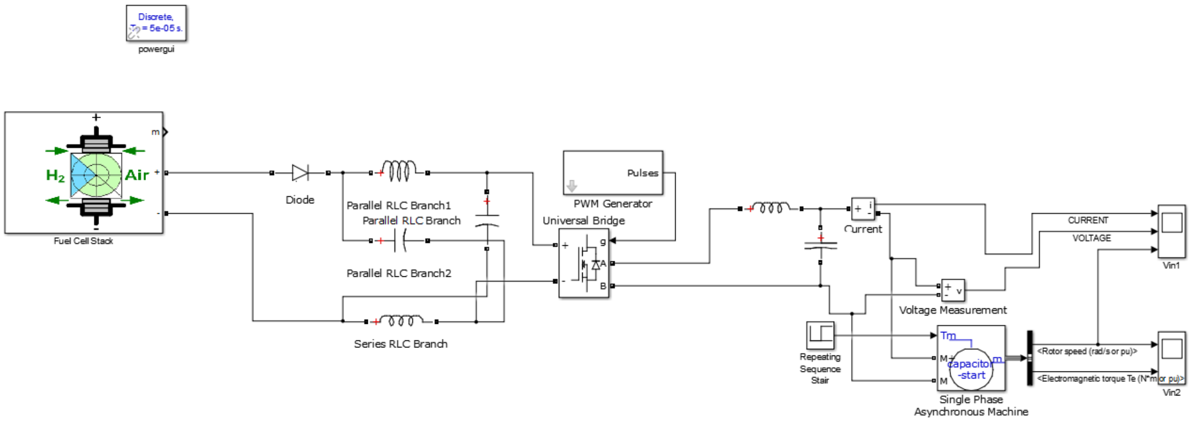

Figure 27 Simulink model of single phase motor connect to fuel cell

4.4.1 VOLTAGE OUTPUT OF SINGLE PHASE MOTOR WITH VARIOUS LOADS

This is voltage output of single phase motor with various loads. Here there are two loads applied to the motor each to time period of 5 sec. In following output we can see the change in voltage w.r.t loads on the motor. Here the voltage change use due to change in load. At the point of change motor will draw more current.

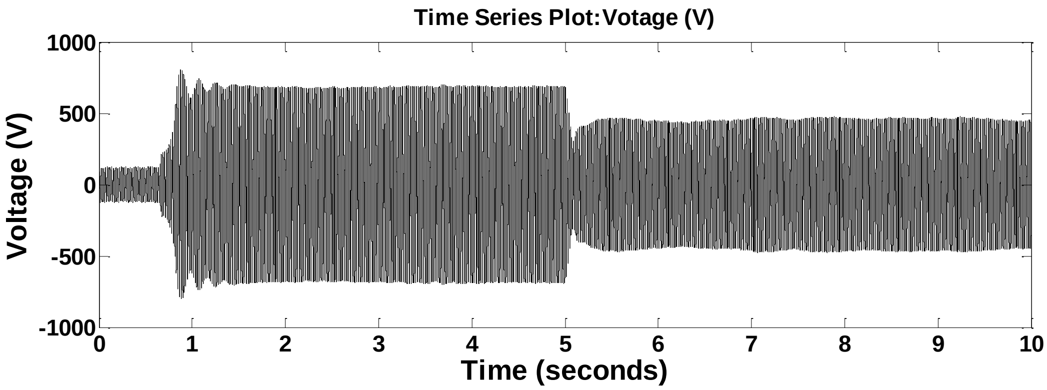

Figure 28 voltage output of single phase motor with various loads

4.4.2 CURRENT OUTPUT OF SINGLE PHASE MOTOR WITH VARIOUS LOADS

This is current output of single phase motor with various loads. Here there are two loads applied to the motor each to time period of 5 sec. In following output we can see the change in current w.r.t loads on the motor. . Here the voltage change use due to change in load. At the point of change motor will draw more current.

