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THESIS

IMPEDANCE SOURCE INVERTER WITH COMPENSATED BOOST AND QUADRATIC REFERENCE PULSE WIDTH MOULATION FOR LOW POWER PEM FUEL CELL

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CHAPTER 1 – INTRODUCTION

Although we are going to continue using petroleum for some time, the world societies must decide to use a cleaner fuels and energy sources. It is well known that the oil reserves have been significantly reduced and it is a matter of time when they will not be able to provide the power demands of the increasing world population. "Worldwatch" Institute experts calculate that in next 30 years the consumption of energy in the world may be tripled [1]. Renewable Energies have been evaluated such as wind, solar and fuel cells; and it is a common thinking within the scientific community that the renewable energies have the great potential to fulfill the future power demand of the increasing population on reliable and efficient ways and, what is very important with lower pollution emissions [2].

Fuel cells technologies have the potential to revolutionize the areas of power generation and transport systems, there are very diverse application for the fuel cells that range from small portable applications as cellular phones to great stationary systems of combined heat and power generation of megawatts [2], This flexibility allows the Fuel Cells to be a suitable option for automotive applications, as well as to power up remote communications installations and be self-supplying energy source for rural communities. The main constrain in the use of Fuel Cells is their unpredictable costs which are initially higher because of the research and development investments needed, but there is the general expectation that their great benefits may eventually overcome their challenges.

In order to have Fuel Cells technologies available to a greater number of potential consumers more research and development is needed to reduce the cost of the Fuel Cells power modules itself and also huge investments are needed to develop a hydrogen production and distribution and because the main purpose of the Fuel Cells is to serve as electric generators therefore more efficient power converters have to be developed at a lower cost. The optimization of the power converters has a key role in the overall Fuel Cells system performance and also on the intended price reduction. Better power electronics circuits and control techniques have to be designed for the power converters with the goal of transfer the electrical power generated by the fuel cells stacks with the highest efficiency to the connected loads. This research work is about the design and implementation of an Impedance Source Inverter for a 1kW Fuel Cell Power Module.

The ITESM purchased a 1kw PEM Fuel Cell Stack (Nexa Power Module, fabricated by Heliocentris) for the Fuel Cells & Nanostructured Materials Laboratory and there is a need of a power converter to connect alternate current -AC- loads to this Fuel Cell Stack Power Module. There is also the motivation that once designed this Power Inverter could eventually be utilized for wind turbines or solar panels or in general in applications where there is a variable DC power source that needs to be regulated, amplified and inverted. Additionally, there is an interest to demonstrate the potential use of these emerging fuel cells technologies and, in this way, contribute to promote the investments on research in the area of Energy Systems, Fuel Cells and Power Electronics.

The objective of this research work is and to design and implement a power inverter for a 1kw Fuel Cell Stack and to demonstrate a new proposed control technique. A better power converter performance is expected because the idea of a better control with a specific type on inverter circuit: The Impedance Source Inverter (ZSI). An algorithm will be proposed to achieve maximum modulation index of the power inverter while the amplification factor compensates the voltage drop of the Fuel Cell. The expectative is to reduce THD and obtain higher efficiency in the power conversion. The control system will be implemented on a Field Programmable Gate Array (FPGA) development kit, and the hardware design will be focus to be simple avoiding the necessity of isolation transformers, ultra-capacitors or batteries with the implied cost reduction. The expected results for this proposed work are summarized in three main targets: gain knowledge in power electronics applied to fuel cells system; publish an article in either area of power electronics or fuel cells technologies and to implement a prototype.

CHAPTER 2 – REVIEW OF FUEL CELL TECHNOLOGY

2.1. Fuel Cells Background

Even that the Fuel Cells basis principles were discovered 150 years ago, until the recent years and because of the increasing interest on cleaner energy sources the development of Fuel Cells technologies have been promoted and lately so because also on commercial interest because of the wide range of potential applications from small objects like cellular or computers to energy supply for transportation systems and power generation.

2.1.1. Brief History

In 1839, William Robert Grove (1811-1896) realized in 1845 the first experiments and laboratory prototypes of what actually it is known as Fuel Cell, however, the theory basic principles were discovered few years before, in 1838, by the Swiss teacher Christian Friedrich Schoenbein (1799 –1868).[3] The last century when the Fuel Cells gained interest because of the spatial race, The Apollo and Gemini projects used Alkaline Fuel Cells to generate electric power and water and the Soviet projects used similar systems too. It was until 20 years ago that was a renewed interest in the fuel cells in United States and Japan and later in Europe due to the Oil energy crises, the appearance of environmental protective policies. In more recent years a incremental number of companies worldwide had supported the research of Fuel Cell Technologies and will it be so.

2.1.2. Description and Types

Fuel Cell is an electrochemical device that continuously converts chemical energy into electrical energy (and some heat) for as long as fuel and oxidant are supplied [4]. The most suitable fuel for such cells is hydrogen or a mixture of compounds containing hydrogen. While there are a few different types of fuel cells, all share the same basic setup. Layers of materials with distinct electrochemical properties are assembled together to form a single galvanic cell. A fuel cell consists of an electrolyte sandwiched between two electrodes. The oxydant passes over one electrode and the hydrogen or hydrogen container is fueled over the other, and they react electrochemically to generate electricity, water, and heat.

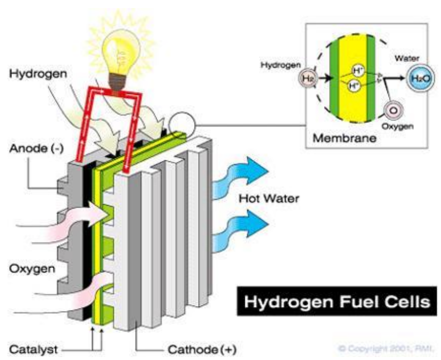

Figure 1: Fuel cells operation.

SOURCE: http://www.rmi.org/sitepages/pid537.php

At the center there is liquid or a solid membrane that can only be crossed by charged molecules. The solid gas-permeable electrodes coated with a catalyst are in contact with the electrolyte. Single Cell are connected in series to form Stacks and then connected to an electric load which creates a complete electrical circuit. Here are different types of fuel cells currently und research and development and even with some commercial applications [4].

Fuel Cell Type	Electrolyte	Charge Carrier	Operating Temperature	Fuel	Electric Efficiency (System)	Power Range/ Application
Alkaline FC (AFC)	KOH	OH^-	60–120°C	Pure H_2	35–55%	<5 kW, niche markets (military, space)
Proton exchange membrane FC (PEMFC)[a]	Solid polymer (such as Nafion)	H^+	50–100°C	Pure H_2 (tolerates CO_2)	35–45%	Automotive, CHP (5–250 kW), portable
Phosphoric acid FC (PAFC)	Phosphoric acid	H^+	~220°C	Pure H_2 (tolerates CO_2, approx. 1% CO)	40%	CHP (200 kW)
Molten carbonate FC (MCFC)	Lithium and potassium carbonate	CO_3^{2-}	~650°C	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2)	>50%	200 kW–MW range, CHP and stand-alone
Solid oxide FC (SOFC)	Solid oxide electrolyte (yttria, zirconia)	O^{2-}	~1000°C	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2)	>50%	2 kW–MW range, CHP and stand-alone

Table 1: Currently Developed Types of Fuel Cells and Their Characteristics and Applications.

The alkaline fuel cell, AFC, has one of the longest histories of all fuel cell types, as it was first developed, the other low temperature Fuel Cells: The proton exchange membrane fuel cell, (PEMFC), takes its name from the special plastic membrane that it uses as its electrolyte and can achieve moderate current densities, it also can operate on a methanol/water mix and air and work as Direct methanol fuel cell (DMFC). The Phosphoric acid fuel cells (PAFCs) operates at temperatures of 200°C and has been developed 200 kW units for the medium-scale power generation market. The two high-temperature fuel cells, solid oxide and molten carbonate (SOFC and MCFC), have mainly been considered for large-scale (MW) stationary power generation because they can achieve high electric efficiencies and allow direct internal processing of fuels such as natural gas[3].

