

FUEL CELL INVERTER SYSTEM: A SUSTAINABLE ENERGY SOURCE

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ



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Abstract

The necessity of new or alternative power sources gives rise to the fuel cells which can be sustainable energy sources. The research and development in the area of fuel cells are becoming popular day by day due to their various advantages. But the conversion process needs to be modified to connect the fuel cells to the grid. The dc voltage from the cells should be efficiently converted to ac as the voltage gives higher amount of fluctuation. New types of inverters like Z-source inverters which are efficient, EMI noise free and employed to reduce the ac output voltage fluctuation can meet these demands. This type of inverters also eliminates the necessity of additional boost converters. This paper tries to develop an adaptive control mechanism of the Z-source inverters using DSP board (DS- 1104) so that a quality power from fuel cells can be supplied to the grid.

Keywords

Fuel cell, Voltage source Inverter, Z-source inverter, adaptive control, DSP board (DS- 1104)

Declaration

We hereby declare that this thesis for the achievement of the Bachelor of Science in Electrical and Electronic Engineering is entirely our own work and has not been taken from the work of others. We also declare that as required, we have fully cited and referenced all material and results that are not original to this work. We would also like to mention that we have not submitted any part of this thesis anywhere else.

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CHAPTER 01

1. INTRODUCTION

1.0 Introduction

The power crisis is centre of the talk for last few years. The conventional energy sources haven't been able to meet the demand quietly. Energy sources like fossil fuel (coal, oil, gas) are depleting day by day. Burning fossil fuels cause emission of the greenhouse gases that contribute to global warming. There is negative impact on the environment too. For sustainable development the fossil fuels are one of the threats.

Developments of clean energy sources are becoming very important to the environment. The role of sustainable energy sources such as solar energy, wind energy, hydro energy, geothermal energy, tidal energy, biomass, ocean current energy is increasing day by day. Fuel cell is one of the new sustainable energy sources on which the research is going on.

As most sustainable energy sources are used to produce electricity, electric power conversion technology is crucial for the economic feasibility of the use of sustainable energy. In this chapter the alternative energy sources, especially fuel cell and its conversion process are described briefly.

1.1 Alternative energy sources

Alternative generation systems utilize renewable energy sources. They are gaining popularity due to their high operation efficiencies and low CO₂ emission levels. In the fields of electric power systems and power electronics a lot of research is going on to

develop alternative electricity generation systems. We are turning to clean and safe sustainable energy sources such as wind, photovoltaic, and fuel cells that, as believed, will contribute to a secure energy future.

1.1.1 Solar energy

Solar energy is a renewable energy source. Sunlight can be directly converted into electricity by a photovoltaic (PV) system, which uses the photovoltaic effect of semiconductors. Except high initial installation cost, PV systems are very promising as the alternative energy. The easiest way to use electricity generated by PV systems is to connect the solar panels to the utility grid through an inverter. The problem of PV arrays is they produce power only when illuminated. The production of electricity from solar sources depends on the amount of light energy. Batteries are used to store the captured electrical energy so that the energy can be made available for use when the sun is not shining.

1.1.2 Wind energy

The amount of wind energy around the world is enormous. Wind energy is clean, renewable, and widely distributed. In small scale individual turbines wind power is used to supply electricity to locations where the power grid is not accessible. To convert the kinetic wind energy into electricity, wind turbines are used. In fact, in remote areas small wind turbines in combination with battery storage have been used for household electricity generation over many decades.

1.1.3 Other types of bio-fuels

Though the production of algae to harvest oil for bio-fuels has not yet been undertaken on a commercial scale, but feasibility studies have been conducted to arrive at a certain level. In addition to its projected high yield, algaculture— unlike food crop-based bio-fuels — does not cause a decrease in food production, since it requires neither farmland nor fresh water. Many companies are pursuing algae bio-

reactors for various purposes, including scaling up bio-fuels production to commercial levels.

1.1.4 Disadvantages

Disadvantages of Solar Energy

Energy can be trapped only during daytime and only at places receiving desired amount of sunlight. Efficiency of solar panels is generally low, around 10-15%. Therefore, for a good power supply, large surface area is required. Solar power is costly to use in daily life.

Disadvantages of Wind Energy

Wind energy is clean. However, it does cause significant amount of noise pollution. Initial investment is quite high and efficiency is low, around 30%. And many feel that wind towers ruin the scenery of the adjoining place.

Disadvantages of Bio-fuel & Biomass

Areas which gather bio-fuels can sustain soil erosion. Bio-fuel is an excellent solvent so it generally dissolves the deposits in the filters. Because of this, the engine may need to be replaced more often. Biomass is a good alternative to using fossil fuels. However, it ends up doing the same thing as fuel. Combustion of biomass produces carbon dioxide and similar greenhouse gases. Another disadvantage of biomass is that it's generally produced from corn, wheat, barley, and similar crops all of which are seasonal. Thus biomass can only be produced only in certain seasons.

1.2 Fuel Cell

Fuel cells convert chemical energy directly into electricity without the combustion process. As a result, a fuel cell is not governed by thermodynamic laws, such as the

Carnot efficiency associated with heat engines, currently used for power generation. Fuel cells can achieve high efficiencies in energy conversion terms, especially where the waste heat from the cell is utilized in cogeneration situation.

A high power density allows fuel cells to be relatively compact source of electric power, beneficial in application with space constraints. In a fuel cell system, the fuel cell itself is nearly dwarfed by other components of the system such as the fuel reformer and power inverter. Fuel cells, due to their nature of operation, are extremely quiet in operation. This allows fuel cells to be used in residential or built-up areas where the noise pollution is undesirable.

The only disadvantage of the fuel cells associated with the cost. High costs compared to other energy systems technology. Operation requires replenishable fuel supply.

1.3 Fuel Cell inverter

In Fuel cell systems the load requires higher voltage than the dc source voltage. This inevitably requires dc-dc boost converter. The other topology which is used is flyback and current fed converters. The transformer based boost converters are flyback converter and it is derived topology of buck boost converter. When the power requirement is high then the voltage stress on the switch is high. So in such applications they are not good. Voltage-fed full-bridge converter with step-up transformer and current-fed full-bridge converter can be used for boost applications. Voltage-fed full-bridge converter for step-up applications display low voltage spike on the switches at the primary side. Thus, lower voltage rated MOSFETs can be used in voltage-fed converter. But the transformer of the voltage-fed step-up full-bridge has high leakage inductance and parasitic capacitance. High leakage inductance and parasitic capacitance increase the switching loss, together with the voltage and the current spikes on the components. Also, high currents through the switches on the

primary side and voltage ringing on the rectifier diodes are the other disadvantages of the voltage-fed full-bridge converter.

Current-fed converter is more suitable for high voltage applications than the voltage-fed converter because of the semiconductor losses, transformer dimensions and the voltage stress on rectifier diodes.

But the parasitic capacitances of the switches are too small compared to the amount of the transferred energy to them. The switches are damaged because the voltage spike exceeds the break down voltage. This fact decreases the reliability of the converter. The reliability problem can be solved in the current-fed full-bridge converter by using Z source structure instead of a single inductor.

1.3.1 Z source inverter

We need a new type of inverter to solve the problems of two-stage power conversion and low efficiency. High cost for the extra converter can be eliminated by the z source inverter. Other issues are stated below

- ❖ Difficult to start up (in-rush)
- ❖ Reliability problem (vulnerable to EMI)
- ❖ To have a new power conversion technology

1.4 Controller

1.4.1 PI Controllers

PID controller reduces the steady state error and also increases the stability . PI controller does not change anything in the stability. But now-a-days pi controller is also selected for some ac to dc application.

1.4.2 Fuzzy logic Controller

The fuzzy logic control is used for nonlinear system. It has simple structure and no mathematical model is needed. The other advantage is it has faster time response compared to PID controllers.

1.5 DSP Board

Analogue control is typically designed specifically for a single converter model. As a result, converter upgrade is impossible without replacing it with new hardware .The DS1104 R&D Controller Board is a new piece of hardware that upgrades the PC to a powerful development system for rapid control prototyping.

1.6 Conclusion

This work investigates how electricity can be generated from fuel cells with the best integration in energy systems suitable for domestic application. Power electronic converters provide the electrical interface between the sources, storage, and loads, and the availability of reliable, low-cost and efficient converters will produce current wave shapes exactly what the grid requires.

CHAPTER 02

2. FUEL CELL AND ITS APPLICATION IN POWER SYSTEM

2.0 Introduction

A fuel cell is an energy conversion device that generates electricity by a chemical reaction. It converts the chemicals hydrogen and oxygen into water, and in the process it produces electricity.

Most fuel cells available today use hydrogen and oxygen as the fuel. But hydrocarbons such as natural gas and alcohols like methanol are sometimes used. Difference between a fuel cell and a battery is, a battery has all of its chemicals stored inside and eventually it "goes dead". But in a fuel cell, as long as there is a flow of chemicals into the cell it never goes dead. In case of a fuel cell refueling can be done easily by replacing the fuel tank & it takes less time compared to recharging of a battery which gives less and less energy back every time it is recharged. Besides, battery can be recharged as long as chemical is available inside the battery.

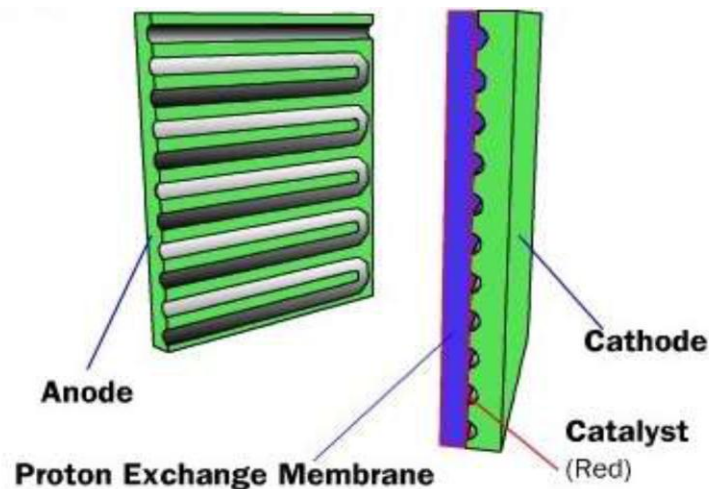


Fig.2.1: Fuel cell [1]

2.1 Working principle of a fuel cell

The working principle of a fuel cell is discussed below briefly:

1. At the anode hydrogen atoms enter a fuel cell and become 'ionized' through a chemical reaction.
2. Produced electrons travel through the external circuit.
3. Oxygen enters the fuel cell at the cathode.
4. Recombination of oxygen, electrons and hydrogen ions take place.

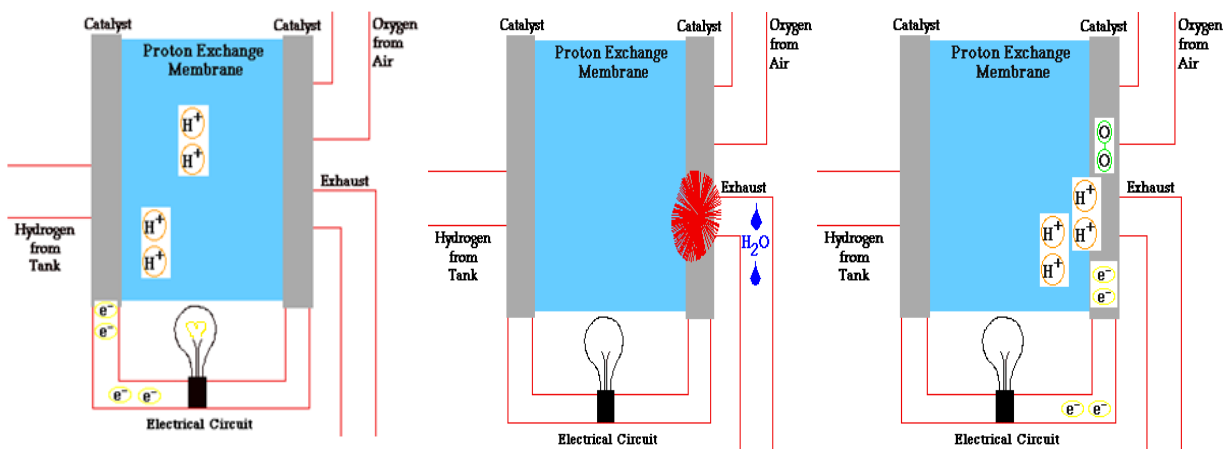


Fig.2.2: Working Principle of Fuel cell [1]

2.2 Types of fuel cells

2.2.1 Polymer exchange membrane fuel cell (PEMFC)

Electrolyte used : Polymer electrolyte in the form of a thin sheet

Efficiency : About 40 to 50 percent

Operating temperature : About 80 degrees Centigrade

Output Power : 50 to 250 kW

In PEMFCs, the solid, flexible electrolyte does not leak or crack. They are suitable for homes and cars due to their low operating temperature. But their fuels must be purified. On both sides of the membrane a platinum catalyst is used.

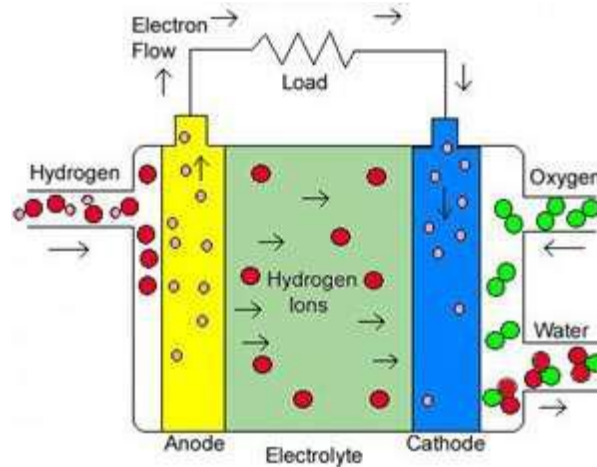


Fig.2.3: Polymer exchange membrane fuel cell [1]

2.2.2 Solid oxide fuel cell (SOFC)

Electrolyte used : Hard, ceramic compound of metal (like calcium or zirconium) Oxides (chemically, O₂)

Efficiency : About 60 percent.

Operating temperature : About 1,000 degrees Centigrade

Output Power : Up to 100 kW.

In SOFCs, reformer is not required to extract hydrogen from the fuel due to their high operating temperature. Waste heat can be recycled to produce steam which can be channeled into turbines to generate additional electricity. This process is called cogeneration of heat and power (CHP) and it improves the overall efficiency of the system. These fuel cells are best suited for large-scale stationary power generators. They have some disadvantages also. Their high temperature makes reliability a problem, because parts of the fuel cell can break down after cycling on and off repeatedly.

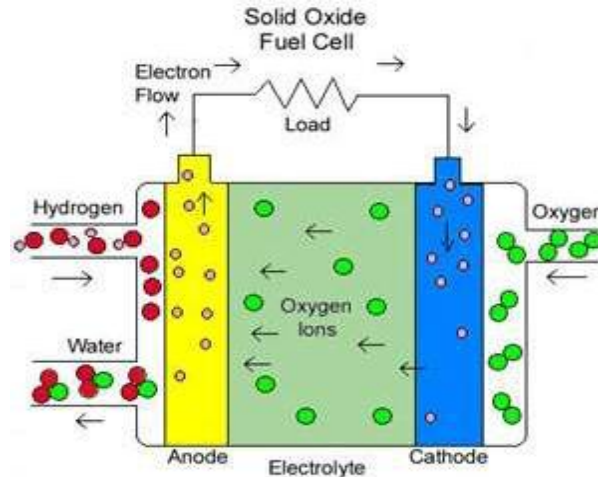


Fig.2.4: Solid oxide fuel cell [1]

2.2.3 Alkaline fuel cell (AFC)

Electrolyte used : A solution of potassium hydroxide (chemically, KOH) in water.

Efficiency : About 70 percent.

Operating temperature : 150 to 200 degrees Centigrade

Output Power : From 300 watts (W) to 5 kilowatts (kW).

The AFC is very susceptible to contamination, so it requires pure compressed hydrogen and oxygen. Its platinum electrode catalysts are expensive. So this type of fuel cell is unlikely to be commercialized. And like any container filled with liquid, it can leak.

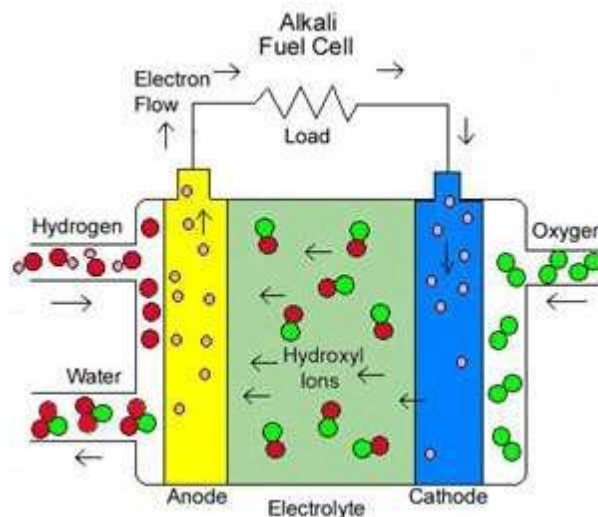


Fig.2.5: Alkaline fuel cell [1]

2.2.4 Molten-carbonate fuel cell (MCFC)

Electrolyte used	: High-temperature compounds of salt (like sodium or magnesium) carbonates (chemically, CO ₃)
Efficiency	: 60 to 80 percent
Operating temperature	: 600 degrees Centigrade
Output Power	: Best suited for large stationary power generators.

Like the SOFC, MCFCs are also best suited for large stationary power generators. They don't need exotic materials like SOFCs due to their relatively low operating temperature than SOFCs. This makes the design a little less expensive. Waste heat can be recycled to produce steam which can be channeled into turbines to generate additional electricity. Damage from carbon monoxide "poisoning" of the cell is limited by high temperature. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But the high temperature also limits the materials and safe uses of MCFCs—they would probably be too hot for home use.

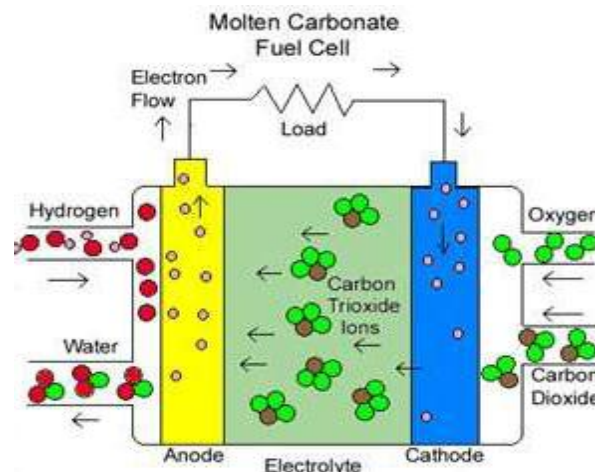


Fig.2.6: Molten-carbonate fuel cell [1]

2.2.5 Phosphoric-acid fuel cell (PAFC)

Electrolyte used	: Phosphoric acid
Efficiency	: 40 to 80 percent
Operating temperature	: 150 to 200 degrees Centigrade
Output Power	: Up to 200 kW.