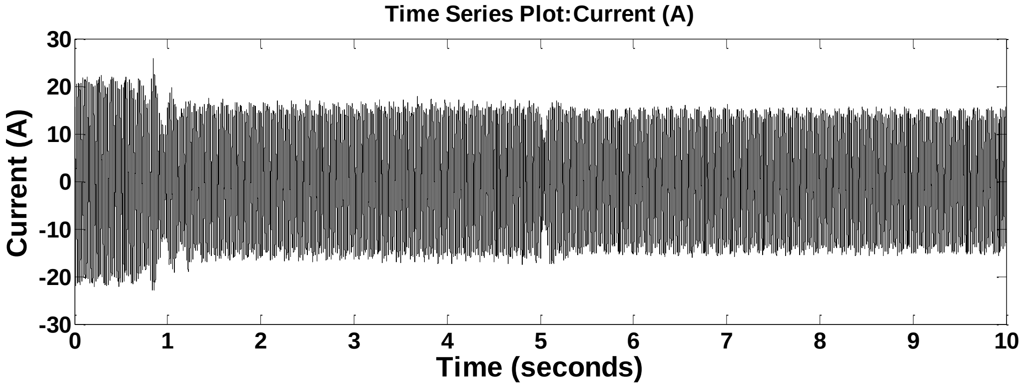

Figure 29 current output of single phase motor with various loads

4.4.3 SPEED OF SINGLE PHASE MOTOR WITH VARIOUS LOADS

This is speed output of single phase motor with various loads. Here there are two loads applied to the motor each to time period of 5 sec. In following output we can see the change in speed w.r.t loads on the motor. Here the change in speed is due to change in load. By changing the load from 10 to 40 there is change in speed from 185-190 rps to 160rps. So about 8% of change on the speed of motor.

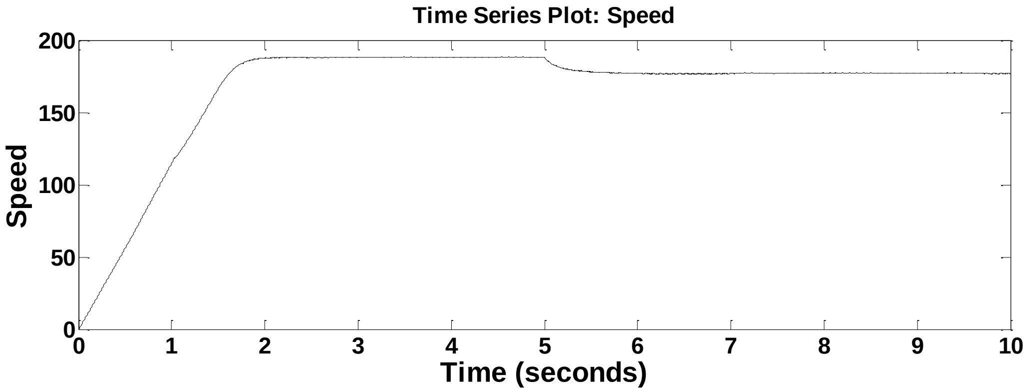

Figure 30 Speed of single phase motor with various loads

4.5 SIMULINK MODEL OF SINGLE PHASE MOTOR WITH CONTROLLED OUTPUT OF FUEL CELL AT VARIOUS LOADS

In this figure we have deigned Simulink model in this PEMFC 50 kW 625V dc fuel cell stack model is connected to Z-Source Inverter which has two inductors and capacitors .There are 4 inverter switches used in the inverter to converter dc to ac. Then a single phase motor is connected to that ac supply at various load connected to motor. In this case we have two loads each of time period of 5 sec. Here loads is changed from 10 to 15 N-m.

