CHAPTER 1
INTRODUCTION

1.1 GENERAL

Multilevel inverter is an effective and practical solution for increasing power demand and reducing harmonics of AC load. This thesis investigates the potentials of a single-phase HCMLI fed from fuel cells.

Among several types of fuel cells, based on the type of electrolyte used, PEMFC is attractive and is a suitable candidate for power generation (Saha et al 2007) because of its features like low operating temperature, fast start-up, low sensitivity to orientation, long cell and stack life and low corrosion. Hence, static and dynamic models of PEMFC have been developed in this thesis. Novel feature of these models is the integration of all possible dynamic equations for dynamics of the charge double layer capacitance, lumped fuel cell body dynamics and channel dynamics into a single model.

Fuel cells operate at low DC voltages (typically 600 mV per cell) and therefore a number of cells are connected in series. As a long string of cells is difficult to operate, DC-DC boost converter is generally used to further boost the voltage to the required level. Various topologies such as boost, buck and series resonant full-bridge and push-pull converters have been proposed in the literature. But these topologies add objectionable ripples in the current flowing out of the fuel cell. To minimize the ripples, an IBC has been proposed as an interface between the fuel cell and the inverter (Choe et al 2007). In addition the interleaving provides high power capability, modularity and improved reliability. A three-phase directly coupled IBC
using CoolMOS switches has been proposed in this work instead of the conventional 2-phase IBC.

DC output voltage of IBC is inverted to get the desired AC output. Several different types of inverters have been proposed in the literature (Rodriguez et al 2000). This thesis however, proposes a single-phase HCMLI based on transformerless topology (Zhong et al 2006). It uses a hybrid approach involving SiC power BJT and Si IGBT operating in synergism. SiC BJT switch is attractive for inverters because unlike Si BJTs it does not have the thermal runaway and slow switching problems. The advantage of chosen HCMLI topology is that the modulation, control and protection requirements of each bridge are modular and it requires only a single DC source in each phase while the other DC source is replaced by a capacitor or low ampere-hour rechargeable battery to generate seven level equal step multilevel outputs.

Switching losses and harmonics of a multilevel inverter are mainly decided by its modulation strategies. For the cascaded multilevel inverter there are several well known sinusoidal pulse width modulation strategies (Radan et al 2007). Compared to the conventional triangular carrier based PWM, the inverted sine carrier PWM has a better spectral quality and a higher fundamental output voltage without any pulse dropping (Jeevananthan et al 2007). This thesis presents a hybrid modulation strategy combining the fundamental frequency switching scheme and VFISPWM. VFISPWM provides an enhanced fundamental voltage, lower THD and minimal switch utilization among the various bridges in inverter leading to reduced switching losses. A prototype of single-phase HCMLI has been developed to verify the proposed modulation strategy. The voltage and current waveforms are obtained for different loading conditions (linear and non-linear loads). The
performance of HCMLI is compared with asymmetrical topology in terms of switching losses and THD.

Fuzzy logic controllers have been designed to control the flow rate of hydrogen, regulate the output voltage of IBC and output voltage of HCMLI (Georgakis et al 2005). A MATLAB/SIMULINK model of the controller for the overall system has been developed to achieve the desired output power and its performance is compared with PI controller. Effect of step change in real power output has been analyzed in all the parameters like fuel cell voltage, PEMFC power, hydrogen flow rate, IBC output voltage and multilevel inverter output voltage.

In this thesis, issues of the PEMFC based HCMLI are addressed. Solutions are provided by developing models of different power converters. Proper control strategies are also developed to achieve the desired output. The following literature review lists the issues related to the research on fuel powered HCMLI.

1.2 LITERATURE REVIEW

Literature reviews in the following areas are presented:

(i) Modeling of PEMFC
(ii) Interleaved Boost Converter
(iii) HCMLI and modeling of SiC BJT
(iv) Modulation strategy for HCMLI
(v) Controller for fuel cell based HCMLI
1.2.1 Modeling of PEMFC

Ali (2008) has developed a dynamic electrochemical model of a standalone PEMFC. This model incorporates the effects of different dynamic conditions in load current, pressure of input reactant gases, fuel cell operating temperature as well as the mass heat transfer features in the fuel cell body. It finds application in the integration of fuel cells into distribution systems. In the model developed by Saha et al (2007), the dynamic behavior of the fuel cell system with a step load change is studied. A PI controller is used to control the fuel flow to the reformer of the fuel cell systems.