The phosphoric-acid fuel cell can be used in small stationary power generation systems. It has a longer warm-up time due to its relatively high operating temperature than PEMFCs. This makes it unsuitable for use in cars. Platinum electrode-catalysts are needed, and internal parts must be able to withstand the corrosive acid.

2.2.6 Direct-methanol fuel cell (DMFC)

Methanol fuel cells are comparable to a PEMFC in regards to operating temperature, but are not as efficient. Also, the DMFC requires a relatively large amount of platinum to act as a catalyst, which makes these fuel cells expensive.

2.3 Advantages & disadvantages of fuel cells

2.3.1 Advantages

Some advantages of fuel cells are listed below in brief:

1. Sustainable energy source
2. Higher efficiency (49 %) & longer lifetime than the solar cell
3. Per unit (electricity) generation cost is lesser than solar cell
4. Environment friendly (i.e. harmless byproduct water)
5. High power density
6. Quiet operation (low noise and vibrations) and less maintenance cost
7. Availability of the fuel

2.3.2 Disadvantages

Some typical drawbacks of fuel cells are listed below in brief:

1. Setup cost is very high
2. Hydrogen is one of the most volatile, prone to combustion

3. Most common material used as a catalyst, platinum, is expensive
4. High operating temperature makes reliability a problem

2.4 Conclusion

The use of fuel cell to meet the present power crisis is increasing day by day. Although it works like a battery but it can supply power as long as there is fuel supply. The present power crisis of Bangladesh can be met if power production of Bangladesh doesn't entirely depend on fossil fuels specially gas which can't be replenished over time. Pressure on fossil fuels will be reduced greatly if the contribution of renewable energy sources can be increased by a great amount. Fuel cell can play an important role in this case. The challenge in front of us is to find a more convenient, more cost effective way to convert the DC power available from the fuel cell to AC & supply it to the grid.

CHAPTER 03

ANALYSIS OF VOLTAGE SOURCE AND Z-SOURCE INVERTER

3.0 Introduction

A detailed analysis & simulation of VSI & ZSI with their advantage & disadvantage is performed. Some papers suggest that that ZSI could increase the efficiency of the inverter by a few percent, while some argue the difference is not much. Finally the Performance parameters of VSI & ZSI is reviewed to choose the best topology to convert the DC voltage available from the fuel cell stack to ac.

3.1 Three-phase voltage-source inverter

The topology of standard three-phase VSI is shown in Fig.3.1. The eight valid switch states are given in Table 3.1. Shorting the load terminals by both the upper and lower switching devices of any phase leg is forbidden in the traditional inverters to avoid ST. However, to avoid short circuit across the dc link voltage supply, S1 and S4, S3 and S6, or S5 and S2 cannot be switched on simultaneously. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity. Of the eight valid states, two of them (7 and 8 in Table 3.1) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states (1 to 6 in Table 3.1) produce nonzero ac output voltages. The inverter moves from one state to another in order to generate a given voltage waveform. Thus the resulting ac output line voltages consist of discrete values of voltages that are V_s , 0 and $-V_s$ for the topology shown in Fig.3.1. Modulating technique is used to select the states in order to generate the given waveform. Modulating technique ensures the use of the valid states only.

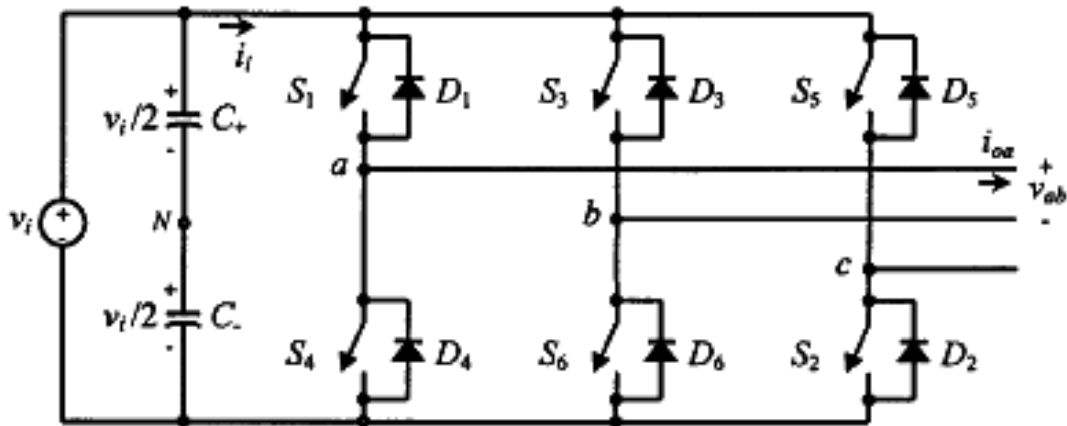


Fig 3.1: Three Phase bridge inverter [5]

Table 3.1: Valid switch states for a three-phase VSI

State	State No	Valid switch states	V_{ab}	V_{bc}	V_{ca}
S1, S2, and S6 are on and S4, S5, and S3 are off	1	100	V_s	0	$-V_s$
S2, S3, and S1 are on and S5, S6, and S4 are off	2	110	0	V_s	$-V_s$
S3, S4, and S2 are on and S6, S1, and S5 are off	3	010	$-V_s$	V_s	0
S4, S5, and S3 are on and S1, S2, and S6 are off	4	011	$-V_s$	0	V_s
S5, S6, and S4 are on and S2, S3, and S1 are off	5	001	0	$-V_s$	V_s
S6, S1, and S5 are on and S3, S4, and S2 are off	6	101	V_s	$-V_s$	0
S1, S3, and S5 are on and S4, S6, and S2 are off	7	111	0	0	0
S4, S6, and S2 are on and S1, S3, and S5 are off	8	000	0	0	0

3.1.1 Sinusoidal PWM

To vary α to control the inverter gain, PWM control is incorporated within the inverters. The sinusoidal PWM (SPWM) method is very popular in industrial applications and is extensively reviewed here. In multiple-pulse modulation, all pulses have the same width. But in SPWM, the pulse width is varied according to the amplitude of a sine wave evaluated at the center of the same pulse. In SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference of the desired frequency of the modulated pulse. The PWM scheme is illustrated in Figure 3.2, in which A_c is the peak value of triangular carrier wave and A_r is that of the reference, or modulating signal. When sinusoidal wave has magnitude higher than the triangular wave the comparator output is high, otherwise it is low. The magnitude ratio of A_c/A_r is called the modulation index (M) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to M . The amplitude of the triangular wave is generally kept constant.

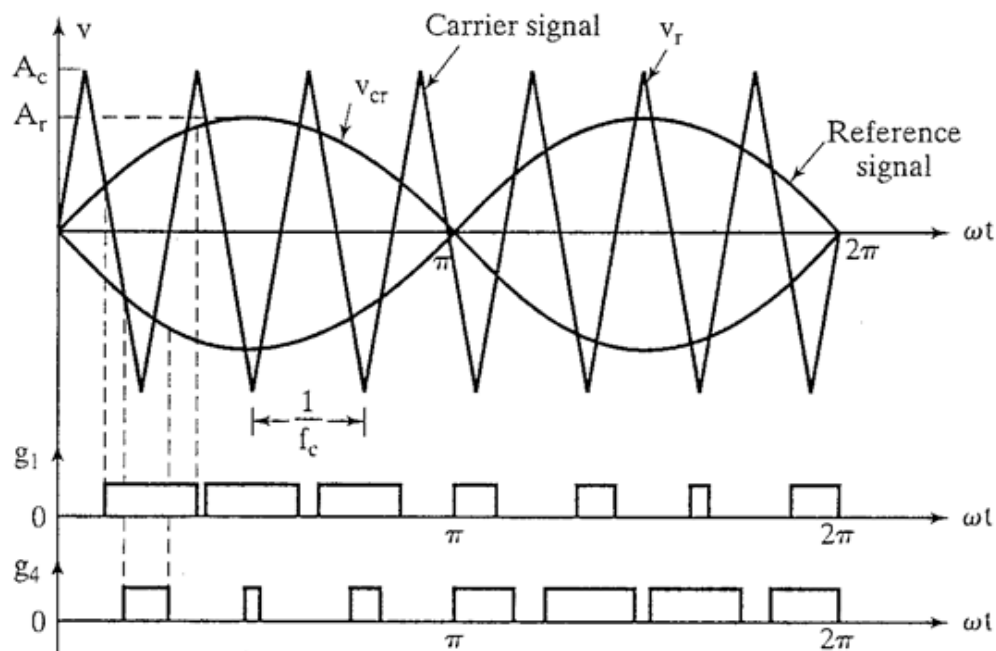


Fig. 3.2: Sinusoidal PWM for single phase inverter [4]

In SPWM, g_1 signal is generated by comparison with v_r & g_4 signal is generated by comparison with $-v_r$. Output voltage is low when g_1 and g_4 are both high which is illustrated in fig. 3.3.

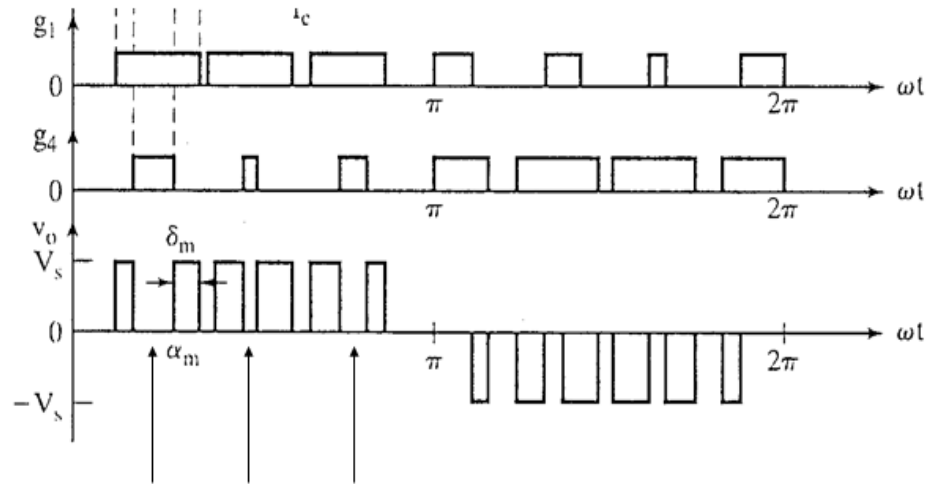


Fig. 3.3: Generation of output voltage, [4]

The harmonic profile is shown in fig. 3.4. From the figure it is obvious that the DF is significantly reduced in SPWM. The SPWM basically removes all harmonics less than or equal to $2P-1$.

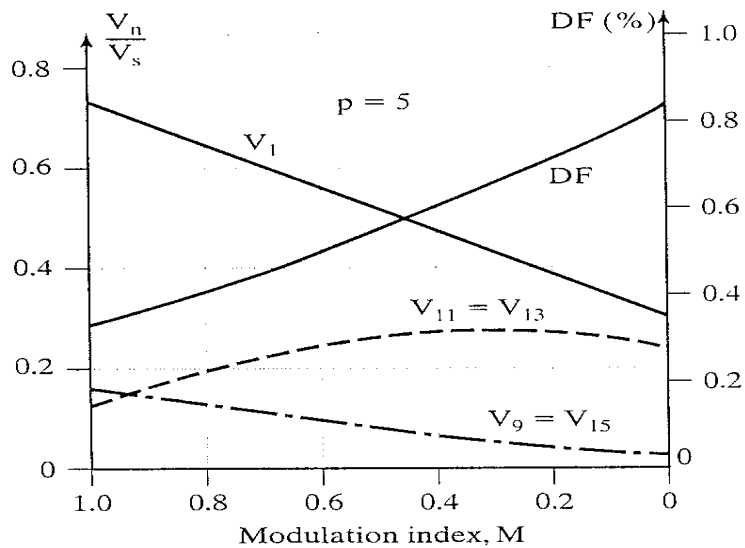


Fig. 3.4: Harmonic profile of sinusoidal pulse width modulation [4]

3.1.2 Sinusoidal PWM for three phase inverter

In SPWM for three phase inverter, to produce 120° out-of-phase load voltages, three modulating signals that are 120° out of phase are used. The ideal waveforms of three-phase VSI SPWM is shown in Figure 3.5. The instantaneous output voltage is $v_{ab} = V_i(S_1 - S_3)$.

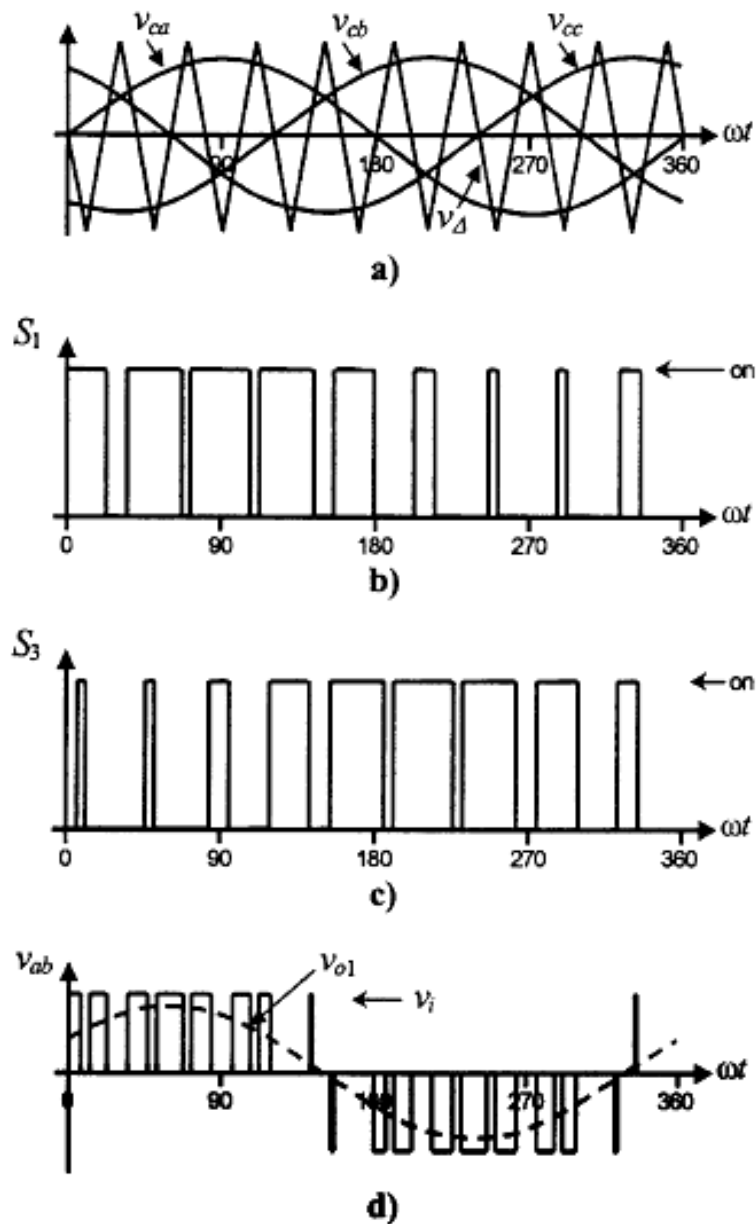


Fig. 3.5: Sinusoidal PWM for single phase inverter [5]

3.2 Z source inverter

The ZSI has two inductors and two capacitors in X- shape, as shown in Figure 3.6. Whether the traditional VSI that has eight switching states, the ZSI has nine permissible switching states. Like the traditional VSI, the ZSI has six active states when the dc voltage is impressed across the three-phase load, and two zero states when the load terminals are shorted through either the lower or upper three switching devices, respectively. But when the load terminals are shorted by both the upper and lower switching devices of any phase leg which is forbidden in the traditional inverters to avoid ST fault, the shoot-through state occurs. This ST state is actually the ‘third zero state’. The ST state can be achieved by seven different ways: ST via any phase, combinations of any two phase legs and all three phase legs. In ZSI, the traditional PWM techniques (Sine PWM) can be used with slight modification to the zero states due to the fact that the ZSI uses the traditional eight states as in traditional inverters with an extra state. The ST states are inserted only into the zero states while the active states remain unchanged and hence the ac output voltage of the inverter remains similar to a traditional inverter. This shoot-through zero state gives a unique buck-boost feature to the inverter, which makes it distinct from a traditional VSI or CSI.

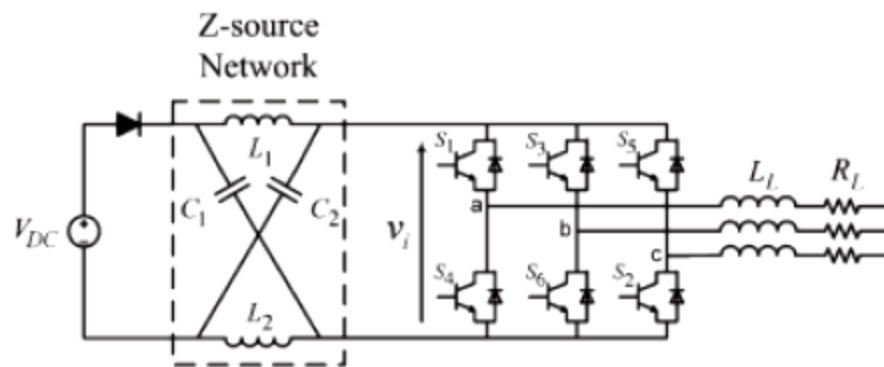


Fig 3.6: Three Phase bridge inverter [11]

3.2.1 Z-Source inverter operation

The operation modes of ZSI can be divided into three on the basis of the switching states of the inverter bridge which are described below:

Mode 1:

The inverter bridge can be represented by an equivalent current source as shown in Fig. 3.7(b) when it is operating in one of the six active states. The dc source voltage appears across the 'inductor and the capacitor' during this mode. Capacitor is charged. Energy flows to the load via the inductor.

Mode 2:

The inverter bridge can be viewed as a current source with zero value (i.e., an open circuit) when it is in one of the two traditional zero states. During this mode, the bridge 'short circuits' the load through either the upper or lower three switching devices. Fig. 3.7(a) shows the equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in one of the eight non shoot-through switching states. Voltage of the dc source appears across the 'inductor and the capacitor', except that no current flows to the load, from the dc source.