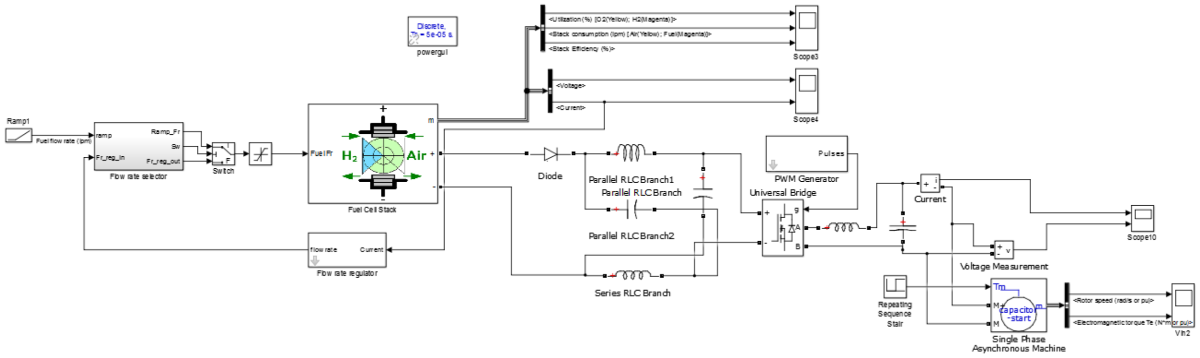

Figure 31Simulink model of single phase motor with controlled output of fuel cell at various loads

4.5.1 CONTROLLED FUEL CELL VOLTAGE OUTPUT AT VARIOUS LOADS

In this output we have showed that when the output voltage of fuel cell is controlled and then the change in output voltage of single phase motor at various loads. In this case we have two loads each of time period of 5 sec.

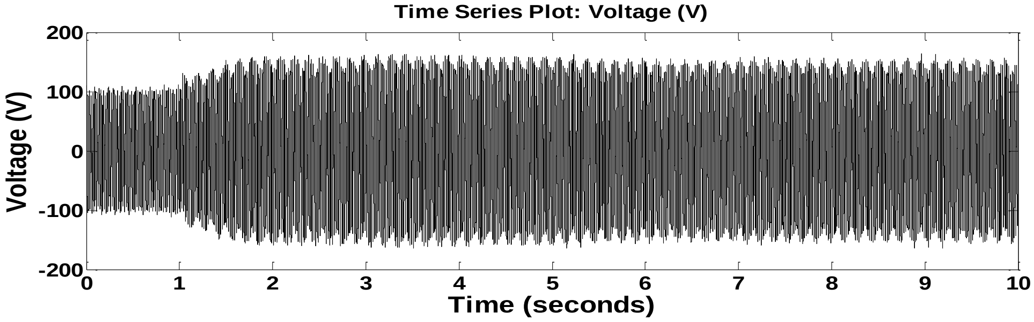

Figure 32 voltage output of single phase motor with controlled output of fuel cell at various loads

4.5.2 CONTROLLED FUEL CELL CURRENT OUTPUT AT VARIOUS LOADS

In this output we have showed that when the output voltage of fuel cell is controlled and then the change in output current of single phase motor at various loads. In this case we have two loads each of time period of 5 sec.

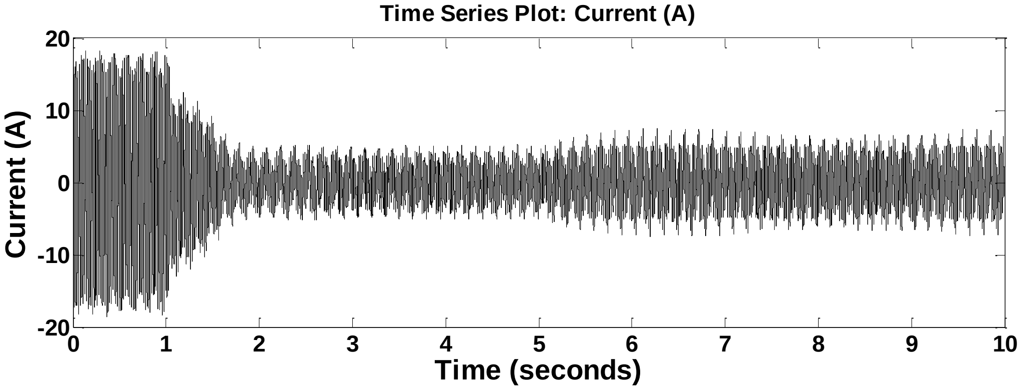

Figure 33 current output of single phase motor with controlled output of fuel cell at various loads

4.5.3 SPEED OF MOTOR AT VARIOUS LOADS

In this output we have showed that when the output voltage of fuel cell is controlled and then the change in speed of single phase motor at various loads. In this case we have two loads each of time period of 5 sec. So here change in speed is about 6%.

