Implementation of a Digital Signal Processing (DSP) Boost Inverter for Fuel Cell Energy Generation

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ABSTRACT

This thesis investigates and implements the use of a microprocessor called Digital Signal Processors (DSP) as a controller in the design of a low power inverter used in Fuel Cell energy source. The fuel cell used in this research is a Heliocentris “Constructor”, a 50W proton exchange membrane (PEM) fuel cell. Fuel Cells are becoming popular and are likely to be used in applications such as a backup power, portable electronic devices, independent power source generator, promising alternative fuel for vehicles and a source generator to supply the electrical grid.

To further use the importance of fuel cell in alternating current (AC) application, inverters are incorporated in the system. The widely used inverter in the market is the conventional inverters or the transformer based inverters. These conventional power inverters have the characteristics of being bulky in size, expensive and less efficient.

The introduction of power electronics made a huge improvement in the inverter technology. One of which, is the computer based electronic component, microprocessor, which was first used on digital and signal processing in control system. The most popular microprocessors used for electronic and digital controllers in an inverter, are the Microcontrollers and the Digital Signal Processors (DSP).

Abstract

The DSP power inverters has the feature of being electronically controlled, compactly built, optimal versatility, cost effective and efficient. It operates in a digital domain and produces a controlled pulse width modulation (PWM) in an inverter.

In this thesis research, the TMS320F2808 eZdsp from Texas Instruments (TI) and the Digital Motor Controller (DMC) 550 modules are used as a power electronic inverter for Fuel Cell energy generation. It was simulated and computed under the specifications of the DSP to fulfill the actual results of the prototype. Hence, the result of this thesis satisfies that the DSP is an excellent controller of a PWM signal in the design of a low power inverter for fuel cell power generation.

DECLARATION

“I, **JOEVIS JULIAN CLAVERIA**, declare that the Master by Research thesis entitled, “***Implementation of a Digital Signal Processing (DSP) Boost Inverter for Fuel Cell Energy Generation***”, is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

Signature: .... Date: 18 March 2014

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And above all, to **HIM**.

PUBLICATIONS

The following are the list of publications related from the thesis.

(a) Journal Paper:

[1] Claveria, J. and Kalam, A, "**Power transfer analysis of a hybrid fuel cell / battery as portable power source generator**", Journal of Petroleum Technology and Alternative Fuels, Vol. 2(7). pp. 103 – 110 July 2011.

(b) Conference Paper:

[1] Khrisnan K, Claveria J, Varadharajan L, and Kalam A, **"Experimental and Computational analysis of a 1.2kW PEMFC designed for communication back-up power applications"**, International Conference on Energy Systems And Technologies, Islamabad, Pakistan, Nov. 28 – Dec. 2, 2010, pp. 184 – 190. ISBN: 978-969-9635-00-7.

ACRONYMS

AC	Alternating Current
AFC	Alkaline Fuel Cell
CCS	Code Composer Studio
CMOS	Complementary Metal Oxide Silicon Field Effect Transistor
DC	Direct Current
DMC	Digital Motor Controller
DMFC	Direct Methanol Fuel Cell
DSP	Digital Signal Processing
EMI	Electromagnetic-Interference
EMF	Electromotive Force
ePWM	Enhanced Pulse Width Modulation
FC	Fuel Cell
GTO	Gate Turn-off Transistor
GUI	Graphical User Interface
IC	Integrated Circuit
IGBT	Insulated Gate Bipolar Transistor
JTAG	Joint Test Action Group
MATLAB	Matrix Laboratory
MCFC	Molten Carbonate Fuel Cell
MOSFET	Metal Oxide Silicon Field Effect Transistor
NASA	National Aeronautics and Space Administration
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
PWM	Pulse Width Modulation
RAM	Random Access Memory
RGFC	Regenerative Fuel Cell
SCR	Silicon Controlled Rectifier
SEPIC	Single Ended Primary Inductor Converter
SOFC	Solid Oxide Fuel Cell
SVPWM	Space Vector Pulse Width Modulation
TI	Texas Instrument
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus

NOTATIONS AND SYMBOLS

Δi	ripple current
ΔG	change in Gibbs free energy
ΔH	is the enthalpy of reaction formation
ΔV	the voltage drop of the resistive equivalent in the fuel cell,
CO_2	Carbon Dioxide
e^-	electron
H^+	Hydron
H_2	Hydrogen
H_2O	Water
K	Potassium
NaOH	Sodium Hydroxide
η	Ideal efficiency of Fuel Cell
O_2	Oxygen
C	Capacitor
C_1	filter Capacitor
D	duty cycle
L	Inductor
L_1	filter Inductor
R	Resistor
E_{ideal}	ideal EMF of the fuel cell
E_{fc}	theoretical EMF of the fuel cell
f_r	resonant frequency
i	instantaneous current, current density of fuel cell
i_{load}	load current, output current
i_o	minimum inductor current
i_{peak}	peak inductor current
P_{fc}	power density of fuel cell
T_{on}	transistor "on", conduction
T_{off}	transistor "off", non-conducting
V_{ac}	AC source voltage
$V_{activation}$,	voltage activation loss
$V_{concentration}$	voltage concentration loss
V_{dc}	DC source voltage,
V_d	diode voltage drop
V_{fc}	operating voltage of the fuel cell
V_{in}	input voltage
V_{out}	output voltage,
V_{ohmic},	voltage resistive loss

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CHAPTER 1

Introduction and State of the Art

Science is the great antidote to the poison of enthusiasm and superstition.
Adam Smith, *The Wealth of Nations, 1776*

This Chapter gives an overall overview and introduction of the thesis topics. The basic concepts of alternative and renewable energy, electric energy generation, overview of power electronics and conversion process are discussed. The motivations and objectives for the development of this research project are also presented.

1.0 Introduction

Electricity is being generated from various sources of energy for more than hundred years for the prime purpose of sustaining human requirements. The increase of energy consumption, fuel cost, growing worldwide demand for electricity, and aggregating concerns on global climate change is responded by utilizing the use of alternative energy generation [1, 2]. Although, the majority of energy produced and used worldwide comes from the conventional energy sources, which has the downside of environmental concerns, expensive in cost production and limited source of fuel.

The use of alternative and renewable energy source is the fastest growing source of electricity generation. The estimated total generation from renewable resources increases by 3% annually, and the renewable share of world electricity generation grows from 18% in 2007 to 23% in 2035 [3]. The increase in the use of renewable resources is remarkable and accepted globally, promoting the green revolution of power energy.

One of the countries supporting this noble cause is Australia. Australia is endowed with abundant, high quality and diverse energy resources, including both renewable and non-renewable resources. Australia has a large, widely distributed wind, solar, geothermal, hydroelectricity, ocean energy and bioenergy resources. These renewable energy resources are growing rapidly and largely develop for different applications [4].

The US Center for Sustainable Systems has also released a simplified factsheet regarding the production of renewable and non-renewable energy. At present, most primary energy produced are from unsustainable and depleting natural resources. More than 82% of the nation’s energy comes from fossil fuels, 8% is derived from nuclear and 9% comes from renewable sources. Renewables also play a significant role in alleviating other pressing problems such as energy security by providing distributed, diversified energy infrastructure. Wind is the fastest growing renewable source but contributes only 1% of total energy used in the US [5].

1.1 Alternative Energy Systems

Alternative energy is a term used for any energy source that is an alternative to conventional power generating sources. An alternative energy system includes renewable energy, green energy and clean energy. The primary sources of fuel of alternative energy come from the sun, water, wind and natural gas which are abundant, endless and environmental friendly. The energy produced from these sources is clean and non-polluting emissions in the environment.

On economic point of view, the cost of production is low in the long run compared to conventional energy. Alternative energy minimizes the undesirable consequences of the burning of fossil fuels, such as high carbon dioxide emissions, which is considered to be the major contributing factor of global warming [6].

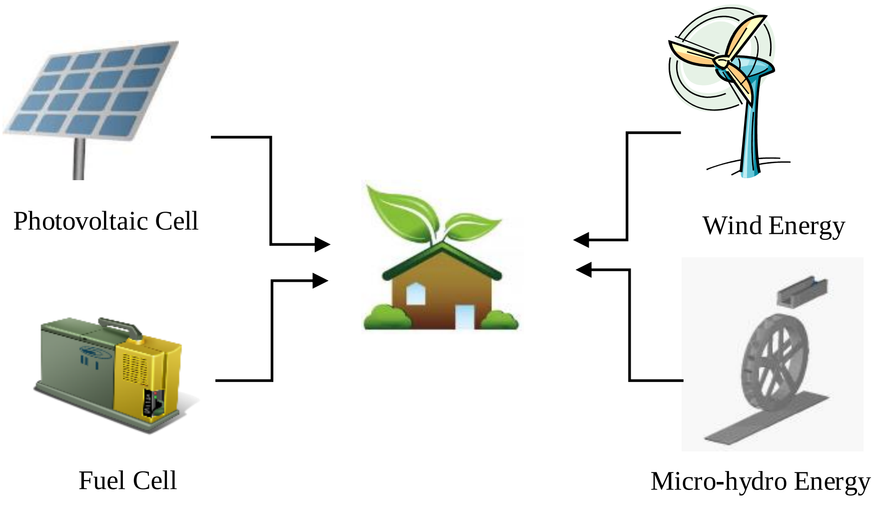


Figure 1.1 Types of Alternative Energy Resource

Figure 1.1 demonstrates the types of alternative energy resource which has a distinct characteristic in terms of its operations and principles. Portable types of alternative energy resources such as Photovoltaic (PV) and Fuel cell, Wind and Water energy generators are the new technologies used for stand-alone and grid connected applications. For industrial and commercial applications, an inverter is integrated in the system to produce a 50 - 60 Hertz, 240V_{ac} to power large equipment in industries and for feeding energy back to the grid.

1.1.1 Wind Energy

Wind Power uses energy from moving air to turn large blades of wind turbines that is coupled to a generator. The generator is a device used to convert mechanical energy to electrical energy. There are two important parts of a generator. The rotor is called the rotating part and the stator is the stationary part. Wind turbine is coupled to a shaft of a rotor. Once the wind turbine rotates, the movement of the rotor to the magnetic field creates a voltage difference that causes the electrons to flow, thus generating an unregulated AC voltage.

However, the unpredictable strength of wind is the main concern of the wind energy systems. The strength of wind can vary from none to storm force on given month and location. As a result, the wind turbine is unable to produce the same amount of electricity at all times [7].

1.1.2 Micro-hydro Energy

The wind and micro-hydro power have the same principle in operation. Both use turbines and generators to generate energy. The distinct operating principle of hydro power depends on pressure and volume of water falling to the turbine. The head (pressure) is the vertical distance between the water take-off and the turbine, while the flow (volume) is the measurement of water that hits the turbine to rotate.

The lowest point of production of power for the micro hydro power is on summer. During summer months the flow of water would be less. Hence, less flow of water less power generated.

1.1.3 Photovoltaic Cell (PV)

The Photovoltaic cell collects and converts solar radiation from the sun by chemical reaction into an electric energy. These PV cells have the same characteristic as a large semiconductor diode that has a *p–n* junction. When a photon of electromagnetic energy from the sun strikes the PV cell, electrons knocked loose and move in one direction through a conductor and generate direct current (DC) electrical voltage.

The DC generated voltage is unregulated and must be converted to a more suitable voltage if used on DC application. The power output of a PV depends on the sun rays it absorbs. Reference [8] shows that potential geographical location is another factor in the utilization of high usage of solar energy. Cyprus has no conventional source of energy and is dependent on imported oil. However, its geographical position is one of the countries where the potential for solar energy utilisation is very high. Nine percent (9%) of the total electricity consumption in this country depends on solar energy.

The power output of PV is affected due to temperature, shading, soil age, cloud cover, weather and during night time. It cannot produce its maximum output due to these reasons. Hence, to compensate the losses in the absorption process, a high efficient and flexible converter and inverter must be used in the energy conversion for further use of AC application.

1.1.4 Fuel Cell

PV and fuel cell convert chemical to electrical energy in the same process without any combustion. PV has the photon as its fuel to shift the electrons in one direction and generate electricity, whilst fuel cell is an electrochemical energy conversion device that produces electricity from external supply of hydrogen (H_2). Fuel Cell consists of cathode, anode and electrolyte. The electrolyte allows the positive ions to pass through the membrane and the electron travels to an external circuit generating electricity. The generated output is also a DC unregulated voltage.

Fuel cell has the characteristic of being slow in operation and needs an outside power source to feed the parasitic elements in start-up cycle. It has a slow response to transients in load. In addition, the changeable H_2 storage used is one of the aspects that make the fuel cell uncomfortable.

1.2 Alternative Energy Conversion

In spite of the positive justifications in using these renewable energy sources, there are still glitches on how to optimize the energy produced from these sources. The energy produced from these sources must be used in full capacity, and this can only be achieved in the conversion of energy.

In technical terms, energy conversion is the process of transforming energy from one form to another. For instance, the energy produced by wind and micro-hydro generator is from mechanical to electrical energy. The force moving the turbine continuously is a mechanical movement that makes the generator produces electrical energy. In this energy conversion, there are moving parts involved that causes unnecessary losses in the process of conversion. The maximum theoretical efficiency of wind generators is high but in practice, most wind turbines are much less efficient. In reference [9] a detailed analysis of wind farm in Scotland was conducted from November 2010 to December 2010 which shows that wind turbines generate an average 30% of their rated capacity over a year.

On the other hand, the PV and the fuel cell have a common denomination in terms of energy conversion. Both generating sources produce energy by a process of chemical to electrical energy. The process in the production of energy by PV and fuel cell is the theory of movement of electrons in the system. Both generating sources do not have moving parts, which means that the energy produced has a high conversion equivalent.

Reference [10] found out that PV efficiencies have exceeded 40% in recent years. The keys to achieving these high efficiencies include, the quality of the material used that span the solar spectrum, growth of materials with near-perfect quality by using epitaxial growth on single-crystal substrates, and use of concentration.

Alternatively, according to the World Energy Council, a hydrogen fuel cell operating at 25°C has a maximum theoretical efficiency of 83%, even though the fuel cell is extracting all the electrical energy possible. This compares to a maximum theoretical efficiency of 58% for internal combustion engines [11].

1.3 Overview of Power Electronics

The origin of power electronics came into existence when the bipolar transistors were invented in 1948 that overpowers the use of vacuum tubes in exchange for transistor operations. These vacuum tubes are operated by several hundreds of anode voltage to run small home electronic devices. The revolution of power electronics emerged in 1963 in the form of a digital electronics [12, 13]. The progress and development of power electronics was illustrated in reference [12]. The utilization of these bipolar transistors was established when the integrated circuits are invented in 1970's. The integrated circuits (IC's) are called chips, where large number of tiny transistors is integrated in a small device and functions as multiple transistors. Power Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Gate Turn–Off Transistor (GTO) and Insulated Gate Bipolar Transistor (IGBT) became matured and made a remarkable impact on the power electronics industry in the 1980's.

Figure 1.2 shows the development of Complementary Metal-Oxide-Semiconductor (CMOS) integrated circuits is far better compared with the conventional integrated circuits. CMOS technology is used in intelligent microcontrollers, microprocessors and other digital logic circuits.

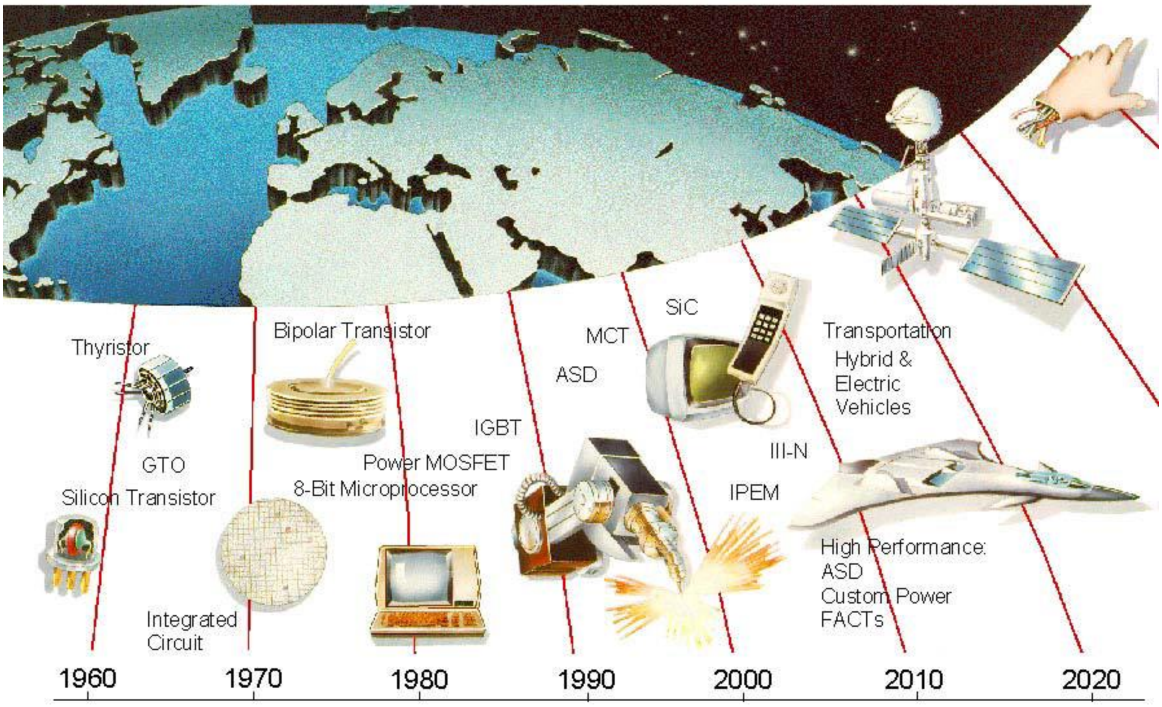


Figure 1.2 Power Electronic Trends and Applications [14]

1.4 Application of Power Electronics

Power electronics is the application of solid-state electronics for the control and conversion of electric power in a form where it is optimally suited to the load. The application of power electronics in conversion and modification of electrical energy (i.e. change its voltage, current, frequency, system efficiency, etc.) is significant in the process of energy configuration. Hence, power electronics has high expectations in the field of alternative and renewable energy systems.

The output energy produced by a generating source is unregulated and unstable. It will be an unregulated DC power for PV and fuel cell, and an unregulated AC power for wind and micro hydro generator. The presence of power electronics in the conversion of renewable energy is a must when stability of the system is concerned. Although the unregulated output power of the generating sources is not suitable to be used directly to a load. It easily varies with the input voltage, it dissipates power more quickly and the ripple is not suitable for electronic applications.

Basically, power electronics is effective for converters, rectifiers, inverters, frequency controllers and as power factor correction in a system. The power conversion systems can be categorized according to the type of the input and output power, as an alternating current AC and direct current DC source. It may be applied for rectifier, inverter, DC-DC conversion and AC-AC inversion.

1.5 Power Electronics for Alternative Energy

The growth of global electrical energy consumption continues to rise and double the power capacity demand within 20 years. Other generating sources, like green and renewable energy are in place to satisfy the demand of energy production. The practical use of renewable and distributed energy offers smart alternative for power generation and being less of a burden to the existing transmission and distribution network in the grid. Distributed generations using renewable energy sources eliminate construction of large scale power plants, transmission and distribution infrastructure that saves millions of dollars on the part of power producers [15].

It is a demand that production, distribution and use of electrical energy are done as efficient as possible to save energy at the end user application. Of many options, two major technologies are presented in references [16] and [17] that play an important role to solve parts of those future problems. Further, the emerging climate changes are arguing to find sustainable future solutions.

- One is to change the electrical power production from conventional, fossil based energy sources to renewable energy sources.
- Another is to use high efficient power electronic principles, power and control systems in power generation, power transmission and distribution.

Power electronics is being changed from minor commodity of energy sources to a highly important aid in the energy system. Further application of power electronics is for power factor correction in a network.

The promising future of power electronics is on the system of integration of electronic power processing, power system, distributed generation, energy storage, automotive applications, improvement in system performance and standardized power supply [18].

1.6 Scope of the Thesis

1.6.1 Motivation of the thesis

There have been considerable advances in the design of different converters and inverters over the last decades. Recent developments of power inverters have motivated the power and control engineers to make use of different sorts of power electronic controllers to enhance the use of renewable energy. This petite equipment is highly significant for industrial and commercial applications.

The objective of this research thesis is to implement an intelligent controlled power inverter using a DSP for fuel cell energy generation. Latest studies show the comparison of the conventional inverters to the new design of inverters using microprocessors. The comparison is based from the cost production, size and efficiency of the inverter. The size of the inverter is directly proportional to the component used in the production. The bigger the inverter, the more components are used and more energy losses are wasted.