Mode 3:

Inverter bridge is operating in Shoot-through zero state when the load terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are gated on), any two phase legs, or all three phase legs. So, basically there seven different ways to generate shoot-through zero state. The bridge can be viewed as a 'short-circuit' from the dc link of the inverter as shown in Figure 3.7(c). No voltage appears across the load during this mode like in the zero state operation. The dc voltage of the capacitor is boosted to the required value according to the ST duty ratio. Sometimes the PV panel is unable to provide the required voltage due to the changing irradiance and temperature. At that moment, this ST interval (T_o) is inserted into the zero states to boost the voltage. The dc source (PV) is separated from the inverter bridge by the diode during this mode because $V_d > V_o$, $V_d = 2V_c$. The voltages

across C_1 and C_2 appear across L_1 and L_2 respectively causing the inductor currents to ramp up. In non Shoot-through states, that is, in both modes 1 and 2, the diode is forward biased & conducts while it is reversed biased during mode 3 (ST).

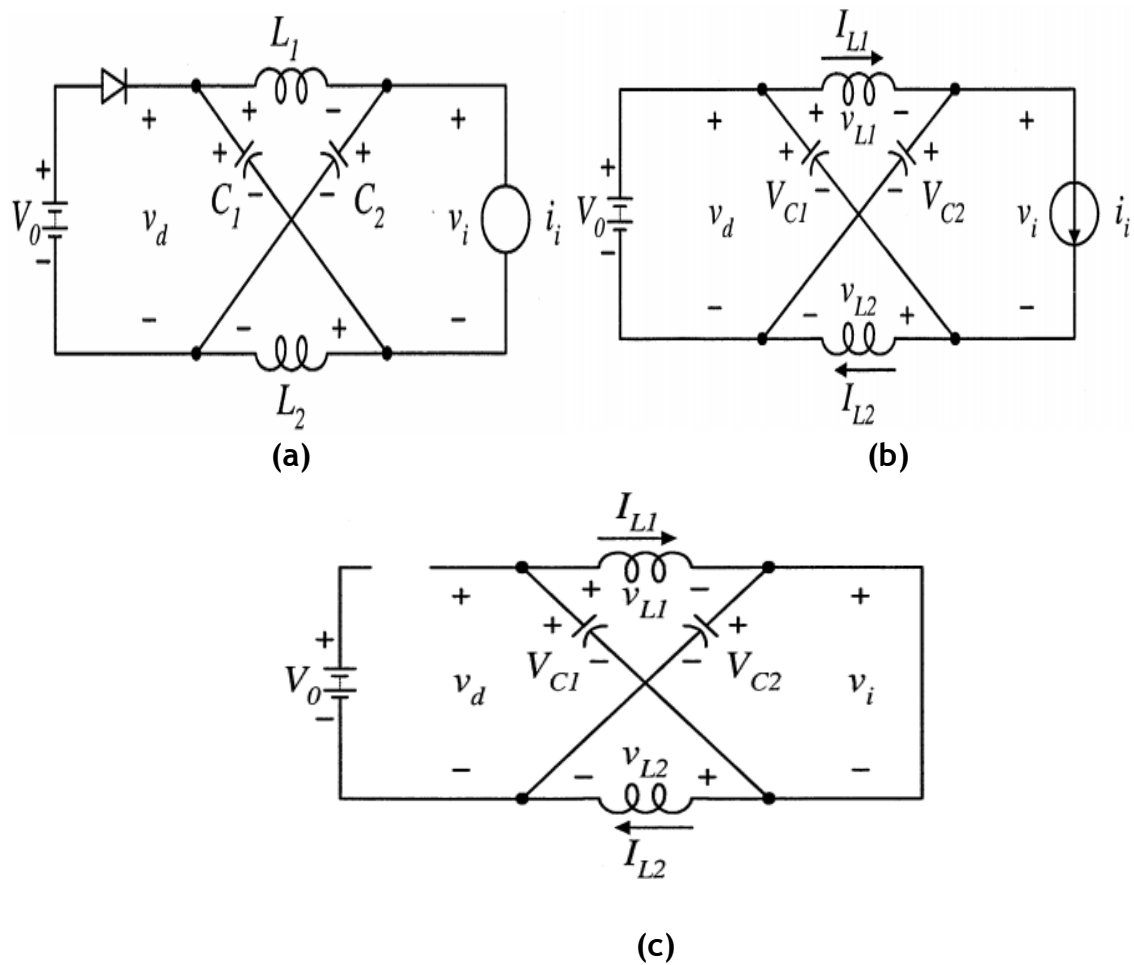


Fig 3.7: Equivalent circuits of ZSI: (a) viewed from the dc link (b) Non-Shoot-through mode (c) Shoot-through mode [10]

3.2.2 Circuit analysis and obtainable output voltage

Let assume that the inductors and capacitors have the same inductance and capacitance respectively. From the symmetry and the equivalent circuits, we have

$$V_{c1}=V_{c2}=V_c \quad v_{L1}=v_{L2}=v_L \quad (1)$$

Let assume that the inverter bridge is in the shoot-through zero state for an interval of T_0 , during a switching cycle, T . From the equivalent circuit, Fig. 3.7(c),

$$v_L = V_c \quad v_d = 2V_c \quad v_i = 0 \quad (2)$$

Again let assume that the inverter bridge is in one of the eight non shoot-through states for an interval of T_1 , during the switching cycle, T . From the equivalent circuit, Fig.3.7 (b),

$$v_L = V_o - V_c \quad v_d = V_o \quad v_i = V_c - v_L = 2V_c - V_o \quad (3)$$

Where V_o is the solar PV dc voltage & $T = T_0 + T_1$.

The average voltage of the inductors over one switching period (T) should be zero in steady state. From (2) and (3), thus, we have

$$V_L = \overline{v_L} = \frac{T_0 \times V_c + T_1 \times (V_o - V_c)}{T} = 0 \quad (4)$$

or

$$\frac{V_c}{V_o} = \frac{T_1}{T_1 - T_0} \quad (5)$$

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

$$V_i = \overline{v_i} = \frac{T_0 \times 0 + T_1 \times (2V_c - V_o)}{T} = \frac{T_1}{T_1 - T_0} V_o = V_c \quad (6)$$

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

$$\hat{v}_i = V_c - v_L = 2V_c - V_o = \frac{T}{T_1 - T_0} V_o = B \cdot V_o \quad (7)$$

Where

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2\frac{T_0}{T}} \geq 1 \quad (8)$$

is the boost factor resulting from the shoot-through zero state. The peak dc-link voltage \hat{v}_i is the equivalent dc-link voltage of the inverter. The output peak phase voltage from the inverter can be expressed as:

$$\hat{v}_{ac} = M \cdot \frac{\hat{v}_i}{2} \quad (9)$$

Where M is the modulation index. Using (7), (9) the output peak phase voltage from the inverter can be further expressed as

$$\hat{v}_{ac} = M \cdot B \cdot \frac{V_o}{2} \quad (10)$$

For the traditional V-source PWM inverter, $\hat{v}_{ac} = M \cdot \frac{V_o}{2}$. Equation (10) shows that the output voltage can be stepped up and down by choosing an appropriate buck-boost factor B_B .

$$B_B = M \cdot B \quad (0 \sim \infty) \quad (11)$$

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

$$V_{C1} = V_{C2} = V_C = \frac{1 - \frac{T_0}{T}}{1 - 2\frac{T_0}{T}} V_o \quad (12)$$

Modulation index M and boost factor B determines the buck-boost factor B_B . Using duty cycle of the shoot-through zero state over the non shoot-through states of the inverter PWM, the boost factor B as expressed in (8) can be controlled.

3.3 Performance measurement of three-phase voltage-source inverter & Z-source inverter

3.3.1 Performance parameters of an inverter

1. Harmonic factor of nth harmonic (HF_n)

Harmonic factor indicates the contribution of the nth individual harmonic.

$$HF_n = \frac{V_{on}}{V_{o1}} \quad \text{for } n > 1$$

V_{o1} = the rms value of the fundamental component

V_{on} = the rms value of the nth harmonic component

2. Total Harmonic Distortion (THD)

The total harmonic distortion indicates the closeness in shape between a waveform & its fundamental component.

$$THD = \frac{\left(\sum_{n=2,3,\dots}^{\infty} V_{on}^2 \right)^{1/2}}{V_{o1}}$$

3. Distortion factor (DF)

The distortion factor indicates the amount of harmonic distortion that remains in a particular waveform after the harmonics of that waveform have been subjected to second-order attenuation. It actually indicates the measurement of each harmonic component.

$$DF = \frac{\left(\sum_{n=2,3,\dots}^{\infty} \left(\frac{V_{on}}{n^2} \right)^2 \right)^{1/2}}{V_{o1}}$$

4. Lowest order harmonic (LOH)

The lowest order harmonic is the harmonic whose frequency is closest to the fundamental one & its amplitude is greater than or equal to 3% of the fundamental component.

3.3.2 Performance parameters of 3 phase VSI for 45V PEMFC

1. The rms line voltage, $V_L = 0.8165V_s = 0.8165 \times 45 = 36.7425V$

2. The rms phase voltage, $V_p = \frac{\sqrt{2}}{3} \times V_s = 0.4714V_s = 0.4714 \times 45 = 21.213V$

3. The rms line voltage at fundamental frequency,

$$V_{L1} = \frac{4V_s \sin 60^\circ}{\sqrt{2\pi}} = 0.7797V_s = 0.7797 \times 45 = 35.0865V$$

4. The rms phase voltage at fundamental frequency, $V_{p1} = V_{L1} / \sqrt{3} = 35.0865 / \sqrt{3} = 20.26V$

5. Total Harmonic Distortion Calculation

The rms line voltage at fundamental frequency, $V_{L1} = 0.7797V_s$

$$\left(\sum_{n=5,7,\dots}^{\infty} V_{Ln}^2 \right)^{1/2} = (V_L^2 - V_{L1}^2)^{1/2} = 0.24236V_s$$

Total Harmonic Distortion, THD = $0.24236V_s / (0.7797V_s) = 31.08\%$

6. Distortion factor Calculation

$$V_{Lh} = \left[\sum_{n=5,7,1}^{\infty} \left(\frac{V_{Ln}}{n^2} \right)^2 \right]^{1/2} = 0.00941V_s$$

Distortion factor, DF = $V_{Lh} / V_{L1} = 0.00941V_s / (0.7797V_s) = 1.211\%$

7. Harmonic factor & Distortion factor Calculation of the Lowest order harmonic (LOH)

The LOH is the fifth.

The rms line voltage at fifth harmonic, $V_{L5} = V_{L1}/5$

Harmonic factor of the fifth harmonic, $HF_5 = V_{L5}/V_{L1} = 1/5 = 20\%$

Distortion factor of the fifth harmonic, $DF_5 = (V_{L5}/5^2)/V_{L1} = 1/125 = 0.8\%$

3.3.3 Performance parameters of 3 phase ZSI for 45V PEMFC

$C_1=C_2=100 \mu F$

$L_1=L_2=1mH$

DC output voltage from fuel cell, $V_o=45V$

Modulation index, $M=0.742$

The shoot-through duty cycle, $T_o/T=0.428$

Boost factor from the shoot-through zero state, $B = \frac{1}{1-2\frac{T_o}{T}} = \frac{1}{1-2 \times 0.428} = 6.92$

The capacitor voltage, $V_{C1} = V_{C2} = V_C = \frac{1-\frac{T_o}{T}}{1-2\frac{T_o}{T}} V_o = 178.75V$

Buck-boost factor, $B_B = M \cdot B = 5.132$

The output peak phase voltage from the inverter, $v_{ac}^{\wedge} = M \cdot B \cdot \frac{V_o}{2} = 115.47V$

The peak line-to-line voltage = $\sqrt{3} \cdot V_p = 200V$

The rms line-to-line voltage = 141.42V

3.4 Performance & Characteristic comparison of Three-phase voltage-source inverter & Z-source inverter

A brief comparison between VSI & ZSI is listed in table according to their advantages & disadvantages. ZSI introduces a new cost effective power conversion technology compare to expensive VSI. Less distortion occurs in ZSI output voltage.

Table 3.2: Performance & Characteristic comparison of Three-phase voltage-source inverter & Z-source inverter

No.	Characteristics	VSI	ZSI
1	No of stages required	Two-stage power conversion.	Provides the buck-boost function by one stage conversion.
2	Start-up(in rush)	Difficult to start up (in-rush).	Has low or no in-rush current compared with the V-converters.
3	Reliability	Vulnerable to EMI.	Is immune to EMI noise and misgating.
4	PWM used	Traditional Sine PWM used.	Traditional Sine PWM used with modification to zero states (shoot through inserted).
5	Unwanted shoot through	Unwanted shoot through can cause damage to inverter.	ZSI can handle unwanted shoot through. Shoot through deliberately inserted and causes no damage.
6	Self-boost	No self-boost.	ZSI can boost itself which is it's unique feature.
7	Efficiency	Efficiency low.	Efficiency comparable at high loads.
8	Modulation index and Boost factor	Modulation index and Boost factor are not directly dependent.	Modulation Index (M) and Boost factor (B) are directly dependent on each other, a higher M, reduces B.
9	Control of dc link voltage	Control of dc link voltage is simple.	Control of dc link voltage is complex because dc link voltage is pulsating.
10	Capacitor & inductor requirement	Large Capacitor & inductor is required if boost converter is used.	Two small capacitors & two small inductors are required for Z-network.

3.4 Conclusion

We have made detail analysis about two different inverters VSI and ZSI. However, ZSI is a new topology compared to VSI. The Z-source converter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter and current-source converter and provides a novel power conversion concept. Circuit equations, operation modes, control methods and component design of ZSI were investigated to demonstrate its concept and superiority. A concluding comparison table was laid down in previous section. Simulation results for both the converters were produced in a Simulink environment.

CHAPTER 04

4. SYSTEM DESIGN AND SIMULATION

4.0 Introduction

This chapter includes a brief discussion on Simulink, modeling of fuel cell stack, PWM inverter, resonant inverter, Z-source inverter, PI controller and Fuzzy logic controller in Simulink. Also, Fuel Cell based inverter system is simulated for six different set-ups along with output wave shapes and error plot in Simulink. A comparison table is presented to compare the results for six different systems.

4.1 Simulink

Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi rate, i.e., have different parts that are sampled or updated at different rates (this feature is used to run different controls at different speeds).

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, one can draw the models just as one would with pencil and paper.

Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. One can also customize and create one's own block. Models can be hierarchical, and this approach provides insight into how a model is organized and how its parts interact. The graphical Simulink interface runs on an

underlying MATLAB engine. After one defines a model, one can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in MATLAB's command window.

The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations. Using scopes and other display blocks, one can see the simulation results while the simulation is running. In addition, one can change parameters and immediately see what happens, for "what if" exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization. Because MATLAB and Simulink are integrated, one can simulate, analyze, and revise one's models in either environment at any point. Figure 4.1 below shows a screen shot of MATLAB and Simulink environment with the SimPowerSystems tool box open.

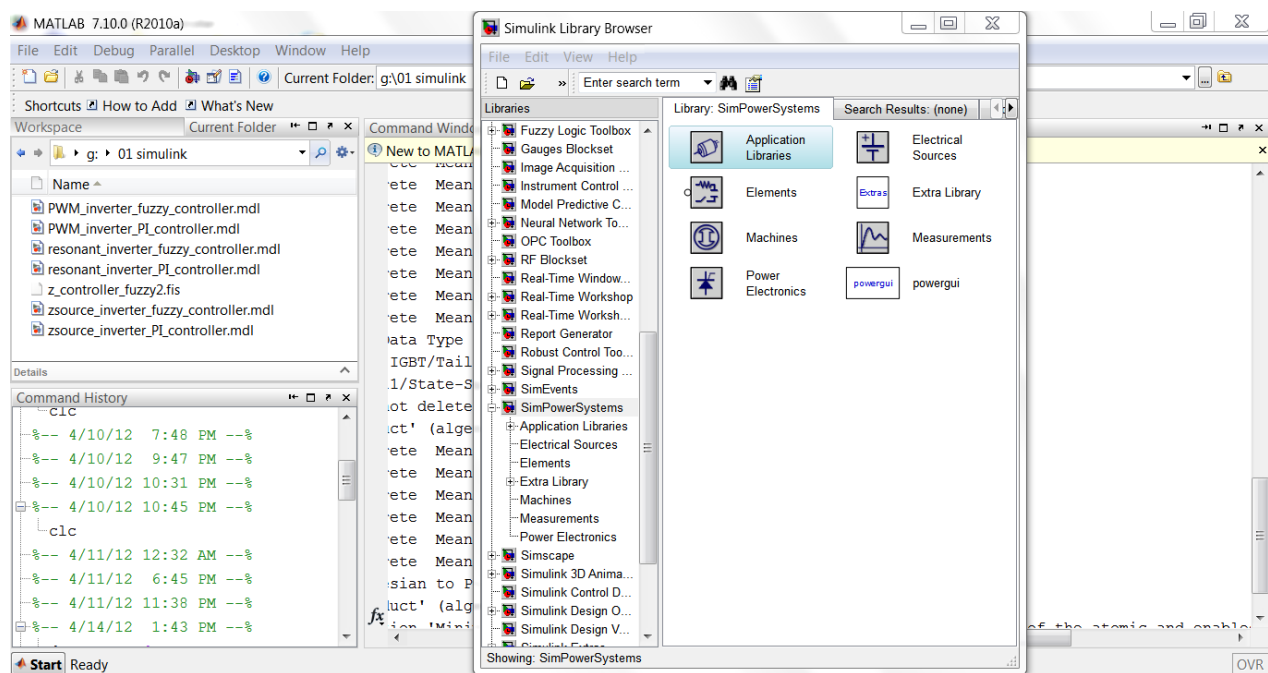


Figure 4.1: Screen shot of MATLAB & Simulink environment

Each component is modeled and evaluated on its own, to check if it gives the expected output, before it fits into the main simulation system. Most of the blocks are built with components available in the ‘SimPowerSystems’ toolbox and using some of the standard Simulink components along with the dSpace library. A few embedded Matlab control blocks are created by writing Matlab codes according to the user requirements. Some subsystems that require slower sampling rate are enabled using a different slower enable switching pulse.