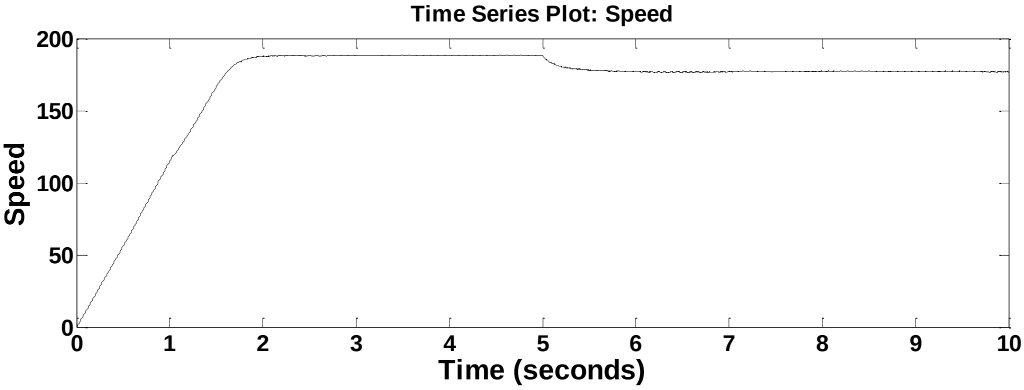

Figure 34 speed of single phase motor with controlled output of fuel cell at various loads

4.6 SIMULINK MODEL OF THREE PHASE INDUCTION MOTOR AT VARIOUS LOADS

In this figure we have deigned Simulink model in this PEMFC 50 kW 625V dc fuel cell stack model is connected to Z-Source Inverter which has two inductors and capacitors .There are 6 inverter switches used in the inverter to converter dc to ac .Then a three phase motor is connected to that ac supply at various load connected to motor. In this case we have two loads each of time period of 5 sec. Here load is changed from 10 to 25 N-m. .

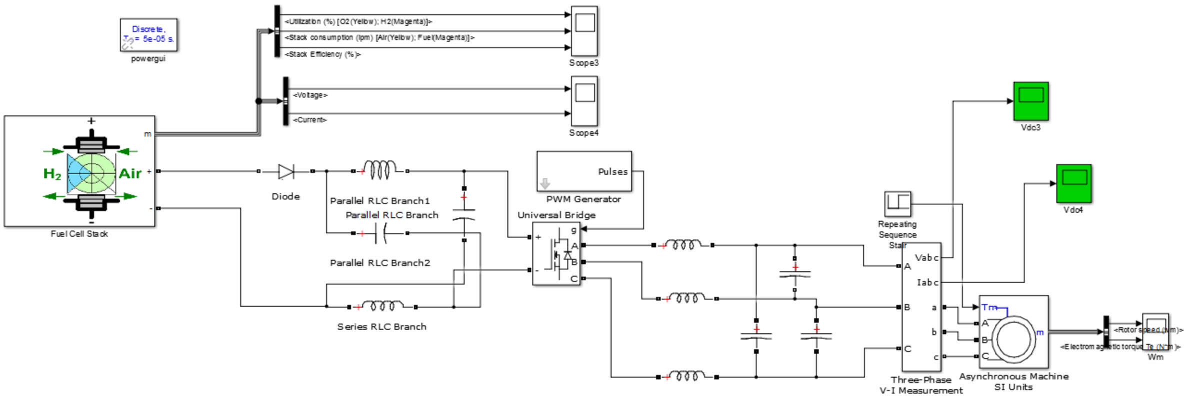

Figure 35Simulink model of 3 phase motor connected to fuel cell

4.6.1 VOLTAGE OUTPUT OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The output voltage of motor will change. In this case we have two loads each of time period of 5 sec.