The following objectives were raised which motivated the conductance of this research:

- To study, simulate and evaluate the different boost inverter topologies used for alternative power generating sources using the Mathworks software.

- To apply different methods of system modeling on the dynamic response of the PEM fuel cell with suitable digital control strategy using DSP for the PWM inverter.
- To devise, construct and test the viability of the prototype inverter using a DSP as a controller for PWM signal inverter.
- To propose an intelligent controlled power inverter using a DSP and a digital motor controller as an effective tool for energy conversion of a PEM fuel cell.
- To develop a smart PWM inverter for energy system for PEM fuel cell used in distributed energy application.

1.6.2 Limitations

The focus of this thesis research is on power electronic circuits that consist of a DSP and a digital motor controller, for the design of a power inverter. The strategies are motivated in the control circuit of the converter and inverter topologies. Alternatively, the auxiliary component and circuits are predesigned in order to make an operational prototype. However, this prototype is not optimized neither in respect to low cost production and low power consumption.

1.6.3 Thesis Flow Chart

The coloured boxes in Figure 1.3 illustrate the detailed thesis flow chart of the research proposal. It starts with the energy demand which is at stake for additional supply of energy coming from alternative energy sources. The addition of energy supply will come from various new types of alternative energy which will harness in the future.

The alternative energy source is divided into renewable and green energy source. Under the green/clean energy source, the fuel cell is a good source of this type. Different types of fuel cell are enumerated and the PEM fuel cell is selected due to its availability for this research experimentation.

A boost DC – DC converter was designed to cater some DC applications and an input for the inverter of fuel cell. For further application such as for large equipment and other sensitive electronic apparatus, an inverter was incorporated for AC use. The involvement of power electronics makes the difference on the control of an inverter. The control system is concentrated on the DSP as the main controller for the PWM inverter. The sensitive part in providing an effective sinusoidal output waveform of inverter is the control of PWM signal which triggers the switching of semiconductor switches to produce a high efficient output.

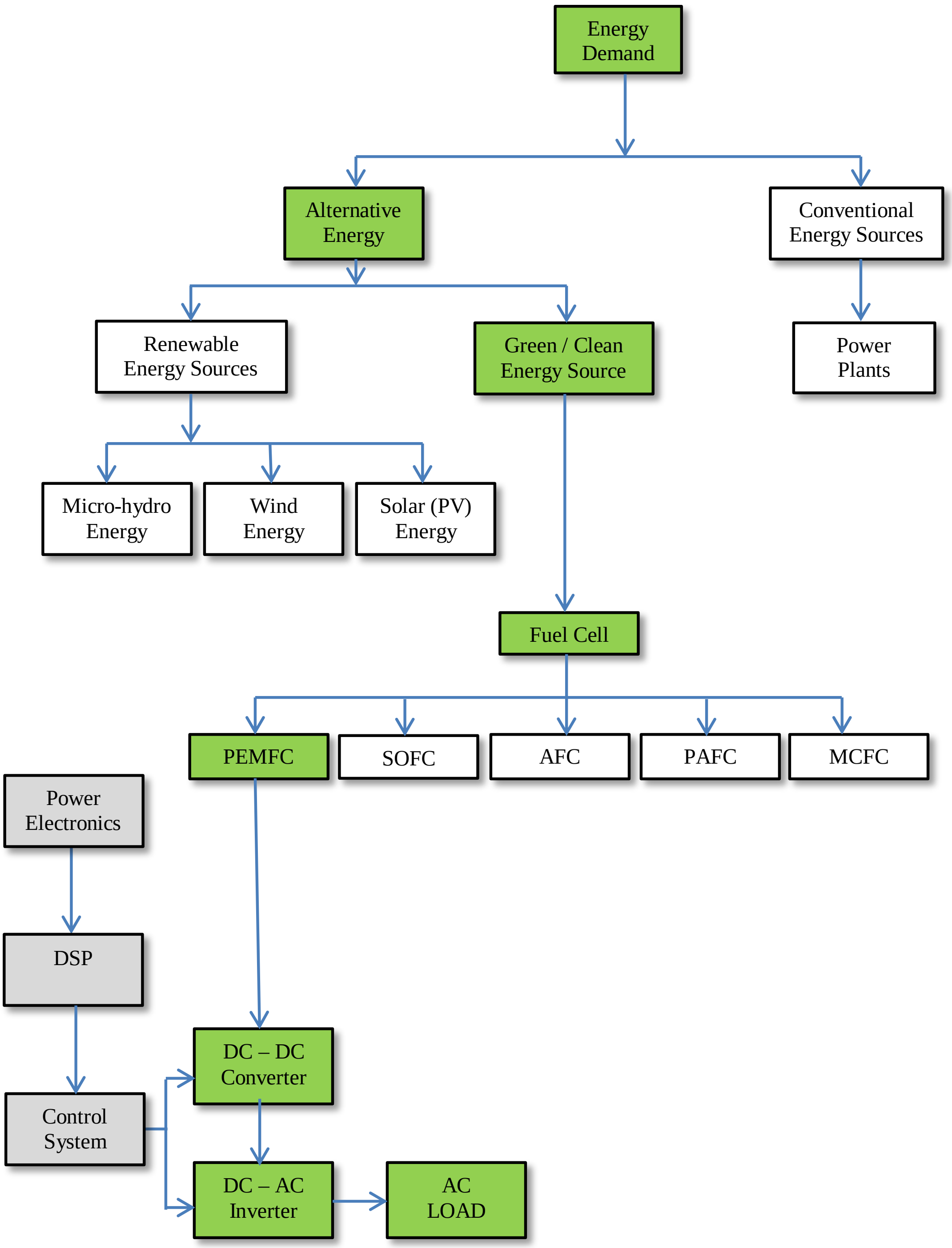


Figure 1.3 Thesis Flow Chart

1.6.4 Organization of the thesis

This thesis consists of six chapters and it is organized as follows:

Chapter 2 presents an outline of fuel cell theory and its background. The fundamentals and different classification of fuel cells, the basic energy generation and description of PEM fuel cell are also discussed.

Chapter 3 explains the overview of the basic theory of a DC – DC converter, selection of converter topology, computational design of converter components for the simulation, and analysis of the result of the simulation.

Chapter 4 is dedicated to the design of an inverter and its simulation, the concept of a PWM technique, effect of duty cycle in an inverter and comparison of a low pass filter in the PWM inverter output.

Chapter 5 enumerates the different components used in the design of a PWM inverter. The overall systems configuration is also discussed. The assembly of programming codes for the CCS software is presented.

In **Chapter 6** presents the concluding remarks, summary of results and suggestions for further research are enumerated.

CHAPTER 2

Fuel Cell Theory and Systems Overview

Theory helps us bear our ignorance of facts.
George Santayana, *The Sense of Beauty, 1896*

This Chapter describes the overview of the basic concepts of fuel cell theory and its background, enumerates the different types of fuel cell, and explains the basic fundamental and description of PEM fuel cell. The energy conversion and efficiency of fuel cell is also discussed.

2.0 Introduction

The present interest in fuel cell is largely known due to the successful applications in various consumer product, electronic equipment, transport application, industrial system and power generation. The evolution of fuel cell is promising and widely accepted for providing an epic substitute for conventional applications.

During the past several years, numerous types of fuel cells emerged and named after the element used in the construction of the fuel cell. The growth of the fuel cell industry is accelerated due to its advantages over the conventional energy sources in the power generation industry.

2.1 History of Fuel Cell

The discovery of the principles of fuel cell technology by Sir William Grove in 1839 is a breakthrough for technological advances in different disciplines and applications. He discovered that mixing hydrogen and oxygen in the presence of an electrolyte produced an electricity and water [19].

The term “fuel cell” was coined in 1889 by L. Mond and C. Langer, who attempted to develop a fuel cell that uses industrial coal gas and air [20]. The technology had no practical use until the 1930’s, when Francis T. Bacon applied an alkaline catalyst in a hydrogen-oxygen fuel cell. In the 1950’s, the first practical application of this high efficient, pollution free technology was in the Apollo space vehicles of the United States, which used the alkaline fuel cells to provide in-flight power, heat, and clean drinking water, a by-product of the electrochemical reaction [21]. From then onwards, the use of the fuel cell was popularized by National Aeronautics and Space Administration (NASA) in the manned space exploration program. However, the price of the fuel cell systems is still expensive and was only used in special applications where good performance was the primary concern.

2.2 Fuel Cell Fundamentals

A fuel cell is defined, as an electrochemical device which can continuously convert chemical energy of a fuel and an oxidant to electrical energy by a process of involving an essentially invariant electrode-electrolyte system [22]. Fuel cells operate in the reverse of electrolysis, with hydrogen and oxygen being combined to produce electricity and reusable heat and water.

Fuel cell has components and characteristics similar to those of a typical battery but differs in several aspects. A battery is a device that stores energy and cease to produce electrical energy when chemical reactant stored within the battery is consumed or discharged. In a secondary battery, the reactants are renewed by recharging the battery from an external source [23]. On the other hand, the fuel cell has the capability of producing electrical energy for as long as the fuel and oxidant are supplied to the electrodes.

There are several types of fuel cell, but all consist of two electrodes – an anode where oxidation occurs, and a cathode where reduction occurs. The electrodes are separated by an electrolyte membrane. Hydrogen (H_2) is continuously fed to the anode and oxygen or air is fed to the cathode. An electrochemical reaction occurs in the electrolyte of the fuel cell which separates the electrons and flow through an external circuit to drive the connected load.

2.3 Classifications of Fuel Cell

The most common types of fuel cells are classified by the types of electrolytes used in its construction. Each fuel cell class differs from the electrolytes used, temperature of operation, system requirements and applications [24, 25, 26].

2.3.1 Solid Oxide Fuel Cell (SOFC)

The solid oxide fuel cell uses a solid, non-porous metal oxide electrolyte and the charge carriers are oxygen ions. It operates between 500 – 1000^{o}C. The potential applications are for power generation and cogeneration up to 100 MW. It is also used for small auxiliary power units for transport. The theoretical efficiency ranges from 45 – 60%.

2.3.2 Phosphoric Acid (PAFC)

The phosphoric acid fuel cell uses a Phosphoric acid material as an electrolyte and platinum as catalyst. It operates between 170 – 210^{o}C. The potential application is for power generation and cogeneration which uses up to 10 MW power generated. It can also be used for bus transport. The theoretical efficiency ranges from 40 – 50%.

2.3.3 Alkaline Fuel Cell (AFC)

The alkaline fuel cell uses a Potassium (K) or Sodium Hydroxide (NaOH) electrolyte and can be either mobile or retained in a matrix material. It operates between 50 – 250^{o}C. The potential applications are for space, transport and military applications, up to 100 kW power generated. The theoretical efficiency ranges from 40 – 60%.

2.3.4 Molten Carbonate Fuel Cell (MCFC)

The electrolyte of molten carbonate fuel cell is usually a combination of alkali carbonates retained in a ceramic matrix. It operates between 600 – 700^{o}C. The potential applications are for power generation and cogeneration, up to 100 MW power generated. The theoretical efficiency ranges from 50 – 60%.

2.3.5 Proton Exchange Membrane Fuel Cell (PEMFC)

The electrolyte in this fuel cell is a solid ion exchange membrane used to conduct protons. It operates between 50 – 125^{o}C. The potential applications are for commercial and residential distributed power generation, portable power supply and transport applications. PEMFC is used up to 500kW power generated. The theoretical efficiency ranges from 35 – 45%.

The Energy Efficiency & Renewable Energy of the US Department of Energy released a comparison of Fuel Cell Technologies in February 2011 for the leading fuel cell types that are widely used for commercial and industrial application [27]. In addition, there are two more types of fuel cells used but not distinguished by their electrolyte. These are the Regenerative Fuel Cell (RGFC), distinguished by its method of operation, and the Direct Methanol Fuel Cell (DMFC), notable by the type of fuel used.

Table 2.1 Comparison of Fuel Cell Technologies [27]

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

2.4 Fuel Cell for Power Generation

Proton exchange membrane fuel cells (PEMFC) are the best candidates for distributed power generation for low power applications. The PEMFC can operate at relatively low temperature, and can vary their output to meet unstable power demand. The potential of market demand is high due to the capability of this fuel cell as portable power generators, back-up power supply, grid-tie power systems, for hybrid power systems and transport applications. In addition, PEMFC are being considered as the best type of fuel cells as the vehicular power source to eventually replace the gasoline and diesel internal combustion engines because they typically have a quality of a rapid start-up time.

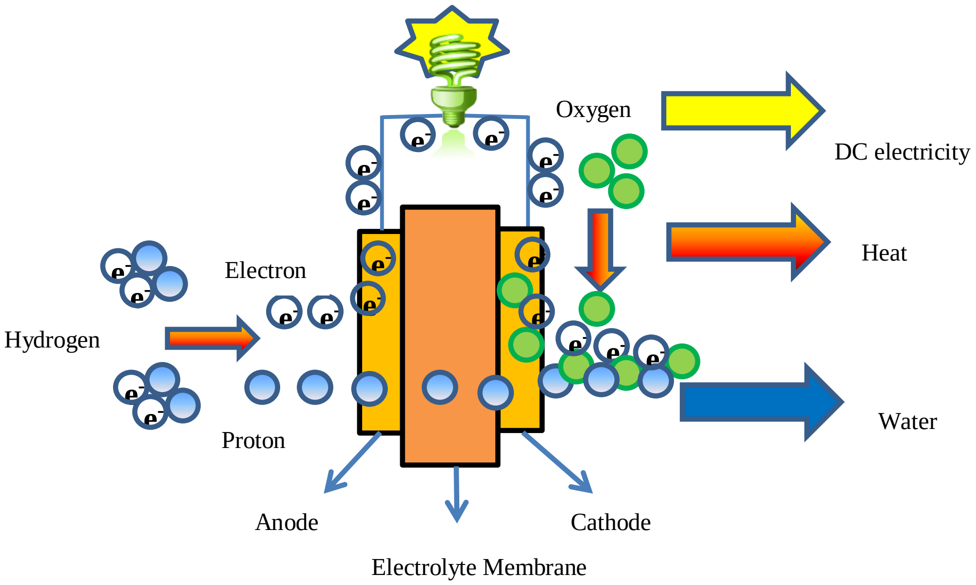
It was predicted that electric utility companies will consider using fuel cell for meeting peak demand and supply additional energy to the grid. From 1998 to 2000, fuel cells are installed in 80 locations in New York to benchmark the reliability as an alternate source of energy for residential used. Industries like factories and hospitals have started replacing the diesel generator with fuel cell in their uninterruptible power supply (UPS) systems. The dynamic performance of fuel cell can draw interest as a primary candidate in automobile industry, telecommunications, banks, government agencies and many other sectors [28].

In spite of these advantages of a PEM fuel cell, there are still shortcomings that limit the use of fuel cell. Some of present problems met are the high cost of manufactured fuel cell, water management problem and the efficiency of energy conversion produced.

2.5 PEM Fuel Cell Unit

Fuel cells come in a variety of sizes. Each individual cell unit produces very small amount of electricity. To increase the voltage and current output of a fuel cell unit, each cell are "stacked" or placed in series or parallel circuit combination. To meet the desired amount of energy needed, the fuel cells can be combined in series circuit to produce a higher voltage and parallel circuits to allow a higher current to be delivered. The cell surface area can be increased, to allow stronger current and larger power produced from each cell.

A PEM fuel cell in operation is presented in Figure 2.1



Anode:	H_2	$\longrightarrow$	$2H^+$	+	$2e^-$		
Cathode:	$\frac{1}{2}O_2$	+	$2H^+$	+	$2e^-$	$\longrightarrow$	H_2O
Overall:	H_2	+	$\frac{1}{2}O_2$	$\longrightarrow$	H_2O		

Figure 2.1 Basic Description of a PEMFC operation

Due to the need of proper representation of a fuel cell in different designs, Mathworks [29] has included a generic circuit equivalent of a fuel cell stack that can be used in simulation modeling. The simplified model represents a fuel cell stack operating at nominal conditions of temperature and pressure, and the parameters can be modified based on the type of fuel cell to be used from the manufacturer's data sheet. The equivalent circuit of a fuel cell feeding a converter is shown in Figure 2.2

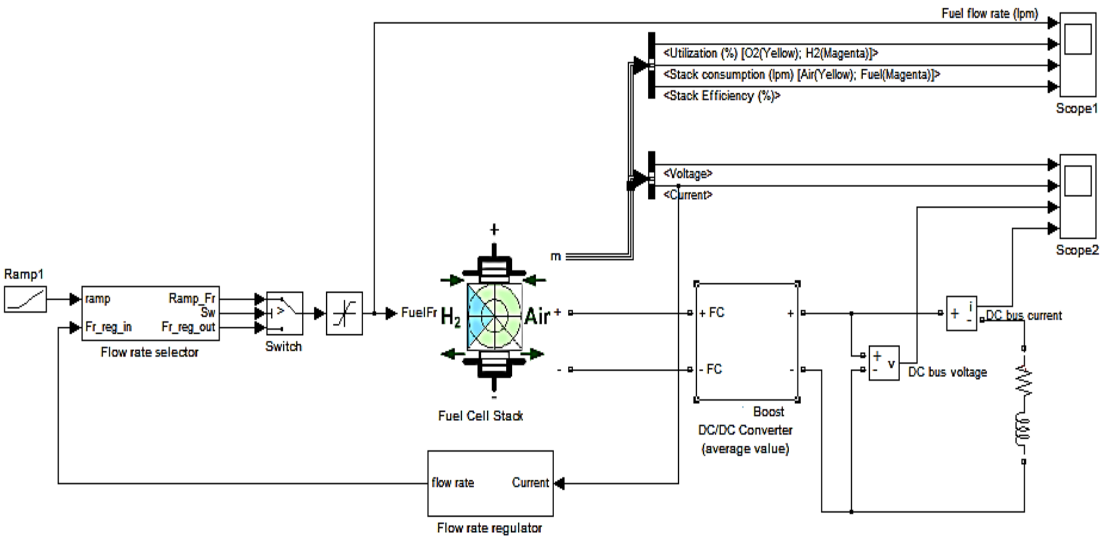


Figure 2.2 Equivalent circuit of a fuel cell stack feeding a DC/DC Converter

2.6 Fuel Cell Efficiency

In comparison with heat engine, it is commonly expressed that a fuel cell is more efficient than a heat engine because it is not subjected to the second law of thermodynamics and the Carnot cycle limitations. According to Reference [26] these statements are misleading. A more suitable statement in differentiating these two theories is based on the limitation of temperatures. The temperature does not limit the fuel cell operation and efficiency. It provides an abundant benefit because it relaxes the material temperature problems when trying to achieve its high efficiency, while the heat engine is affected by its temperature.

In general, efficiency is the percentage of useful electrical energy produced over the total electrical power consumed. In fuel cell operations, the thermal efficiency of energy is the amount of useful energy produced relative to the chemical reaction released from fuel when reacted with an oxidant. The ideal efficiency of fuel cell, operating conclusively, is

$$\eta = \frac{Useful\ Energy}{\Delta H} \tag{2.1}$$

In the ideal case of an electrochemical converter, the useful energy in a fuel cell is the change in the Gibbs free energy, *ΔG* while *ΔH*, is the enthalpy of reaction formation. The ideal fuel cell efficiency operating irreversibly is then

$$\eta = \frac{\Delta G}{\Delta H} \tag{2.2}$$

Thus, the thermal efficiency of an ideal fuel cell operating reversibly on pure hydrogen and oxygen has an 83% factor in standard conditions [26]. The actual fuel cell efficiency based on the higher heating value of hydrogen would be:

$$\eta = 0.83\frac{V(actual)}{V(ideal)} \tag{2.3}$$

where the $V_{(actual)}$ is the measured operating voltage from the cell and $V_{(ideal)}$ is the voltage achieved from Gibbs free energy in the ideal case. The ideal voltage of a cell operating reversibly on pure hydrogen and oxygen at 1 atmospheric pressure and 25°C is 1.229V_{dc}. In terms of the actual voltage of the cell, V_{cell}, based on the heating value of hydrogen, is given by

$$\eta(ideal) = 0.83\frac{V(cell)}{V(ideal)} = 0.83\frac{V(cell)}{1.229\,V} = 0.675\,V(cell) \qquad (2.4)$$

The equivalent cell voltage then determines the efficiency of the fuel cell. Useful electrical energy is acquired when a realistic current is drawn in the energy conversion of the cell. Generally, in any energy conversion process, energy losses are also produced at the same time with the useful energy. In the fuel cell conversion, the losses are often called the polarization loss [26, 30].

The actual cell voltage produced is less than the ideal voltage due to activation loss, ohmic loss, and concentration loss.