The sections below discuss most of the major simulation blocks and their design parameters used in our simulation model. The generalized block diagram of the designed system is shown in figure 4.2:

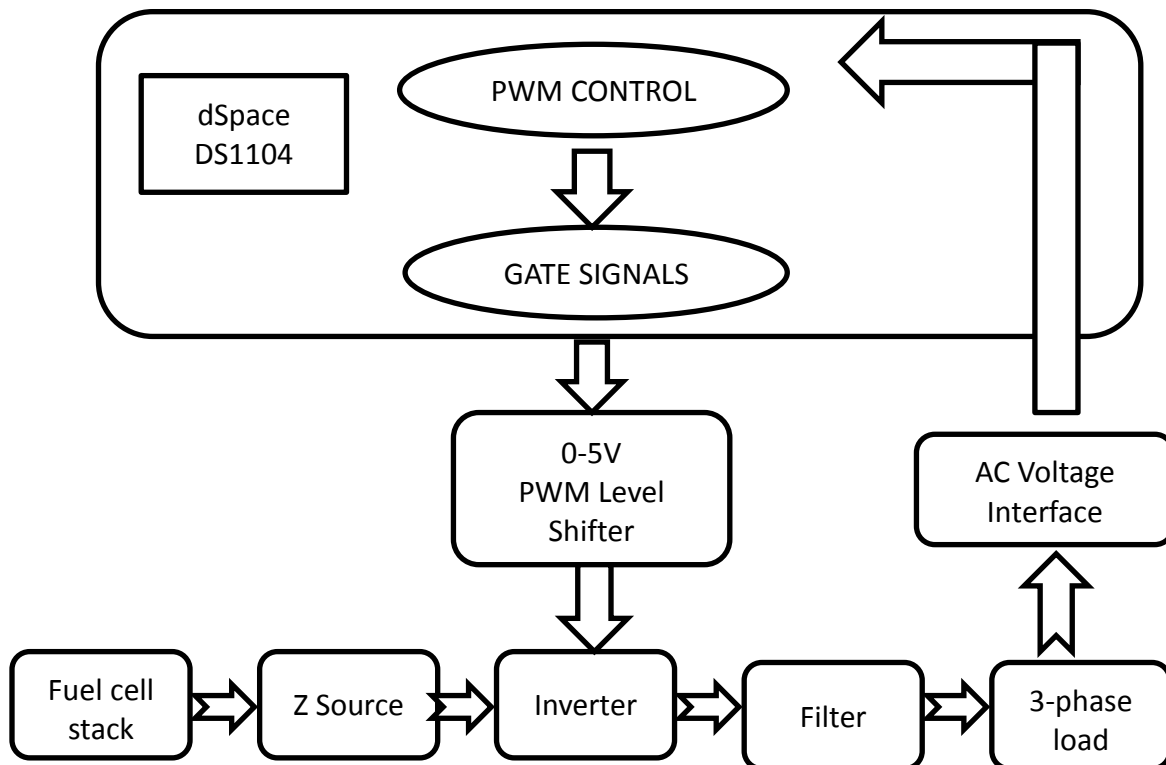


Figure 4.2: The generalized block diagram of the designed system

4.1.1 Modeling of Fuel Cell

Figure 4.3 shows the Fuel Cell Stack in Simulink used for simulation purposes along with its property window.

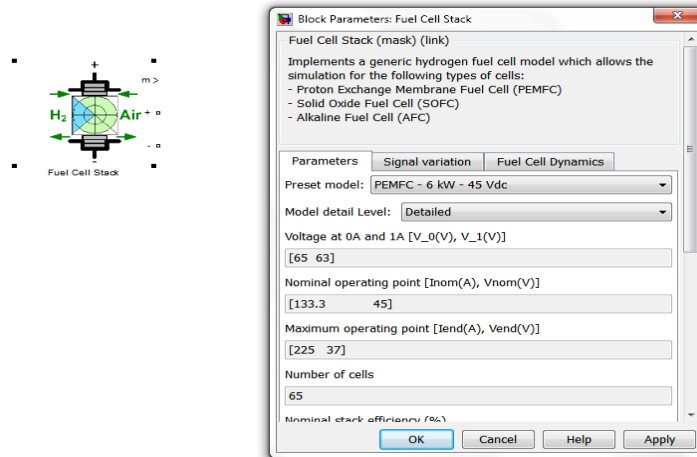


Figure 4.3: The Fuel Cell Stack and its property window

4.1.2 Design of PWM in Simulink

Figure 4.4 shows the PWM inverter block in Simulink used for simulation purposes along with its property window.

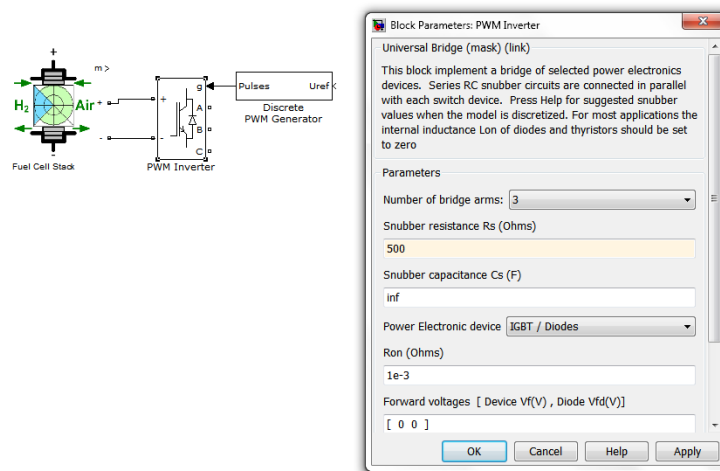


Figure 4.4: The PWM inverter block and its property window.

4.1.3 Design of Resonant Inverter in Simulink

Figure 4.5: shows the resonant inverter block in Simulink used for simulation purposes along with its property window.

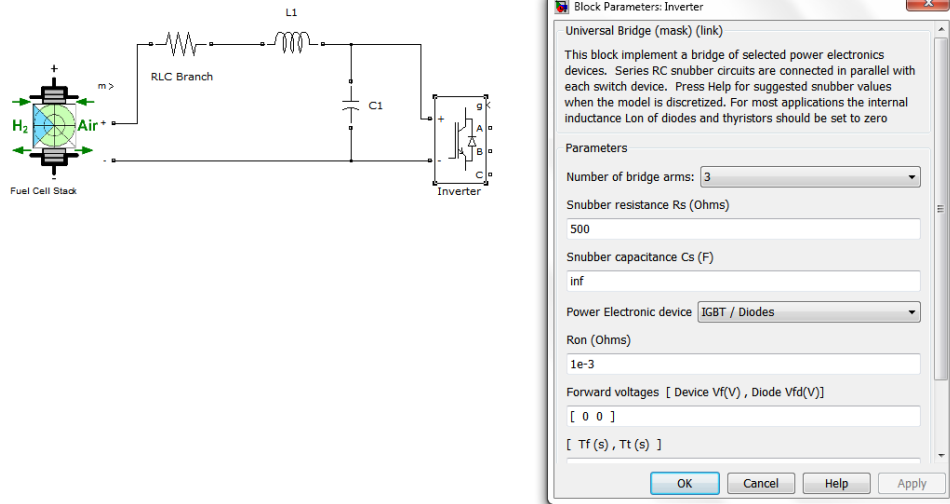


Figure 4.5: The Resonant inverter block and its property window.

4.1.4 Design of Z-source Inverter in Simulink

Figure 4.6 shows the Z-source inverter block in Simulink used for simulation purposes along with its property window.

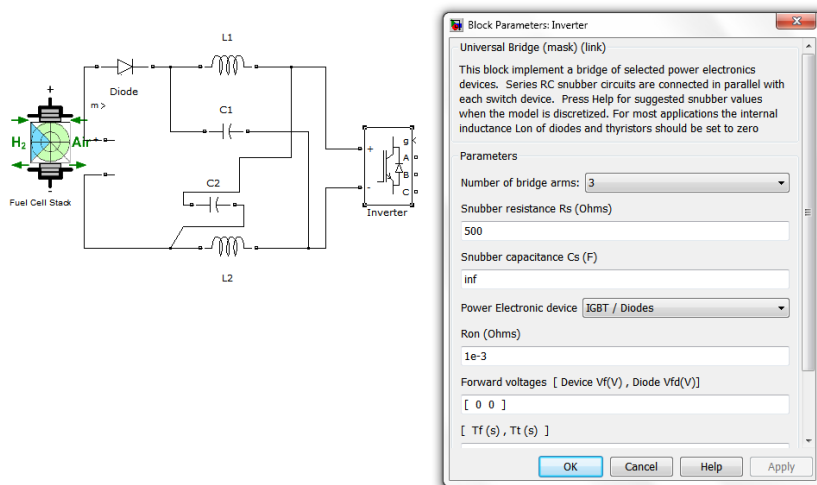


Figure 4.6: The Z-source inverter block and its property window.

4.1.5 Modeling of PI controller

Figure 4.7 shows the PI controller block in Simulink used for simulation purposes along with its property window.

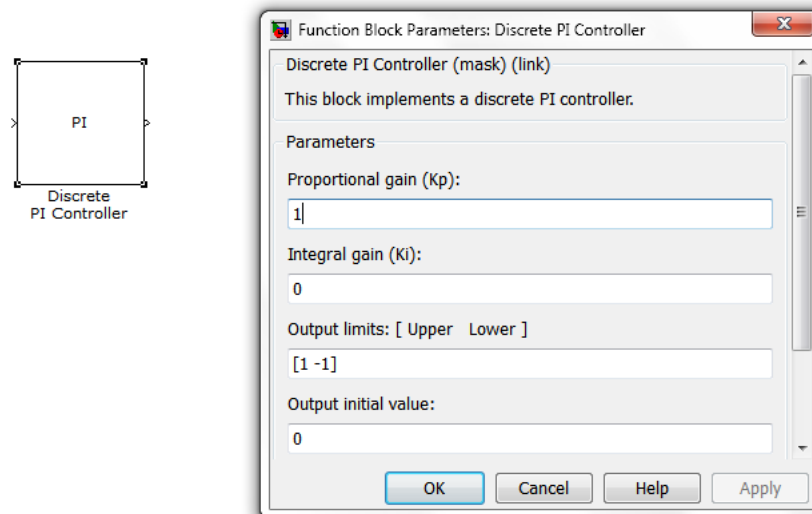


Figure 4.7: The PI controller block and its property window

4.1.6 Modeling of Fuzzy logic controller

A Fuzzy control strategy is developed in to improve the performance of the fuel cell system which is based on system error and its rate of variations. In an online self tuning PID controller for PEM fuel cell systems is described. However, from the literature it can be seen that the fuzzy controller design is widely used for performance enhancement in fuel cell systems.

A fuzzy logic based controller is designed, because the cost of the controller design and implementation is relatively low and it has a high performance/cost ratio. The fuzzy logic controller (FLC) is used to overcome inherent disadvantages such as uncontrollably large overshoot and large current ripple. FLC does not need an

accurate mathematical plant model. Therefore, it is applicable to a process where the plant model is unknown or ill defined. Fuzzy control is also nonlinear and adaptive in nature and offers robust performance under parameter variations and load disturbances.

Fuzzy-logic Control

The Fuzzy logic control is for a variety of challenging control applications, since it is a convenient method for constructing non-linear controllers. Thus, there is a possibility to use fuzzy logic control in place of conventional PI controller in fuel cell based system. The detailed design of fuzzy logic controller for boost converter and for load side inverter is presented. A triangle-shaped membership function has been used for fuzzy logic controller design.

The numbers of rules set for control are 9, which are based upon input variables error and change in error. Simulink model of voltage control scheme for three phase inverter has been designed. The developed FLC controller performance has been studied for isolated operation of fuel cell.

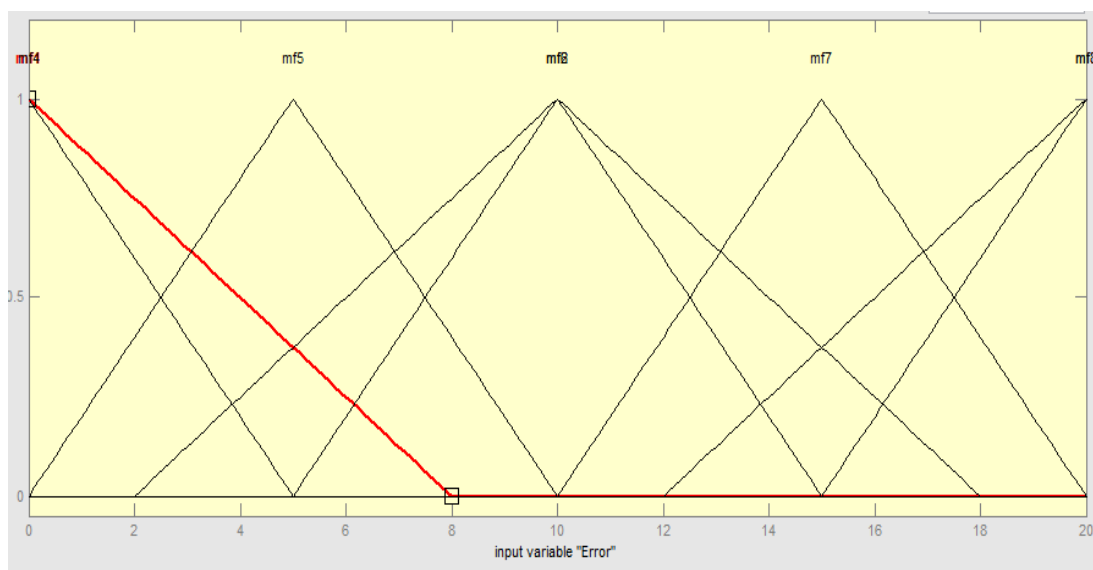


Figure 4.8: Membership function of the input variable Error

Simulation results are analyzed and compared with the results obtained using the conventional PI controller. From the simulated results it is shown that developed fuzzy logic controller can effectively track the reference voltage and is insensitive to the load conditions compared to PI controller.

Working with the Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox provides GUIs to perform classical fuzzy system development and pattern recognition. Using the toolbox, fuzzy inference systems are developed and analyzed, it also helps to develop adaptive neuro fuzzy inference systems, and perform fuzzy clustering. In addition, the toolbox provides a fuzzy controller block that can be used in Simulink to model and simulate a fuzzy logic control system. From Simulink, code can be generated for use in embedded applications that include fuzzy logic.

Building a Fuzzy Inference System

Fuzzy inference is a method that interprets the values in the input vector and, based on user defined rules, assigns values to the output vector. Using the GUI editors and viewers in the Fuzzy Logic Toolbox, the rules set can be built, the membership functions can be defined, and the behavior of a fuzzy inference system (FIS) can be analyzed.

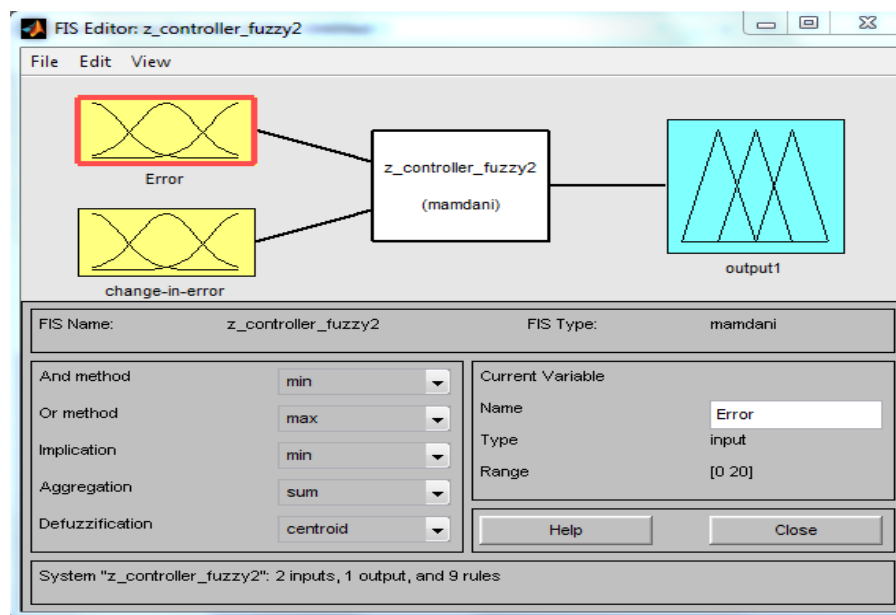


Figure 4.9: Fuzzy Inference System Editor

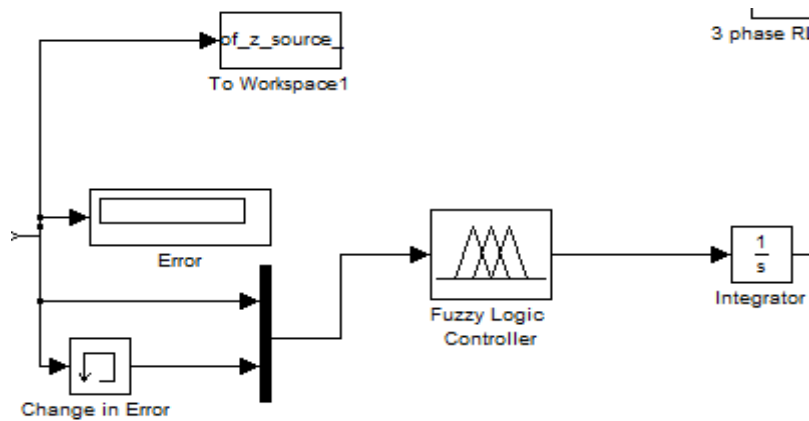


Figure 4.10: Building Fuzzy logic Controller in Simulink

In our simulation the fuzzy logic controller is used to control the output voltage of the inverter. The rms value of the output voltage is compared with the reference voltage 300 v. Then the subtracted value is called error. The error is passed to the memory unit to remember the previous error value.

These two parameter-error and change in error are the inputs of the fuzzy logic controller. The controlled output is integrated and given to the PWM generator as the modulating signal. As per the modulating signal the PWM generator generates the gate pulses for the inverter gate.

The error is passed to the workspace to analyze the error value at each and every step. The error plot has been shown in figure 4.29 and 4.31

In the variable editor the specifications that are used for fuzzy logic controller variable 'z_controller_fuzzy2' is given in figure 4.11.

The screenshot shows a MATLAB/Simulink workspace window titled 'z_controller_fuzzy2 <1x1 struct>'. It displays a table of fields and their corresponding values for a fuzzy logic controller object. The fields include 'name', 'type', 'andMethod', 'orMethod', 'defuzzMethod', 'impMethod', 'aggMethod', 'input', 'output', and 'rule'. The values are: 'z_controller_fuzzy2', 'mamdani', 'min', 'max', 'centroid', 'min', 'sum', '<1x2 struct>', '<1x1 struct>', and '<1x9 struct>' respectively.

Field	Value	Min	Max
name	'z_controller_fuzzy2'		
type	'mamdani'		
andMethod	'min'		
orMethod	'max'		
defuzzMethod	'centroid'		
impMethod	'min'		
aggMethod	'sum'		
input	<1x2 struct>		
output	<1x1 struct>		
rule	<1x9 struct>		

Figure 4.11: The Fuzzy logic controller property

4.2 List of simulations carried out

The following simulations (A) to (F) were performed in this thesis paper:

- A. PWM inverter with PI controller
- B. PWM inverter with Fuzzy logic controller
- C. Resonant inverter with PI controller
- D. Resonant inverter with Fuzzy logic controller
- E. Z-source inverter with PI controller
- F. Z-source inverter with Fuzzy logic controller

Complete Simulink model and responses (output voltage, error plot) of these six systems is going to be presented in the following section.