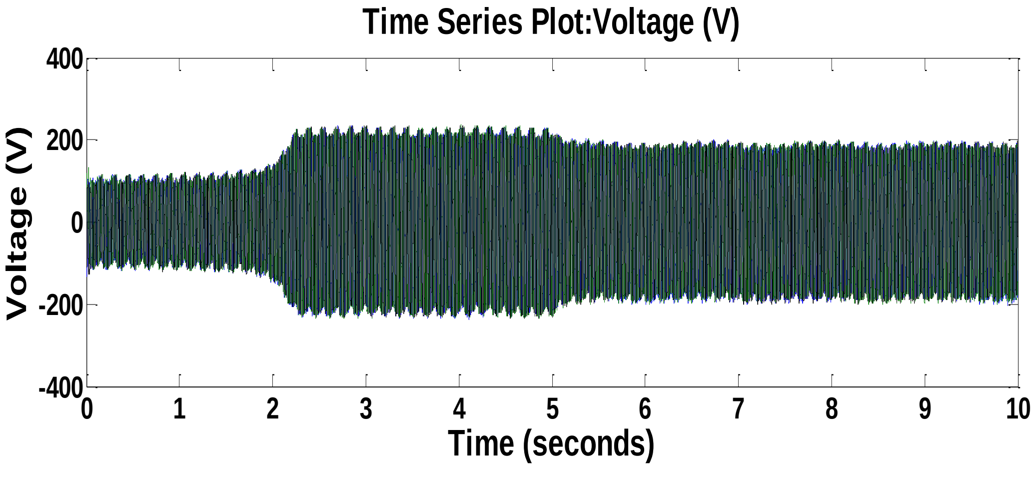

Figure 36 voltage output of motor with various loads

4.6.2 CURRENT OUTPUT OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The output current of motor will change. In this case we have two loads each of time period of 5 sec.

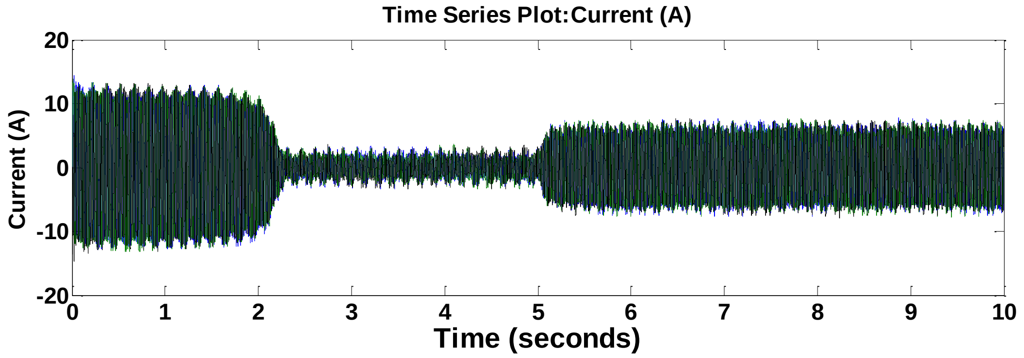

Figure 37 current output of motor with various loads

4.6.3 SPEED OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The speed of motor will change. In this case we have two loads each of time period of 5 sec.

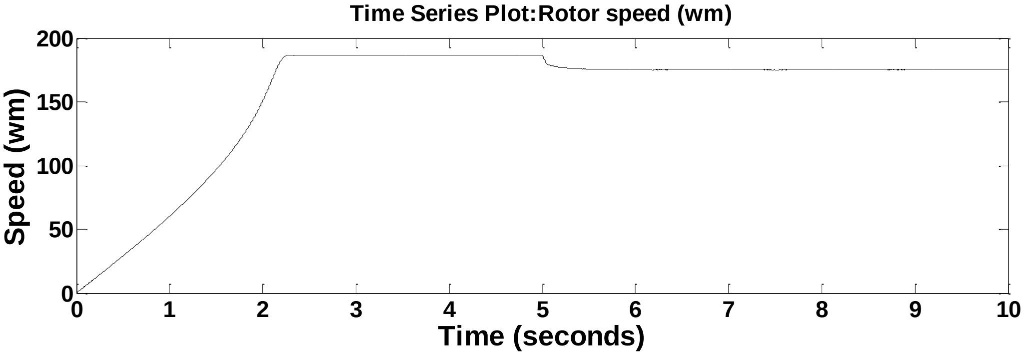

Figure 38 Speed of motor at various loads

4.7 SIMULINK MODEL OF CLOSED LOOP SPEED CONTROL OF THREE PHASE INDUCTION MOTOR AT VARIOUS LOADS

In this figure we have deigned Simulink model in this PEMFC 50 kW 625V dc fuel cell stack model is connected to Z-Source Inverter which has two inductors and capacitors .There are 6 inverter switches used in the inverter to converter dc to ac .Then a single phase motor is connected to that ac supply at various load connected to motor. A loop is used with PI controllers to form a closed loop b/w speed and duty cycle of inverter. Here the load is changed from 10 to 25 N-m.