2.1.3. Fuel and Environmental Issues

The use of hydrogen as fuel presents or displays great advantages: it is an abundant source and after his combustion one only takes place heat and steam of water. In counterpart, it is a highly inflammable gas with which it would suppose that for its use it would be necessary to redesign containers or even the vehicles; in addition the infrastructure accomplishment would be expensive for its distribution. Fossil fuels ranging from petroleum and natural gas to coal can be processed for the generation of hydrogen for fuel cell systems [5]. Another commonly way to produce Hydrogen is to use electricity to electrolyse water, the reverse process of a fuel cell, there is a widen thinking that this could be done in wind farms or solar panels or with other renewable energy sources or even with electrical energy generated by either hidro-plants, combined cycle or even nuclear power plants.

Though fuel cells have been used in space flights and combined supplies of heat and power, electric vehicles are the best option available to dramatically reduce urban air pollution. In the transportation sector, fuel cells are probably the most serious contenders to compete with internal combustion engines (ICEs). They are highly efficient because they are electrochemical rather than thermal engines. Hence, they can help to reduce the consumption of primary energy and the emission of CO_2. What makes fuel cells most attractive for transport applications is the fact that they emit zero or ultra low emissions [4]. Fuel-cell-powered electric vehicles also score over battery operated electric vehicles in terms of increased efficiency.

2.2. Polymer Electrolyte Membrane Fuel Cells

2.2.1. Electrochemistry and Characteristics

The principle of operation of the Polymer Electrolyte Membrane (PEM) Fuel Cell (also called proton exchange membrane fuel cell) is quite simple: the hydrogen fuel is split by catalyst at the anode into hydrogen protons and electrons, the protons pass trough the polymer membrane to the cathode while the electrons are forced to follow the path of the load [4]. Once at the anode the protons and electrons react in the presence of the oxidant (usually air) to generate water and heat (heated water or steam). As it is shown in the figure 1 the PEM Fuel Cell have the following electrochemical reactions occurring at the electrodes [5]:

Anode:	Cathode:	Overall:
$2H_2 => 4H^+ + 4e^-$	$O_2 + 4H^+ + 4e^- => 2H_2O$	$2H_2 + O_2 => 2H_2O$

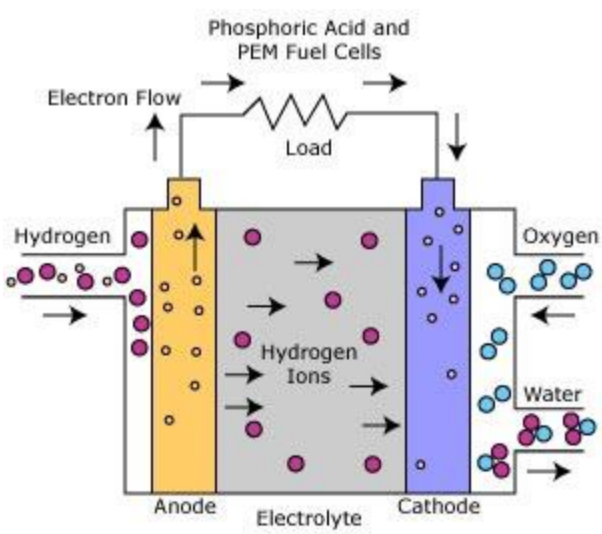

Figure 2: Polymer Electrolyte Membrane Fuel Cell

SOURCE: *http://www.fctec.com/fctec_types_pem.asp*

The membrane relies on the presence of liquid water to be able to conduct protons effectively, and this limits the temperature up to which a PEMFC can be operated. Even when operated under pressure, operating temperatures are limited to below 100°C. Therefore, to achieve good performance, effective electrocatalyst technology is required [5]. Having low operating temperature allows rapid start-up and the ability to rapidly change power output are characteristics that make the PEMFC to be suitable for Portable or Mobile applications, but this is also one of the disadvantages of the PEMFC for cogeneration applications.

The solid electrolyte is made by a sulphonic acid polymer (manufactured by Dupont and commercialized as a NAFION membrane) and being solid makes the sealing of the anode and cathode gases to be simpler and less expensive to manufacture than for liquid electrolytes Fuel Cells. The solid electrolyte is also more versatile with physical orientation and it has much less problems with corrosion, compared to many of the other electrolytes, this characteristic leads have longer cell and stack life. Compared to other types of fuel cells, PEMFCs generate more power for a given volume or weight of fuel cell. This high-power density characteristic makes them compact and lightweight. The efficiency range is from 35 to 45% on Natural Gas HHV.

The Single Fuel Cells are stacked and connected in series to obtain higher voltages and current capacities. The stack engineering in general deals with atmospheric operation, gas manifolding, cooling, water and heat management, sealing concepts are also important in order to ensure proper functioning of the PEMFC.

2.2.2. Stack Operation and Control

The control system for a PEM fuel cells is needed to regulate the air and hydrogen flows to the Fuel Cell Stack to deliver the fuel and the oxidant in a proper combination to allow the chemical reaction [6], valves or compressors are used to regulate the air supply and valves or pressure regulators are used to regulate the hydrogen supply. Maintaining the oxygen partial pressure in the cathode during abrupt changes in the current demanded by the user is necessary to prevent short circuit and prevent membrane damage [6].

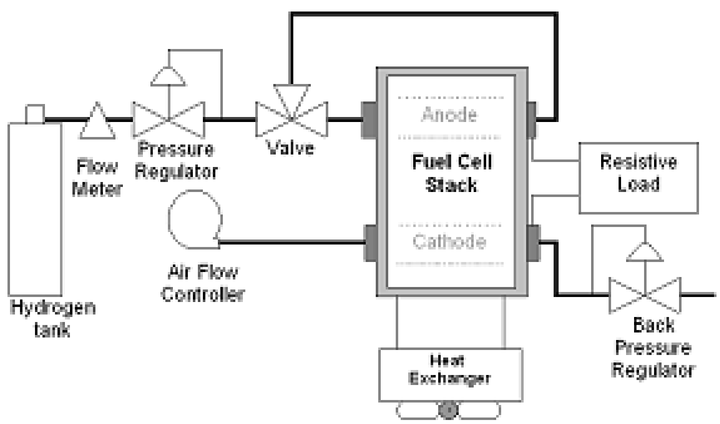

Figure 3: Control of PEM Fuel Cell Stack

For small PEM fuel cells systems the fuels supply is regulated in open loop by setting hydrogen and oxygen flows with pressure regulators in the inlet to the fuel cell stack. When an electronic controller is defined this has the goal to regulate the air inlet flow proportionally to the deviation in the fuel cell output voltage [6]. This simple strategy has the goal to operate the fuel cell in proper ranges in pressure, temperature and humidity to establish good electrochemical conditions within the fuel cell.

2.2.3. Output Voltage Response

The output circuit voltage of an hydrogen fuel Cell can be calculated from the reaction of a single molecule of H2, the two electrons passed round the external circuit for each water molecule produce and each hydrogen molecule used, if the system is reversible can be calculated from the Gibbs Free energy released that is the Ernst Potential (E_{th}) that is 1.14V [4]. There are several internal losses that reduces the output voltage from its theorycal value and can be grouped into three categories: Activation Losses (n_{act}), Ohmic Losses (I_{rm}) and mass transportation or concentration Losses (n_{act}) and The Voltage can therefore be expressed as:

$$V_{cell} = E - V_{ohm} - V_{act} - V_{trans} \qquad (1)$$

The Output voltage versus incremental current density is chart on the figure 4:

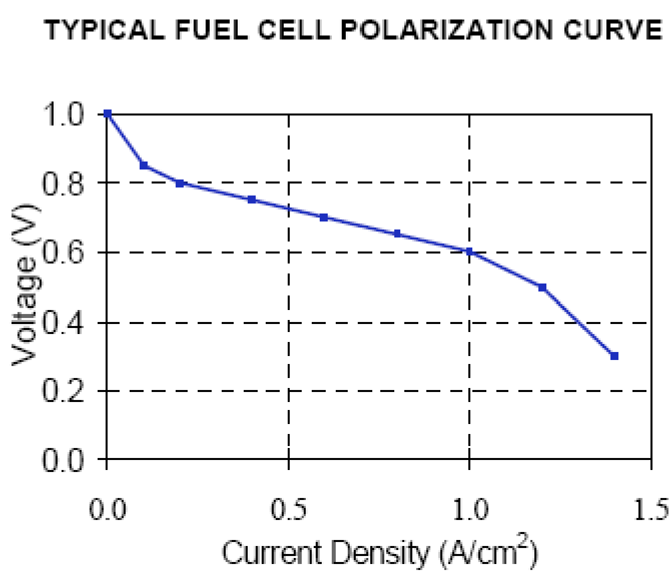

Figure 4: Fuel Cell Voltage Output Characteristic

There are several formulas for modeling the Fuel Cell output characteristic like in the following expression where the ohmic losses are modeled by the lineal factor, activation losses by the logarithmic function and mass transport losses by the exponential expression [4]:

$$V_{cell} = E - iR_{in} - A\ln\left(\frac{i + i_n}{i_o}\right) + m\exp(ni) \qquad (2)$$