4.2.1 PWM inverter with PI controller

Fuel cell based inverter system using PWM inverter and PI controller is modeled in this section. Complete modeling in Simulink, output voltages measured before and after the Low Pass Filter, relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.12, 4.13, 4.14 respectively.

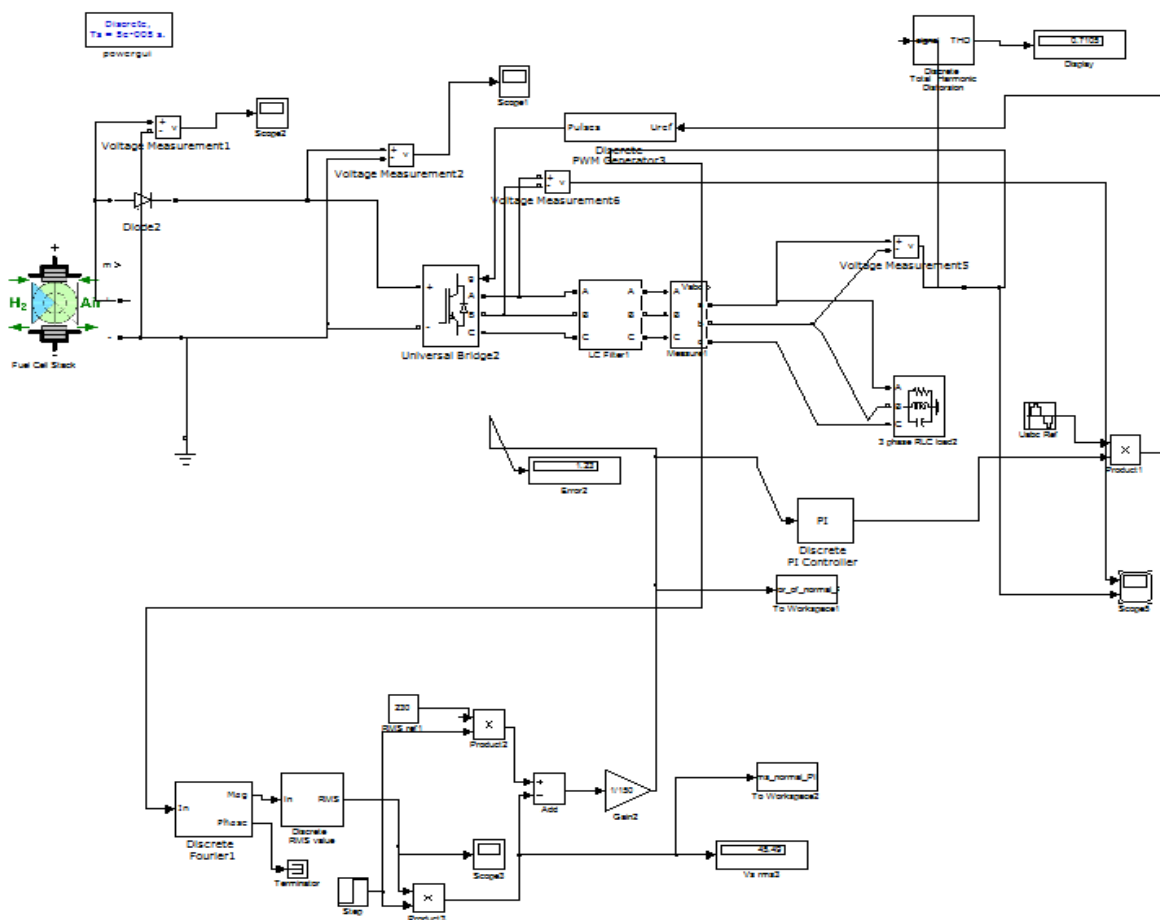


Figure 4.12: Modeling of PWM inverter with PI controller in Simulink

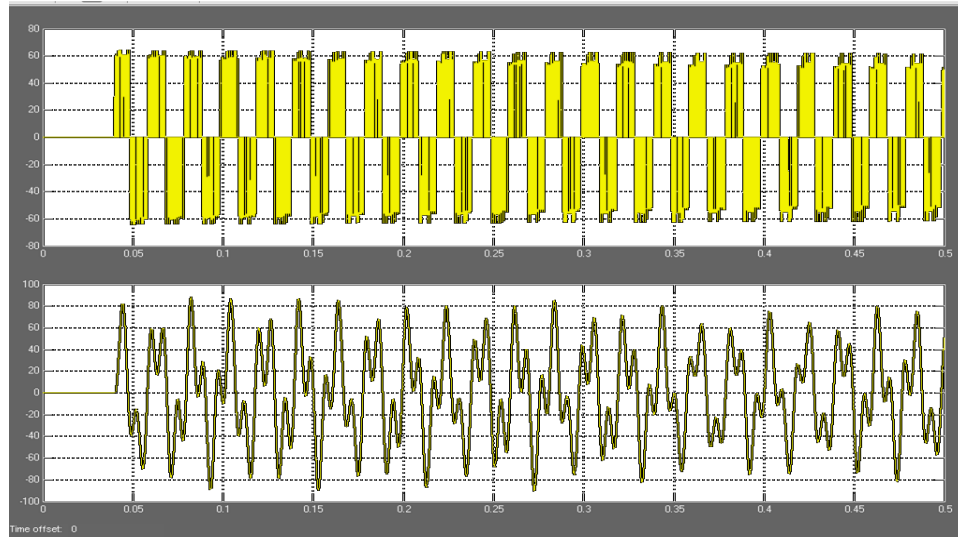


Figure 4.13: Output voltage measured across the inverter and load

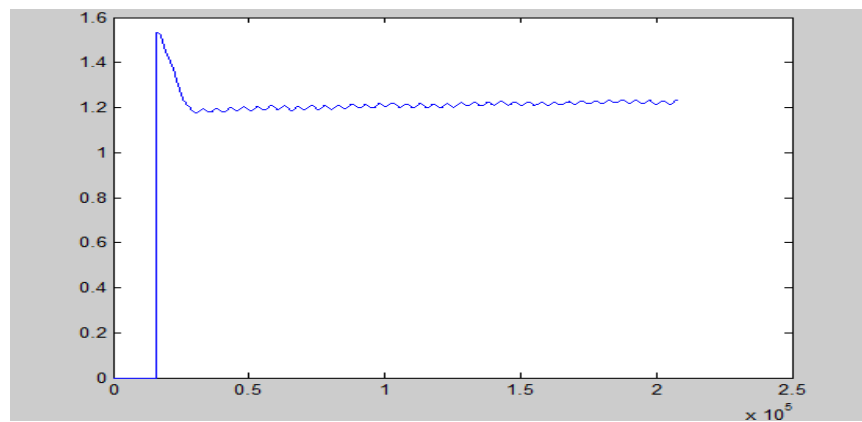


Figure 4.14: Voltage fluctuation (Error plot)

4.2.2 PWM inverter with Fuzzy logic controller

Fuel cell based inverter system using PWM inverter and Fuzzy logic controller is modeled in this section. Complete modeling in Simulink, output voltages measured before and after the Low Pass Filter, relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.15, 4.16, 4.17 respectively.

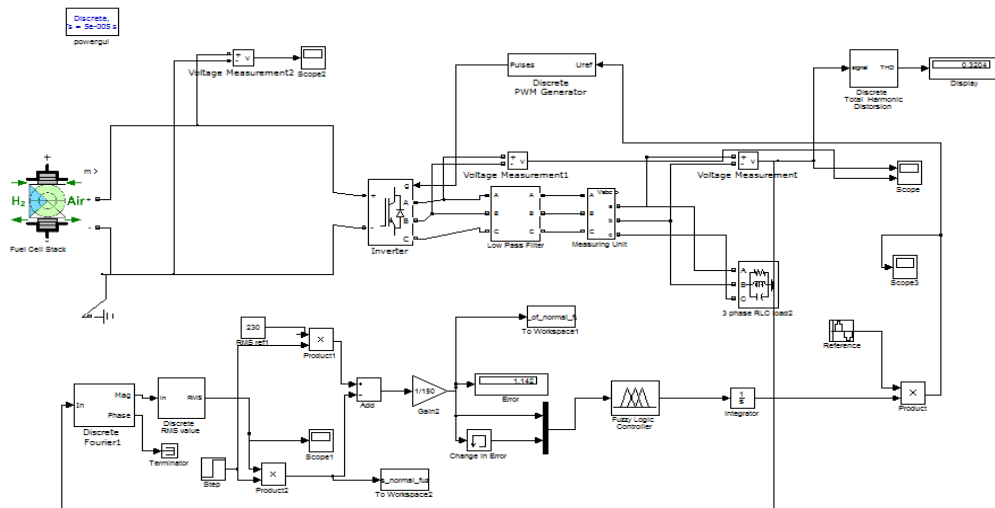


Figure 4.15: Modeling of PWM inverter with Fuzzy logic controller in Simulink

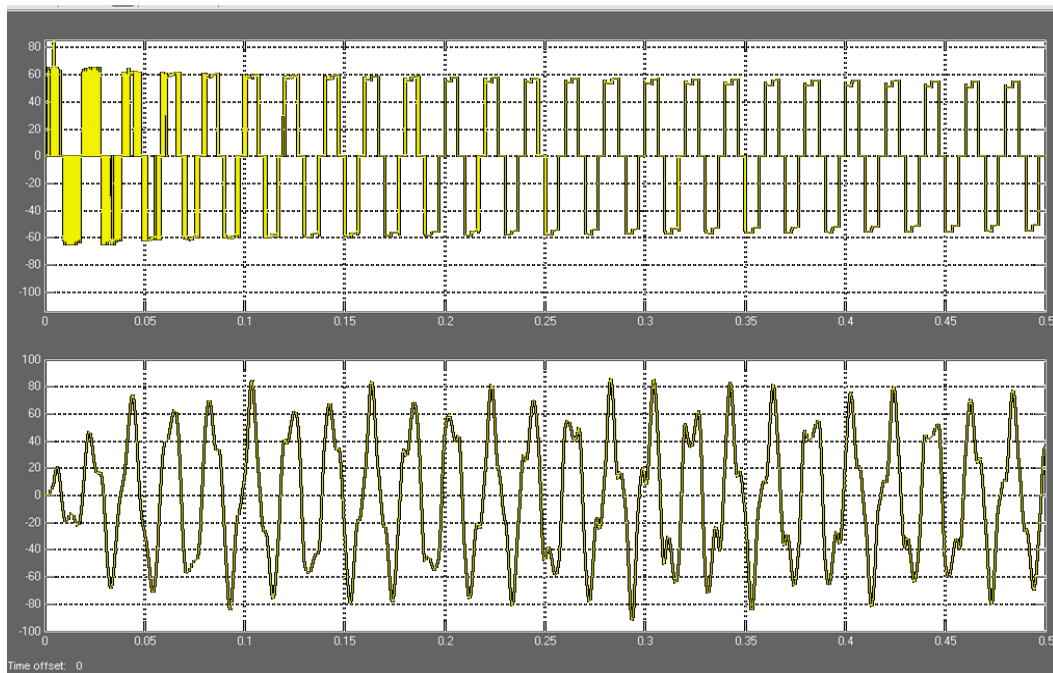


Figure 4.16: Output wave shapes measured across the inverter and load

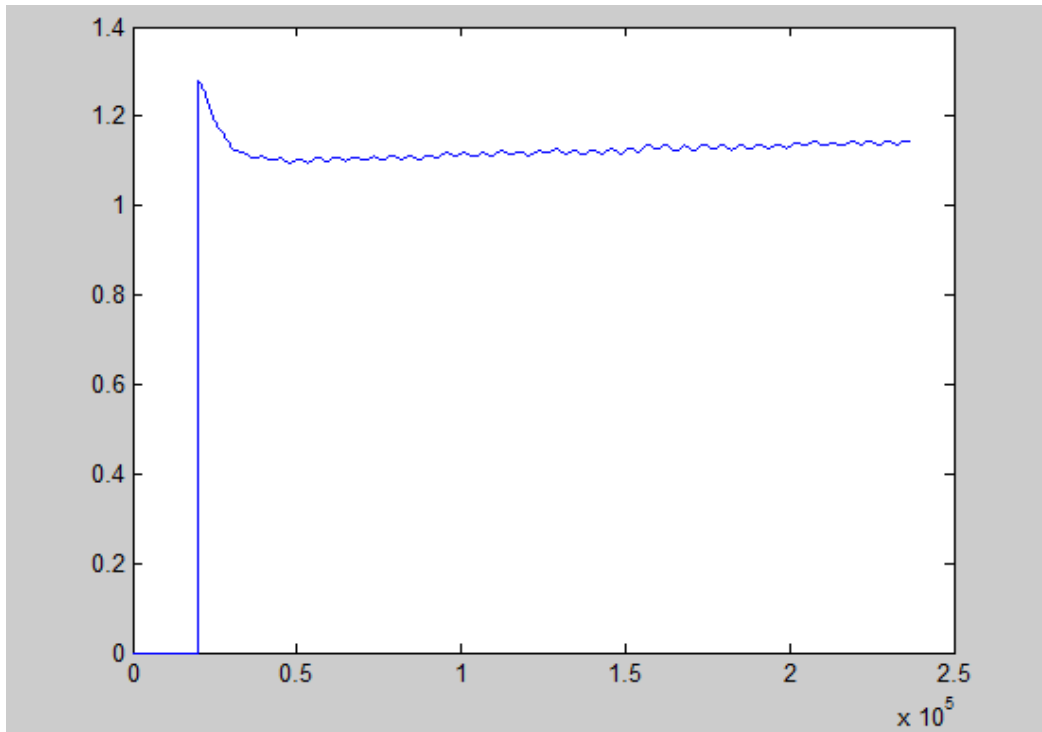


Figure 4.17: Voltage fluctuation (Error plot)

4.2.3 Resonant inverter with PI controller

Fuel cell based inverter system using resonant inverter and PI controller is modeled in this section. Complete modeling in Simulink, output voltages measured before and after the Low Pass Filter, relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.18, 4.19, 4.20 respectively.

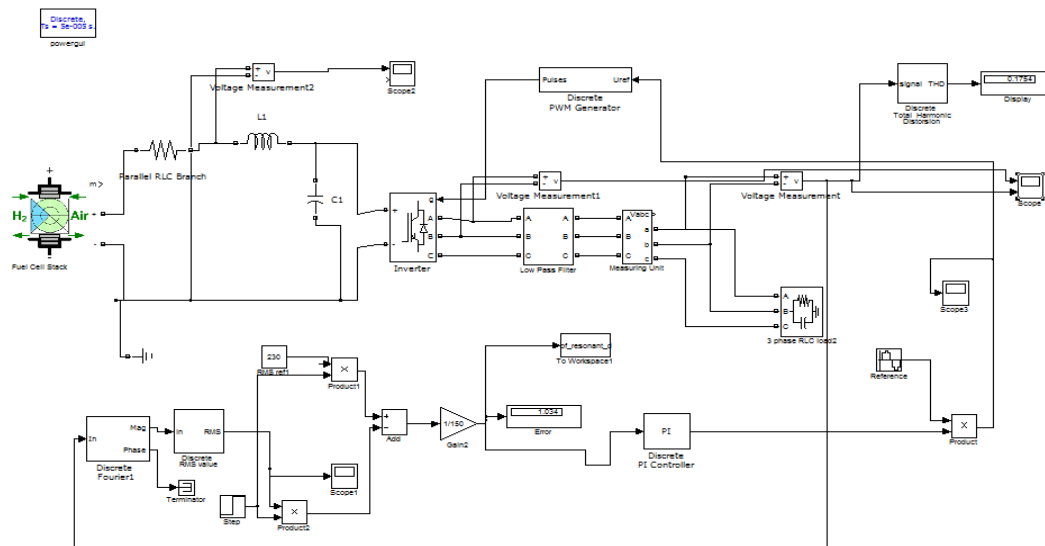


Figure 4.18: Modeling of resonant inverter with PI controller in Simulink

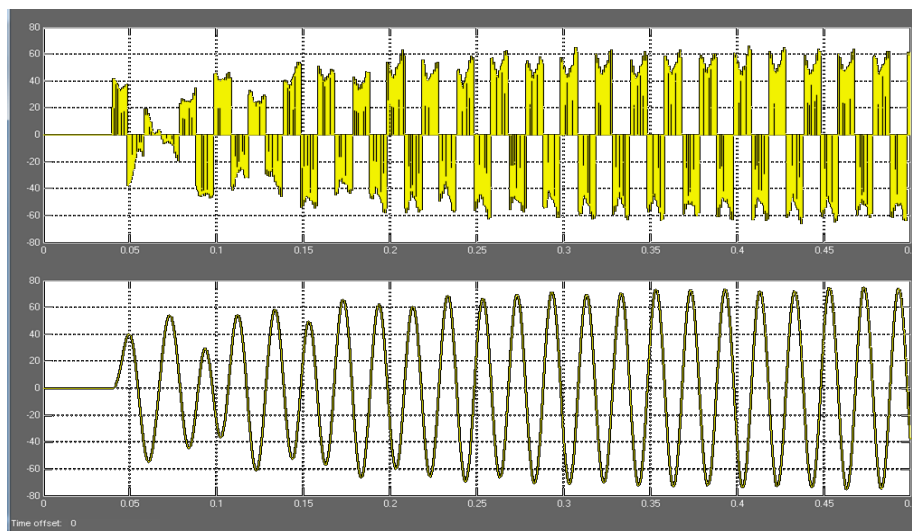


Figure 4.19: Output wave shapes measured across the inverter and load

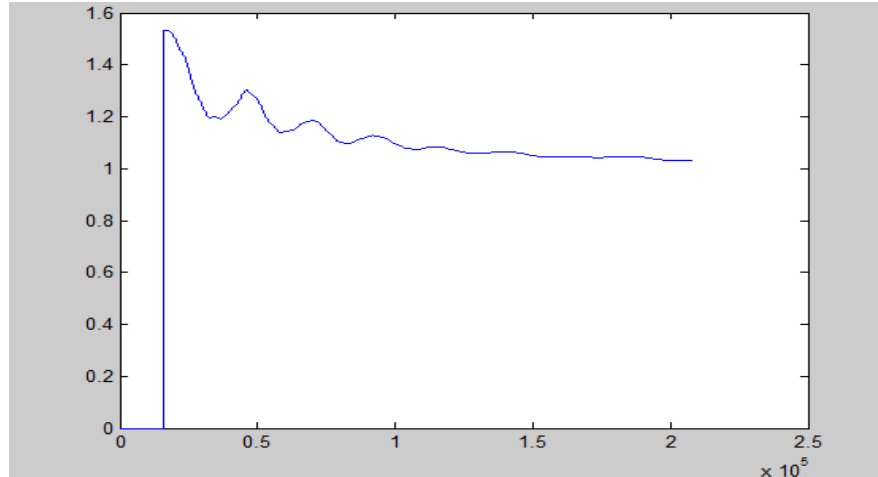


Figure 4.20: Voltage fluctuation (Error plot)

4.2.4 Resonant inverter with Fuzzy logic controller

Fuel cell based inverter system using resonant inverter and Fuzzy logic controller is modeled in this section. Complete modeling in Simulink, output voltages measured before and after the Low Pass Filter, relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.21, 4.22, 4.23 respectively.