The activation loss is a term which refers to an over potential difference of a voltage during a chemical reaction process. This loss is directly related to a cell's voltage efficiency. It requires more energy to drive a reaction and less energy is recovered in the process output.

The ohmic loss is a loss directed to the electrical resistance of the electrode, and the resistance of the ions in an electrolyte in a cell. The ohmic losses are directly proportional to the current, where i is the current density (mA/cm^2) and r is the specific area resistance of the cell (kΩ/cm^2), where, ΔV is the voltage drop of the resistive equivalent in the fuel cell,

$$\Delta V = ir \tag{2.5}$$

The concentration loss is a loss due to the reduction of pressure supplying the electrolytes of the cell. The slight reduction of oxygen and hydrogen supplied in the cathode and anode of a fuel cell respectively, will change the concentration of the partial pressure of the system when the chemical reaction takes place. In both cases, the reduction in gas pressure will result in a reduction of output voltage in a fuel cell.

Figure 2.3 illustrates the theoretical electromotive force (EMF) or ideal voltage of a fuel cell. It shows the different regions of polarization loss. The activation loss represents the loss on the start-up of the fuel cell in operation where the energy is generated and recovered which lower the theoretical voltage of the fuel cell. Added to this loss, is the voltage drop across the resistive element of the cell.

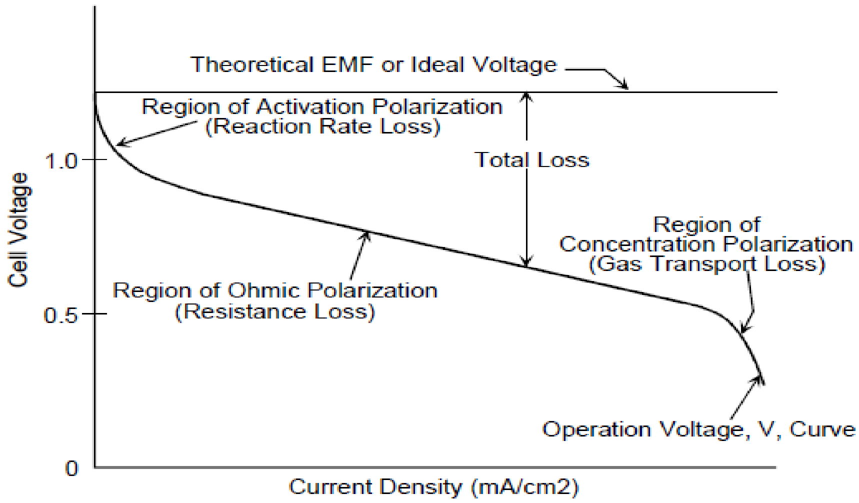


Figure 2.3 Ideal and Actual Fuel Cell Voltage Characteristics

The operating voltage or the usable voltage is obtained based from the strength of the continuous operation of the gas pressure fed to the fuel cell which is the concentration loss.

Considering all these losses, the computational equivalent voltage of a fuel cell and its power density can be written as:

$$V_{fc} = E_{ideal} - V_{activation} - V_{ohmic} - V_{concentration} \tag{2.6}$$

$$P_{fc} = V_{fc} * i \tag{2.7}$$

where V_{fc} – is the operating voltage of the fuel cell

E_{ideal} - is the theoretical EMF of the fuel cell

$V_{activation}$, V_{ohmic}, $V_{concentration}$ – are the polarization losses

P_{fc} - is the power density of the fuel cell

i – the output current of the fuel cell

The power density, current and cell voltage of a fuel cell is considerably correlated with the temperature, gas pressure and humidity of the membrane used. The fuel cell operating parameters (temperature, partial pressure and membrane humidity) has a significant influence to the fuel cell's output power. The characteristic of the power density of the fuel cell is influenced more by the change in temperature than the reactants of partial pressure and humidity of membrane used [31].

The standard diagram of a fuel cell with respect to its power density, current density and cell voltage is shown in Figure 2.4.

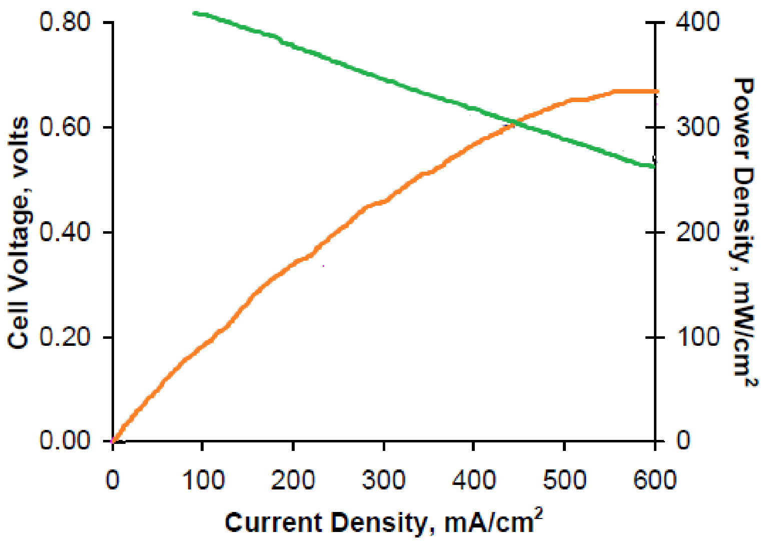


Figure 2.4 Fuel Cell Voltage and Power Characteristics

2.7 Constructor Fuel Cell

The Constructor fuel cell is a 50W, PEM fuel cell manufactured by Heliocentris Company used in the prototype of this research. The fuel cell system consists of a stack assembly that includes a fan for the oxygen supply and cooling, solenoid valves for the hydrogen input and output, a temperature sensor and taps for monitoring the cell voltage.

In Reference [32] the voltage of the fuel cell was boosted to $12V_{dc}$ and loaded with a variable resistance in two configurations. The first configuration is a connection of the boost converter and the variable load to the fuel cell. The second is the hybrid configuration where a supplied battery was added in the system. The result shows that the power generated was increased and the voltage is more stable with the variation of load under the hybrid configuration.

Figure 2.5 is an illustration of a detailed Heliocentris constructor fuel cell.

Figure 2.5 A Heliocentris 50W, Constructor Fuel Cell

Table 2.2 illustrates the working specifications of the constructor fuel cell stack.

Table 2.2 Technical data of the constructor fuel cell stack

Denomination	Specification
Rated output power	40 W
Maximum output power approximately	50 W
Open circuit voltage approximately	9 V
Voltage at rated power	5 V
Maximum current	10 A
Current at rated power	8 A

CHAPTER 3

DC – DC Converter Design Topology

Every science begins as philosophy and end as an art.
Will Durant, *The story of Philosophy, 1926*

This Chapter explains the basic fundamental and theory of operation of different types of DC – DC converter. A detailed computational design of a converter is illustrated and used in MATLAB simulation to further clarify the system process. The results of the simulation are discussed and concluded.

3.0 Introduction

Power electronic is significant in power converters due to their characteristics to operate semiconductor switches at high frequencies. High operating frequencies are used in the conversion of energy process to reduce the electronic components involved in the system. Hence, sizes of components such as transformers, inductors and capacitors are minimized to reduce power losses in the conversion process. The introduction of simulation software makes the process modeling easier and more convenient in real time environment. Lots of simulation software are available in the market that are used on different engineering discipline and projects. However one of the most powerful software widely used for general purpose is the MATLAB/Simulink from Mathworks. The MATLAB/Simulink software package is used for diverse simulation from mathematics, science and engineering. This software is specifically used in this thesis for converter and inverter simulation due to its robustness in analysing and modeling of sample design.

3.1 DC – DC Converter Fundamentals

A converter is used to convert the unregulated DC input of an external power source into controlled DC output at a desired voltage level. The general purpose of these converters is to regulate the DC output voltage of the circuit against the increasing load and line deviations in a system.

Early converters were known as choppers with Silicon controlled rectifiers (SCR's) used as the switching mechanism in a system. The advantage of the DC chopper is its simple operation. However, the obstacle met on this type of converter is the hard switching characteristics of the SCR that causes the presence of high harmonics created in the output voltage.

The most widely used converter at present is the so called transformerless converter which uses power electronics to switch the electronic devices and operates in a desired topology of a circuit. Transformerless converter is a type of converter which falls under the switch mode scheme of control system. Switch mode converters are not often used in combining with a transformer for electrical isolation in DC power supplies. The strength of switch mode converters is used on DC motor drives without isolation.

The five basic types of DC-DC switch mode converters are classified through the different converter topologies. The two basic converter topologies are the step up (boost) converter and the step down (buck) converter. The combination of these two basic topologies could be manipulated as a buck-boost converter and as a Cúk converter. Aside from these, the full bridge converter which is derived from a step-down converter has the ability to be operated in dual function. It could be used as a converter and inverter depending on the scheme of its control system, since the power could be manipulated in a bi-directional manner.

3.2 Theory of Operation

The general theory of operation of a converter is to supply a regulated DC output voltage to a variable load resistance from a fluctuating DC input voltage of an external power source. The theory of operation of the following converters is presented in reference [33].

The step-down (buck) converter consists of DC input voltage source V_{dc}, a power transistor (MOSFET, IGBT), a diode, an Inductor L, a filter capacitor C, and a load resistance R. The operation of the buck converter is done in two stages. The voltage source charges and stores energy in the inductor, and discharges energy from the inductor to the load. The output voltage depends only on how much charge does the inductor obtained from the voltage source and delivered it to the load which is lesser than the input voltage of the circuit (Figure 3.1).

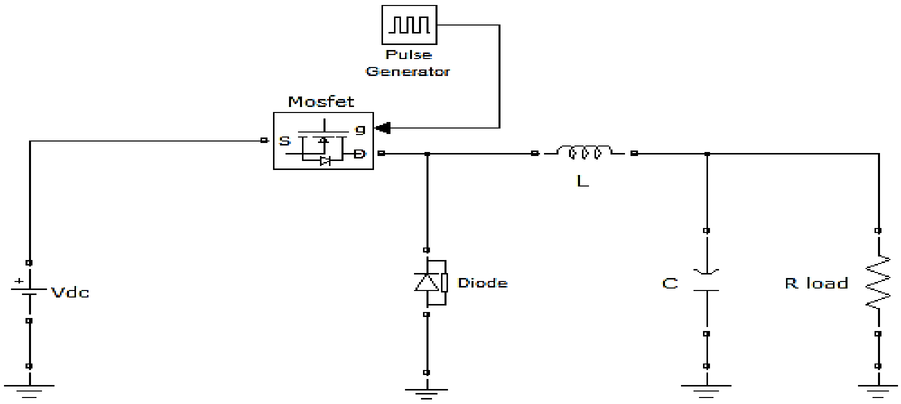


Figure 3.1 Step-down (buck) converter

The step-up (boost) converter consists of DC input voltage source V_{dc}, a power transistor (MOSFET, IGBT), a pulse generator, a diode, a boost Inductor *L*, a filter capacitor *C*, and load resistance *R*. The operation of the boost converter is focused on the inductor how it resist current changes in charging and discharging state in the circuit. When being charged, it acts as a load and absorbs energy. When being discharged, it acts as an energy source and accumulated with the voltage source that makes the output voltage higher that the input voltage (Figure 3.2).

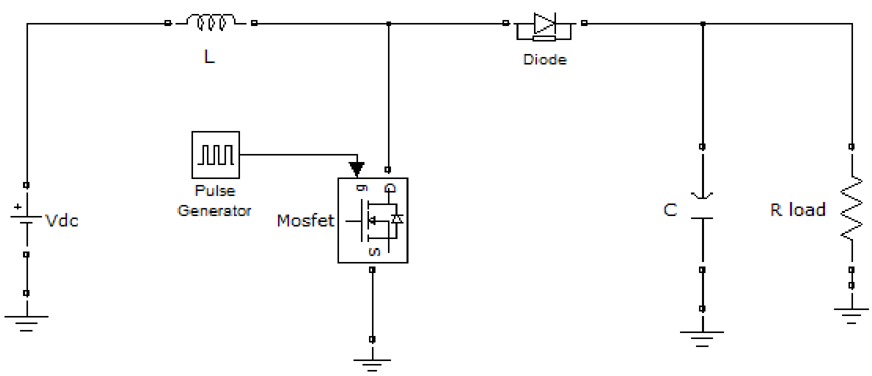


Figure 3.2 Step-up (boost) converter

The step-down / step-up (buck-boost) converter consists of DC input voltage source V_{dc}, a transistor (MOSFET, IGBT), a diode, an inductor *L*, a filter capacitor *C*, and load resistance *R*. This converter operates based on the duty cycle of the switching transistor and can either produce greater than or less than the input voltage magnitude. In addition, it produces a wide range of output voltage from the maximum output voltage to almost zero (Figure 3.3).

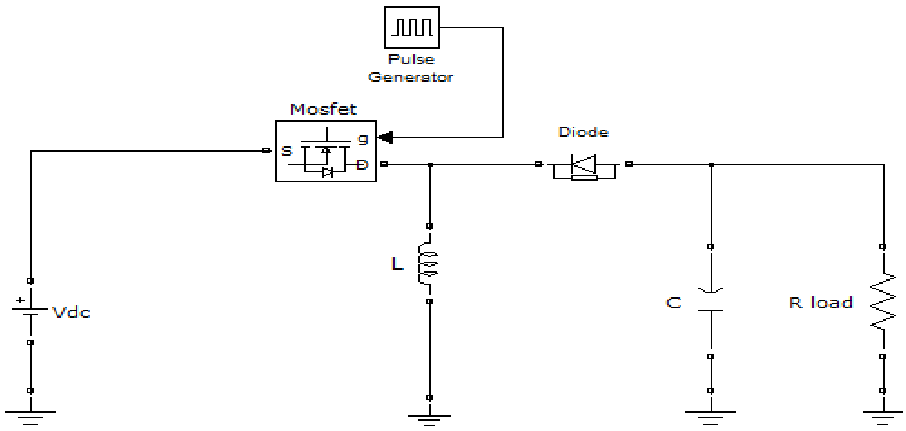


Figure 3.3 Step-down / Step-up (buck-boost) converter

The Cúk converter consists of DC input voltage source V_{dc}, diode, input inductor *L*, filter inductor L_1, energy transfer capacitor C_1, filter capacitor *C* and load resistance *R*. This type of converter is similar to the buck-boost converter that can vary its output voltage from maximum to almost zero. It uses a capacitor as its main energy storage component; unlike other converters use an inductor as storage. The added capacitor in the voltage source limits associated energy loss. Thus, the converter produces higher energy efficiency compared to other types of converters. It also operates either in continuous or discontinuous current mode (Figure 3.4).

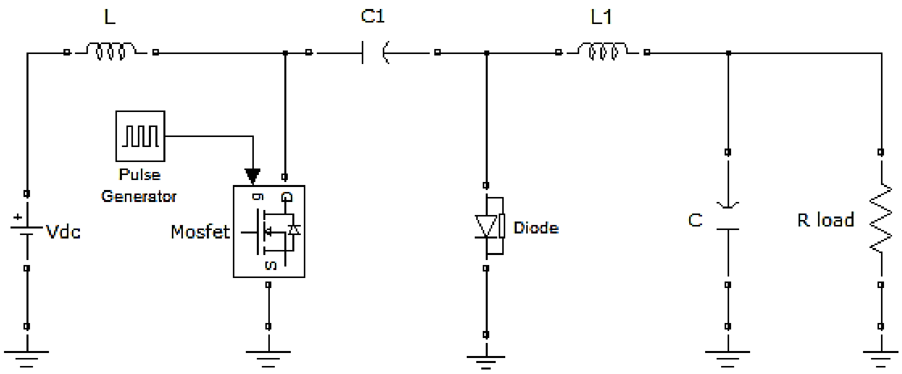


Figure 3.4 Cúk converter

Another type of converter derived from the Cúk converter is the Single-ended Primary-inductor converter (SEPIC). The difference from the Cúk converter is the position of the diode and the end inductor, L1, which was interchanged. A SEPIC is similar to a traditional buck-boost converter which has a non-inverted output and can respond to short circuit gracefully. It has the ability to transfer all its energy through the series capacitor, C1, with high capacitance and current handling capability. When the output voltage drops to "0" volts, it dumps large amount of transient charge which means it is unforgiving compared to boost converter (Figure 3.5).

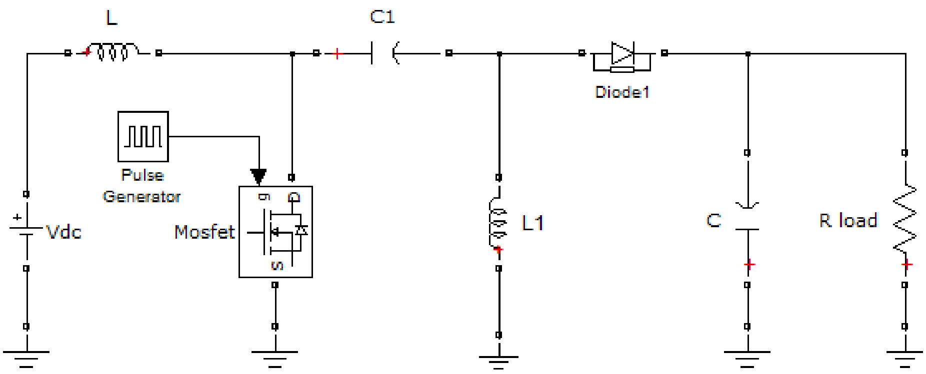


Figure 3.5 SEPIC converter

The Full bridge converter usually comprised of four available transistors (MOSFET, IGBT), a DC input voltage source V_{dc}, a transformer, two diodes, inductor *L*, a filter capacitor *C*, and load resistance *R*. The four transistors are driven by a pulse generator which is operated in pairs. When S_1 and S_4 are *on*, V_{dc} is applied to the primary switch of the transformer and diode D_1 operates. With S_2 and S_3 are *on*, the voltage is $-V_{dc}$ and D_2 operates. When all controllable switches are *off*, both diodes conduct at the same time (Figure 3.6).

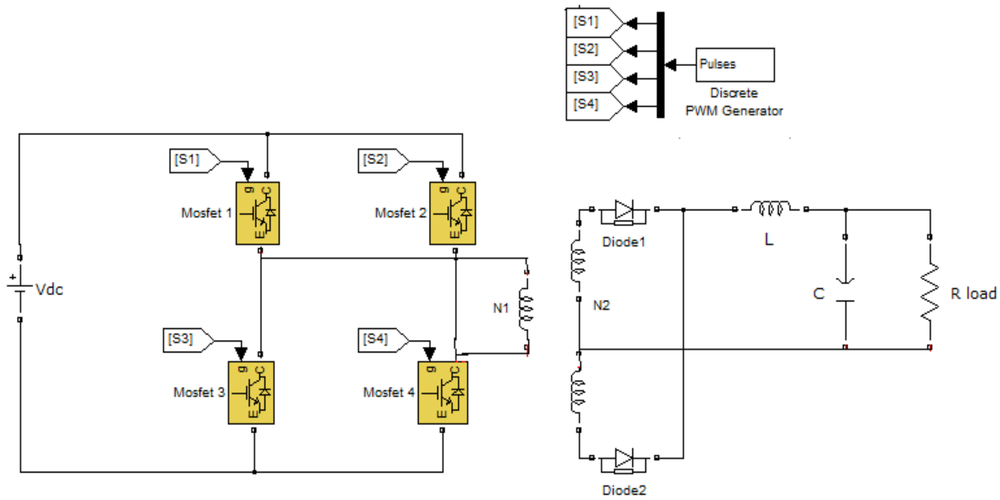


Figure 3.6 Full bridge converter

The full bridge topology is a very nifty type of converter. This can operate on bi-directional power flow and can be used for both converter and inverter function. The conversion process is controlled with different algorithms suitable for the purpose of an inversion and conversion topology.

3.3 Design of a DC – DC Boost Converter

The design of a boost converter is based on the equivalent circuit of the boost topology. Typical converter uses a transistor switch, usually a MOSFET to modulate a pulse from a generator source. The values of the electronic elements are computed to satisfy the acquired values needed for the circuit. For boost converter, a high value of current is expected to flow in the circuit. The inductor rating must be in the specification to allow the current to pass without damaging other electronic components in the system. The ripple current is also another thing to consider in obtaining the output capacitor. A high ripple current could cause an internal rise of temperature which causes a power loss within the output capacitor. With these things to consider, the design of the converter is based from references [33, 34, 35].