Activation voltage is important for open circuit voltage. The mass transport and concentration losses are important at higher currents densities. Ohmic Losses are fairly lineal for stable fuel cell operation conditions and there is another effect that takes place within the fuel cell membrane that is the Capacitive double layer that is considered into the electrical circuit model of a Fuel Cell:

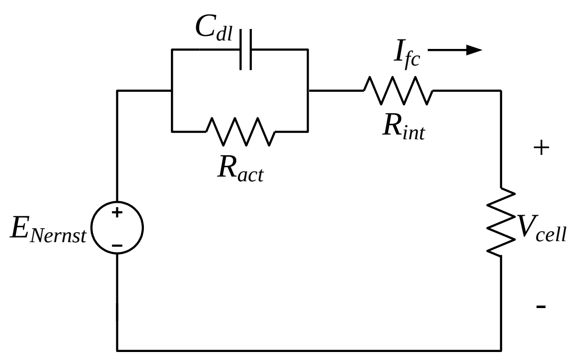

Figure 5: Fuel Cell Electrical Model Circuit

Since the Fuel Cell Stack Voltage is the sum of all the single cells voltage, then the individual single cell characteristic can extend to the Fuel Cell Stack Characteristic. The voltage output of the Fuel Cell Stack is then an unregulated DC (direct current) with a nonlinear incremental voltage reduction as higher current is required, this characteristic needs to be carefully considered and compensated in the design of the Power Converters.

CHAPTER 3 – FUEL CELL POWER DELIVERY

The basic purpose of a fuel cell is to generate electrical power, therefore the area of electrical engineering and power electronics are relevant for fuel cells. The electrical problems brought by the fuel cells can be solved using standard technologies for electrical power systems, particularly the related with voltage regulation and inverters [4]. In this chapter the DC/DC converters and DC/AC Inverters are presented as existing configurations and characteristics of power conditioners for Fuel Cells are discussed.

3.1. Power Converters Background

3.1.1. DC to DC Converter (Choppers)

A DC chopper can be used as a DC transformer to step-up or step-down a fixed DC voltage, the chopper can also be used for switching mode voltage regulator and for transferring energy between two DC sources. The principle of operation of the DC Choppers is to switch a DC Power Supply over a cycling period with a variable duty cycle to either step up or step down the average voltage seen by the Load [7]. There are different circuits of Chopper Circuits and several switching mode regulators: Buck Regulator, Boost regulator, Buck-Boost regulator and the Cuk Regulator. The DC regulators are widely used in applications of Switching power Devices or for Control of DC Motors. The Buck and Boost configurations, their voltage gain characteristics and efficiency practical considerations are explained in this section.

<u>Buck Regulator (Step Down Chopper):</u>

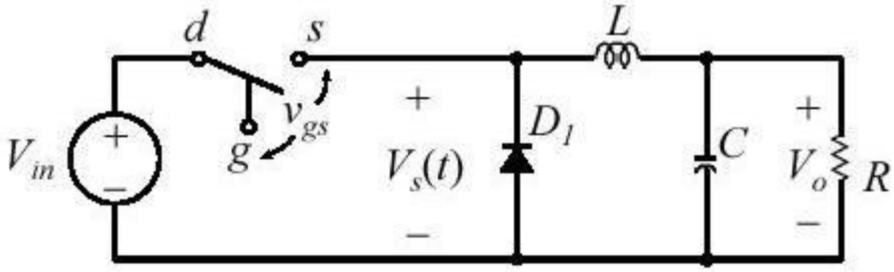

Figure 6: Buck Converter Circuit

The average output voltage applied to the Load R over a switching period is the simple relation:

$$Vo = Vin * D \qquad (3)$$

Where D is called the duty cycle that is when the gate is turned on, the output will be a fraction of the Input Voltage (Source Voltage)

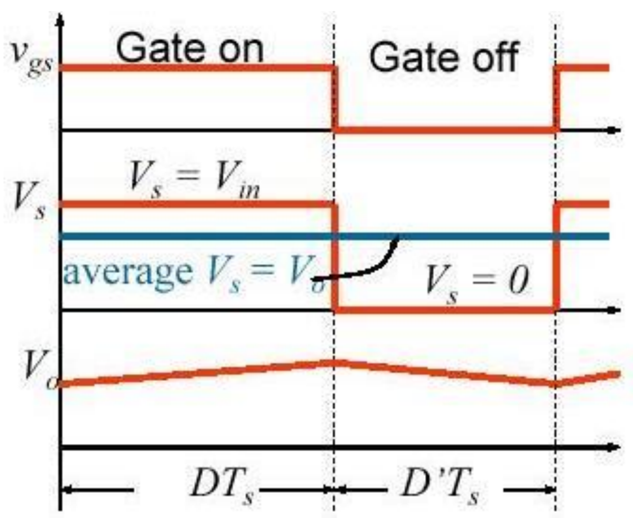

Figure 7: Buck Converter Cycle

Boost Regulator (Step Up Chopper):

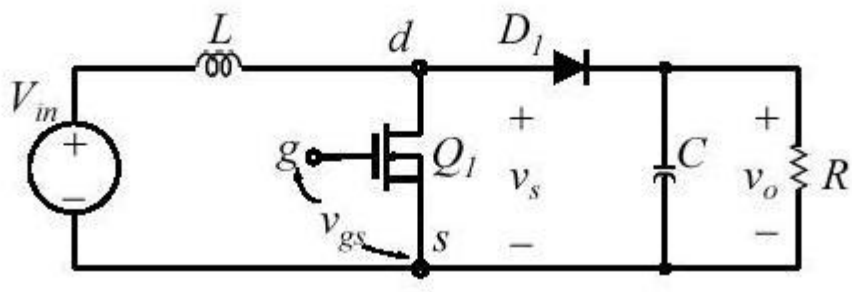

Figure 8: Boost Converter Circuit

The average output voltage applied to the Load R over a switching period is the following equation:

$$Vo = Vin\left(\frac{1}{1-D}\right) \qquad (4)$$

Where D is also called the duty cycle, when the gate is turned on, and the output will boost or amplified from the Source Voltage.

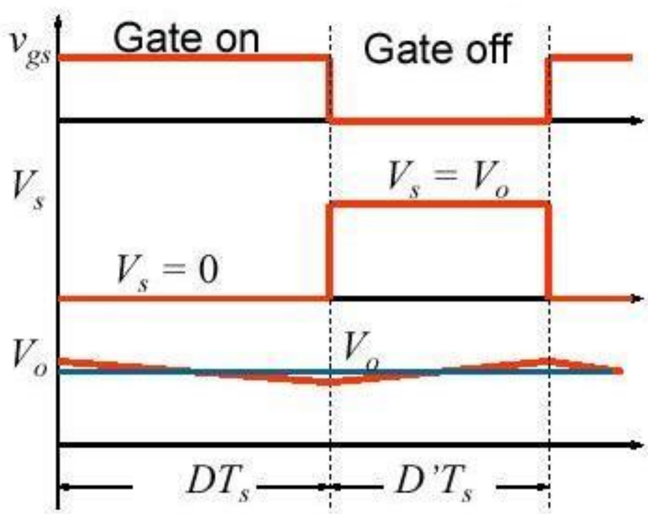

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Figure 9: Boost Converter Cycle

Boost Converter Efficiency:

The Step-Up Chopper in theory can give an infinite voltage, but in practice there is a limit when the current in the inductance becomes discontinue and the efficiency drops as the boosting factor (duty cycle) is incremented [8]

$$Vo = Vin\left(\frac{1}{\left(\frac{R_L}{R\,(1-D)}\right)+1-D}\right) \qquad (5)$$

The practical efficiency is represented in the chart1, for this reason the step up regulator have to be designed to operate in a range where the inductance current is continuous and with good efficiency.