Pasricha et al (2007) have developed steady-state fuel cell electrical terminal models by considering the physical effects in a PEMFC. The simulation results of the model are verified using experimental data from Avista laboratories. Wang et al (2005) have proposed a dynamic model for PEMFC using electrical circuits. The models have been implemented in MATLAB/SIMULINK and PSPICE environment. The model responses obtained at steady-state and transient conditions are validated by experimental data.

Mammar and Chaker (2009) developed a fuel cell stack model for residential power generation. The model includes the electrochemical and fluid dynamic aspects of chemical reactions occurring inside the fuel cell stack. A fuzzy logic controller has been used to control active power of PEMFC system. Correa et al (2004) have presented an electrochemical model incorporating the physical and electrochemical processes taking place in a fuel cell. The results of the model are used to predict the output voltage, efficiency and power of fuel cell as a function of actual load current and operational parameters of the cells.
In the model proposed by Friede et al (2004), the equations governing the transient behavior of PEMFC is presented with special emphasis on water management of the fuel cell. The research work of Dachuan and Yuvarajan (2005) is focused on the development of electrical and mathematical models of PEM fuel cells. These models are based on passive elements, a diode and a pair of BJTs for modeling the non-linear part of the V-I characteristics of fuel cell.

Based on the above review, it is found that it is essential to develop a mathematical model in order to analyze the dynamic behavior of fuel cells by including the effect of capacitor double layer which is not taken into account in most of the literature.

1.2.2 Interleaved Boost Converter

Choe et al (2007) have presented the design methodology of an interleaved boost converter for fuel cell applications. Input current ripple, output voltage ripple, losses and capacity of electrical components are mainly compared with the conventional boost converters. Theoretical analysis has been performed and informative simulation and experimental results are provided. Kosai et al (2009) have modeled a coupled inductor type IBC. Design equations for IBC for operation under Continuous Inductor Current Mode (CICM) have been derived. The effects of inverse and direct inductor coupling on the converter performance have been studied.

Shin et al (2005) have developed analytical model of IBC with coupled inductor. Generalized and explicit expressions for converter performance such as efficiency, input and inductor current ripples and output voltage ripple have been derived and characterized according to the inductor DC couplings and number of phases. Thounthong et al (2008) have presented the design and implementation of a high power DC distributed system.
supplied by a fuel cell generator. A parallel power converter with interleaving algorithm is chosen to boost a low DC voltage of fuel cell to a DC bus utility level. The design and experimental verification of 1.2-kW prototype converter at a switching frequency of 25 kHz connected with a Nexa™ PEM fuel cell system (1.2kW, 46A) in a laboratory are presented.

Veerchary et al (2001) have presented the modeling of interleaved boost converter operating in the discontinuous current mode. In the modeling of the converter system, a state-space averaging technique is used. Various steady-state performance expressions are derived. Simulation studies are carried out in MATLAB. Xu et al (2005) have proposed a novel topology of high power IBC for fuel cell applications. State space averaged model of the converter in continuous conduction mode and discontinuous conduction mode are developed. Based on the transfer function, the two-loop controllers are designed and a prototype of 150 kW converter that is controlled by DSP320F2407 has been constructed. Wai and Duan (2005) have investigated a high step up converter with coupled inductor. They have shown that this topology promotes the voltage gain of a conventional boost converter with a single inductor and deals with the problem of the leakage inductor and demagnetization of transformer for a coupled-inductor based converter.

1.2.3 Hybrid Multilevel Inverter and Modeling of SiC BJT

Rodriguez et al (2000) have presented the most important topologies of multilevel inverter like diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor) and cascaded multicell with separate DC sources. Emerging topologies like asymmetric hybrid cells and soft-switched multilevel inverters are also discussed along with the modulation method for multilevel inverter. Zhong et al (2006) have proposed a cascade multilevel inverter using only a single DC power source and capacitors. A fundamental frequency switching pattern is employed to
maintain the DC voltage level of the capacitors and to obtain a nearly sinusoidal output.

Haiwen et al (2008) have explained a hybrid multilevel inverter using only a single DC power source to supply a standard 3-leg inverter along with three full H-bridges supplied by capacitors. Multicarrier based PWM method is used to produce a five-level phase voltage. The inverter can be used in Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV) (Zhong et al 2006a). Manjrekar et al (2000) have investigated a hybrid multilevel power conversion system typically suitable for high-performance high-power applications. This topology employs a hybrid approach involving Integrated Gate Commutated Thyristors (IGCTs) and Insulated Gate Bipolar Transistors (IGBTs) operating in synergism. By employing different devices under different operating conditions, it is shown that one can optimize the power conversion capability of the entire system.