The relationship of voltage and current for an inductor can be represented as;

$$V = L\frac{di}{dt} \tag{3.1}$$

$$i = \frac{Vt}{L} + io \tag{3.2}$$

When the voltage is at constant pulse, the equivalent current when the transistor is "on" is;

$$ipeak = \frac{(Vin - Vtrans)\,Ton}{L} + io \tag{3.3}$$

Or it can be represented using the ripple current formula when switch is "on"

$$\Delta i = \frac{(Vin - Vtrans)\,Ton}{L} \tag{3.4}$$

And when the transistor is switch “off”, the current is;

$$io = ipeak - \frac{(Vout - Vin + Vd)\,Toff}{L} \tag{3.5}$$

$$\Delta i = \frac{(Vout - Vin + Vd)\,Toff}{L} \tag{3.6}$$

The ripple current of the inductor can also be computed using the formula;

$$\Delta i = ipeak - io \tag{3.7}$$

where

Δi	-	ripple current
io	-	minimum inductor current
$ipeak$	-	peak inductor current
L	–	inductance
T_{on}	–	transistor is “on”
T_{off}	–	transistor is “off”
V_d	–	voltage drop across the diode
V_{in}	–	input voltage of the circuit
V_{out}	–	output voltage of the circuit
V_{trans}	–	voltage drop across the transistor

The continuous/discontinuous boundary of the circuit occurs when the current i_o reaches zero in a given period of time. The output voltage, V_{out} can be attained by equating Δi from equations (3.3) and (3.4).

$$\frac{(Vin - Vtrans)\,Ton}{L} = \frac{(Vout - Vin + Vd)\,Toff}{L} \quad (3.8)$$

$$Vin\,Ton + Vin\,Toff = Vout\,Toff + Vtrans\,Ton - Vd\,Toff \quad (3.9)$$

However the duty cycle, *D* and *Ts* is equal to;

$$D = \frac{Ton}{Ts} \quad (3.10)$$

$$Ts = Ton + Toff \quad (3.11)$$

Therefore:

$$Vout = \frac{(Vin - Vtrans\,D)}{1-D}\ Vd \quad (3.12)$$

By manipulating equation (3.9), the duty cycle (*D*) can be derived as;

$$D = \frac{(Vout - Vin + Vd)}{(Vout + Vd - Vtrans)} \quad (3.13)$$

From equation (3.10) when the voltage drop across the transistor, V_{trans} and diode, V_d, are negligible, the output voltage is directly proportional with the duty cycle, *D*.

$$Vout = \frac{Vin}{1-D} \tag{3.14}$$

The parameters in designing a switch mode DC – DC boost converter falls on the characteristic of the circuit with high inrush current from the inductor and the presence of ripple current on the output voltage.

$$L = \frac{(Vout - Vin + Vd)\,(1-D)}{\min(i\;load)\,f} \tag{3.15}$$

To reduce this problem, a large enough inductor must be used, and assumed to be operating on continuous mode always.

3.4 Computational Design of a DC – DC Boost Converter

The computational design is based from the different formulas in finding the values of the electronic components to be used in the converter. The technical specification of the Heliocentris constructor fuel cell is given in rated and maximum values. For a rated power of 40W, the operating voltage and current is $5V_{dc}$ and $8A_{dc}$, respectively. The maximum power of the fuel cell is 50W when the maximum current is $10A_{dc}$. The no-load or open circuit voltage of the fuel cell stack is given as $9V_{dc}$.

The design is to boost the rated voltage of $5V_{dc}$ to $16V_{dc}$ and serves as the input voltage of the inverter for the module boards. The maximum output current of the converter is assumed to be $2.5A_{dc}$ and the minimum current is $1.75A_{dc}$. The inductor current ripple is chosen to be 3% of the inductor current, while the output voltage ripple is assumed to be 1%.

The values of the component obtained from the computational design of Table 3.1 will be used in the simulation of the boost converter using MATLAB/Simulink.

Table 3.1 Computed Values of Inductor and Capacitor

Boost Topology	
Duty cycle, *D*	73.125%
Inductor, *L*	2.1 mH
Capacitor, *C*	571.3 uF

3.5 MATLAB/Simulink Software

MATLAB/Simulink software was developed by Mathworks used for the purpose of simulating, modeling and analysing linear and non-linear systems. It is a powerful software used in synchronising and interfacing hardware with a personal computer.

MATLAB was termed from Matrix Laboratory and intended primarily for numerical computing using basic programming languages such as C, C++, Java and FORTRAN. These programming languages are manipulated and used to allow the implementation of algorithms in plotting functions, matrices, arrays and symbolic computing [36].

Figure 3.7(a) is the standard form of MATLAB workspace where basic programming languages are used and manipulated.

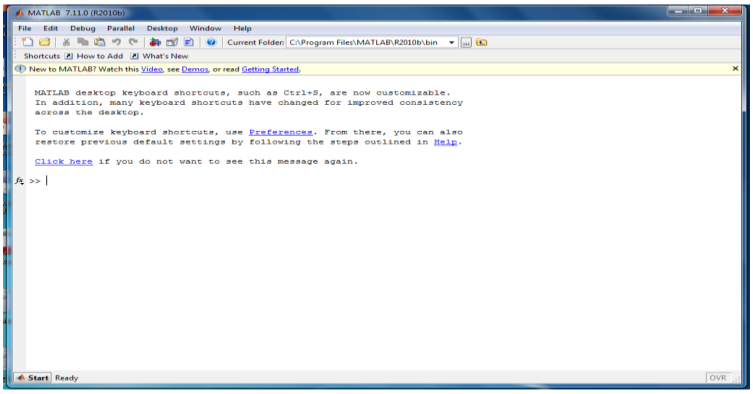


Figure 3.7(a) MATLAB workspace

Figure 3.7(b) is a simulink workspace where figures and blocks are used to represent a data as a signal.

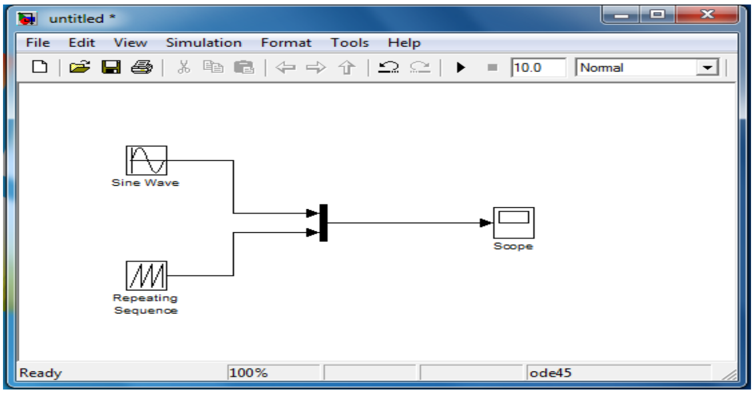


Figure 3.7(b) Simulink workspace

Figure 3.7(c) is a simulink library browser which contains all the operating blocks used in Simulink workspace.

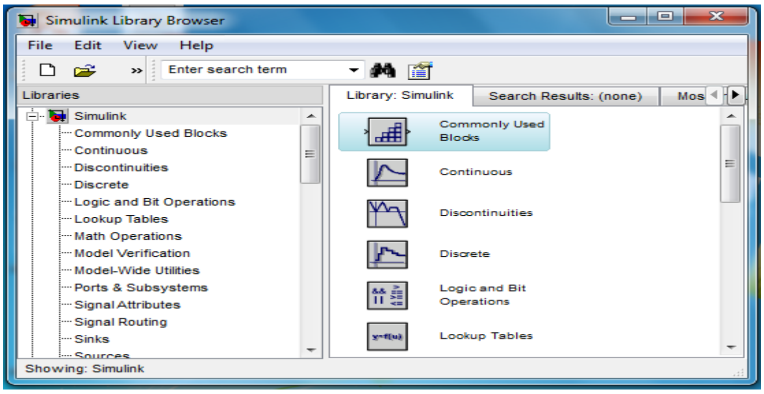


Figure 3.7(c) Simulink library browser

On the other hand, Simulink is an integral part of the MATLAB environment. This is a primary interface for multi-domain in dynamic systems. Simulink provides a graphical user interface (GUI) for building models as block diagrams. The graphical block diagram tool is a customised set of blocks used in modeling a system. Simulink is widely used as a model based design for simulation especially in the field of control system theory and digital signal processing.

3.6 Simulation of a DC – DC Boost Converter

For the simulation of a DC-DC boost converter, the Simulink interface is more applicable in modeling this system because of its feature of associating a block diagram and ideal components in a circuit.

The design requirements of a DC – DC converter are generally based from the technical data and specifications of the fuel cell, which is the external source, and the chosen inverter topology of the circuit. The operating specification of the DMC 550 and DSP boards must be considered to achieve a satisfactory outcome from the simulation and prototype results. The maximum input voltage for the DMC 550 is approximately $20V_{dc}$ which is suitable for the DSP signal to drive the inbuilt transistor of the board.

Hence, the output of the converter should be less than $20V_{dc}$ and will become the input voltage of the inverter. Figure 3.8 illustrates the set-up for the boost converter diagram in MATLAB/Simulink.

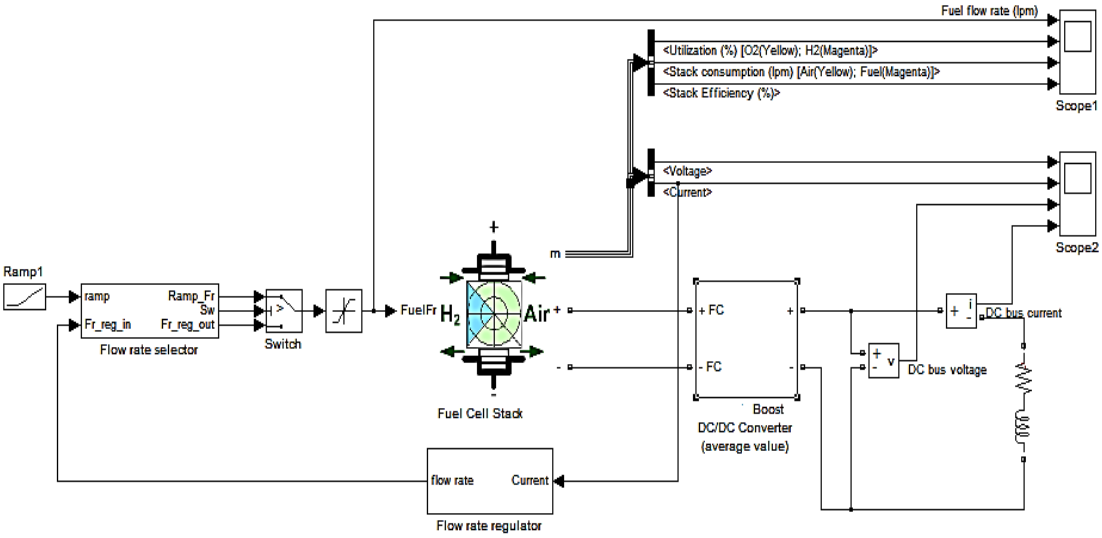


Figure 3.8 Fuel Cell - Boost Converter Simulation Set-up

The computed values of the components are entered in the simulation to check the different results when the duty cycle varies from 25% to 75%.

Figure 3.9 shows the graphical result of load current and output voltage of the simulated boost converter when the PWM duty cycle is 25%. At 25% duty cycle, the output current and voltage is low. The inrush current and the presence of ripple is significant.

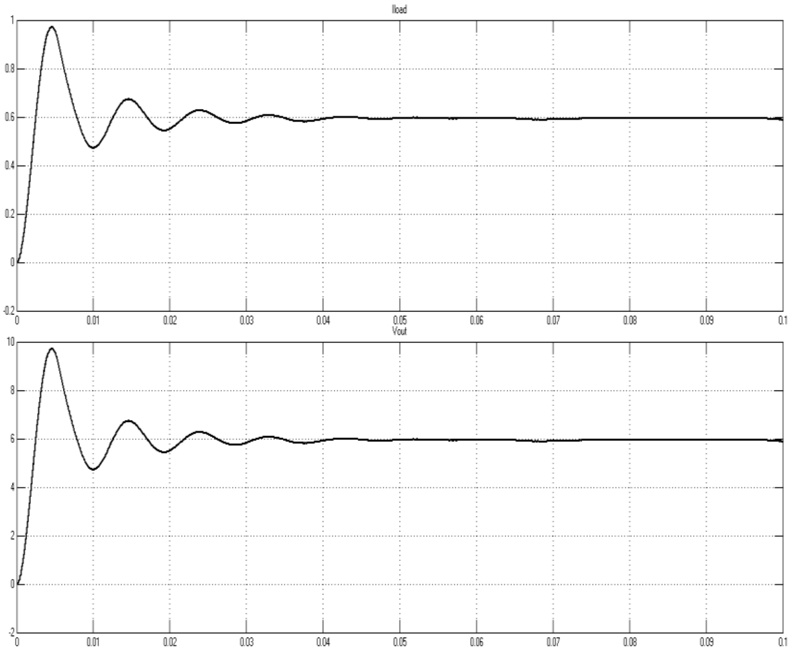


Figure 3.9 I_{load} and V_{out} at 25% PWM duty cycle

Figure 3.10 shows the graphical result of load current and output voltage of the simulated boost converter when the PWM duty cycle is 50%. At 50% duty cycle, the maximum output current and voltage rises to approximately more than 1.3A and more than 13V, respectively. The inrush current is still significant and ripples are lesser before it settles down. As the duty cycle increases, the value of the load current and output voltage also increases.

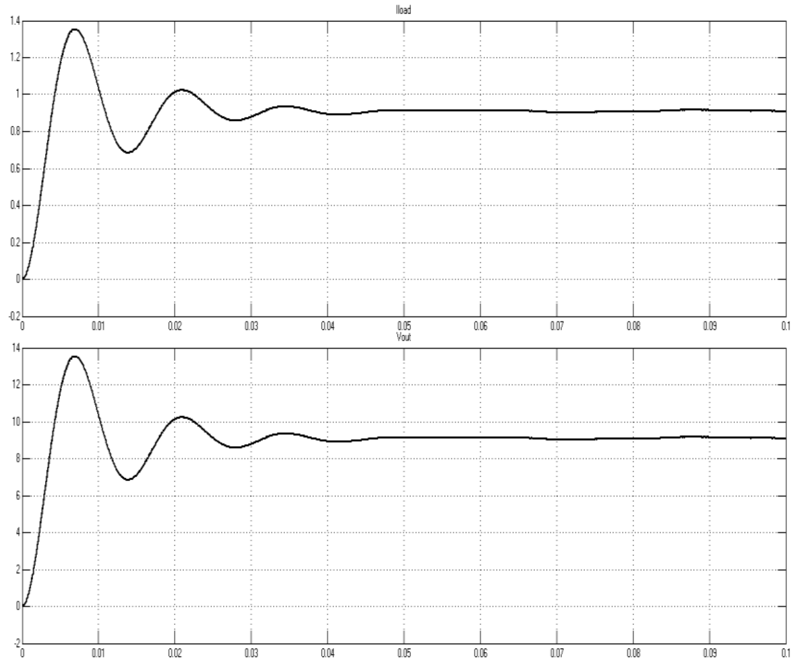


Figure 3.10 I_{load} and V_{out} at 50% PWM duty cycle

Figure 3.11 shows the graphical result of load current and output voltage of the simulated boost converter when the PWM duty cycle is 73.125%. At 73.125% duty cycle, the maximum output current and voltage reaches approximately 2A and 20V, respectively. The average current and voltage is very close to the value that is expected. The inrush current and ripple is acceptable.

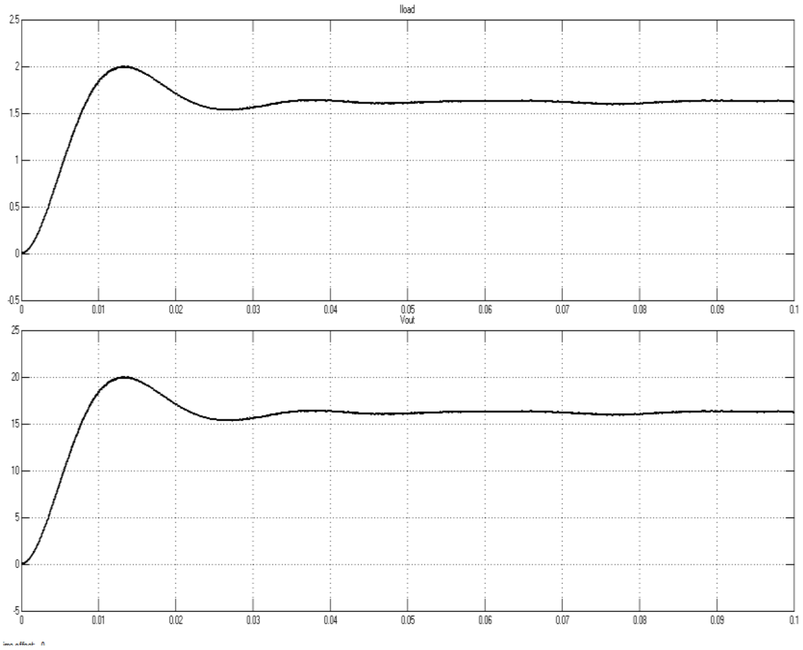


Figure 3.11 I_{load} and V_{out} at 73.125% PWM duty cycle

Figure 3.12 shows the graphical result of load current and output voltage of the simulated boost converter when the PWM duty cycle is 75%. At 75% duty cycle, the maximum output current and voltage is more than 2A and more than 20V, respectively. The average current and voltage is higher than the expected value of both. The inrush current and ripple is acceptable

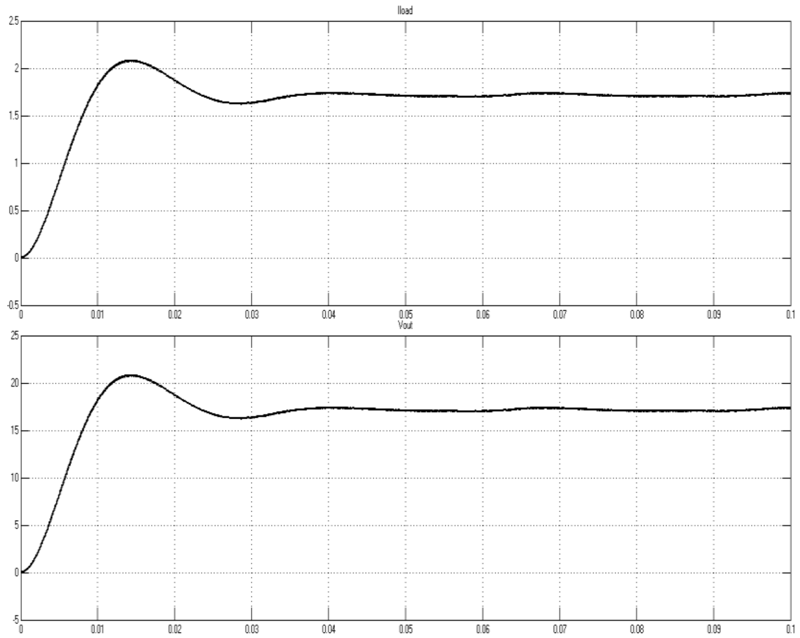


Figure 3.12 I_{load} and V_{out} at 75% PWM duty cycle

The result of the simulation is significant to the projected results on the design of the boost converter. The simulation was done in four different duty cycles from the pulse generator which produces the PWM to switch the transistor. The result was plotted in a graph showing the output current and voltage of the converter.

3.7 Conclusion

The efficiency of a design lies on the factors affecting the purpose of the system. The factors affecting the design of a boost converter are the component ratings and specifications, the minimum and maximum allowable output current and voltage, the duty cycle and the load factor. Aside from these, a very important thing also to consider is the presence of inrush current in an electrical circuit. Inrush current is the maximum, instantaneous input current drawn by an electrical device when first turned on. This is the instantaneous peak at the start of the graph. This can be safely secured by an overcurrent device.

The computational design is technically the most effective way of attaining the projected result. Furthermore, the simulation result is accurate in the sense that it runs only on the ideal environment where power losses are insignificant.

Based from the computational design, the calculated value of the duty cycle, *D*, is 73.125%. The simulation shows that below 73.125% duty cycle, the average output current and voltage is low, and the presence of ripple is significant. Above 73.125% duty cycle, the maximum output voltage is high and the current is close to its maximum value. Hence, for the 73.125% duty cycle, the maximum and average current and voltage is very close to the expected result.

CHAPTER 4

Power Inverter Design Topology

For every fact there is an infinite hypothesis.
Robert M. Pirzig, *Zen and the Art of Motorcycle Maintenance,1974*

This Chapter describes the fundamental theory of an inverter and its operation. A methodical analysis of a duty cycle, low pass filter and PWM technique of a full bridge inverter is discussed and illustrated. The operation of an inverter using a PWM is demonstrated in the MATLAB simulation of a full bridge inverter. The results of the simulation are explained and concluded.