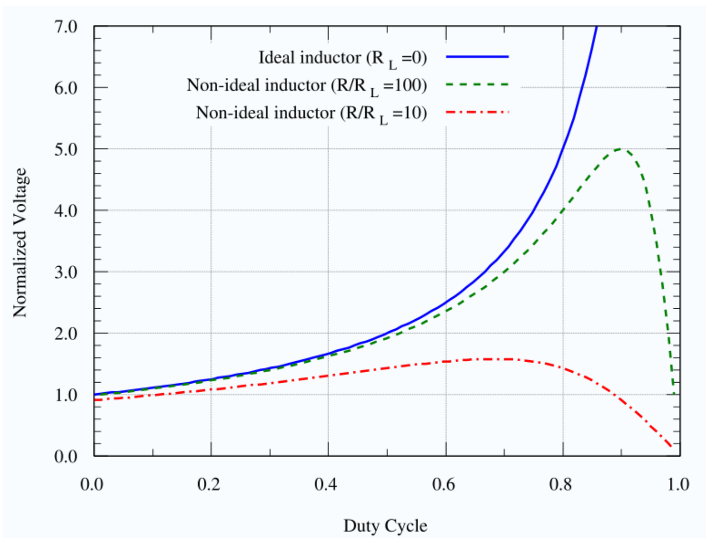

Figure 10: Boost Converter Efficiency

Harmonics are also generated at the input and load side of the choppers, and these harmonics can be reduce by input or output filters. A chopper can operate at either fixed (more often used) or variable frequency which are choppers that generates harmonics of variable frequency [7].

3.1.2. DC to AC Converters (Inverters)

DC to AC converters, also named Inverters, are needed because most of the electric loads require alternating current AC supply such as transformers, induction motors or when the power generated by a DC source is connected to the main grid. Inverters can provide single-phase and three phase AC voltages from a fixed or variable DC voltage. Inverter have become popular for motor control applications where Variable Frequency Drives (VFD) utilizes an inverter as a key component to regenerate the alternating signal applied to an AC motor at a desired frequency to control the motor speed. Inverters are also utilized in Un-interrupting power supplies (UPS) devices to back up power from DC battery banks [7]. The principle of operation for a single phase basic configuration called H-bridge composed of four power electronics switching devices S1 to S4 as it is shown in next figure2:

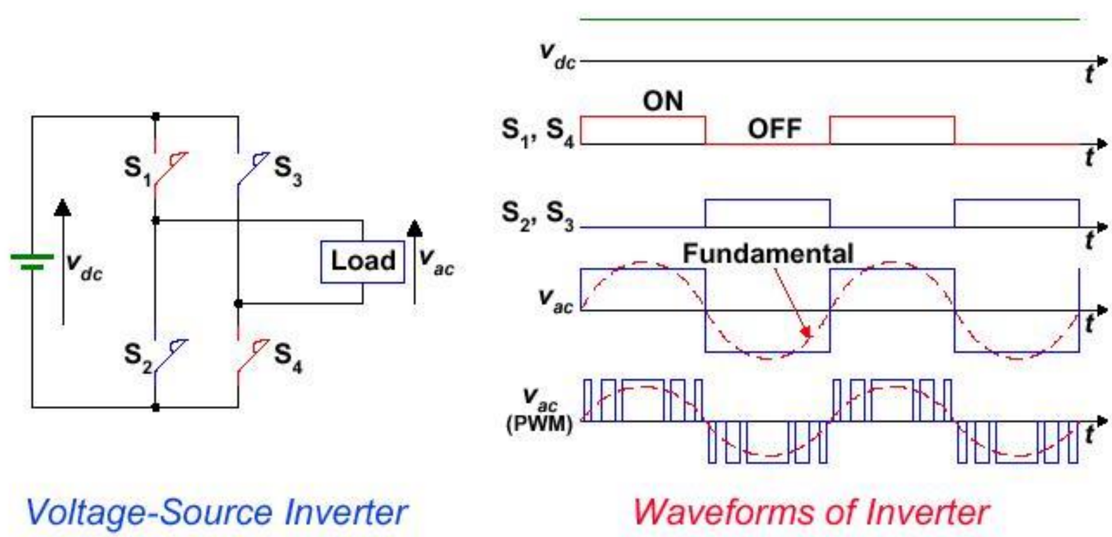

Figure 11: Inverter Circuit and Timing Chart

For inductive loads that are designed to work a certain frequency such electrical motors or transformer the Voltage signal that is doing work corresponds to the fundamental and the other harmonic content is dissipated in form of heat [7], therefore the voltage control technique used has a very important impact in the performance parameters and overall inverter efficiency of the Power Inverters.

PWM control techniques:

The most utilized voltage control techniques are: Pulse Amplitude Modulation (PAM) and Pulse Width Modulation (PWM). PWM is generated by a triangular or saw tooth carrier signal compared against a reference signal and can be classified based on single or multiple pulses or in the shape of the reference signal and there is even more complex techniques based on state space vector control:

- PWM Simple: Single pulse per semi-cycle
- Multiple PWM: Multiple pulses per period
- Sine PWM: Sine wave as reference
- PWM with Harmonic Injection: Sine wave with third or fifth harmonic summed as reference signal.
- State Space PWM: Techniques with state space matrices used to generate the gate triggers.

The root mean square rms output voltage of a Voltage Signal applied to a Load over a period can be found from the general equation:

$$Vo_{rms} = \frac{1}{T_0}\sqrt{\int_0^{T_0/2} Vs^2 dt} \qquad (6)$$

Depending on the Modulation technique the output rms voltage can be expressed in function of number of pulses and the pulse width as follows:

Multiple PWM:

$$Vo_{rms} = \sqrt{\frac{2p}{2\pi}\int_{(\pi/p-\delta)/2}^{(\pi/p+\delta)/2} Vs^2 d(\omega t)} = Vs\sqrt{\frac{p\delta}{\pi}} \qquad (7)$$

For simple PWM the Multiple PWM expression is still valid just considering p=1

Sinusoidal PWM:

$$Vo_{rms} = Vs\sqrt{\sum_{m=1}^{P}\frac{\delta_m}{\pi}} \qquad (8)$$

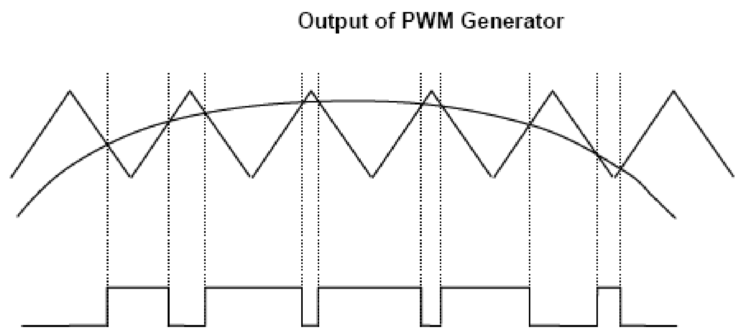

Figure 12: Reference and Carrier Signal of Sine PWM

Depending on the modulation technique used there are different effects on the performance parameters obtained: efficiency, total harmonic distortion (THD) and lower order harmonic (LOH). The Modulation Index affects directly proportional the Efficiency, as a lower modulation index the lower the efficiency. Efficiency in Power Inverter is also affected by the static and dynamic losses, the static losses are the power dissipated by the power transistors when they are conduction mode and the dynamic losses correspondent to the voltage and current peak of the transients presented when the devices are turned on and off.

3.2. Fuel Cell Power Conditioning

The power conditioning is required at the fuel Cell systems output to regulate the variable DC voltage delivered by the fuel cells stack and, if needed, an Inverter to convert the regulated DC voltage to an AC voltage that is the power supply required by the most of the electric loads. In this section two options of Power Conditioning are presented: one with the two stage power converter and other with the novel Impedance Source Inverter.

3.2.1. Two Stage Converters

In fuel cells applications with AC loads the conventional PWM inverter can be used whenever the FC output voltage is high enough to provide the amplitude of the RMS voltage required by the loads, but since output voltage of a PEM Fuel Cell is typically low DC voltage then it needs to be conditioned using a DC voltage regulator. Two Stage Power converters are often proposed [9] as a Power Conditioning solution as it is shown of figure 4.