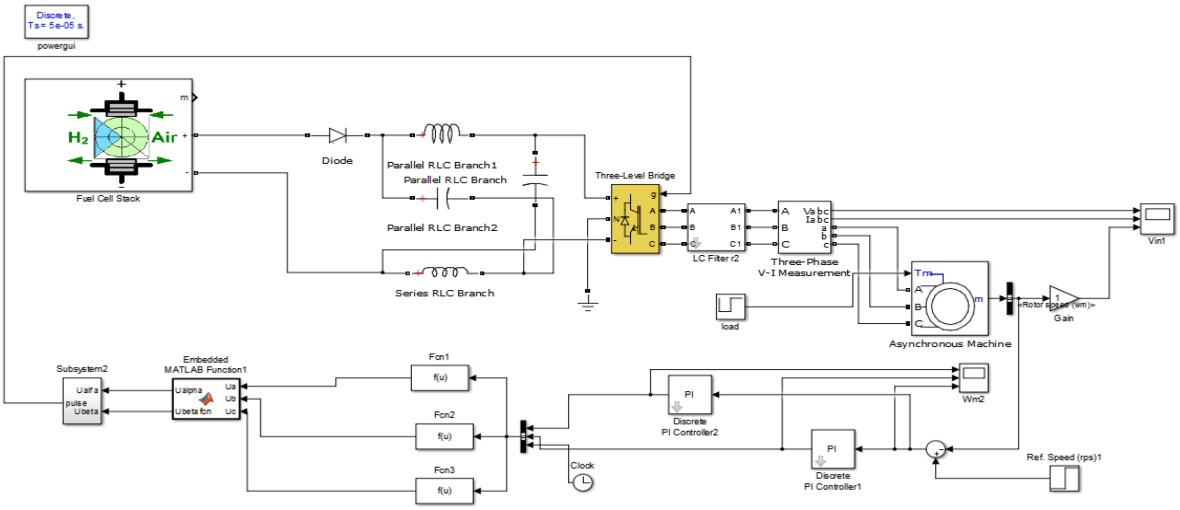

Figure 39Simulink model of closed loop speed control of three phase motor connected to fuel cell

4.7.1 VOLTAGE OUTPUT OF CLOSED LOOP SPEED CONTROL OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The output voltage of motor will change. In this case we have two loads each of time period of 5 sec.

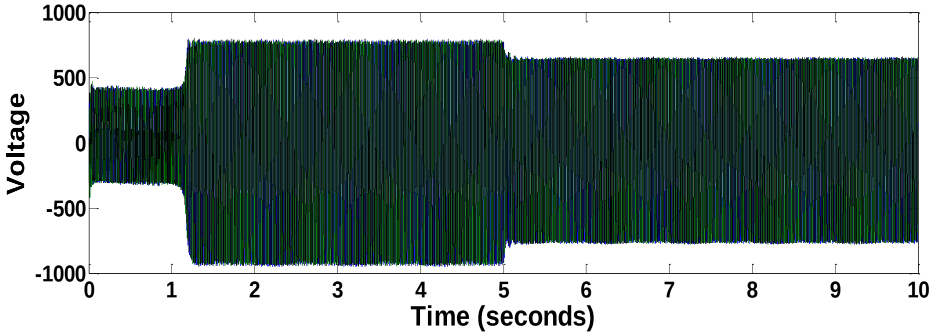

Figure 40 voltage output of motor with various loads

4.7.2 THREE PHASE INPUT VOLTAGE TO THE MOTOR

Here we have showed the variation in the voltage of one of the three phases of motor. Here the load is changed at 5sec. So from here we can see the variation in the voltage w.r.t load. Here in the following figure we can see change in voltage at lesser load to more load. At this point the motor will draw more current. Due to which voltage will drop.