4.0 Introduction

The aim of this project is to design and simulate a low power inverter used for fuel cells. The type of inverter topology to be used in the simulation is a full bridge inverter. The full bridge inverter was chosen to represent the DMC 550 module which has an inbuilt full bridge component. The pulse generator will also represent the DSP to provide the PWM signal in the simulation. The simulation result will be analyzed for the prototype building.

The main objective of a power inverter is to produce an AC output waveform from a DC power supply. A waveform is a shape or form of a signal which is varying against time or period. There are different types of waveforms produced by an inverter. The different waveforms are generally dependent on the control of magnitude, frequency and phase angle of the inverter. The PWM signal controls the switching of a transistor to produce an alternate signal for the inverter. Controlling the PWM signal will make the inversion of a DC supply to an AC output efficient.

4.1 Types of Inverter Waveform

Generally, there are three types of waveform produced by an inverter. These are the square wave, modified square wave and pure sine wave.

(a) Square Wave

The Square wave inverters were the first type of inverters that were manufactured and used for a long time. The efficiency of this inverter is uncertain due to the uneven delivery of power to the load. This type of inverter is not suitable for certain AC load such as transformers, motors and most of the electronic equipment due to the high harmonic signals. The square waveform is illustrated in Figure 4.1.

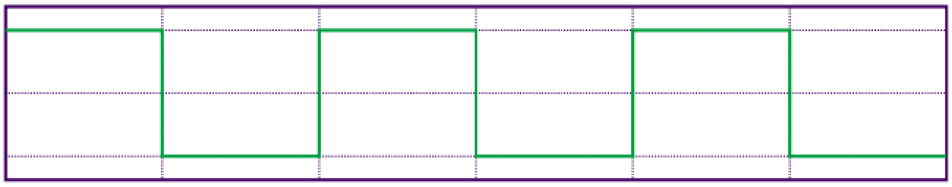


Figure 4.1 Square waveform

(b) Modified Square Wave (Modified Sine Wave)

The modified square wave or modified sine wave inverters were the improved type of a square wave inverter. The quality of this type of inverter is analogous to the square wave output except that the output voltage goes to zero for a specific period of time before switching to positive and negative signal. It is compatible to most electronic devices except for the specialized electronic equipment. It also runs most motors but low in efficiency. The modified square waveform is illustrated in Figure 4.2.

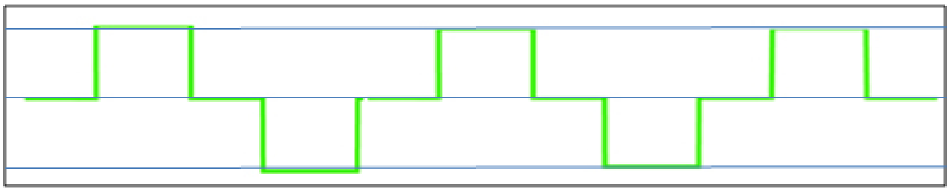


Figure 4.2 Modified square waveform

(c) Pure Sine Wave (True Sine Wave)

The pure sine wave inverter yields a nearly perfect sine wave output that is basically the same as the power delivered by the electric utility. Hence, it is well-suited for all electronic equipment and devices. This type of inverter is perfectly used for the grid-tie inverters usually for renewable energy source (solar modules, fuel cell etc). A pure sine waveform is shown in Figure 4.3.

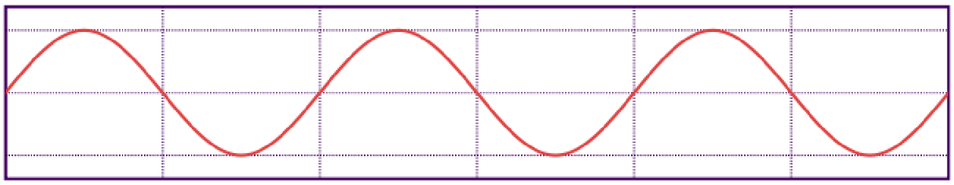


Figure 4.3 Pure sine waveform

4.2 Full Bridge Inverter Topology

There are two types of inverter topologies generally used in single phase inverter circuit. These are the half bridge and full bridge configuration mainly used for low and high power applications. These topologies differ on physical configuration where the half bridge uses two switches and the full bridge is in need of four switches to operate. Figure 4.4 illustrates a full bridge inverter topology with a four PWM switches.

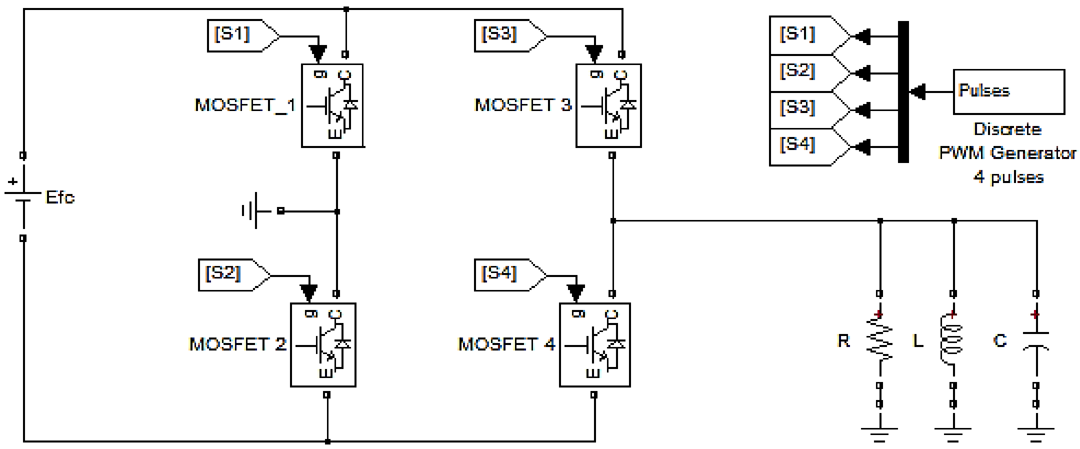


Figure 4.4 Full bridge Inverter Topology

A full bridge inverter topology consists of four switching elements and four defined states of switching operation on the circuit. A full bridge inverter is more convenient for low and high power application by using a controlled PWM technique while the half bridge inverter is suitable for specific low power application. Table 4.1 illustrates the four state switch conduction of a full bridge inverter.

Table 4.1 Switch Conduction of Full bridge inverter

Switch Conduction	State	Output Voltage
S1 and S4	1	E_{fc}
S1 and S3	2	0
S2 and S3	3	$- E_{fc}$
S2 and S4	4	0

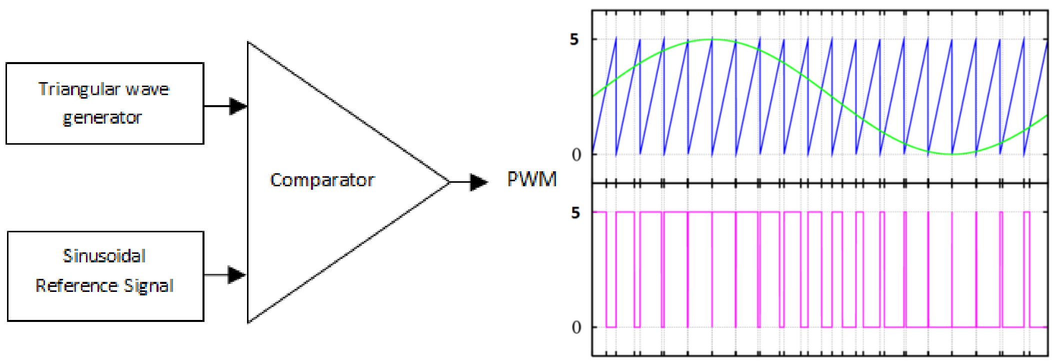
The output voltage of the inverter changed from positive to negative periodically. The synchronized conduction of the switches prevents the occurrence of short circuit in the system.

4.3 Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a powerful technique for controlling analog circuits with a processor's digital outputs and employed in a wide variety of applications, ranging from measurement and communications to power control and conversion [37]. This type of modulation technique generates controlled variable-width pulses to represent the amplitude of an analog input signal. The PWM signal remains digital all the way from the processor to the controlled system; no digital-to-analog conversion is necessary. But by keeping the signal digital, noise effects are minimized.

The power loss generated from the switching device when using a PWM technique is very low. When the device is switched "off", no current passes the switch. And when the switch is "on", the voltage drop across the switch is almost negligible. In both cases, the power loss of the switching device is close to zero or insignificant. The only problem met in using a PWM technique is the electromagnetic interference produced due to the complex and hard switching of the components when used on motors and transformers.

The basic PWM is generated by comparing a reference sinusoidal waveform with a triangular carrier waveform into a comparator (Figure 4.5). The reference waveform may come as sine wave or a distorted sine wave depending on the application of the inverter topology. Usually, sinusoidal waveform signal is used for PWM inverter which shapes the output waveform close to a pure sine wave.



(a) (b)

Figure 4.5 Basic PWM signal generation

The term duty cycle describes the ratio of the "on" state of a signal to the specific period of same signal. The duty cycle has no unit; it is represented by a percentage value. For instance, 100% duty cycle means the signal is in fully "on" state and 0% describing the fully "off" state. The parameters consist in a pulse width modulation signal are the amplitude, frequency and duty cycle of a signal.

Figure 4.6 shows the different duty cycles and "on" state of a signal in a period.

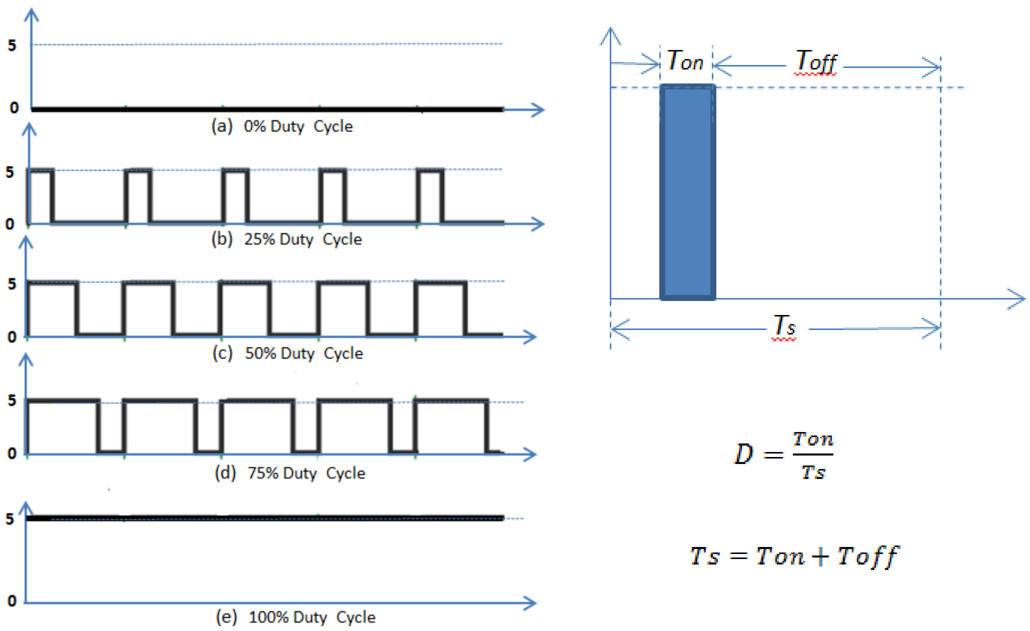


Figure 4.6 PWM output Duty Cycle

4.4 Simulation of Fuel Cell Boost Inverter

A compared simulation was done with the full bridge type of inverter. Figure 4.7 is a full bridge inverter without a filter and Figure 4.8 is a full bridge inverter with a low pass filter. The low pass filter is coupled from the output of the inverter. The comparison was completed to improve the output of the chosen inverter topology.

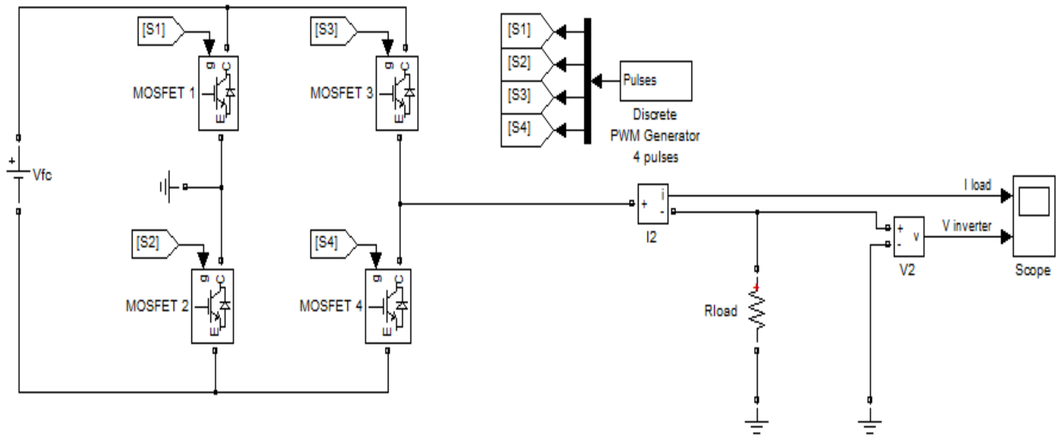


Figure 4.7 Full Bridge Inverter without Low Pass Filter

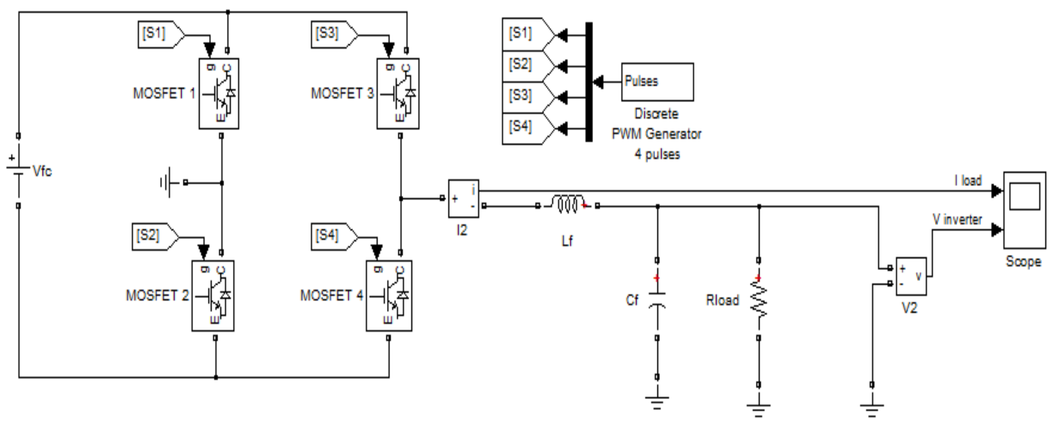


Figure 4.8 Full Bridge Inverter with Low Pass Filter

The difference of the inverters used for simulation is the coupling of an *LC* low pass filter from the output of the inverter. A low pass filter is usually consists of an inductor and a capacitor coupled in a circuit. The purpose of an *LC* low pass filter is used for picking out a signal at a particular frequency from a complex signal. It is also used to oscillate a signal with minimal damping. Furthermore, it is an idealized model as a low pass filter since it has no resistance to dissipate energy.

The frequency selected of operation is also another factor in selecting the values of an *LC* filter. The selected frequency is also called the resonant frequency. A resonant frequency is defined as the frequency occurs when the inductive and capacitive reactance are equal in absolute value. The resonant frequency for an *LC* circuit is;

$$fr = \frac{1}{2\pi\sqrt{LC}} \tag{4.1}$$

where: fr – resonant frequency

L – inductor

C – capacitor

The values of *L* and *C* are selected such that the corner frequency is much lower than the PWM frequency. At times the selection of values for inductor *L* and capacitance *C* in a low pass filter is a degree of choice. The technical selection can be done by computational solution using different methods and attaining the optimum performance of a filter by simulation and experimentation.

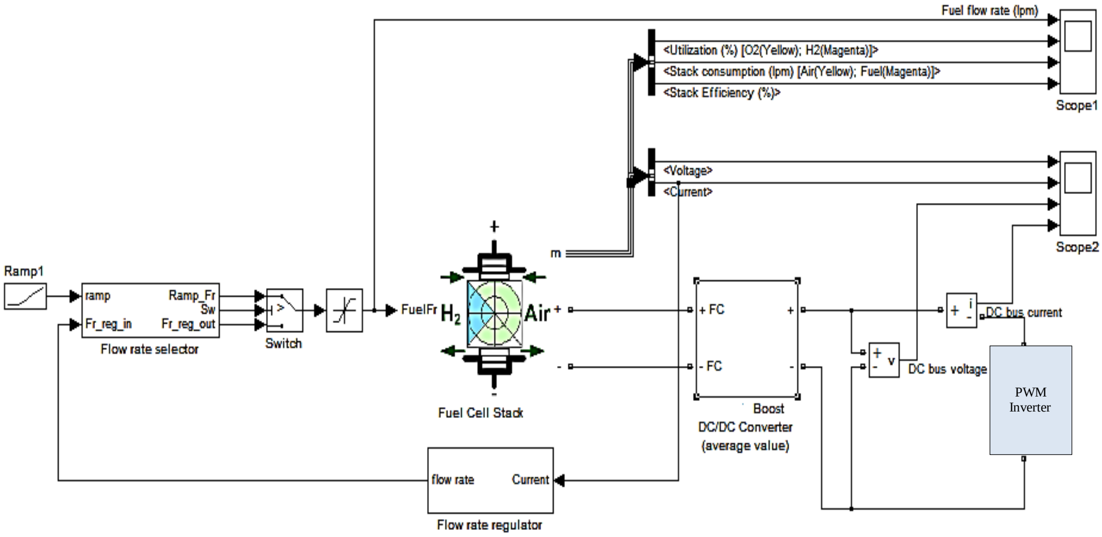
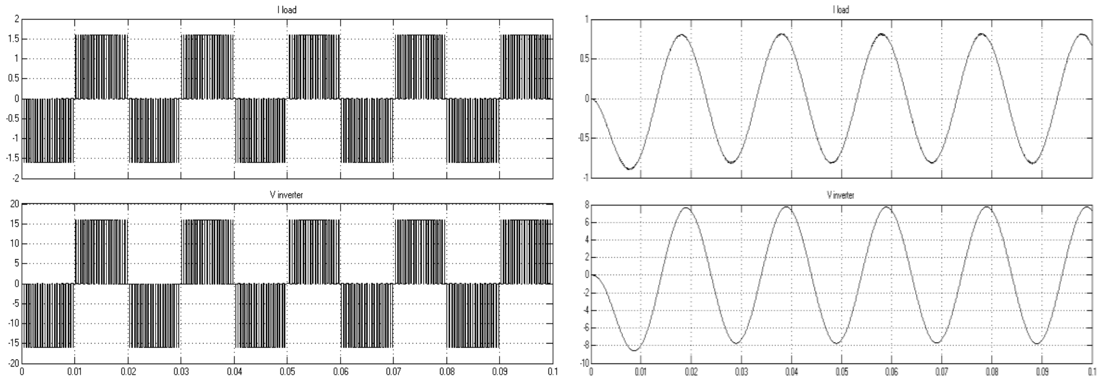


Figure 4.9 Simulation of Fuel Cell Boost Inverter Configuration

Figure 4.9 illustrates the three phase configuration of a dynamic fuel cell boost inverter. A PEM fuel cell is represented using a fuel cell stack, while the converter and inverter are illustrated using the general block diagram. The subsystem of the PWM inverter is the full bridge inverter with low pass filter of Figure 4.8.

Based from the result of the simulations, the inverter without a filter has a square output waveform, while the inverter with a filter has a sinusoidal output waveform (Figure 4.9).

It was proven that the waveform quality of the load is improved when a low pass filter is incorporated at the output of the PWM inverter.



(a) (b)

Figure 4.10 Full Bridge Inverter Output (a) without filter (b) with filter

4.5 Simulation Results and Discussions

A rule of thumb in control theory is that the frequencies of such configuration have to at least a factor of 10 between them to decouple the effects. According to this rule, for 50Hz fundamental frequency, the resonant frequency has to be at least 500Hz, and a pulse frequency has to be at least 5,000Hz [38].

The simulation of the full bridge inverter is carried out with the coupling of *LC* low pass filter. The filter inductor was chosen as 20mH and the capacitor is 100uF. PWM source is the comparison of the fundamental frequency of 50Hz to the different values of the carrier frequency. The carrier frequency of the inverter ranges from 1 kHz to 4 kHz. The load is a pure resistive load and constant throughout the simulation.