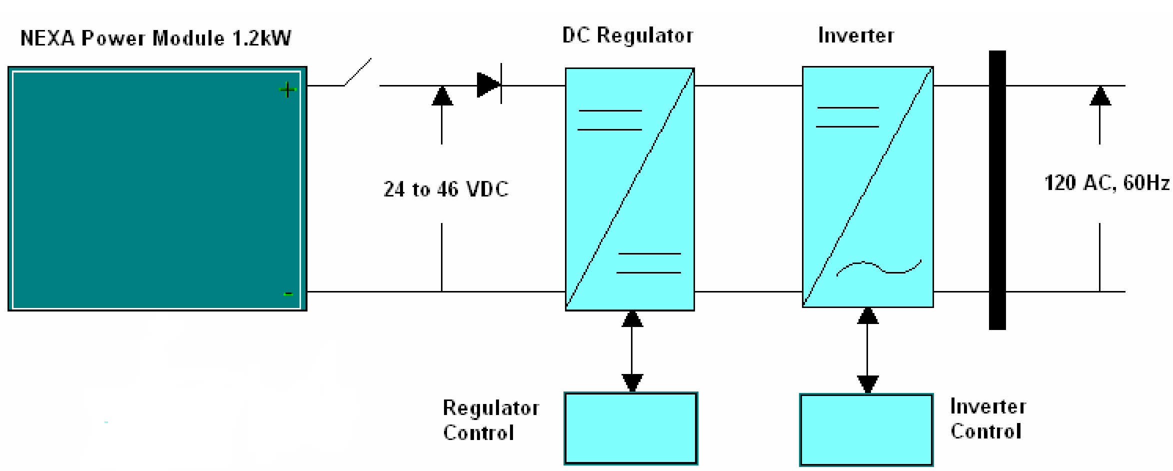

Figure 13: Power Converters used in Fuel Cells

The (unregulated) Low Output Voltage from the Fuel Cell is amplified by the DC/DC Converter and then is inverted to a single-phase or three-phase with a conventional PWM Inverter. This configuration usually includes in between the two converters some intermediate storage devices such as super-capacitors or back-up batteries. The advantages of this configuration are that several DC converters or Inverters circuits and control techniques can be selected to better match the performance specifications of the application and a complete control strategy can be implemented, in counterpart the overall system is more complex and needs more power electronic devices and also the efficiency is the result of multiplying the efficiency of the DC converter by the efficiency of the Inverter.

3.2.2. Impedance Source Inverter (ZSI)

The Impedance Source Inverter is a configuration proposed by Dr. Peng from Michigan University [10] it has been used and tested for Fuel Cells Application. This inverter is composed for an impedance network in series with a conventional PWM inverter as it is shown in figure 14.

There are several intuitive advantages and some studies shown performance advantages. Having less Power Electronic Devices, implies less cost but also less static and dynamic switching losses and therefore more efficiency. Related to performance there have been some comparison articles showing better performance than the conventional inverters or the two stage converters for application of three phase systems.

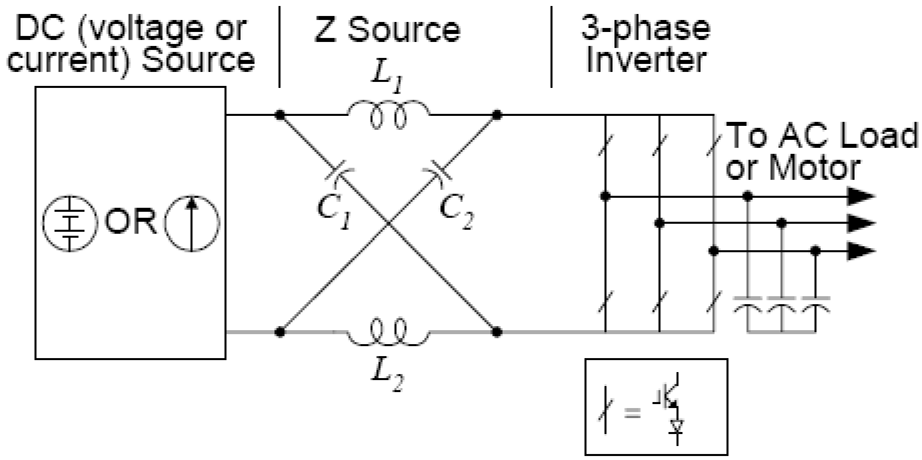

Figure 14: Impedance Source Inverter

The unique feature of the Z-source inverter is that the output ac voltage can be any value between zero and infinity regardless of the fuel-cell voltage. That is, the Z-source inverter is a buck–boost inverter that has a wide range of obtainable voltage. The traditional V- and I-source inverters cannot provide such feature [10]

$$Vac = \frac{M\,B}{2} Vin = \frac{M}{2}\left(\frac{1}{1-2K}\right) Vin \qquad [9]$$

All the traditional pulse width-modulation (PWM) schemes can be used to control the Z-source inverter and their theoretical input–output relationships still hold. When the dc voltage is not high enough to generate the desired ac voltage, a modified PWM with shoot-through zero states will be used to boost voltage, the equivalent dc-link voltage to the inverter is boosted because of the shoot-through states. The shoot trough states can be evenly distributed among the PWM pulses as it is shown for a three phase circuit in the figure:

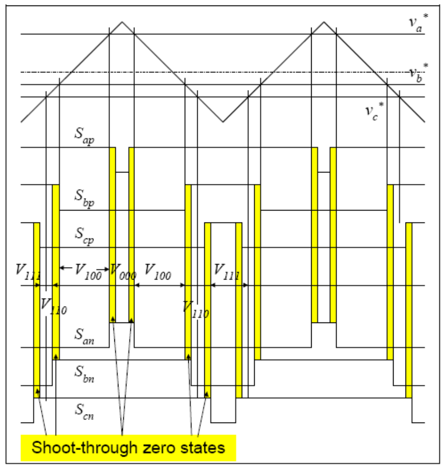

Figure 15: ZSI three phase Shoot-Trough states

There have been comparison in reference to which type of power converter is suitable for Fuel Cells, there is a very interesting report from the United States Department of Energy [11] that shows advantages of the Impedance Source Configuration over the conventional PWM inverter and the two stage DC Regulator and Inverter configuration. The comparison results show that the Z-source inverter can increase inverter conversion efficiency by 1% over the two existing systems. The Z-source also reduces the static and dynamic losses of the power electronics devices.

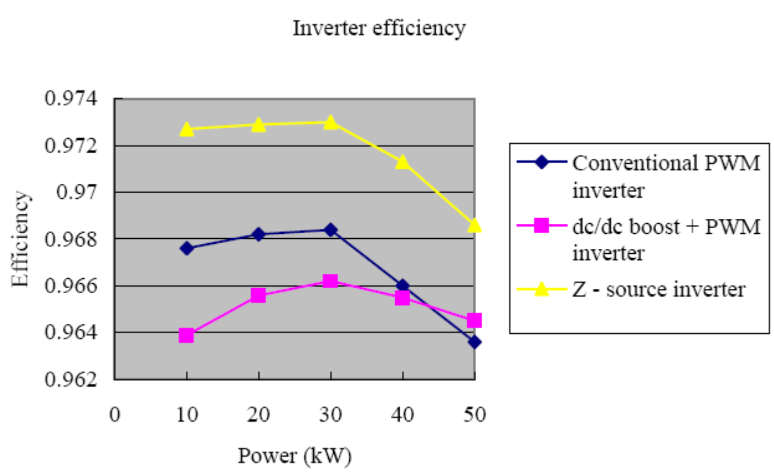

Figure 16: Inverter Efficiency Comparison

CHAPTER 4 – IMPEDANCE SOURCE INVERTER DESIGN

The Impedance Source Inverter was selected to incorporate its advantages into the Power Converter designed for the Fuel Cell Stack. The Proposed configuration will boost the Nexa Power Output Voltage from its operational range from 26 to 46 Volts to give the 120 Volts rms require to feed AC load as shown in the figure:

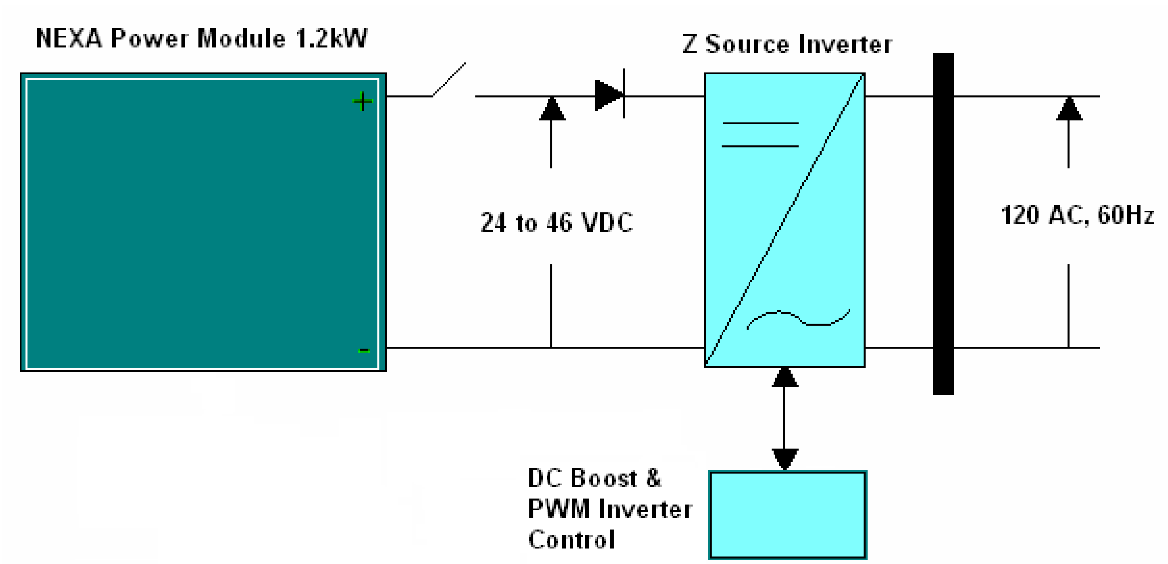

Figure 17: Suitable Configuration for Fuel Cell Power Converter

In order to design the Complete Power Converter, three circuits or modules have to be considered for the complete design: The Power Circuit itself, the Interface circuitry that includes the gate drivers and voltage sensing and finally a controller board has to be selected to implement the proposed control technique of this Thesis work.

4.1. Power Circuit

An existing design implemented and used at the Industrial Electronics Laboratory of the ITESM Electrical Engineering Department was used as reference for the design of the inverter bridge, This circuit uses two legs of Isolated Gate Bipolar Transistors (IGBT) and has the proper dv/dt protections (Snubber circuits). The impedance network with the inductors and capacitors was added to complete the Impedance Source Inverter Configuration as it is shown in the Figure.

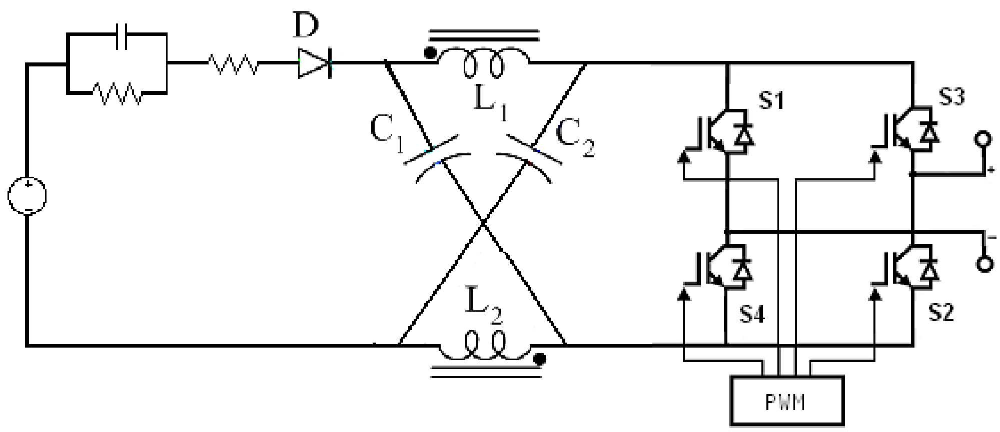

Figure 18: Proposed Power Circuit

The Values of the Capacitor and Inductor are important and the calculations are shown in the Appendix B.

4.2. Interfase Circuit

The Gate Driver circuit uses commercially available IR2112 components specially designed to trigger IGBTs Legs and opto-couplers 4N25 to isolate the control signals from the power circuit voltage. Two gate drivers and four opto-couplers are used as shown in figure. The VEE needs to be 15 Volts and the VCC is a different power Supply to the Open Collector control triggers.

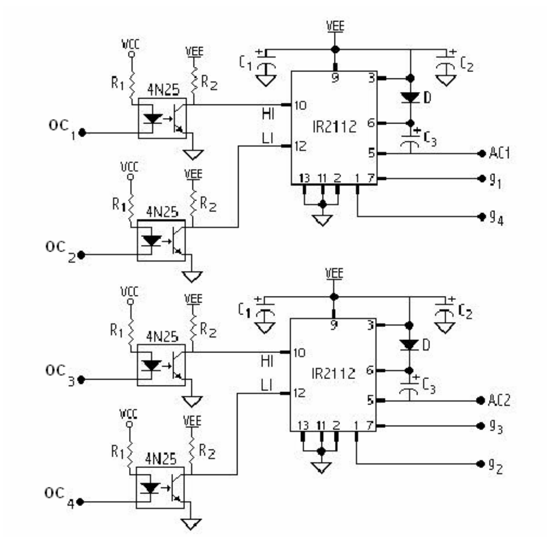

Figure 19: Gate Drivers

The sensing of the Fuel Cell Voltage requires also isolation and it was done using an LM-25 component the R1 and RM resistor where matched to transduce the Power Module to the 0 to 5 Volts required for the Analog to Digital Converter.

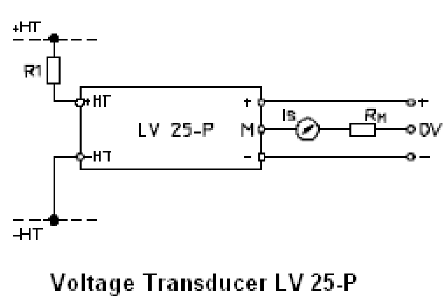

Figure 20: Hall Effect Transducer

4.3. Controller Board

A system board with the Spartan 3 Field Programmable Gate Array (FPGA) was selected as a controller. This FPGA board provides an inexpensive, robust, and easy to use platform where all the functionality and fast sampling and control required for the Power Inverter can be implemented.

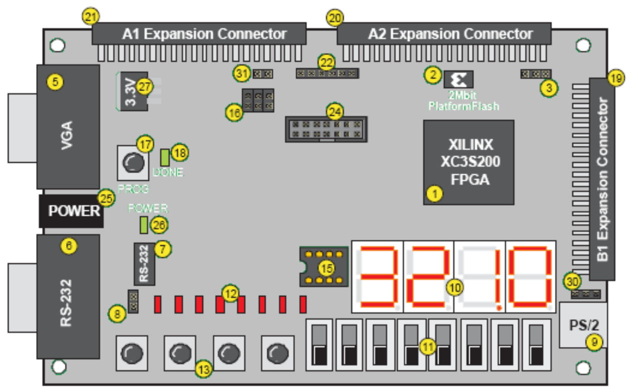

Figure 21: Spartan 3 Controller Board

It is important to mention that this control implementation could be also done on existing microcontrollers like the PICS F1877, but the advantage of the FPGA is that they are programmed in Hardware Description Language (HDL) what allows to have a portable code. The code can be programmed with the Xilinx ISE tools, with a JTAG (describe) programming cable. This system board has pushbuttons and selector to implement control or configuration functions and leds and seven segments displays to monitor status or parameters during the development and the test of the HDL code.