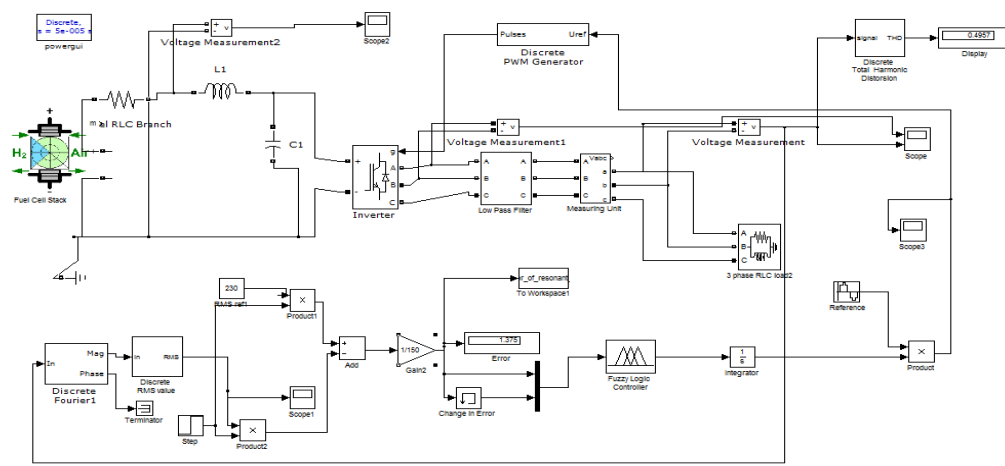


Figure 4.21: Modeling of resonant inverter with Fuzzy logic controller in Simulink

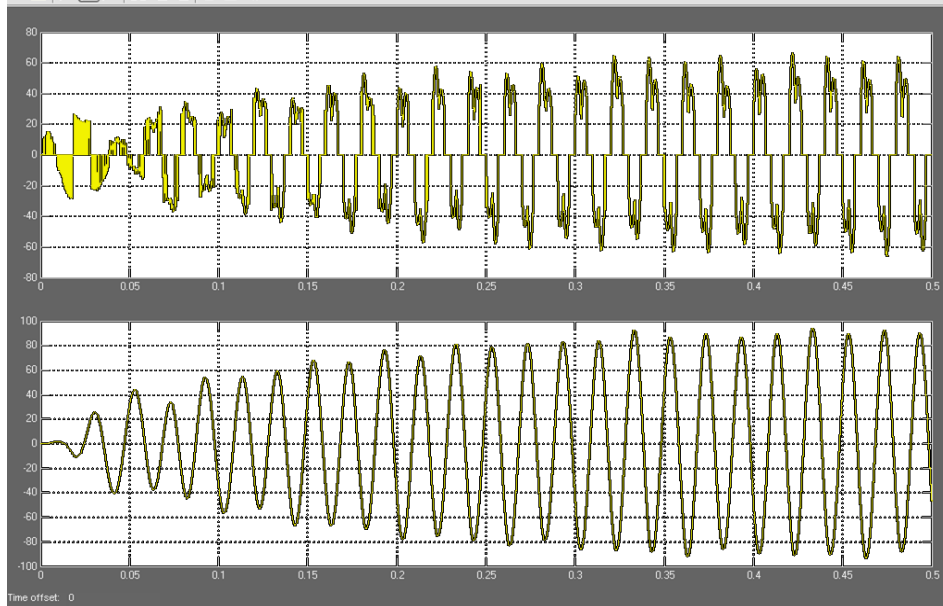


Figure 4.22: Output wave shapes measured across the inverter and load

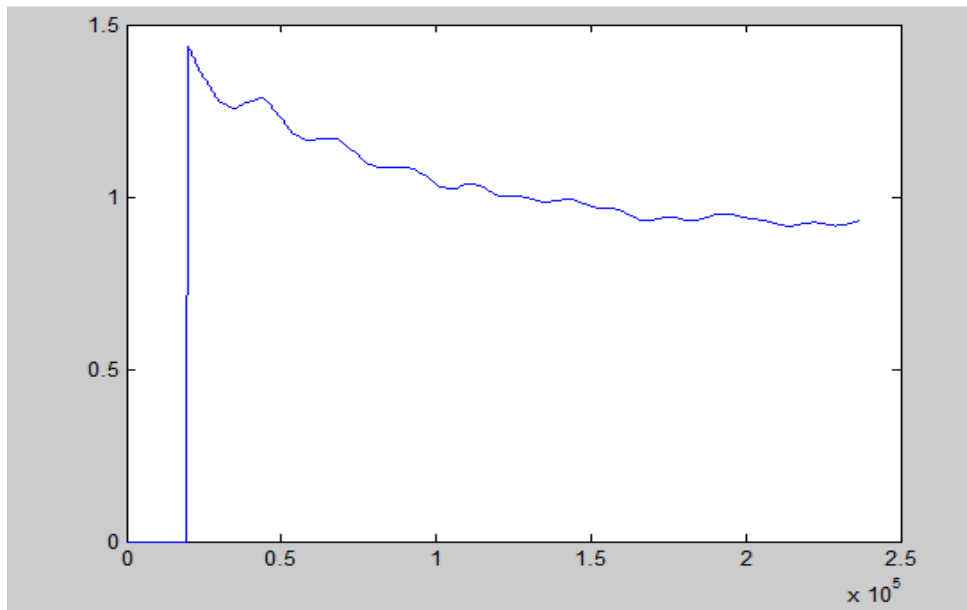


Figure 4.23: Voltage fluctuation (Error plot)

4.2.5 Z-source inverter with PI controller

Fuel cell based inverter system using Z-source inverter and PI controller is modeled in this section. Complete modeling in Simulink, Output voltages measured before and after the Low Pass Filter, Relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.24, 4.25, 4.26 respectively.

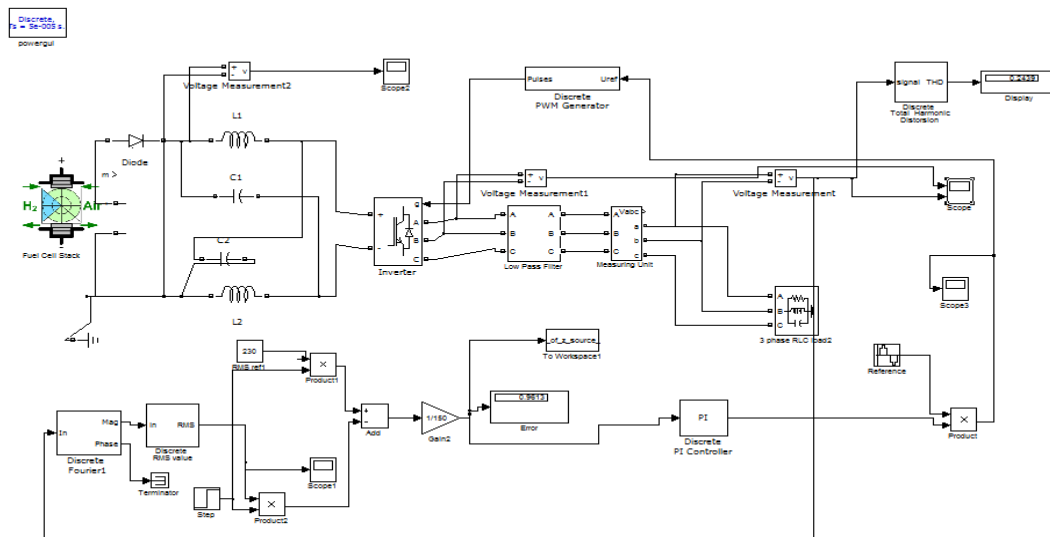


Figure 4.24: Modeling of Z-source inverter with PI controller in Simulink

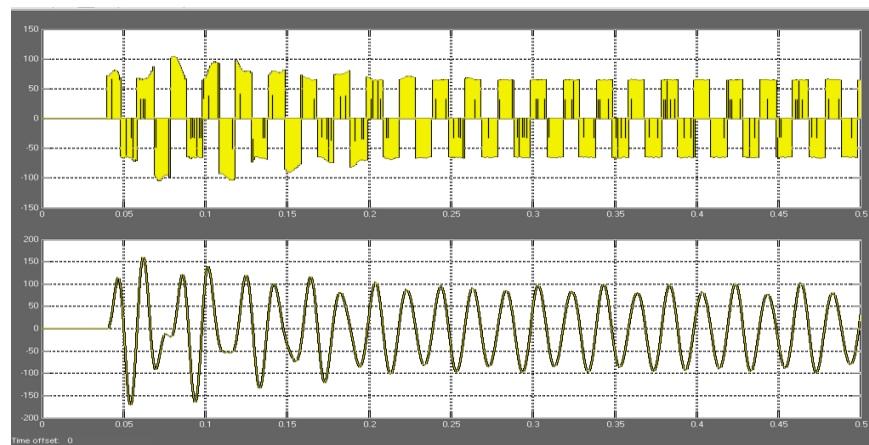


Figure 4.25: Output wave shapes measured across the inverter and load

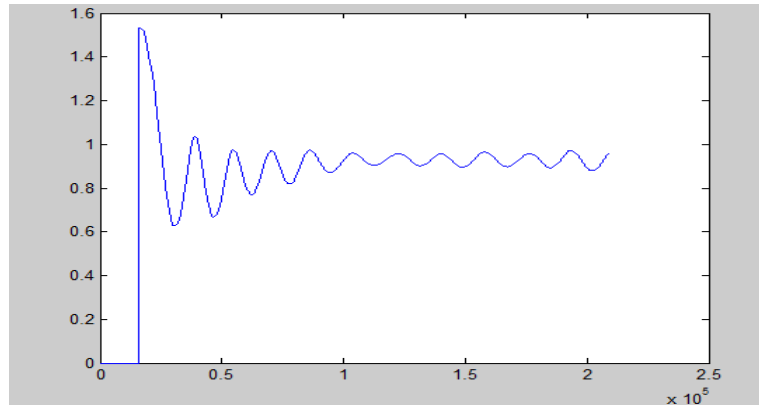


Figure 4.26: Voltage fluctuation (Error plot)

4.2.6 Z-source inverter with Fuzzy logic controller

Fuel cell based inverter system using Z-source inverter and Fuzzy logic controller is modeled in this section. Complete modeling in Simulink, Output voltages measured before and after the Low Pass Filter, Relative output voltage fluctuation in comparison with the reference voltage are shown in Figure 4.27, 4.28, 4.29 respectively for the value of $C1=C2=100\mu\text{F}$, $L1=L2=100\text{mH}$. Figure 4.30 and 4.31 represent the output response and error plot for $C1=C2=100\mu\text{F}$, $L1=L2=1\text{mH}$.

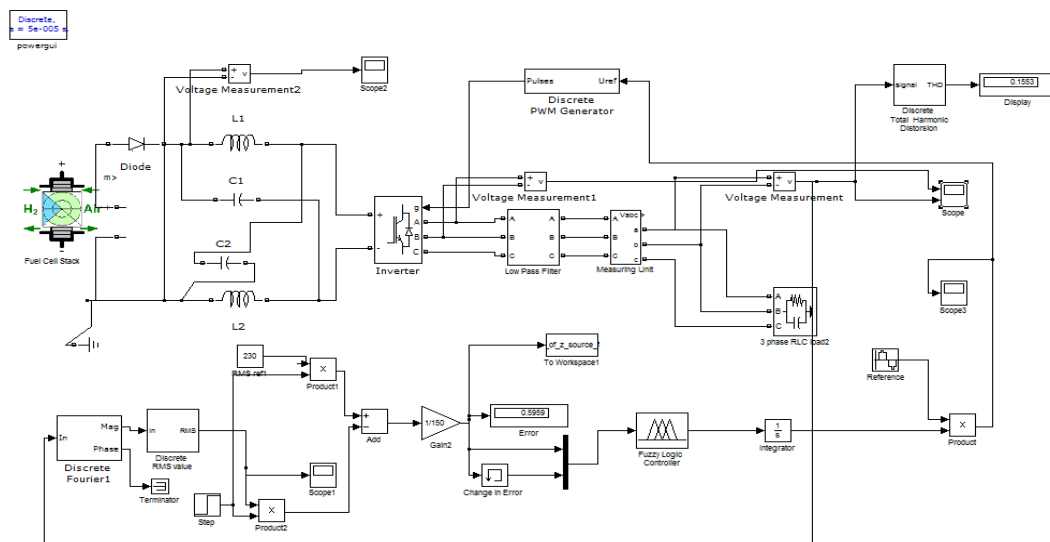


Figure 4.27: Modeling of Z-source inverter with Fuzzy logic controller in Simulink

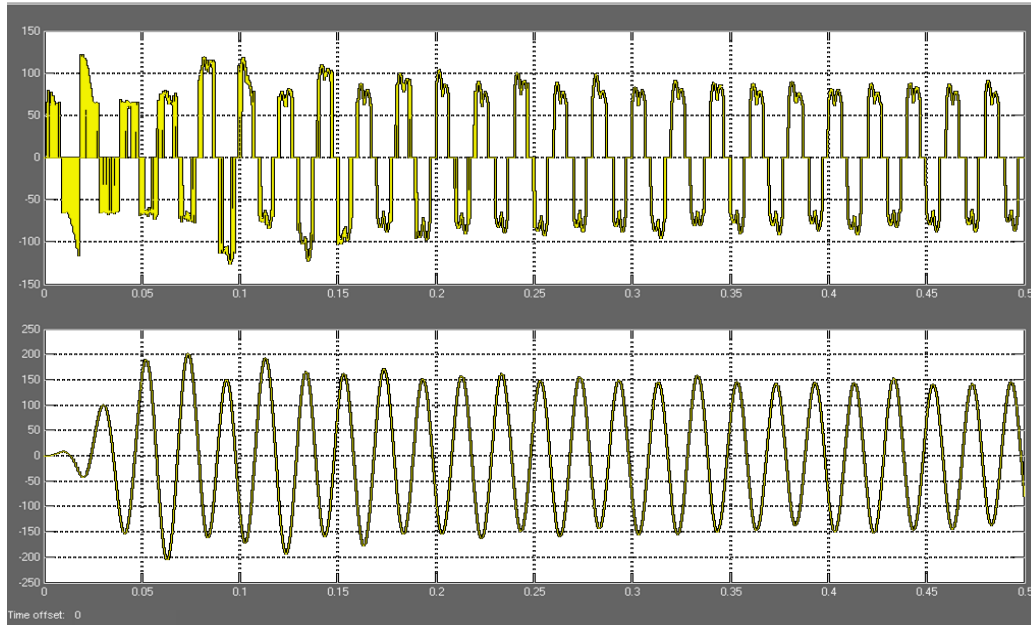


Figure 4.28: Output wave shapes measured across the inverter and load

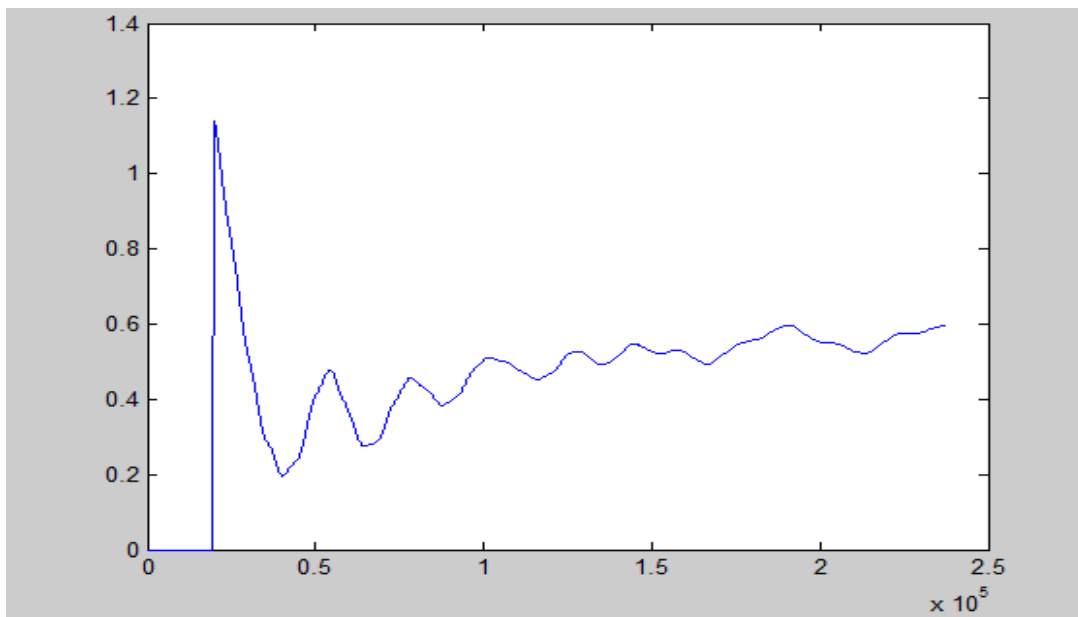


Figure 4.29: Voltage fluctuation (Error plot)