Figure 4.11 is the output of the PWM inverter when the 50Hz fundamental frequency is compared to 1 kHz carrier signal.

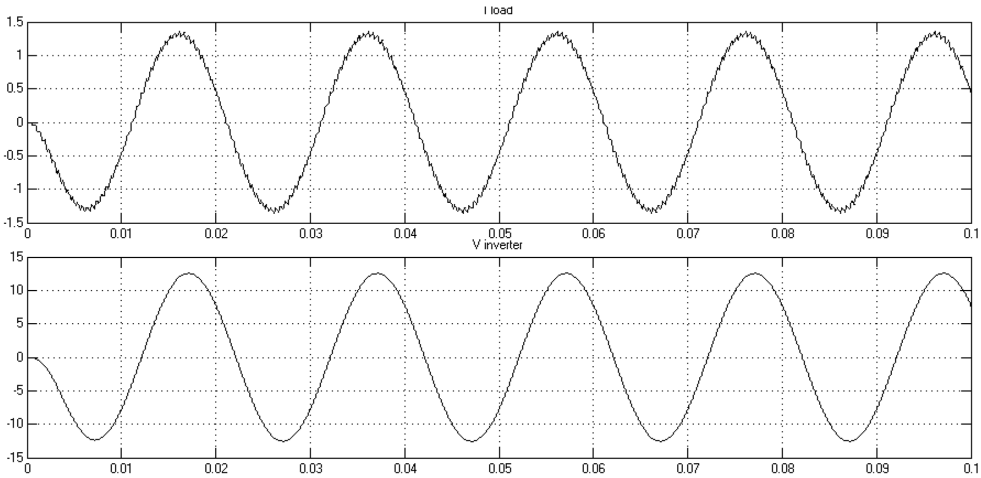


Figure 4.11 PWM Inverter Output (50Hz compared to 1kHz carrier signal)

Figure 4.12 is the output of the PWM inverter when the 50Hz fundamental frequency is compared to 2 kHz carrier signal.

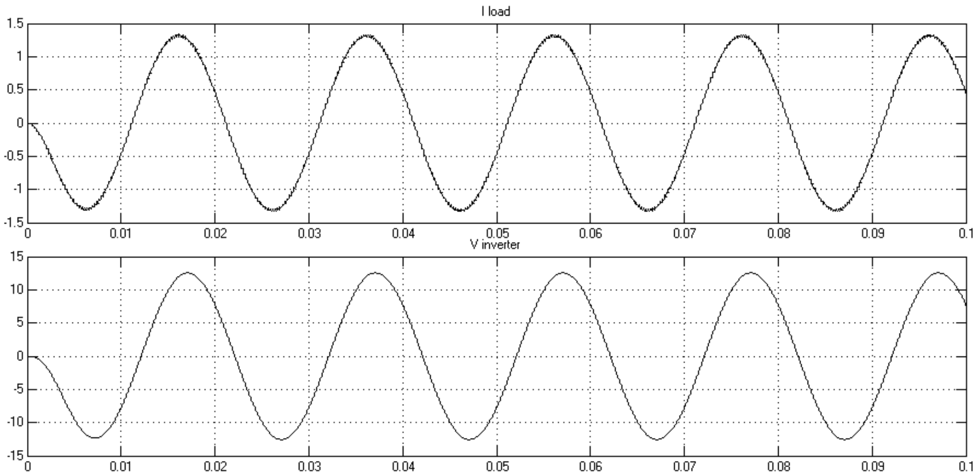


Figure 4.12 PWM Inverter Output (50Hz compared to 2 kHz carrier signal)

Figure 4.13 is the output of the PWM inverter when the 50Hz fundamental frequency is compared to 3 kHz carrier signal.

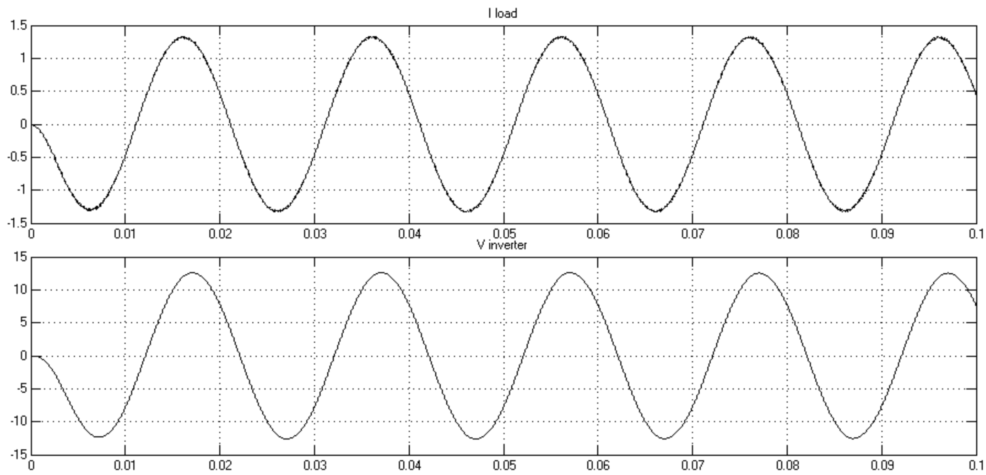


Figure 4.13 PWM Inverter Output (50Hz compared to 3 kHz carrier signal)

Figure 4.14 is the output of the PWM inverter when the 50Hz fundamental frequency is compared to 4 kHz carrier signal.

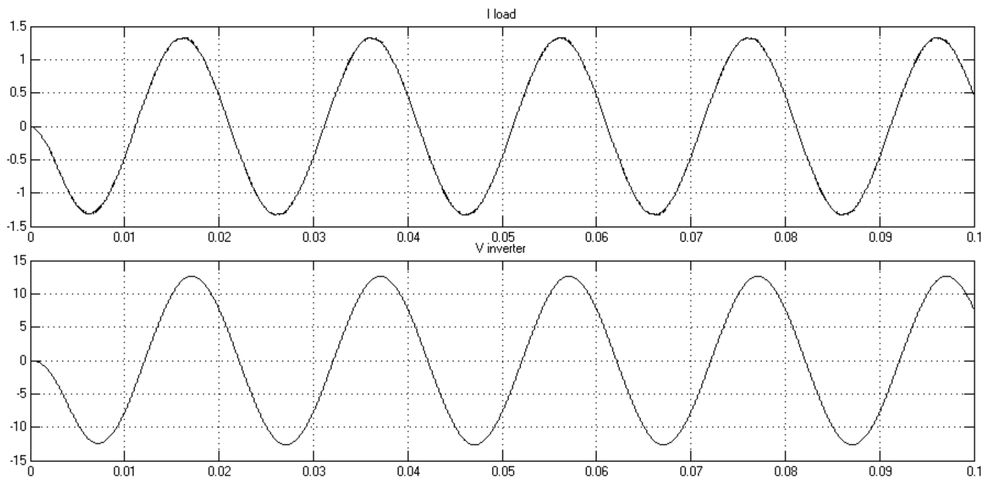


Figure 4.14 PWM Inverter Output (50Hz compared to 4 kHz carrier signal)

The results of the simulation show the different characteristics of a PWM inverter when a fundamental frequency of 50Hz is compared to the different values of the carrier signal. It was confirmed from the simulation that the higher the carrier or switching frequency used, the smoother the output current and voltage of the waveform of the PWM inverter.

Another simulation is done using variable duty cycle for the PWM inverter. The variable duty cycle is simulated using the highest carrier or switching frequency value of 4 kHz which is considered a smooth waveform from the sample. Everything stays the same, the fundamental frequency of 50Hz, the carrier signal of 4 kHz and the load. Only the duty cycle varies.

Figure 4.15 is the output of the PWM inverter with a 25% duty cycle.

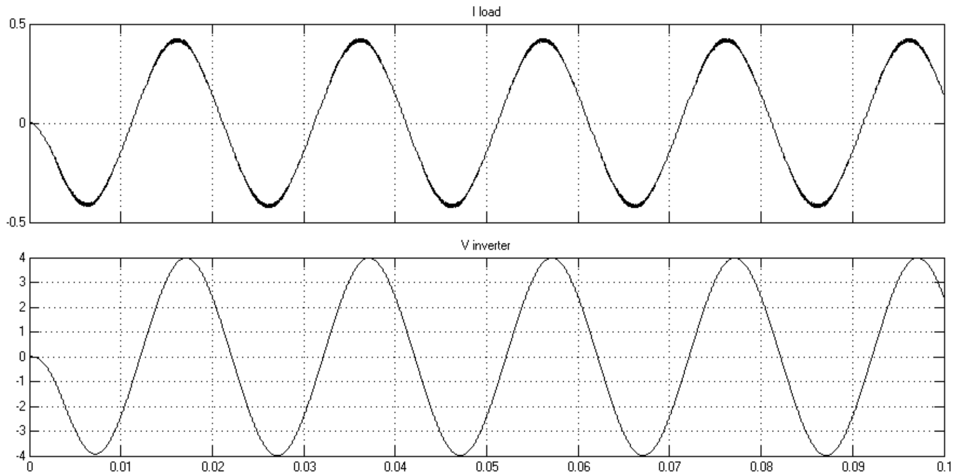


Figure 4.15 25% PWM duty cycle

Figure 4.16 is the output of the PWM inverter with a 50% duty cycle.

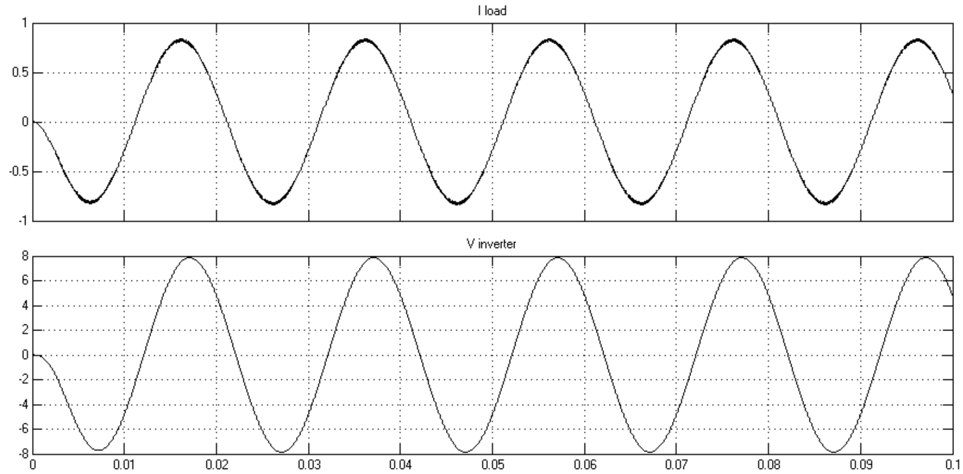


Figure 4.16 50% PWM duty cycle

Figure 4.17 is the output of the PWM inverter with a 75% duty cycle.

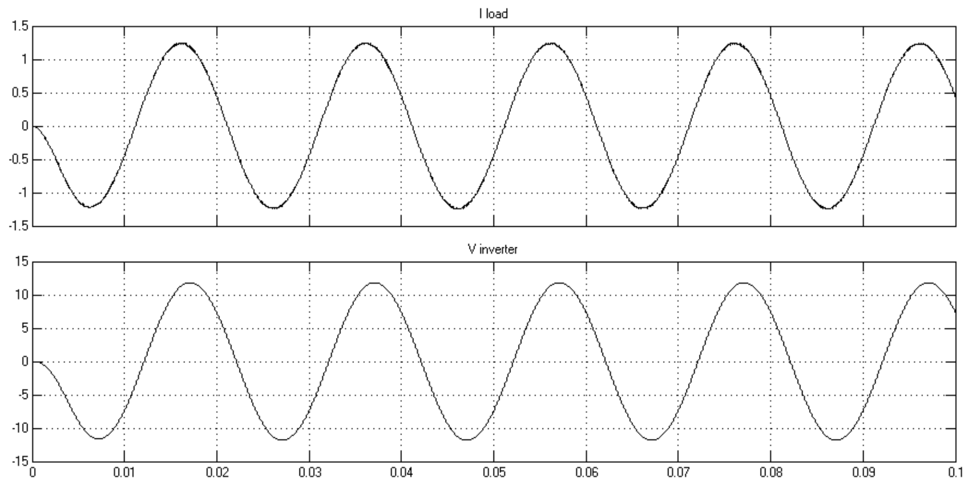


Figure 4.17 75% PWM duty cycle

Figure 4.18 is the output of the PWM inverter with a 80% duty cycle.

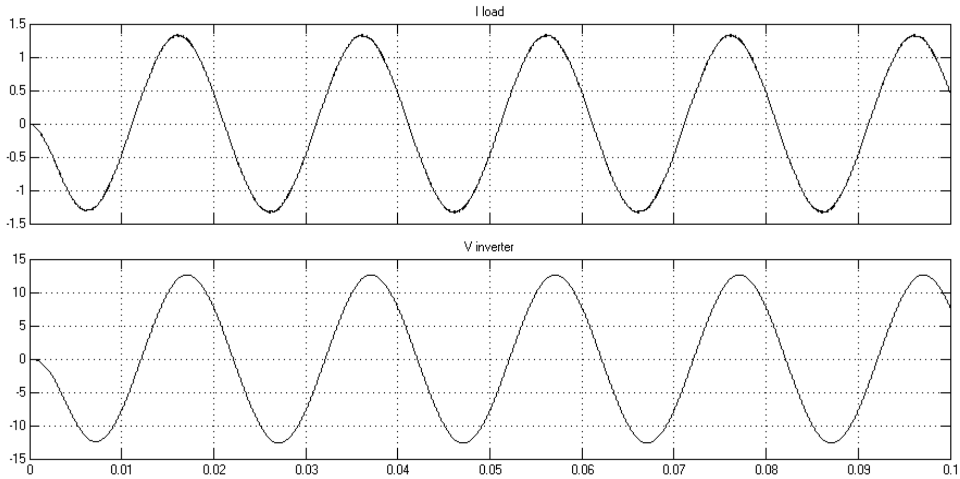


Figure 4.18 80% PWM duty cycle

The results of the simulation shows the different characteristics of PWM inverter output when a variable duty cycle is applied. The load current and voltage increases as the duty cycle increases. Another point of observation in the simulation is the presence of ripple in the waveform. As the duty cycle rises, the presence of ripple also decreases. This denotes that duty cycle is significant in the circuit design of a PWM inverter.

4.6 Conclusion

The design of power inverter using a PWM technique is a very powerful tool as a controller in switching an electronic device. The basic PWM is generated by comparing a reference sinusoidal waveform with a triangular carrier waveform into a comparator. It was also proven in the simulation that by integrating a low pass filter, in the output of a PWM inverter, the output waveform improves. The purpose of a low pass filter is to eliminate the harmonics of the output voltage. It was also verified from the result that by comparing the 50 Hz reference frequency to an increasing carrier frequency signal makes the output waveform smoother.

Furthermore, the selection of duty cycle is also important for the design of a PWM inverter. The duty cycle commands the correct magnitude of the output of the inverter. As the duty cycle increases to the specified value, the output current and voltage of the inverter increases and become stable. Similarly, ripples also decreases to make the waveform looks smoother.

CHAPTER 5

Systems Configuration and Results

Science is organized knowledge. Wisdom is organized life.
Immanuel Kant (1724 – 1804)

This Chapter presents the systems equipment, schematic and project prototype of the thesis. A comprehensive analysis of the overall systems configuration of the prototype are discussed and illustrated. The experiment and hardware operation is demonstrated using the CCS software. The actual results of the research are explained and concluded.

5.0 Introduction

The introduction of DSP has started in the early 1980's when electronic technology is moving in a fast pace. Research came in a long way by digitizing signals for analysis in complex computer runs of programs. Early signal processors require an extra external circuit to produce fast analog to digital converters. The basic problem met in integrating an external circuit to a system is an intrusion of small signal in the system's environment; small signals are significant interference in signal processing.

The improvement of DSP eliminates the external source circuit in the system and became the sole heart of a controller system. The influence of DSP has much more to offer in the synchronization of computer and electronic hardware devices. It is an exciting development on electronic technology. The involvement of DSP in power electronics flourished the unimaginable progress in the power industry. The applications are found in the range of power systems, uninterruptible power supplies, controller for variable speed drives and interfacing other devices of several types.

The advantage of using a DSP digital control technique is making the design of control circuit simple and more flexible compared to analogue controlled techniques [39]. The authors of reference [40] illustrated the use of a Modified Space Vector PWM (SVPWM) technique; it makes the inverter immune to the variations of dc input voltage acquired from an alternate source of energy. The SVPWM produces a high quality output voltage that can be maintained at the point of common coupling.

Aside from the advantages of using a PWM signal for inverter, there are still negative feedbacks present in the system. Reference [41] states that in a PWM inverter, the problems of existence of electromagnetic-interference (EMI) and high frequency harmonics. These are common for switching high frequency semiconductor devices used in an inverter. However, the solution lies on the DSP which has built-in extra sensor equipment needed to feedback the voltage and current signals to the control scheme. Furthermore, reference [42] adds up important applications of the DSP. Using a DSP as a controller, it protects DC-DC and DC-AC inverter designs to over-voltage, over-current, over-temperature and shutdown conditions to prevent damage to equipment.

5.1 Project Description

The research project has the summary of incorporating a computer, a DSP and a digital motor controller for a PWM inverter. The general system works on the generated PWM signal from the DSP and feeds to the Full bridge inverter of the DMC 550.

The implementation of this research is based on the combination of the DSP controller TMS320C2808 eZdsp and a Digital Motor Controller 550 (DMC550). The Code Composer Studio (CCS) software is used to compile algorithm and transfer the command to DSP board. It is used in synchronizing the source computer to the development prototype modules. The results obtained from the simulation serve as the basis on the construction of the prototype. Although the components used in the simulation are expected to be ideal and varies from the actual manufactured component.

The specific use of the DSP in this project is to generate a PWM inverter for a fuel cell source. There are different researches that fall in this category using different DSP hardware. A suitable digital motor controller with an in-built full bridge inverter is chosen to be driven by the eZdsp F2808 unit.

Summary of the system's equipment and general schematic:

- Code Composer Studio Software
- TMS320C2000 Developer's kit board (TMS320F2808 ezDSP)
- Digital Motor Controller (DMC 550)

5.1.1 Code Composer Studio Software

The Code Composer Studio software is an integrated development environment for TI embedded processor families. In general, it comprises a suite tools used to develop and debug embedded applications. The robustness of this software includes compilers, source code editor, project build environment, debugger profiler, simulators, real-time operating system and many others [43]. Figure 5.1, illustrates the workspace of the code composer studio software.