The Data acquisition required to consider an Analog to Digital A/D converter with a peripheral module that is connected to the FPGA board as an I/O device (Figure). Schematic of the ADC converter module is shown in figure:

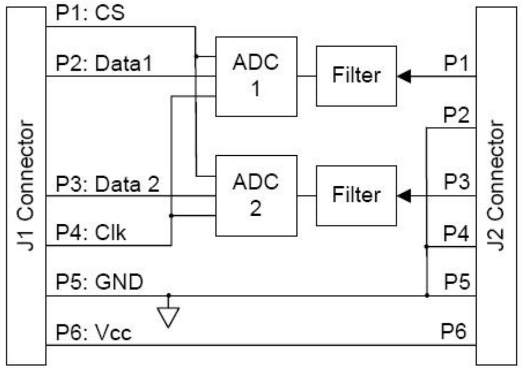

Figure 22: Schematic of the ADC Module

Another pheriferal module with four open collector transistor was utilized to handle the gate drivers. The Schematic of the Open Collector Module is showm in figure:

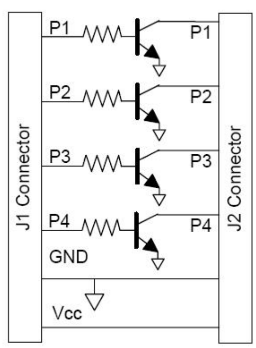

Figure 23: Schematic of the open Collector Module

CHAPTER 5 – CONTROL ALGORITHM

This chapter presents some control guidelines for the ZSI Inverter, to show the designs criteria followed and then a new method to calculate both Boost Factor and Modulation Index is proposed and explained detailed.

5.1. ZSI Control Guidelines

There are different methodologies in the literature for controlling the Impedance Source inverter. In the actual methods the PWM pulses are generated with conventional PWM techniques using either multiple pulses with third harmonic injection or state space PWM. The shoot-through states are evenly accommodated among the PMW pulses to boost the DC Link Voltage. To obtain the maximum boost given by the Equation (9), we need to consider that the Modulation index is restricted by the boost factor within the period: M=T-D or D=T-M, this restriction gives a pair of values M and D that can be charted. The Boost factor (B) versus the combined Modulation Index (M) and Duty Cycle (D) is shown in the chart:

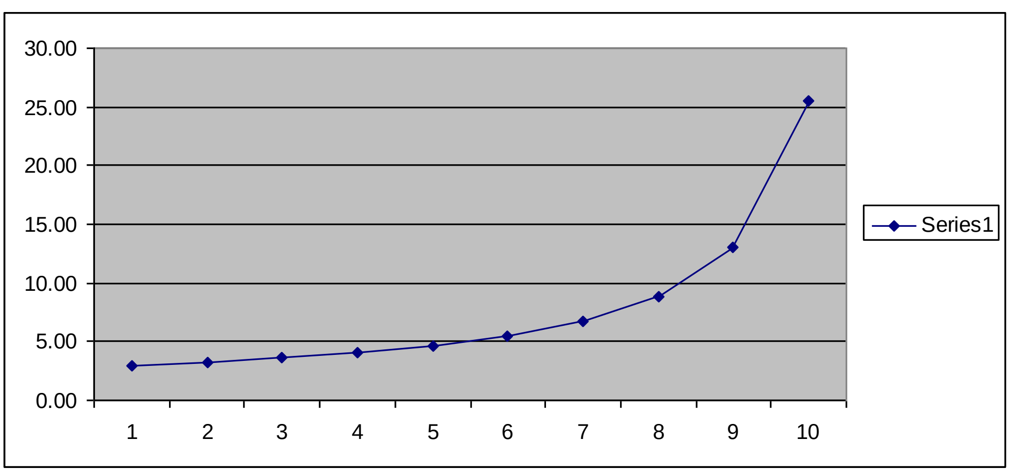

Figure 24: Boost versus Modulation Index and Duty Cycle

All the existent methods look for either a constant boost or a maximum boost control to follow the criteria of reducing the voltage stress across the power electronic devices. Main implementations have done for three phase circuits, but this work is about a single phase configuration and there is a special consideration to keep the current continuous.

5.2. Proposed Control Method

The objective is to propose a control algorithm to determine the boost factor and the modulation index based on the following criteria:

1) Obtain a Regulated DC Link Voltage considering the voltage output response of the Fuel Cell and compensate it with the Boost Factor “D”.
2) Maximize the Modulation Index “M” to reduce the THD and therefore increase the power inverter efficiency.

5.2.1. FC Compensated Boost Control

We expect higher efficiency if we reduce the boost factor, at the same time higher boost factors reduce the Modulation Index available what also reduces Efficiency. Then we need to define a method to restrict the Boost Factor while Maximizing the Modulation Index. If we calculate the boost Factor based on a constant DC link voltage then when the Fuel Cells Voltage Drops the Boost Factor will be incremented drastically, if we set the boost factor to a constant value the DC link voltage will Drop in proportional amount of the Fuel Cell Voltage Drop.

The solution two the two scenarios explained could be an approach based on the following criteria: We can tolerate a DC Link voltage drop and at the same time require a variable Boost factor to compensate the Fuel Cell Voltage Drop. In order to do this we can define a DC link voltage reference calculated in function of the Fuel Cell output voltage to calculate the boost factor. First we propose to calculate a drop tolerance or drop factor directly proportional to the Fuel Cell Output Voltage Deviation from the Open circuit voltage.

$$df = 1 + 2\left(\frac{Voc - Vin}{Voc - Vin\min}\right) \quad (10)$$

The deviation factor df can vary from 1 to 3 when Vfc is from Voc to Vfc min and the VDC Link Calculation can be expressed:

$$Vlink = Vin + \left(\frac{Voc - Vin}{df}\right) \quad (11)$$

If we combine the two equations we have a complete equation that is non-linear and intends to compensate the Voltage Drop in the Fuel Cell:

$$Vlink = Vin + \left(\frac{Voc - Vin}{1 + 2\left(\frac{Voc - Vin}{Voc - Vin\min}\right)}\right) \quad (12)$$

If we chart this relation we found a interesting shape very similar to the response of the fuel cell output voltage.

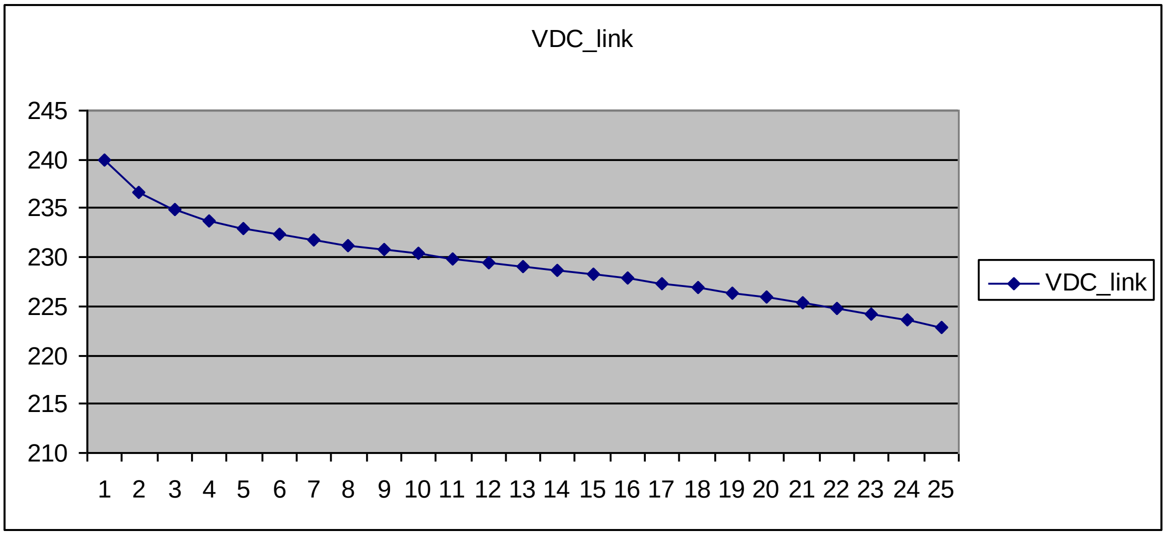

Figure 25: Compensated Reference

Now with the previous formulas and restrictions the VDC link, Boost Factor and Modulation Index are calculated for the range of Fuel Cell Output Voltages. This method proposes to control the Boost Factor “k” by allowing a voltage drop tolerance on the DC Link Voltage after the impedance network of the ZSI. This tolerance will reduce the amplification needed while the Fuel Cell Voltage is dropping because of incremental current.

The peak voltage “Vm” or amplitude of a sine wave is given by the relation:

Vm = Sqrt(2) * Vrms.