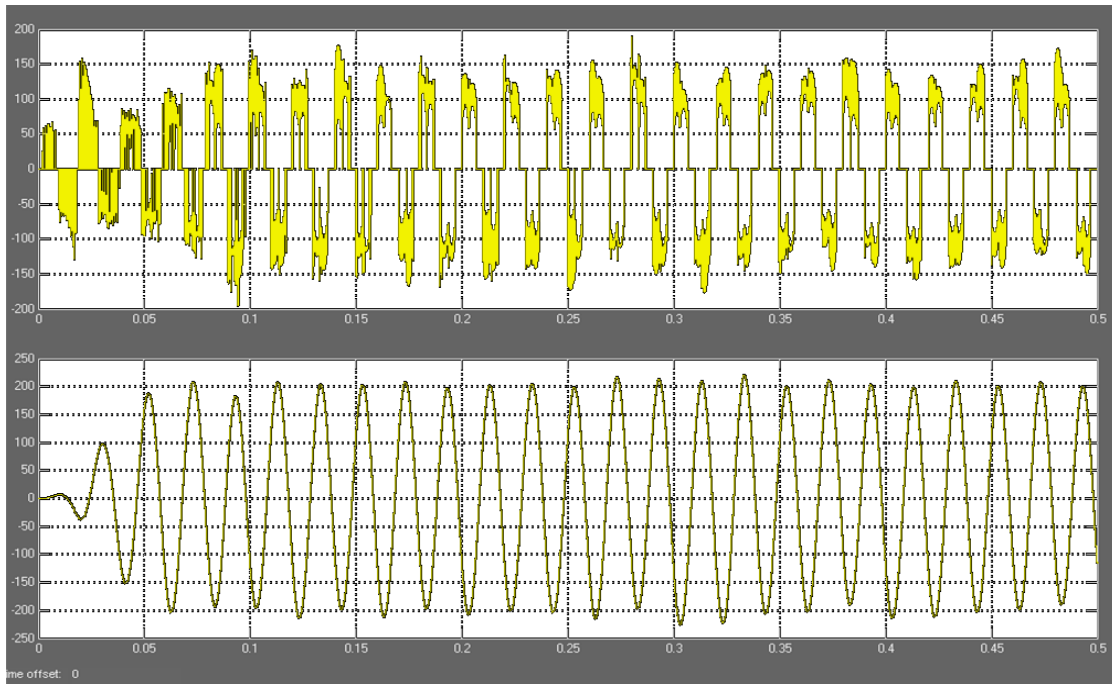


Figure 4.30: Output wave shapes measured across the inverter and load

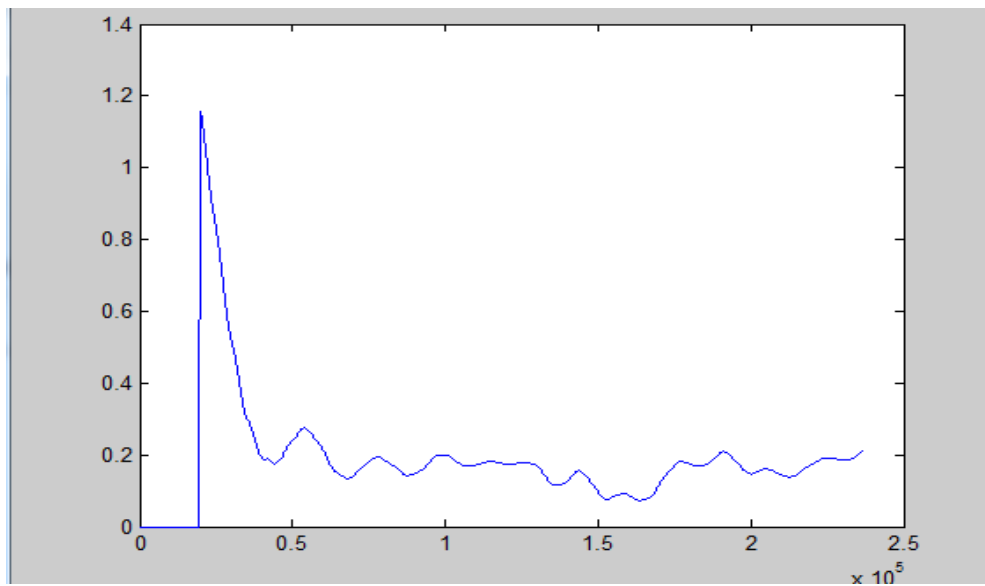


Figure 4.31: Voltage fluctuation (Error plot)

Table 4.1 Comparison of the simulations

System	O/P peak value (Volt)	Voltage fluctuation(from error plot) measurement(relative)	
		Peak	At 200000 th sample
1. PWM inverter with PI controller	60-80	1.55	1.3
2. PWM inverter with Fuzzy logic controller	60-80	1.3	1.15
3. Resonant inverter with PI controller	80	1.55	1.1
4. Resonant inverter with Fuzzy logic controller	90	1.45	1
5. Z-source inverter with PI controller	85-100	1.55	.9
6a. Z-source inverter with Fuzzy logic controller(C1=C2=100uF, L1=L2=100mH)	140-150	1.15	.55
6b. Z-source inverter with Fuzzy logic controller(C1=C2=100uF, L1=L2=1mH)	200	1.15	.2

4.3 Conclusion

This Chapter contains most of the sections that cover the background and literature study required to achieve the goals stated in Chapter one, two and three. It looked into detailed design of the parts that make up the full simulation model such as modeling of fuel cell stack, PWM inverter, Resonant inverter, Z-source inverter, PI controller, Fuzzy logic controller etc and the results seen are as expected with the theory.

CHAPTER 05

5. CONTROL SYSTEMS DEVELOPMENT AND IMPLEMENTATION WITH DSPACE

5.0 Introduction

Implementation of power electronic converters traditionally employs analogue control. Major advantage of this type of control was cost effectiveness. But analog control has many drawbacks such as, the number of component counts and connections, aging and thermal drift. These adverse effects directly degrade the performance of converters and cause expensive routine maintenance. In addition, analogue control is typically designed specifically for a single converter model. As a result, converter upgrade is impossible without replacing it with new hardware .The DS1104 R&D Controller Board is a new piece of hardware that upgrades the PC to a powerful development system for rapid control prototyping. The real-time hardware based on PowerPC technology and its set of I/O interfaces makes the board an ideal solution for developing controllers in various industrial fields. The new DS1104 R&D Controller Board is impressive proof that power does not necessarily have to be expensive. This way, the DS1104 is available at a reasonable price, making it the perfect development system for industrial application.

Currently, the price of a single DSP chip has fallen substantially to a lower value but its performance and capability of executing millions of instructions (MIPS) is significantly increased.

The DSP board available in the laboratory is DS1104. Figure 5.1 shows the block diagram of the available DSP controller

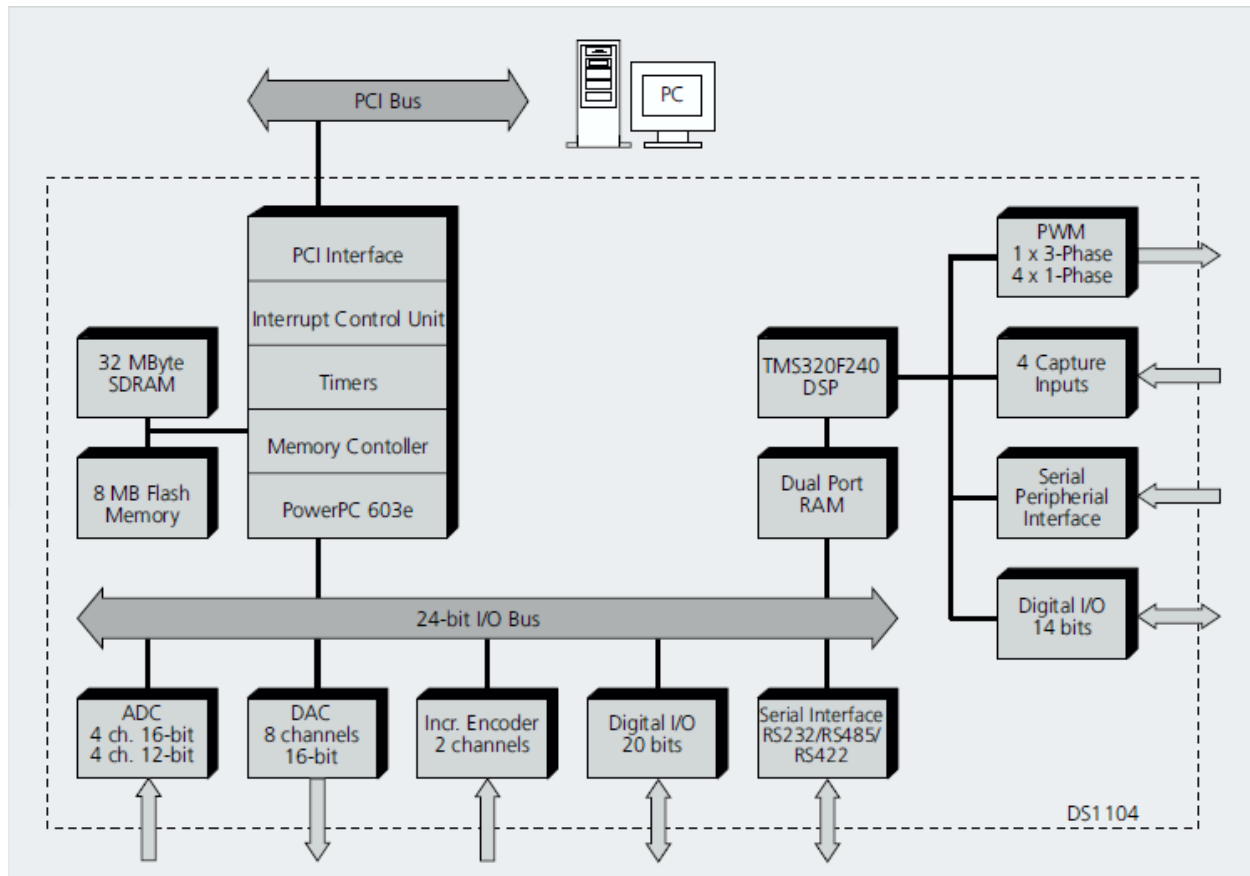


Figure 5.1: The block diagram of the DSP controller

5.1 DS1104 R&D controller board

The DS1104 R&D controller board is a standard board that can be plugged into the PCI slot of a PC. The DS1104 is specifically designed for the development of high speed multivariable digital controllers and real-time simulations which suited our grid connected inverter application. It is a complete real-time control system based on a 60371. PowerPC floating point processor (better precision compared to the previous one) running at a 250 MHz (much faster compared to the previous one). For advanced I/O purposes the board includes a slave-DSP subsystem based on the TMS320F240 DSP microcontroller. The controller board comes with a connector panel CP1104 which provides easy access to all the input and output signals of the DS1104 controller board. Devices can be individually connected, disconnected or interchanged without

soldering via BNC connectors and Sub-D connectors. This simplifies some parts of the additional hardware circuitry that needs to be designed in order for safe usage of the DSP controller.

5.2 Programming with DSP board

A detailed study was carried out on the controller board with special emphasis being given to their peripherals like Analog to Digital Converters (ADC), Timers, General purpose input/output (GPIO), pulse Width Modulation (PWM) output channels.

Programming with the controller board was practiced using Simulink and Control Desk for DS1104 dSPACE board. Programming with dSPACE took very little time as many readily available blocks from Simulink and dSpace could be used to build the software.

5.3 Reason for choosing DS1104

The DSP controller DS1104 from dSpace was chosen for this project as this controller could reduce the programming design time. Simulink programs could be run on this DSP controller via the Real-Time Workshop feature, which means it reduces the development time greatly. The chosen processor is a floating point processor for higher precision and a faster processor. Simple programs were tested initially to read data into the controller via the ADC and simple PWM output were analyzed on the oscilloscope to confirm the correct operation of hardware and software.

5.4 Control Using DS1104

The work with dsp board that meets our demand is shown in figure 5.2. For details the lab manual is gone through.

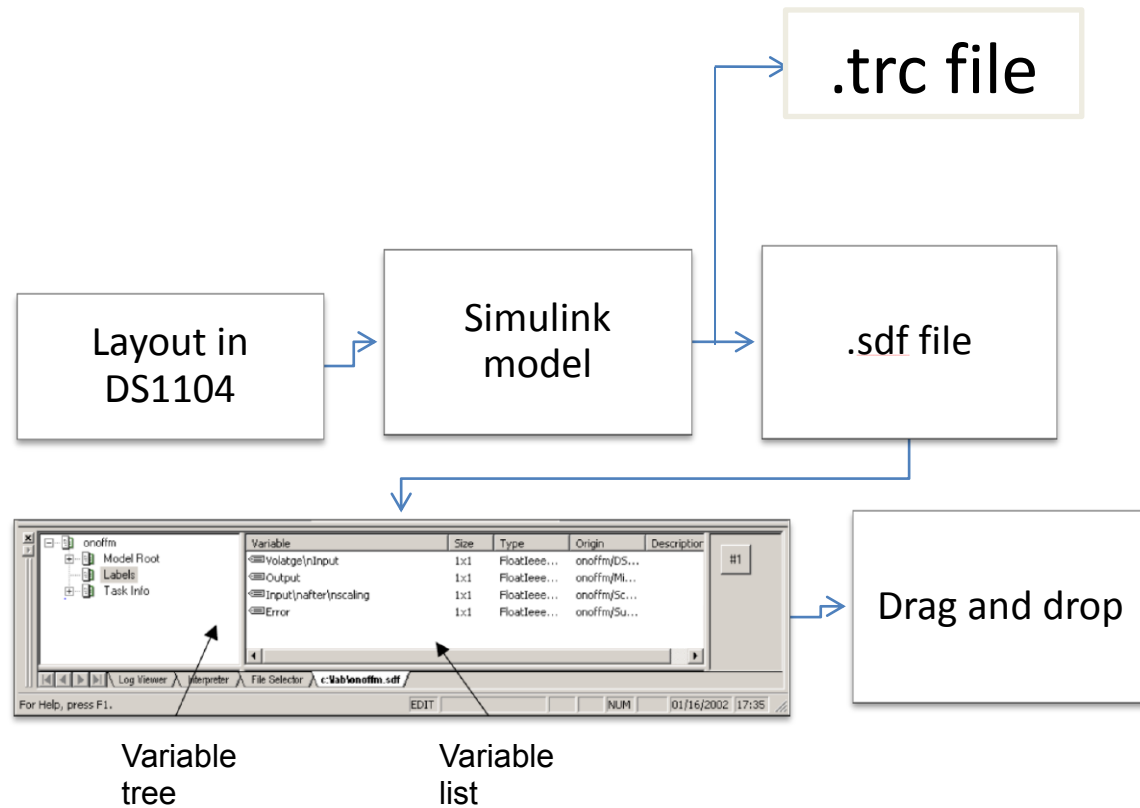


Figure 5.2: Block diagram of control system in dsp board

5.5 Interfacing Circuits

For interfacing the dsp board two circuits were designed in Ltspice. The necessary circuits to interface dsp board are:

- 400 V ac Pk - grid phase voltages (for each phase)
- 1000V dc -for inverter dc link
- 600V dc- for dc source voltage

- d) 25A ac Pk - for injected currents (per phase)
- e) 25A dc- for dc source current

The interface circuitry stages are shown in figure 5.3.

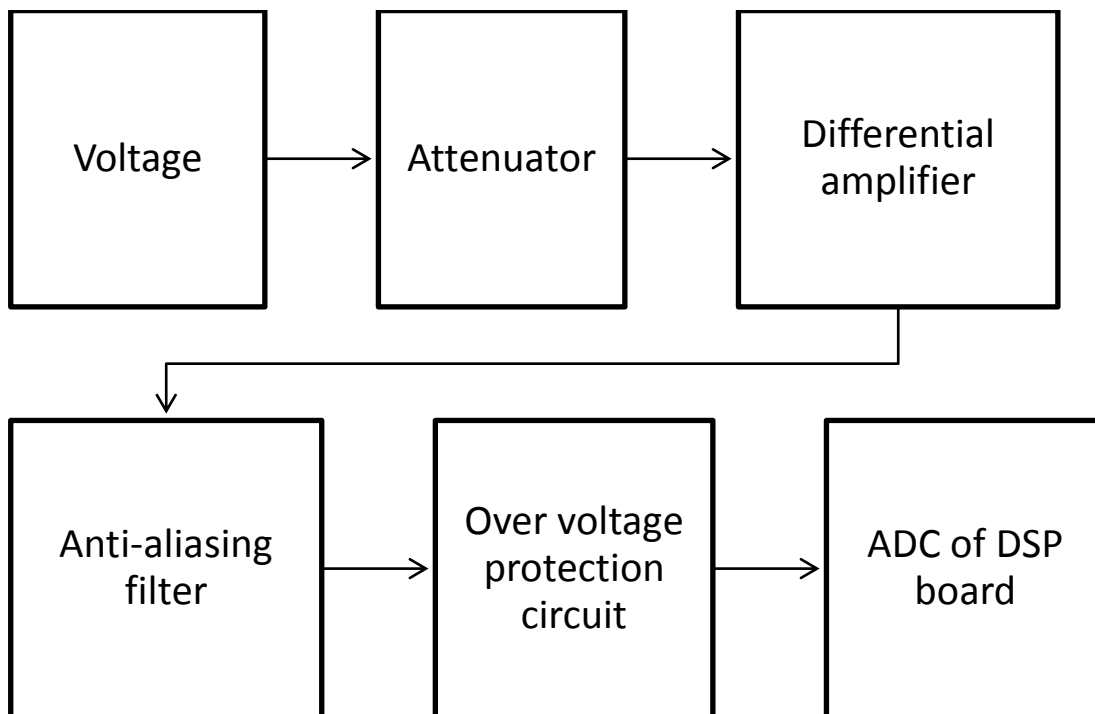


Figure 5.3: Block diagram of the interface circuitry stages

The voltage and current interfacing circuits have the same stages. The stages are described below:

1. Attenuator

The voltage signal is sensed and passed through a resistive network where it is attenuated to a lower level. The live and neutral of each phase are measured

differentially therefore the same resistive network exists on both terminals. 1 % precision resistors are chosen to give accurate measurements and this resistive network avoids use of bulky and costly transformers for the attenuation stage. The current signal is passed through a current transducer (LEM, LTA 200-S) and a voltage signal proportional to that is obtained.

2. Differential amplifier

The difference of the signals at inputs is amplified at this stage. The Common Mode Rejection (CMR) property of this stage helps to reduce the incoming noise and only the signal of the interest is amplified. Differential amplifier stage the ac gain of this stage is designed to be 0.5 for the voltage channels and 1 for the current channels.