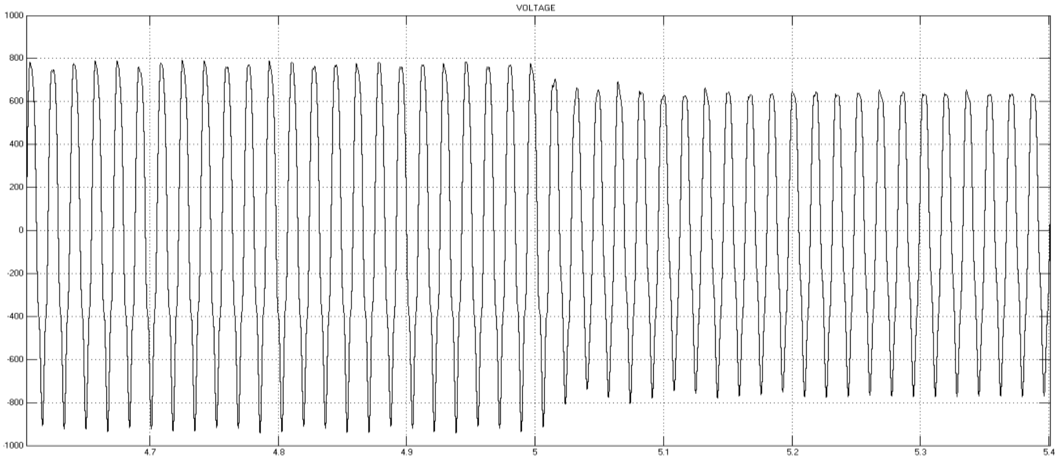

Figure 41 variation in voltage with load

4.7.3 CURRENT OUTPUT OF CLOSED LOOP SPEED CONTROL OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The output current of motor will change. In this case we have two loads each of time period of 5 sec.

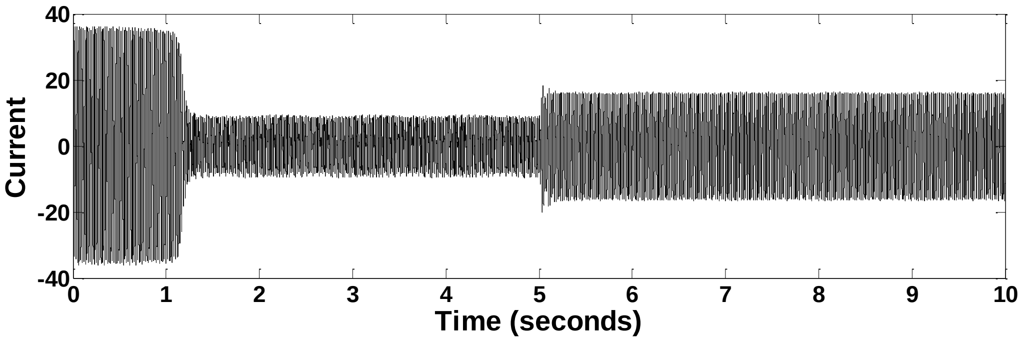

Figure 42 current output of motor with various loads

4.7.4 THREE PHASE INPUT CURRENT TO THE MOTOR

Here we have showed the variation in the current of one of the three phases of motor. Here the load is changed at 5sec. So from here we can see the variation in the current w.r.t load