If we want to boost the Fuel Cell Voltage (Vin for the ZSI) to get the desired Peak Voltage at the DC Link we have:

B = Vm / (M/2 * Vin)

To obtain 120 Volts rms with a Modulation Index of 0.6 the peak voltage is Vm=170. Then we calculate the amplification needed for several Fuel Cell output voltages as follows: open circuit voltage of 48 Volts. If we want to restrict the Boost Factor to a lower range to increase efficiency we need to tolerate a voltage drop at the VD Link to also keep as maximum as posible the Modulation Index. We can define a DC link Voltage Value in function of the Fuel cell Output Voltage finding a relation. This Decay will allow values from *** B and K ranges *** By setting this Vm Limit and considering that the Vlink Drops we are assuring to limit voltage stress across the power electronic devices. This is simple implemented by a look up table following the criteria that a 15% of Voltage Drop is allowed while the DC voltage is at 24 VDC and the nominal peak voltage of 180 correspond to the inlet voltage of 48 VDC

5.2.2. Quadratic Reference Pulse Width Modulation

The Sine PWM is as a good control PWM technique but to implement it a table of sine wave or perform sine wave calculations are needed, to find a simple Reference signal for the PWM we found a Quadratic approximation to the sine wave that could be called “Parabolic PWM”. We define this quadratic or parabolic signal that is a quasi sine waveform as follows:

$$\operatorname{sgn}(n) = \frac{n(1-n)}{\left(p/2\right)^2}$$

This value will be from 0 to 1, p is the number of pulses per period and n is the actual pulse. This quadratic or parabolic signal can be used as a reference, this signals depends on the number of pulses what is directly related to the allocations of the harmonics given the flexibility to adjust the number of pulses. This quasi-sine shape wave reference signal is simple to be generated in the PFGA or microcontroller and reduces the necessity of fixed sine tables these two advantages are the reasons to propose this reference signal.

1) It is defined in function of the number of pulses.
2) Is simple to be implemented in a microcontroller or FPGA.

The other modification to the PWM algorithm is that we don’t use a triangular carrier signal, instead we use a sampling interval for each pulse with in the period. That give use a <<< diente de sierra >>> to more precisely compute the change of states from shoot to inverter the Boost Factor and the modulation Index.

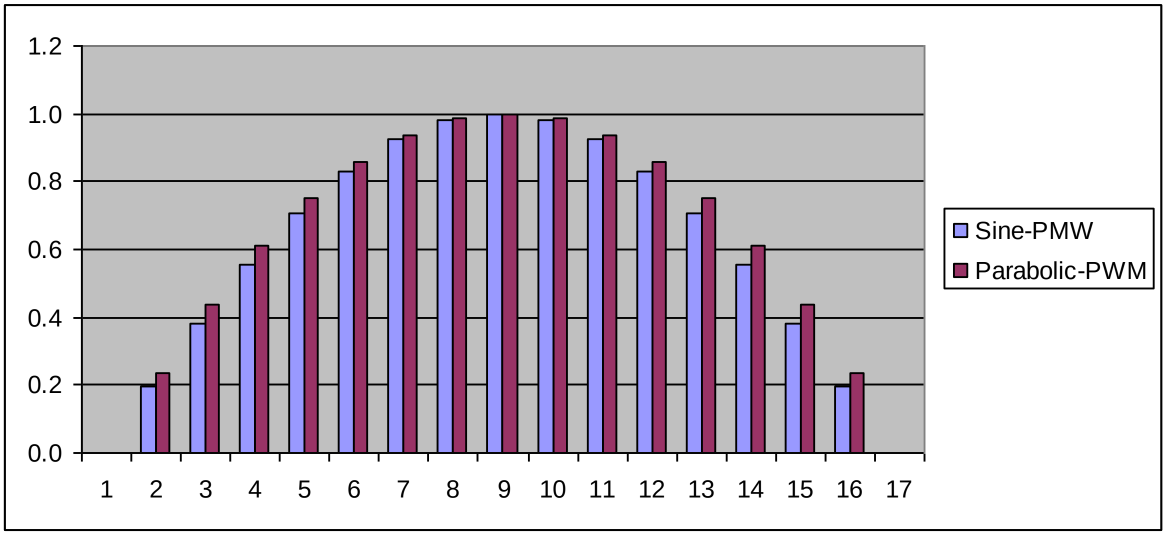

Figure 26: Quadratic Reference signal for PWM

The contribution of the method is that follows some design criteria following several goals:

1) There is a quadratic function implemented as a Voltage reference for the DC Link bus to help the PWM inverter to improve the output waveform.

2) There is a compensation of the voltage drop inherent to the Fuel Cell supply

3) There is a tradeoff between keeping high modulation index to improve THD and limiting the Boost factor to reduce voltage stress across the power electronic devices.

This method is not based on triangular carriers therefore defines one shoot through between each of the modulation pulses to maximize the Boost time. The other idea is that this method assumes that the Modulation Index has to be as max as possible to reduce the THD and the amplitude of the Fundamental Component.

5.3. Control Implementation

<<< Description of HDL Modules and Schematic >>>

*** Main Module Description

*** PWM Module Description

*** ADC Module Description

*** Schematic:

CHAPTER 6 – EXPERIMENTAL RESULTS

6.1. Experimental Setup

Initially we defined to test the inverter with DC Power Supplies and small low power loads to validate the basic functionality of the Power and Interface Circuits. Once validating a simple PWM algorithm without the Inductors and Capacitors the next step was to test the Multiple PWM with 15 Pulses without the Inductors and Capacitors and then with the inductors and Capacitors without triggering the shoot trough states.

6.1.1. Nexa Power Module

The main will be done using the Nexa Power Module of 1200 Watts for what the Inverter has been designed.

*** Describe the following characteristics: Power Rated, Voltage and Current Output, Fuel consumption.

*** Describe the Nexa components: Fuel Cell Stack, Contactor, Diode, Power Supply, On/Off Switch, Monitoring Software

The Inlet is connected to a hydrogen tank and the pressure is regulated with a, The Power Module has a compressor for the air supply to the fuel ceII stack. The software allows the monitoring of the Power Module parameters like the electrical parameters and internal parameter of the fuel cell system like the flow, temperature, etc.

6.1.2. Test Loads & Measurements

Four different test loads under two power supply scenarios were desgined to appreciate the voltage waveforms and the performance response of the Power Inverter. The two small resistive and small inductive loads were defined to test the inverter circuit with a 6 Amp Capacity Power Supply. The combined load and Full load were designed to test the circuit with the Nexa Power Module.

Small Resistive Load with Power Suppply:

Small Inductive Load with Power Suppply:

Combined Load with Nexa Power Module:

Full Load with Nexa Power Module:

Initially we defined to test the inverter with DC Power Supplies and small low power loads to validate the basic functionality of the Power and Interface Circuits. Once validating a simple PWM algorithm without the Inductors and Capacitors the next step was to test the Multiple PWM with 15 Pulses without the Inductors and Capacitors and then with the inductors and Capacitors without triggering the shoot trough states.

6.2. Inverter Test & Validation

6.2.1. Voltage Waveforms

Small Resistive Load with Power Supply:

Measurement of AC Voltage Signal

Measurement of Link Voltage Signal

Measurement of Current Signal

Comments

Small Inductive Load with Power Supply:

Measurement of Voltage Signal

Measurement of Link Voltage Signal

Measurement of Current Signal

Comments

Combined Load with Nexa Power Module:

Measurement of Voltage Signal

Measurement of Link Voltage Signal

Measurement of Current Signal

Comments

Full Load with Nexa Power Module:

Measurement of Voltage Signal

Measurement of Link Voltage Signal

Measurement of Current Signal

Comments

6.2.2. Performance Data

Small Resistive Load with Power Suppply:

Harmonic Content

Efficiency Calculation

Comments

Small Inductive Load with Power Suppply:

Harmonic Content

Efficiency Calculation

Comments

Combined Load with Nexa Power Module:

Harmonic Content

Efficiency Calculation

Comments

Full Load with Nexa Power Module:

Harmonic Content

Efficiency Calculation

Comments

CHAPTER 7 – CONCLUSIONS

7.1. Summary

7.2. Future Recommendations

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[14] ITESM Industrial Electronics Laboratory Practices

[15] Xilinx Spartan3 Site Info

APENDICE

I. Power Electronic Devices

II. Inductance and Capacitor Calculations

III. Cost per KWH of Fuel Cells

IV. VHDL Code

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