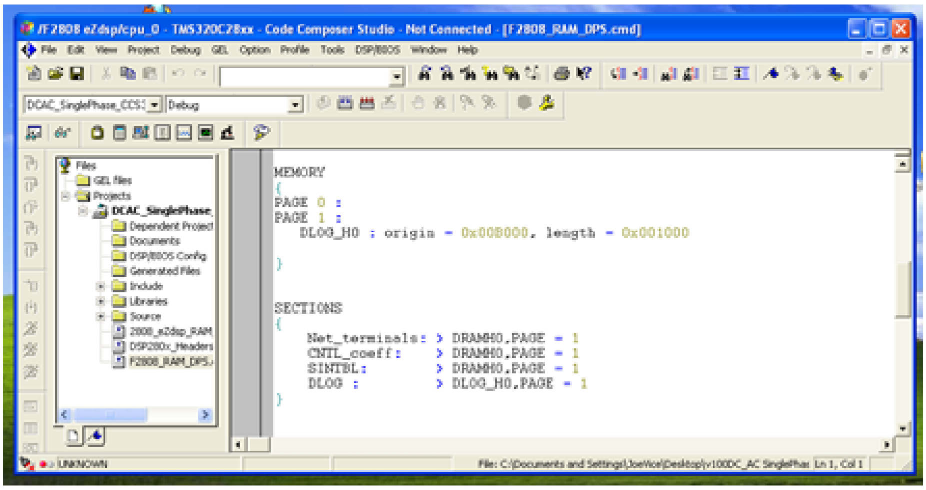


Figure 5.1 Code Composer Studio Workspace

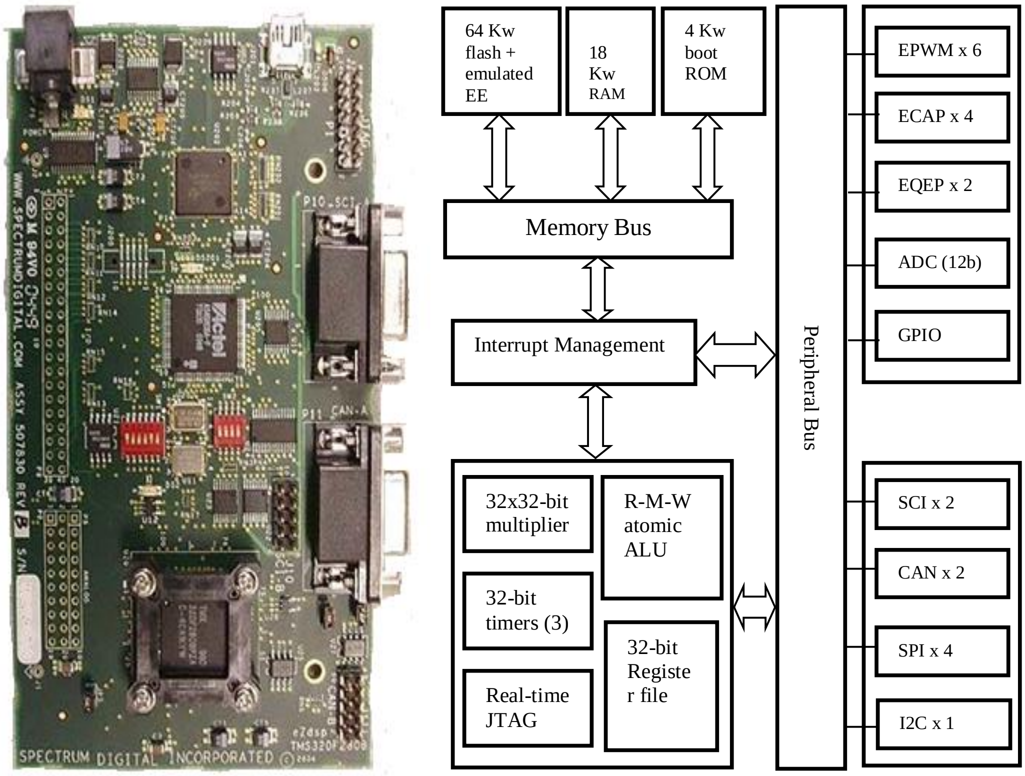
The development flow of most DSP based application consists of four basic phases, application design, code creation, debug and analysis/tuning. The code developed for the DMC 550 can be processed using the DSP with the compiler/assembler/linker and code composer software.

An on board Joint Test Action Group (JTAG) emulator is the serial interface between the computer and the DSP board via parallel port or Universal Serial Bus (USB), depending on the module being used.

5.1.2 TMS320F2808 eZdsp Controller

The TMS320F2808 eZdsp is a type of microprocessor that produces a digital signal for high level real time control. The main purpose of DSP's is to process a digital signal in a near real time response based from the compiled algorithm for a specific application. The DSPs can support high speed mathematical calculations for use in real time control algorithms too. The effective conversion of analog to digital conversions and PWM generation is the most widely used for DSPs.

This TMS320F2808 eZdsp has twelve individual controlled enhanced PWM (ePWM) channels that generates high resolution PWM signals to control a full bridge converter. It has 100 MIPS, 32-bit fixed DSP core and provides 128 kbytes of internal memory and 26 kbytes of on-chip RAM (Figure 5.2.). It has the ability to control the duty cycle from -100% to +100%, both the negative and positive output voltage [44].

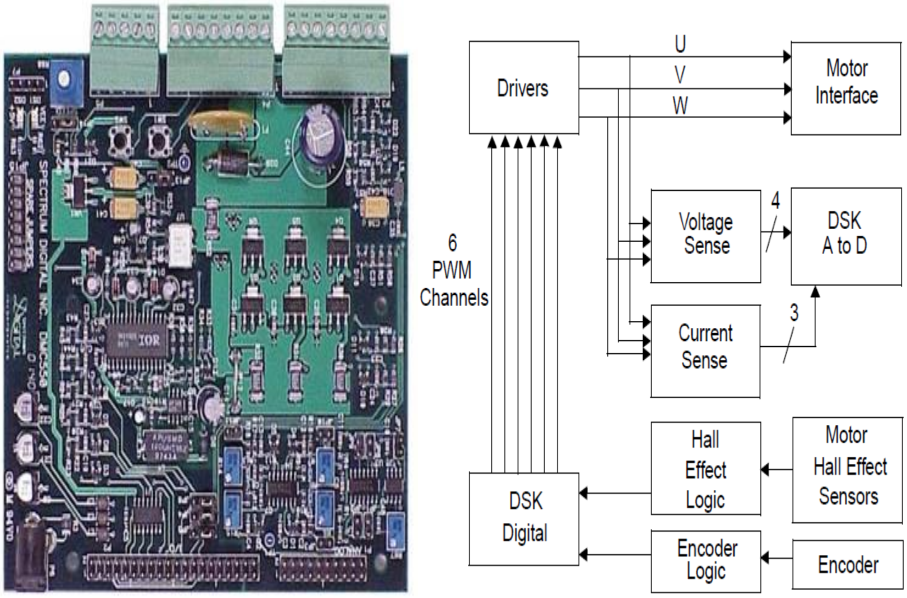


(a) (b)

Figure 5.2 TMS320F2808 eZDSP, (a) Hardware (b) Block Diagram

5.1.3 Digital Motor Controller (DMC 550)

The DMC 550 is a multipurpose digital motor controller that allows to be synchronized with different systems using DSPs. This type of module is an excellent platform to develop and run motor controls; adjustable speed drives, uninterruptible power supply and power factor correction, which are only few applications. Most of the DSP's used are the embedded target for TI C2000 DSP. Figure 5.3 shows the hardware and the basic block diagram configuration of DMC 550. The DMC 550 has the following features; it is compatible to eZdsp TMS320F2808 family.



(a) (b)

Figure 5.3 DMC 550 (a) Hardware and (b) Block diagram

It uses the DSP as computer engine to run algorithms within. The rated bus voltage of this DMC 550 is $24V_{dc}$ and its rated current is 2.5A continuous. The major interfaces of the DMC 550 include, 3 phase DC brushless interface, Hall Effect sensor interface, phase voltage and phase current sense, and encoder interface [45].

5.2 Systems Configuration

The overall experimental set-up is composed of personal computer (PC), the eZdsp F2808 board, the DMC 550 board, fuel cell supply, *LC* filter and an oscilloscope. The proposed topology is to design a 50 Hz sinusoidal waveform for an AC load. The input parameters used for the experimental setup is same for the simulation and only resistive load is tested.

There are two parts that comprises this configuration, the control circuit and the power circuit. The eZdsp represents the control circuit and the DMC 550 board is the power circuit.

The DSP acts as a control circuit because it has the ability to control devices, signals and current flow in the circuit. Control circuits usually carry lower voltages than power circuits. On the other hand, the DMC 550 handles power to the load and often transfers high voltage from the source. Figure 5.4 illustrates the hardware set-up of eZdsp F2808 and DMC 550.

Figure 5.4 Hardware set-up of eZdsp F2808 and DMC 550

Figure 5.5 shows the hardware systems configuration of the research project.

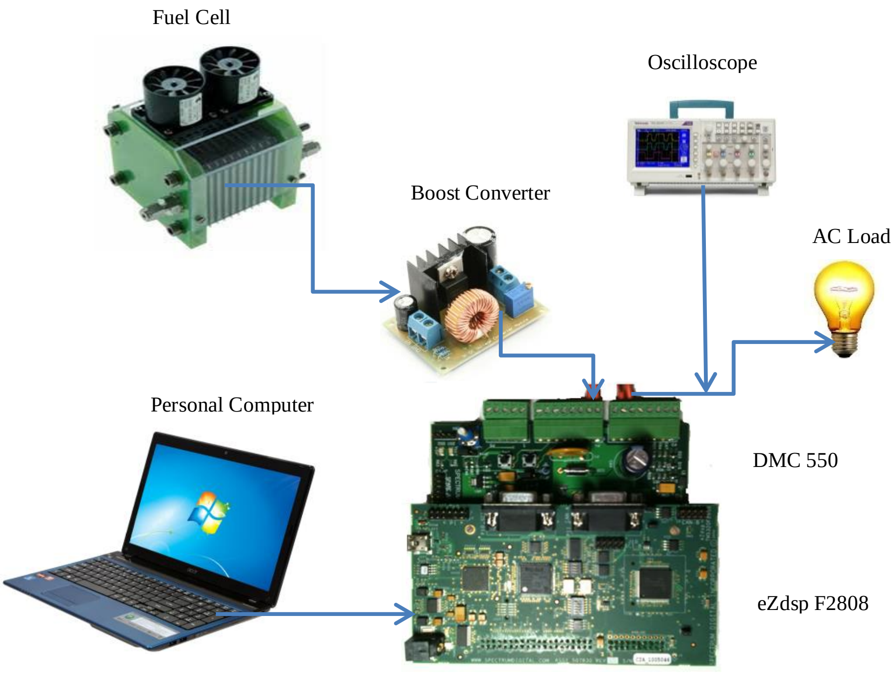


Figure 5.5 Hardware of systems configuration

Figure 5.6 represents the schematic diagram of the system configuration of the project.

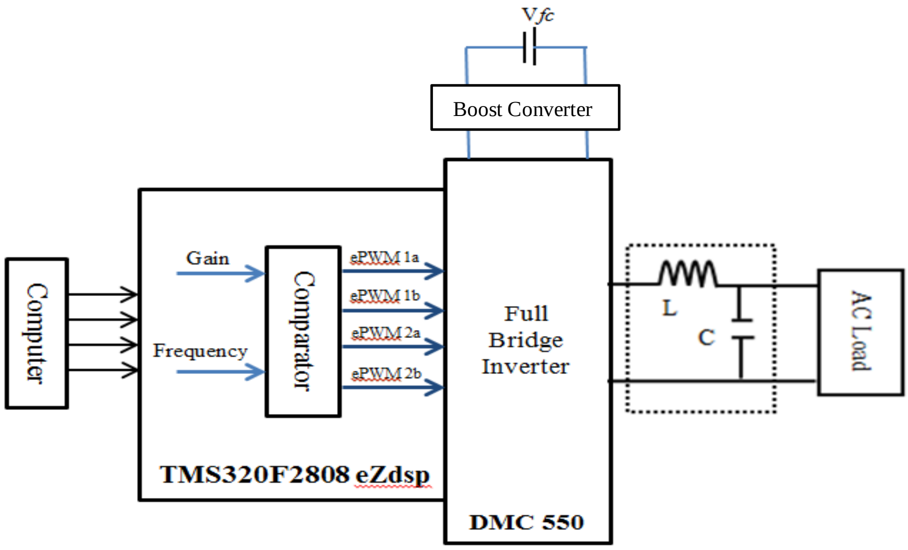


Figure 5.6 Schematic diagram of the system configuration

5.3 Results and Discussion

The assembly codes used in the CCS software has been based from the different microprocessor languages. The code for the interrupt framework is used to trigger the defined ePWM modules. Reference [44] illustrates a simple code to assign a single ePWM module. One ePWM module must be set to "1" and the rest are set to "0". This code can run a full bridge bipolar driver by setting four ePWM modules. Two of which will be triggered at the same time and the other two on different times. Table 5.1 presents the interrupt framework options of assigning an ePWM module.

Table 5.1 ePWM Interrupt Framework Options [46]

```
//=====================================================================
==
// Interrupt Framework options
//---------------------------------------------------------------------
--
#define EPWMn_ISR 1 // ISR triggered by EPWM
#define ADC_ISR 0 // ISR triggered by ADC EOS

// If EPWM_ISR = 1, then choose which module
#define EPWM1_triggers_ISR 1 // ISR triggered by EPWM1
#define EPWM2_triggers_ISR 0 // ISR triggered by EPWM2
#define EPWM3_triggers_ISR 0 // ISR triggered by EPWM3
#define EPWM4_triggers_ISR 0 // ISR triggered by EPWM4
#define EPWM5_triggers_ISR 0 // ISR triggered by EPWM5
#define EPWM6_triggers_ISR 0 // ISR triggered by EPWM6
```

The assembly code will be processed and fed to the DSP and triggers the peripheral bus which turn on the selected ePWM signal to activate. The experimental result shows the different figures and graphs obtained from the overall systems configuration.

The powerful DSP produced a PWM based from the algorithm of the code composer (Figure 5.7). Two of the signals are opposite with each other, which means that there are only two switches operate at the same time.

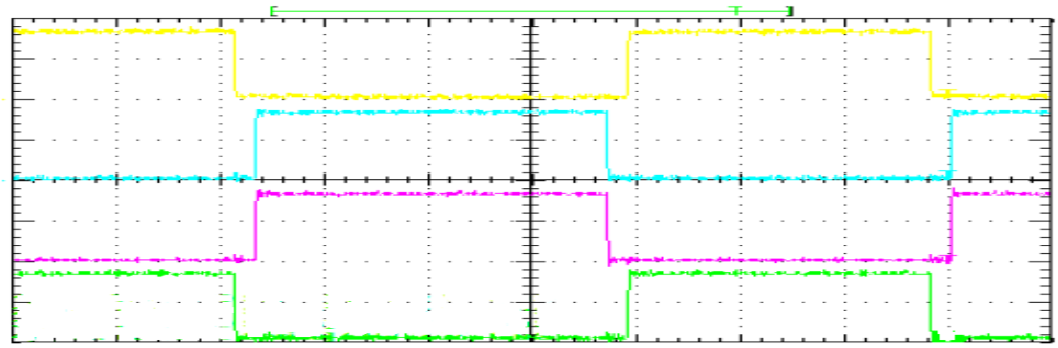


Figure 5.7 PWM waveform (2V/div)

The generated ePWM signal is accomplished by changing the width of the switching frequency generated by the oscillator section. The ePWM signal switches the four transistors in the DMC 550 which is a full bridge inverter. Figure 5.8 illustrates the operation of the ePWM signal switches.

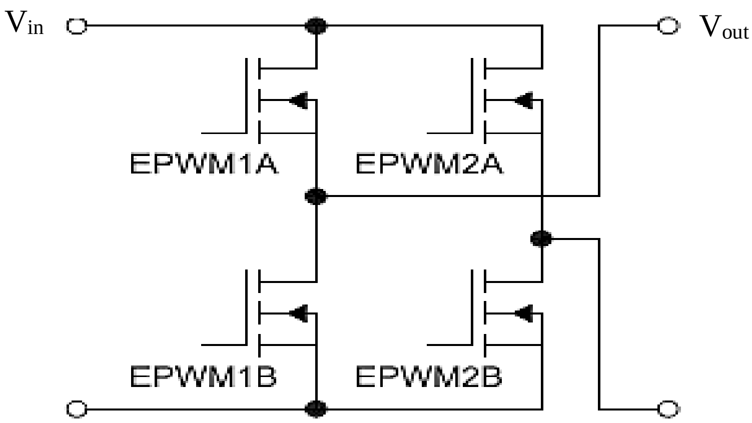


Figure 5.8 **e**PWM signal switches

There are two switches operate at the same time, ePWM1A and ePWM2B are the pairs activated at the same time. The other two, ePWM1B and ePWM2A function oppositely with the other pair.

The synchronized conduction of the switches prevents the occurrence of short circuit and makes the inverter circuit a close loop continuously. This modification in the pulse width of the switching pulse will cancel the changes in the output voltage and the inverter output will stay constant regardless of the load variations.

One of the characteristics of the TMS320x280x family of processors is the control of its duty cycle. Achieving a full 0% - 100% duty cycle can become critical in certain applications.

The ePWM modules can provide 0% - 100% duty cycles with minimal overheads. It can operate in three modes, up-count mode, up-down mode and down-count mode [47].

Figure 5.9 shows the software flow chart of 0 – 100 %duty cycle.

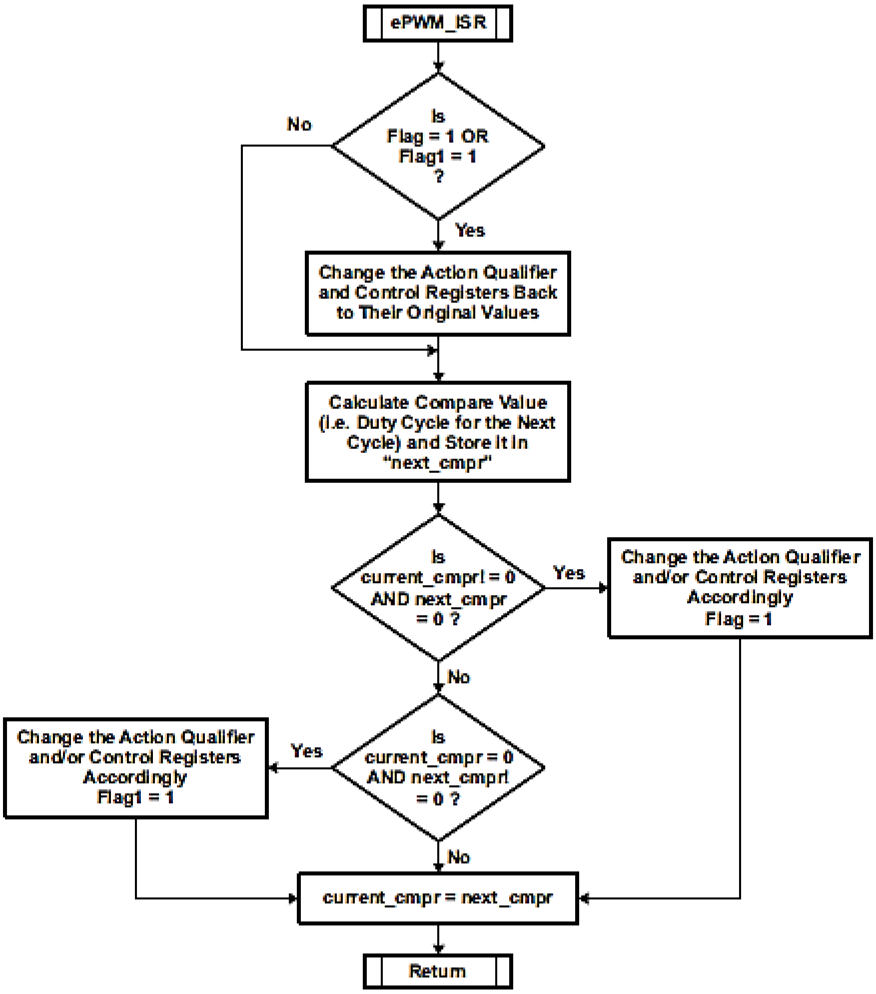
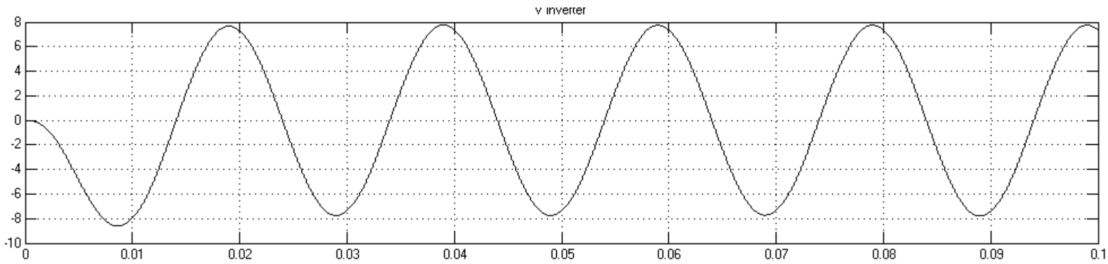
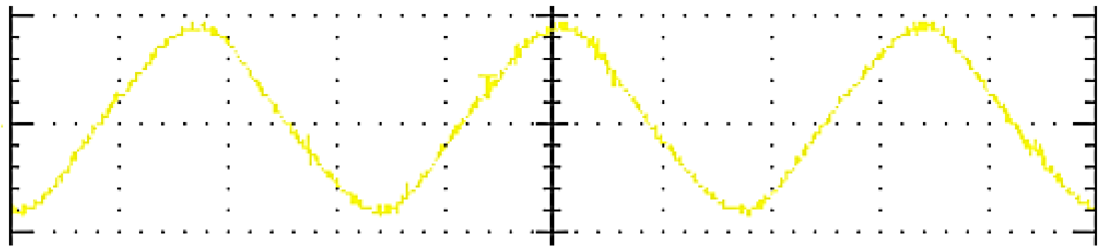


Figure 5.9 Software Flow Chart [47]

Figure 5.10 compares the output voltage of the full bridge inverter. The simulation result has a better waveform compared to the experimental result. The magnitude of the output voltage of the simulation is higher than the experimental result. The advantage of the simulation model is on the components involved in the circuit diagram. It works on the environment where all the components are ideal.