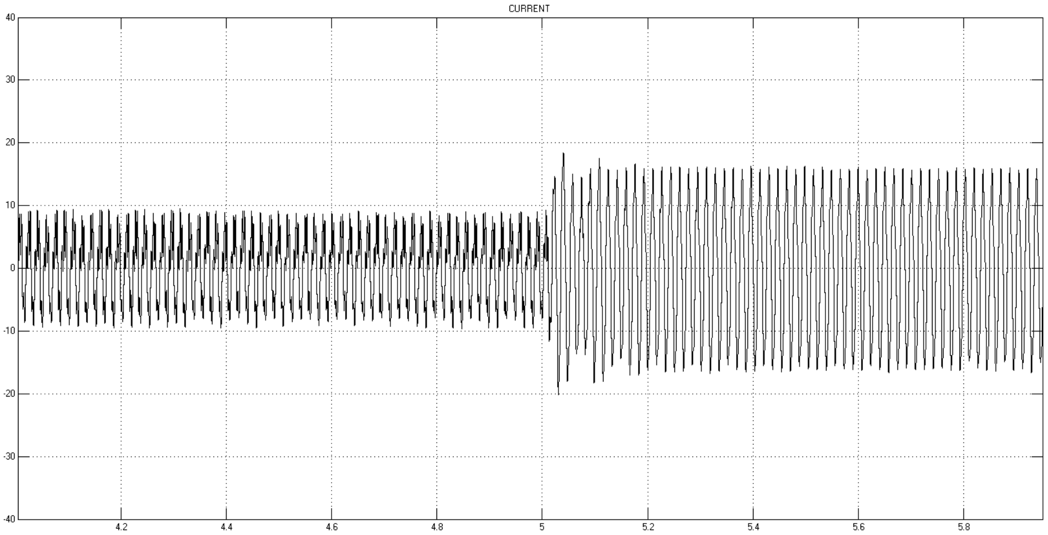

Figure 43 variation of current with load

4.7.5 SPEED OF THREE PHASE MOTOR AT VARIOUS LOADS

In this output we have showed that when the motor is under two different loads. The speed of motor will change. In this case we have two loads each of time period of 5 sec. Here we see there very less in speed even with change in load. Here the change in speed is just up to 2-4 rps.

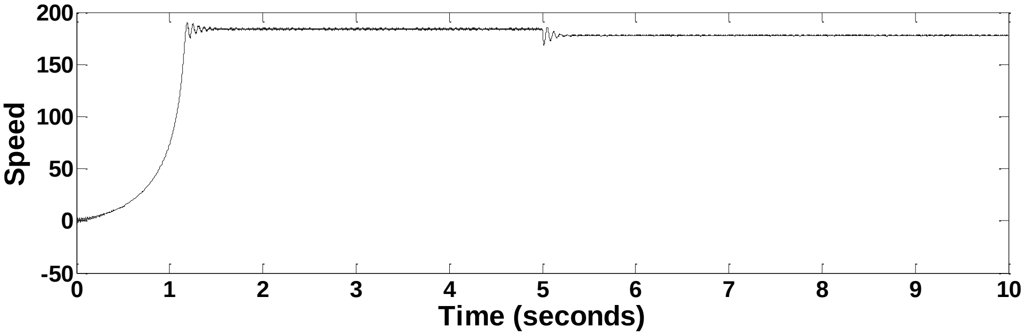

Figure 44 Speed output of motor with various loads

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

The thesis can be concluded as follow,

The modeling and simulation of Z-network with single phase and three phase full bridge inverter is presented in MATLAB-Simulink environment for the verification of the design parameters.

Simple Boost Control strategy is proposed. These are different of inverters like VSI, CSI and Z-SOURCE are described in detail and compared on the basis of simulation in MATLAB/ Simulink.

The ripple of output voltage, current and their harmonics profile are varied with modulation index and switching frequency. Also it focuses the effect of short switched state on the traditional and Z-source inverter.

Similarly different applications are successfully presented, first one is based on performance and simulation analysis of fuel cell (FC) system. Then different application is based on modeling and simulation of Z-source inverter connected to fuel with RL load, single phase and three phase of motor.

Finally, the simulated is done for the control of three phase motor connected with Z-SOURCE. The motor is subject to different load and then controlling is done by using PI controllers for speed control of motor.

The problem with use of fuel cell is that the output voltage of a fuel cell can’t be changed instantly, To change the output voltage of fuel cell, the flow of ions should be increased which is not possible instantly till date. This problem is solved externally by using Z-SOURCE inverter.

5.2 FUTURE SCOPE

In this thesis, the simulation module is built in the MATLAB/Simulink software to verify the proposed single phase and three phase Z-source inverter topology performance.

For the future research, the following improvement can be implemented.

In future various type of new modulation techniques can be used like simple boost, maximum control boost, constant control boost, traditional SVM and modified SVM. Any of these technique can be used to increase the efficiency and performance. The modified PWM control strategies may improve the performance of the inverter up to certain extent. Also by using double switching frequency the component will result better performance and also new modified topologies of Z-source can be used.

With optimization the inductor and the capacitor value of the Z-source network, the sizing of these electrical components could be minimized to the proper value, and also new modified topology of Z-source can used which could reduce the total cost of the proposed topology for the experiment research

This system can be used in HEV to reduce the fuel cost.

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