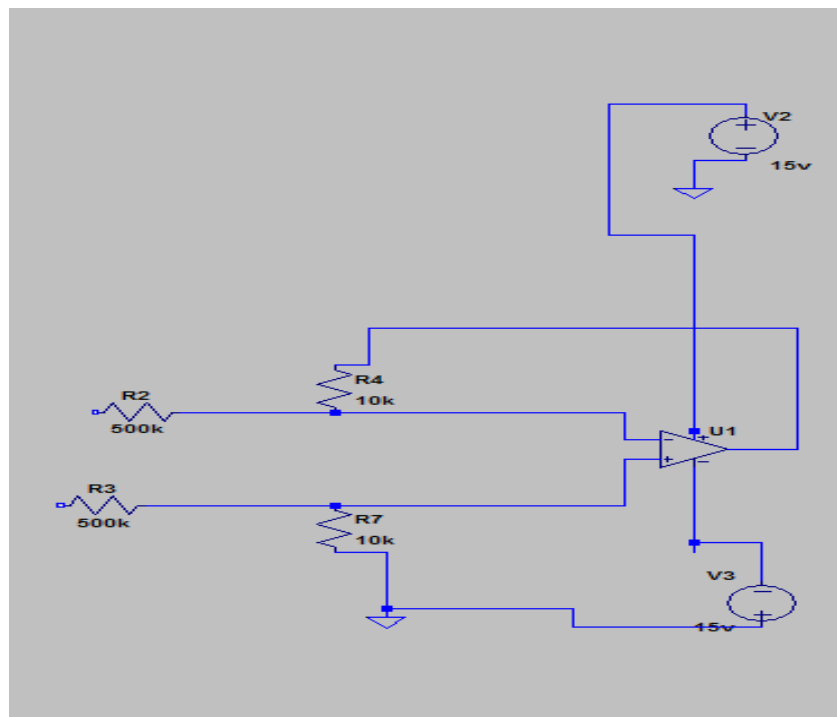


Figure 5.4: Differential Amplifier

3. Anti aliasing filter

Low pass filters help to remove the high frequency noise, which can cause aliasing effects upon sampling of the signal. This filter was designed to remove any noise signals above 500 kHz (-40 dB amplitude distortion) keeping in mind the sampling frequency of the analogue to digital converter (ADC) channels of DSP. It was decided to build Butterworth filters because of their smooth response in pass band frequency range. The cutoff frequency of the filter is given by equation below:

$$F_c = \frac{1}{2\pi R_{13} C_5}$$

The value of R and C can be designed based on this equation by fixing the cutoff frequency. The gain of the filter is given by equation below:

$$G = 1 + \frac{R_{11}}{R_{12}}$$

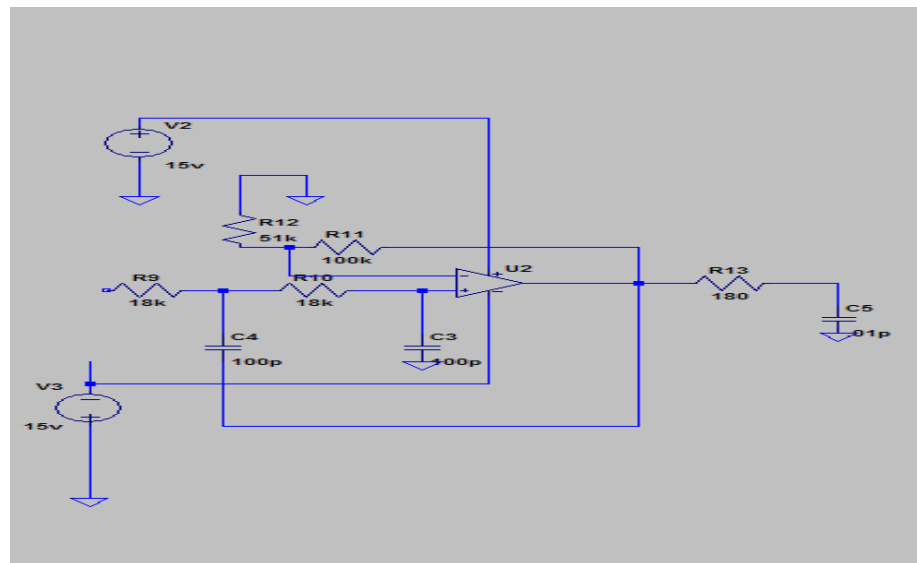


Figure 5.5: 3rd order Butterworth filter

4. Over voltage protection

The signals pass through an over-voltage protection circuit before they are read by the ADC ports of the DSP. The ADC of DSP is very sensitive to voltage input other than the specified level. Therefore, the protection circuit ensures to keep the output voltage between -10 and +10 Volts. Resistors of 1% precision and zener diode BAT54 based voltage clamping circuit is added to the end, of each of the measurement Interface circuits.

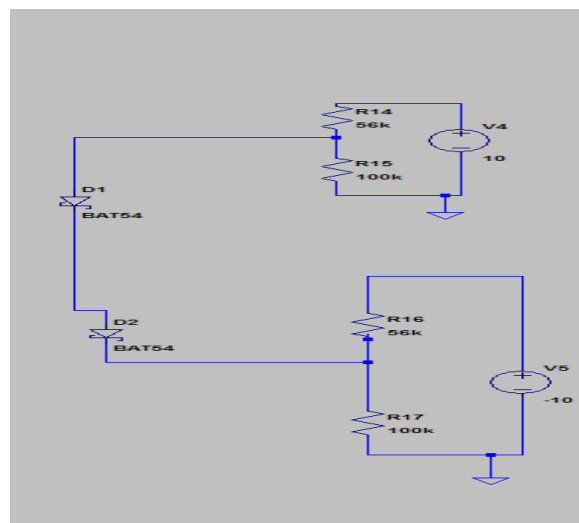


Figure 5.6: Over-voltage protection circuit

5.6 Interface circuit simulation

The simulation study of the designed circuits has been carried out in the LT Spice. The schematic diagrams of the five different measurement circuits and their simulation results are given in Figures 5.3, 5.4 and 5.5. Each stage of the circuit was built and tested individually and then put together for a breadboard testing. Differential mode and common mode tests were carried out on each of the measurement channels of the circuit to ensure their reliable operation. The test

results were satisfactory and show the input signals are conditioned as expected; also ac and dc gains of the circuits were consistent in the tests carried out.

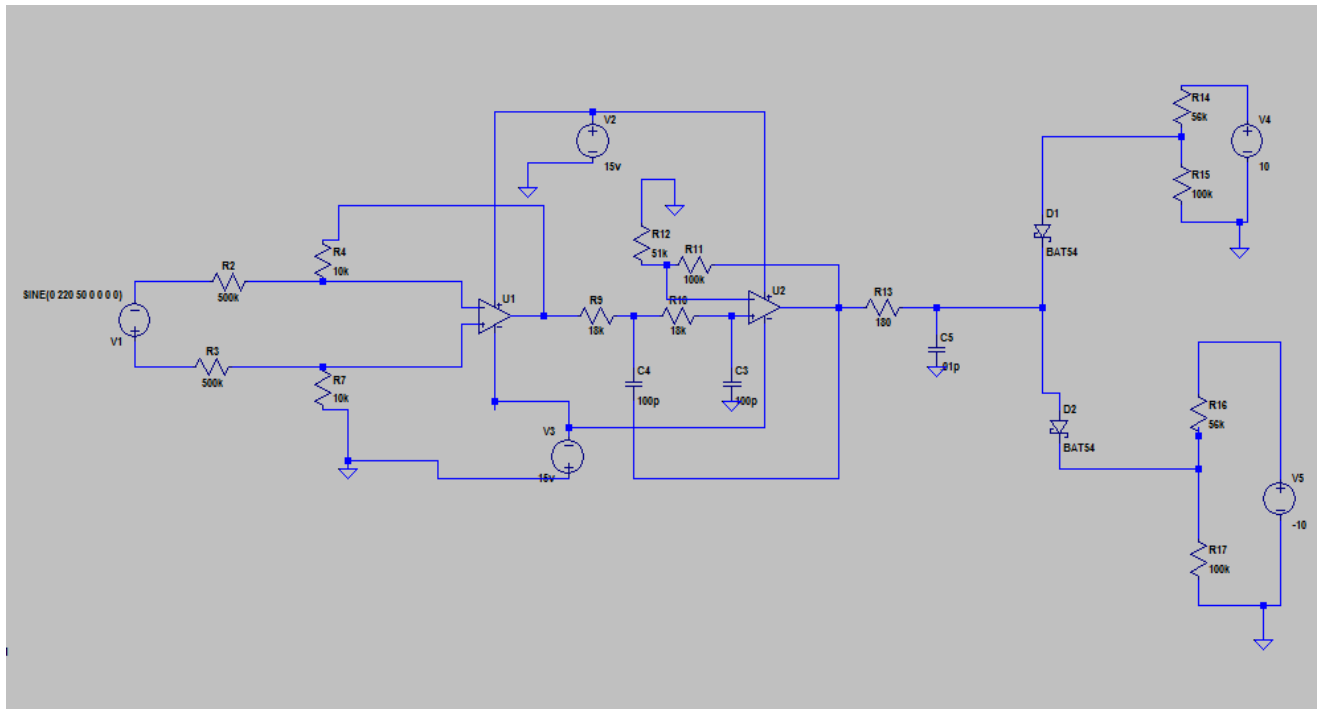


Figure 5.7: Simulation of Interface Circuit

The simulation results are shown below:

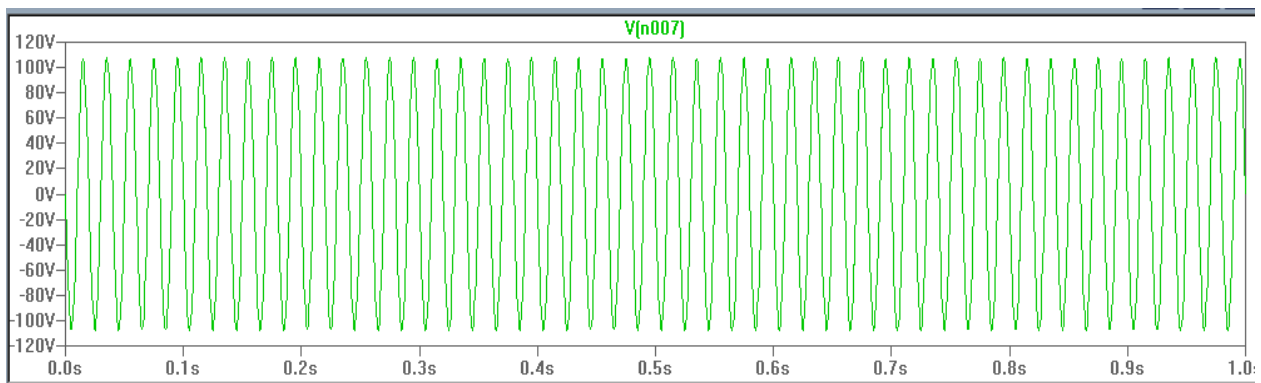


Figure 5.8: AC voltage input

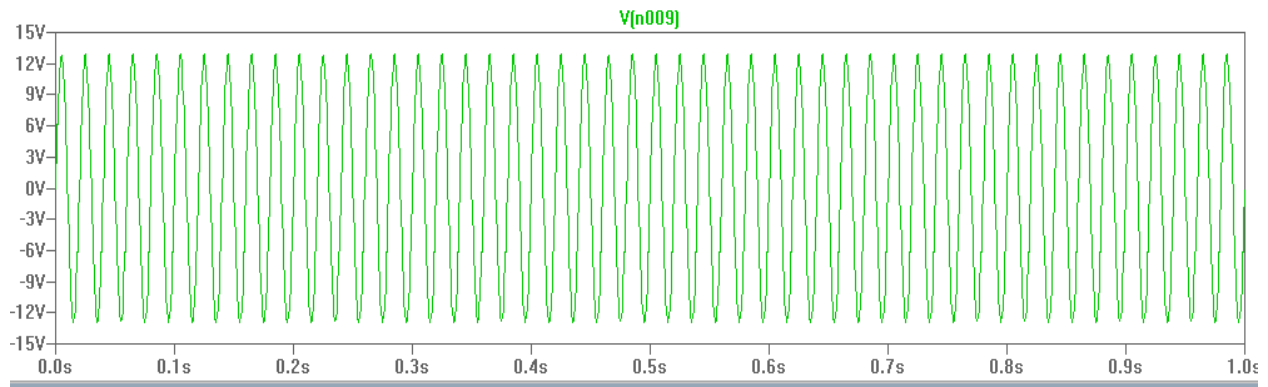


Figure 5.9: Scaled AC for DS 1104

5.7 PWM level Shifter Circuit:

The three phase inverter is controlled using six PWM signals, three PWM signals for the top switches and their complements for the bottom switches with dead band (for protection against shoot-through fault). The boost IGBT switching signal requires a Single PWM signal depending on the boost duty cycle calculated by the dc link controller.

The dSpace PWM blocks can create high frequency PWM with 1-5 μ s dead band as required. These PWM signals from the DSP are of TTL Logic, 0-5V. These have to be converted to 0-15V to be accepted by the gate driver of the inverter and the boost switch. This calls for a PWM level shifter circuit whose simulation design is done using LTSpice. The 0-5 V PWM pulse is compared using a fast comparator (LM339N) to a precise reference (using 1% resistors) of 0.5V to get matching 0-15V PWM pulses.

Figures 5.8 and 5.9 show the circuit simulated and the result expected of the hardware circuit.

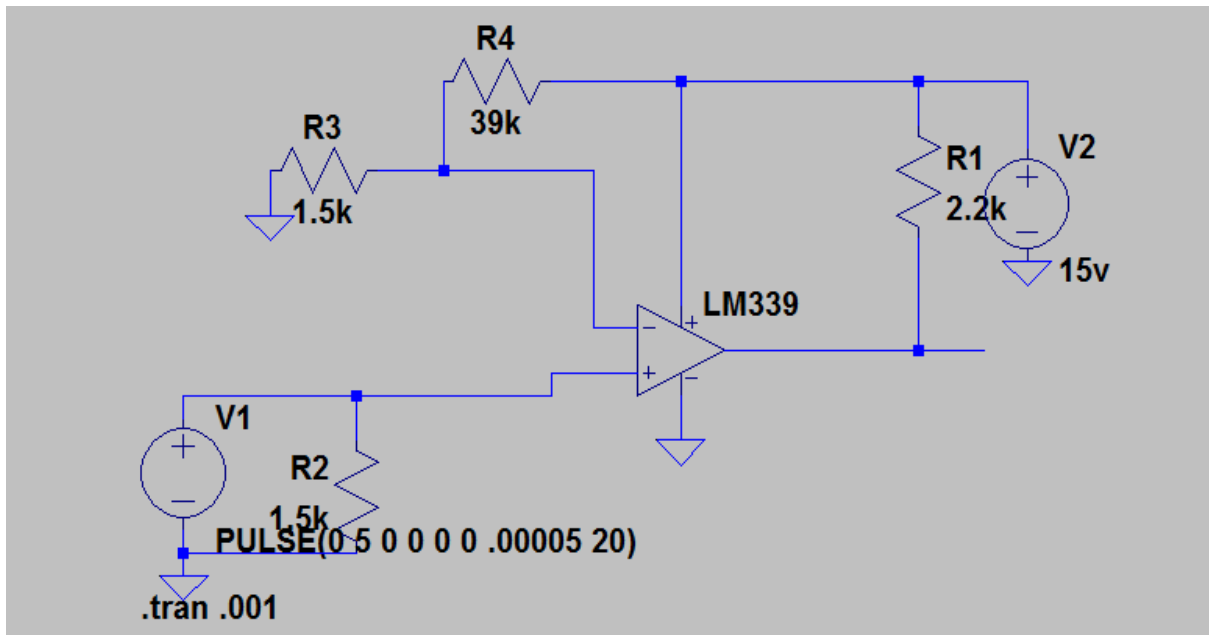


Figure 5.10: PWM level shifter circuit

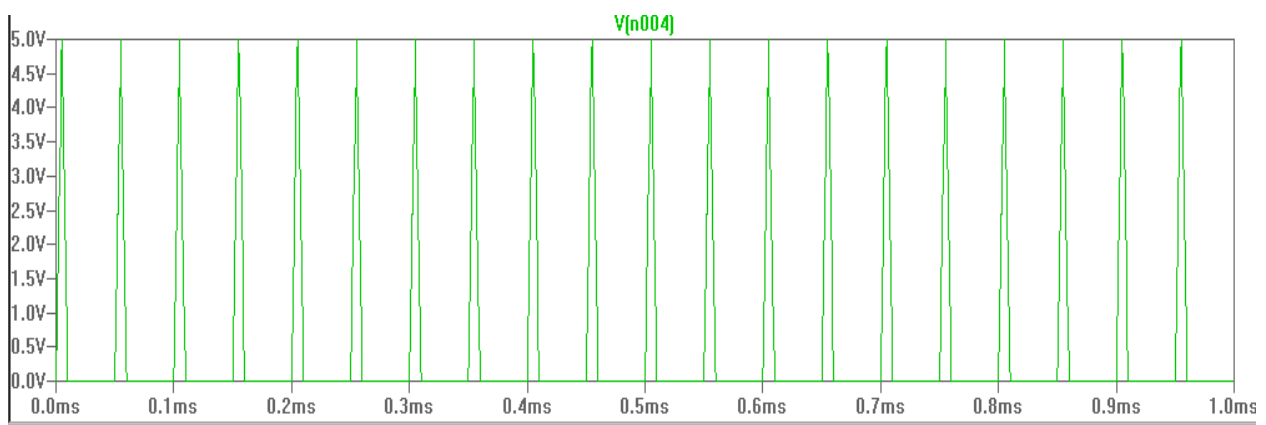


Figure 5.11: Input of level shifter circuit

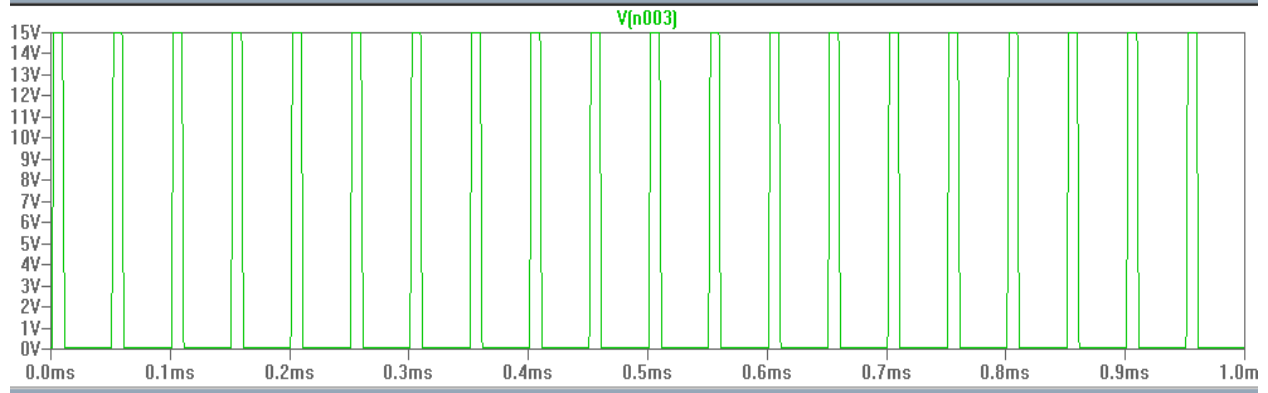


Figure 5.12: Switching pulse for inverter

5.8 Conclusion

This chapter covers the most important part of the experiment. The control mechanism and the interfacing circuits with the DSP board are described in this chapter. The generation of the gate pulse of the inverter was controlled so that the output can be found as desired.

CHAPTER 06

6. CONCLUSION AND FUTURE WORK

6.0 Conclusion

The system design helped us to understand the scheme and its effectiveness. To see the practical effectiveness DSP implementation was appropriate. Software simulations were done by Simulink, Ltspice, Pscad. For micro grid application the proposed scheme may be useful. The laboratory data has to be analyzed though.

The scheme is basically designed and simulated. For different topologies the change in inverter type and the controller caused the analytical data to be different. The practical implementation of this data will be necessary for micro grid application.

6.1 Future work

This work can be extended to the implementation of the inverter topologies used for simulations in hardware and can be analyzed for micro grid application. The Z-source inverter can be a better option if it is analyzed with the best mathematical approach for calculating the capacitance and inductance value. The proposed algorithm can be developed by using different types of fuel cells to determine the best option for meeting up the energy deficiency in the power sector.

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