(a)

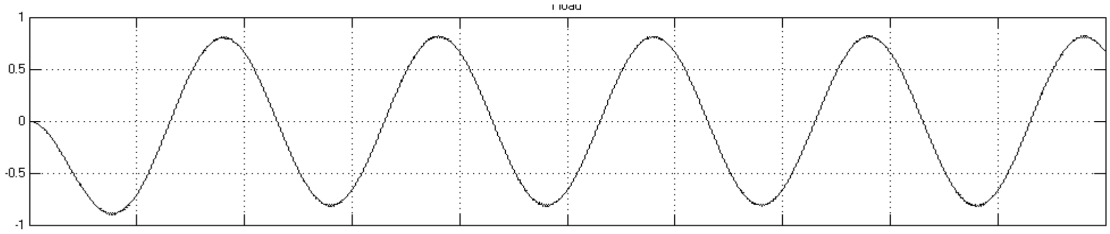


(b)

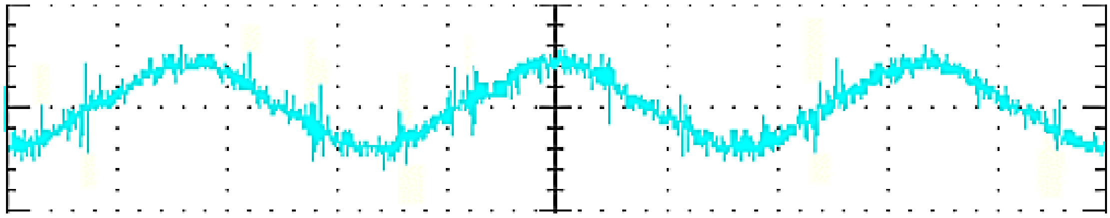
Figure 5.10 Full Bridge output voltage (a) Simulation, (b) Experimental (5V/div)

Figure 5.11 also compares the simulation and experimental output current of the full bridge inverter. The simulation result has a better current waveform and a higher magnitude of the value compared to the experimental result. The principle of ideal component setting makes them different. On the other hand, if both waveforms are critically observed, a ripple can still be found on the simulation result. But the experimental result shows more ripples.

Hence, both simulation and experimental results are susceptible to ripple and interference response.



(a)



(b)

Figure 5.11 Full Bridge output current (a) Simulation, (b) Experimental (0.5A/div)

The system overview represents an efficient energy generation using a PWM inverter from fuel cell. The fuel cell output is unstable, and has a low voltage and a high current characteristic. A boost inverter is connected to the output of the fuel cell to increase and stabilise the voltage for the input of the inverter. The AC output voltage depends on the width of the switching pulses of the inverter which changes from positive to negative periodically. The process is achieved by feed backing a part of the inverter output to the PWM controller section of the DSP. Based on this feedback voltage, the PWM controller will make essential corrections in the pulse width of the switching pulse generated at oscillator section [48].

Finally, the overall result satisfies the objective of providing a PWM inverter using a TMS320F2808 eZdsp and a DMC 550 with inbuilt Full Bridge Inverter for fuel cell energy generation.

CHAPTER 6

Discussions and Conclusions

Research is to see what everybody else has seen,
and to think what nobody else has thought.
Albert Szent-Gyorgyi, *(1893 – 1986)*
Hungarian Biochemist

6.0 Summary of Results

The primary objective and motivation for this research investigation is to propose a robust digital control inverter using a DSP unit for fuel cell energy generation. The overall result is viable and effective. Using the MATLAB/Simulink software makes the research easier in modeling and analysing any type of circuit diagram. One of the most exciting parts is the construction of algorithm for the Code Composer Studio software which synchronises with the DSP and the DMC 550. The simulation and experimental result is fulfilling due to the acceptable comparison of the graph.

6.1 Advantages and Disadvantages of the proposed digital inverter

From the implementation point of view, the designed inverter using a DSP is more complicated than the conventional designs of an inverter. Nonetheless, the implementation of the research is feasible and applicable for a reasonable cost.

The disadvantage of the research comes from the integration of the following:

- The addition of hardware and modular electronic boards, like the DSP and DMC 550 controller board which makes the design complicated.
- The software embedded with the DSP board, Code Composer Studio (CCS) which synchronized with the portable computer to the design system.
- Knowledge on computer programming and software CCS to execute the program in the hardware design.

On the other hand, the advantages are well met to prove the viability of the research project. The advantages of improving an inverter design in addition with modular electronic boards are the following.

- The addition of modular control boards makes the hardware compact and reduces the size of the hardware system.
- It improves the system’s efficiency due to removal of large, bulky and expensive transformers.

- The real time interface of the software between PC and DSP is helpful on the monitoring of hardware output signals.
- It is inevitable trends to make digital inverters realised by using the high performance DSP controllers.

6.2 Fulfillment of the Objectives Outlined in the Introduction

- It was shown that using software for simulation, the implementation and conceptualization of actual design is more reliable.
- The advantage of performing a simulation rather than actually building the design and testing is time saving and more economical. The simulation phase out the building and rebuilding of prototype in the design loop.
- The overall systems configuration is satisfying due to the results obtained from the prototype where the experimental result is acceptable compared to the simulation result. It is anticipated that digital control from the DSP is an efficient tool for PWM power inverter.

6.3 Scope for Future Research

The research can be continued in the following ways:

- The continuation of the research can be tested by implementing a larger scale type fuel cell or other renewable energy sources.
- The specification of the electronic devices and components for inverters must be increased to cater the larger external power source.

- A continuous research for DSP as a controller for hybrid energy generation using, PV, mini-hydro, wind and fuel cell.
- Future research on intelligent controller using DSP for grid-tie inverter for hybrid energy generation.
- Upcoming research using DSP for power factor correction and power system efficiency for batteries and transportation vehicles.

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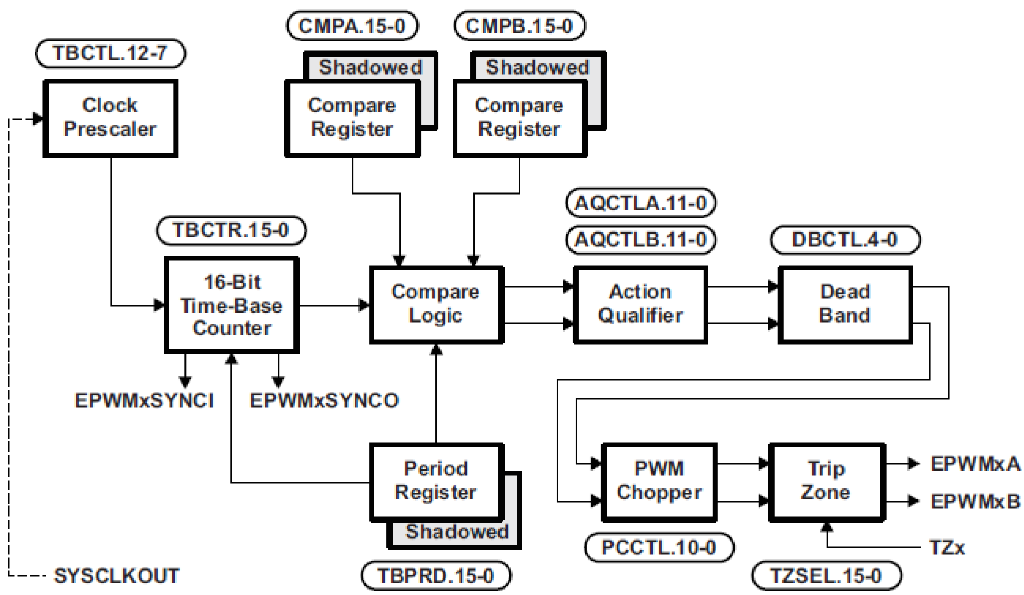
APPENDIX

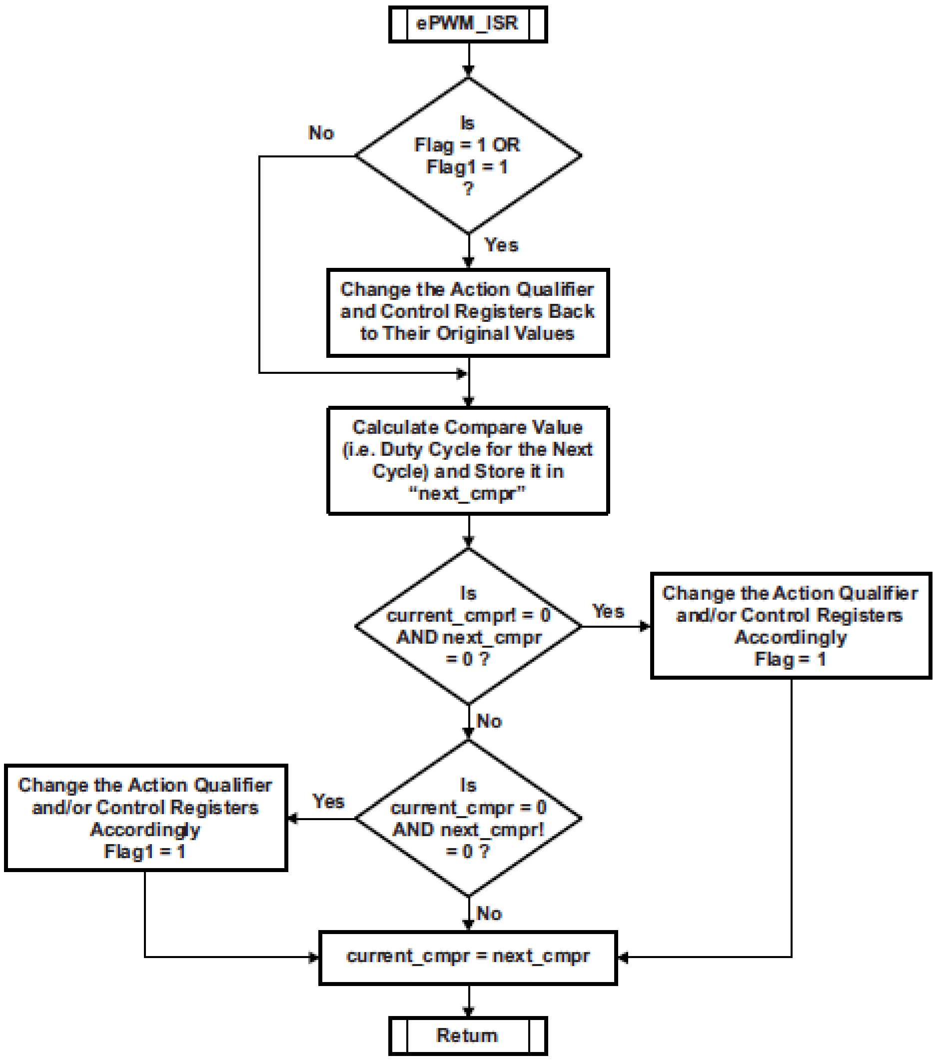
A.1 The ePWM module for 0 – 100 % Duty cycle control:

Application Report



A.1 ePWM Block Diagram

A.2. Software flow chart for the code implementation of 0 – 100% Duty cycle.



A.2 Software flow chart

The following is a sample ISR code that can be used for implementing the ePWM module to generate 0 – 100% duty cycle variation in the up-down count mode. This code provides independent control for the ePWM1A and ePWM1B and also makes the latter complementary to the ePWM1A.

ePWM Assembly Code to Generate Duty Cycle: 0 – 100%

===

```
void update_compare1(EPWM_INFO *epwm_info)
{
if (flag_outta_0 == 1 || flag_into_0 == 1)
{
EPwm1Regs.AQCTLA.bit.CAU = AQ_SET; // Set PWM1A on event A, up count
EPwm1Regs.AQCTLA.bit.CAD = AQ_CLEAR;
EPwm1Regs.CMPCTL.bit.LOADAMODE = 0; // Load on Zero
flag_outta_0 = 0;
flag_into_0 = 0;
}
if (flag_outta_0_b == 1 || flag_into_0_b == 1)
{
EPwm1Regs.AQCTLB.bit.CBU = AQ_CLEAR; // Set PWM1A on event A, up count
EPwm1Regs.AQCTLB.bit.CBD = AQ_SET;
EPwm1Regs.CMPCTL.bit.LOADBMODE = 0; // Load on Zero
flag_outta_0_b = 0;
flag_into_0_b = 0;
}
// Every 6'th interrupt, change the CMPA/CMPB values
if(epwm_info->EPwmTimerIntCount == 5)
{
epwm_info->EPwmTimerIntCount = 0;
// If we were increasing CMPA, check to see if
// we reached the max value. If not, increase CMPA
// else, change directions and decrease CMPA
if(epwm_info->EPwm_CMPA_Direction == EPWM_CMP_UP)
{
if(epwm_info->EPwmRegHandle->CMPA.half.CMPA < epwm_info->EPwmMaxCMPA)
{
epwm_info->EPwmRegHandle->CMPA.half.CMPA = epwm_info->EPwmRegHandle
->CMPA.half.CMPA + Steps; //Steps = programmable duty cycle
} //step change defined at the start.
else
{
epwm_info->EPwm_CMPA_Direction = EPWM_CMP_DOWN;
epwm_info->EPwmRegHandle->CMPA.half.CMPA= epwm_info->EPwmRegHandle
->CMPA.half.CMPA - Steps;
}
}
// If we were decreasing CMPA, check to see if
// we reached the min value. If not, decrease CMPA
// else, change directions and increase CMPA
```

```
else
{
if(epwm_info->EPwmRegHandle->CMPA.half.CMPA == epwm_info->EPwmMinCMPA)
{
epwm_info->EPwm_CMPA_Direction = EPWM_CMP_UP;
epwm_info->EPwmRegHandle->CMPA.half.CMPA= epwm_info->EPwmRegHandle
->CMPA.half.CMPA + Steps;
}
else
{
epwm_info->EPwmRegHandle->CMPA.half.CMPA= epwm_info->EPwmRegHandle
->CMPA.half.CMPA - Steps;
}
}
//Coming out of CMPA = 0
if (temp == 0 && epwm_info->EPwmRegHandle->CMPA.half.CMPA != 0)
{ //temp=previous/current CMP value
EPwm1Regs.AQCTLA.bit.ZRO = AQ_CLEAR; // Set PWM1A on event A, up count
EPwm1Regs.AQCTLA.bit.CAD = AQ_NO_ACTION;
EPwm1Regs.CMPCTL.bit.LOADAMODE = 2;
flag_outta_0 = 1;
}
//Going from CMPA != 0 to CMPA = 0
if (temp != 0 && epwm_info->EPwmRegHandle->CMPA.half.CMPA == 0)
{
EPwm1Regs.AQCTLA.bit.ZRO = AQ_SET; // Set PWM1A on event A, up count
flag_into_0 = 1;
}
temp = epwm_info->EPwmRegHandle->CMPA.half.CMPA;
// If we were increasing CMPB, check to see if
// we reached the max value. If not, increase CMPB
// else, change directions and decrease CMPB
if(epwm_info->EPwm_CMPB_Direction == EPWM_CMP_UP)
{
if(epwm_info->EPwmRegHandle->CMPB < epwm_info->EPwmMaxCMPB)
{
epwm_info->EPwmRegHandle->CMPB = epwm_info->EPwmRegHandle->CMPB + Steps;
}
else
{
epwm_info->EPwm_CMPB_Direction = EPWM_CMP_DOWN;
epwm_info->EPwmRegHandle->CMPB = epwm_info->EPwmRegHandle->CMPB - Steps;
}
}
// If we were decreasing CMPB, check to see if
// we reached the min value. If not, decrease CMPB
// else, change directions and increase CMPB
else
{
if(epwm_info->EPwmRegHandle->CMPB == epwm_info->EPwmMinCMPB)
{
epwm_info->EPwm_CMPB_Direction = EPWM_CMP_UP;
epwm_info->EPwmRegHandle->CMPB = epwm_info->EPwmRegHandle->CMPB + Steps;
}
else
{
epwm_info->EPwmRegHandle->CMPB = epwm_info->EPwmRegHandle->CMPB - Steps;
}
}
if (temp1 == 0 && epwm_info->EPwmRegHandle->CMPB != 0)
{
EPwm1Regs.AQCTLB.bit.ZRO = AQ_SET; // Set PWM1A on event A, up count
EPwm1Regs.AQCTLB.bit.CBD = AQ_NO_ACTION;
```

```
EPwm1Regs.CMPCTL.bit.LOADBMODE = 2;
flag_outta_0_b = 1;
}
if (temp1 != 0 && epwm_info->EPwmRegHandle->CMPB == 0)
{
EPwm1Regs.AQCTLB.bit.ZRO = AQ_CLEAR; // Set PWM1A on event A, up count
flag_into_0_b = 1;
}
temp1 = epwm_info->EPwmRegHandle->CMPB;
}
else
{
epwm_info->EPwmTimerIntCount++;
}
return;
        }
```

```
=================================================================
```

Aside from this, there are also different code samples that show how to implement various ePWM module configurations. These examples use the constant definitions shown below.

Various Assembly Code for ePWM module configurations

```
// TBCTL (Time-Base Control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// TBCTR MODE bits
#define TB_COUNT_UP 0x0
#define TB_COUNT_DOWN 0x1
#define TB_COUNT_UPDOWN 0x2
#define TB_FREEZE 0x3
// PHSEN bit
#define TB_DISABLE 0x0
#define TB_ENABLE 0x1
// PRDLD bit
#define TB_SHADOW 0x0
#define TB_IMMEDIATE 0x1
// SYNCOSEL bits
#define TB_SYNC_IN 0x0
#define TB_CTR_ZERO 0x1
#define TB_CTR_CMPB 0x2
#define TB_SYNC_DISABLE 0x3
// HSPCLKDIV and CLKDIV bits
#define TB_DIV1 0x0
#define TB_DIV2 0x1
#define TB_DIV4 0x2
// PHSDIR bit
#define TB_DOWN 0x0
#define TB_UP 0x1
```

```
// CMPCTL (Compare Control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// LOADAMODE and LOADBMODE bits
#define CC_CTR_ZERO 0x0
#define CC_CTR_PRD 0x1
#define CC_CTR_ZERO_PRD 0x2
#define CC_LD_DISABLE 0x3
// SHDWAMODE and SHDWBMODE bits
#define CC_SHADOW 0x0
#define CC_IMMEDIATE 0x1
// AQCTLA and AQCTLB (Action-qualifier Control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// ZRO, PRD, CAU, CAD, CBU, CBD bits
#define AQ_NO_ACTION 0x0
#define AQ_CLEAR 0x1
#define AQ_SET 0x2
#define AQ_TOGGLE 0x3
// DBCTL (Dead-Band Control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// MODE bits
#define DB_DISABLE 0x0
#define DBA_ENABLE 0x1
#define DBB_ENABLE 0x2
#define DB_FULL_ENABLE 0x3
// POLSEL bits
#define DB_ACTV_HI 0x0
#define DB_ACTV_LOC 0x1
#define DB_ACTV_HIC 0x2
#define DB_ACTV_LO 0x3
// PCCTL (chopper control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// CHPEN bit
#define CHP_ENABLE 0x0
#define CHP_DISABLE 0x1
// CHPFREQ bits
#define CHP_DIV1 0x0
#define CHP_DIV2 0x1
#define CHP_DIV3 0x2
#define CHP_DIV4 0x3
#define CHP_DIV5 0x4
#define CHP_DIV6 0x5
#define CHP_DIV7 0x6
#define CHP_DIV8 0x7
// CHPDUTY bits
#define CHP1_8TH 0x0
#define CHP2_8TH 0x1
#define CHP3_8TH 0x2
#define CHP4_8TH 0x3
#define CHP5_8TH 0x4
#define CHP6_8TH 0x5
#define CHP7_8TH 0x6
// TZSEL (Trip-zone Select)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// CBCn and OSHTn bits
#define TZ_ENABLE 0x0
#define TZ_DISABLE 0x1
// TZCTL (Trip-zone Control)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// TZA and TZB bits
#define TZ_HIZ 0x0
#define TZ_FORCE_HI 0x1
#define TZ_FORCE_LO 0x2
#define TZ_DISABLE 0x3
```

```
// ETSEL (Event-trigger Select)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// INTSEL, SOCASEL, SOCBSEL bits
#define ET_CTR_ZERO 0x1
#define ET_CTR_PRD 0x2
#define ET_CTRU_CMPA 0x4
#define ET_CTRD_CMPA 0x5
#define ET_CTRU_CMPB 0x6
#define ET_CTRD_CMPB 0x7
// ETPS (Event-trigger Prescale)
// = = = = = = = = = = = = = = = = = = = = = = = = = = =
// INTPRD, SOCAPRD, SOCBPRD bits
#define ET_DISABLE 0x0
#define ET_1ST 0x1
#define ET_2ND 0x2
#define ET_3RD 0x3
```