Research work of Mariethoz and Rufer (2002) deal with the switching problems for asymmetrical multilevel inverter. An optimal control strategy based on a geometrical approach has been proposed to minimize the number of commutations and hence the switching losses can be reduced. Tolbert and Peng (2000) have developed multilevel inverter structures for interfacing with renewable energy sources such as photovoltaics or fuel cells or with energy storage devices such as capacitors or batteries. Azli and Choong (2006) have analyzed the performance parameters for a three-phase cascaded multilevel inverter employing Phase Disposition (PD) PWM technique. Rodriguez et al (2007) have presented a review of the state of the art and developments of two level and multilevel inverters for high power drive applications. The modulation methods for various topologies of multilevel inverter have been discussed in detail.
Das and Kazemierczuk (2007) have investigated the performance of three-phase voltage fed induction motor drives with SiC devices. The inverter efficiency in 180 degree mode is compared with that in 120 degree mode of operation by obtaining the losses in the circuit using PSPICE simulation. Tolbert et al (2001) have investigated the effect of SiC based power devices on HEV traction drive. The performance of SiC based power semiconductor switches over Si based switches have been analyzed. Charlotte et al (2007) have achieved a current gain of 70 for SiC BJT which is the highest value recorded in the literature. BJTs having an active area of 4 mm × 4 mm exhibit a specific on-resistance of 6.3 mΩ cm² at 25°C, which increases to 17.4 mΩ cm² at 250°C. $BV_{CEO}$ (the breakdown voltage from collector to emitter with open base) and $BV_{CBO}$ (the breakdown voltage from collector to base with open emitter) of 1200 V were also observed at <5 μA leakage currents at all temperatures up to 250°C.

1.2.4 Modulation Strategy for HCMLI

Zhong et al (2009) have presented a hybrid cascaded multilevel inverter employing only a single DC source and capacitors. Their work is focused on the control of seven-level HCMLI with fundamental frequency switching control and how its modulation index range can be extended using triplen harmonic compensation. Haiwen et al (2008) have analyzed the performance of hybrid multilevel inverter by employing the fundamental frequency switching and high frequency switching PWM methods.

Jeevananthan et al (2007) have proposed an inverted sine carrier PWM method for a single phase voltage source inverter. The proposed Inverted Sine Carrier PWM (ISCPWM) method has a better spectral quality and a higher fundamental component compared to the conventional Sinusoidal PWM (SPWM) without any pulse dropping. The ISCPWM strategy enhances the fundamental output voltage particularly at lower
modulation index ranges while keeping the THD lower without involving changes in device switching losses.

Tolbert and Habetler (1998) have demonstrated a novel multicarrier PWM method to balance device switching for all the levels in a diode-clamped multilevel inverter by varying the frequency for different triangular wave carrier bands. McGrath and Holmes (2002) have analyzed various multicarrier PWM techniques for diode-clamped and cascaded multilevel inverter. Radan et al (2007) have proposed three new multicarrier PWM methods for high power inverter applications. The methods are compared with PD, APOD and PS methods in terms of THD, WTHD and switching losses.

Calais et al (2001) have investigated and analyzed different multicarrier PWM methods for a single phase five level cascaded inverter. Carrier disposition methods, phase shifted method and a hybrid method have been discussed with respect to resulting switching frequencies, complexity of implementation, spectrum of the output wave and the use of inverter state redundancies to perform control tasks such as power flow control from each DC source. Aghdam et al (2008a) have proposed ISCPWM technique for an asymmetric multilevel inverter. This technique has been compared with the conventional triangular carrier based PWM in terms of total harmonic distortion.

Liao et al (2008) have proposed a new phase shift modulation applicable to single DC source cascaded multilevel inverter. The proposed method is more robust and has less computational burden. The main inverter switches at the fundamental frequency and the auxiliary inverter switches at the PWM frequency. Chaturvedi et al (2008) have compared total harmonic distortion and switching losses in two-level inverters with those in multilevel inverters. An optimized switching frequency has been obtained for a lower
level of total harmonic distortion and switching losses. A sinusoidal PWM technique is used to control the switches in the inverter. Casanellas and Notariat (1994) have calculated the forward and switching losses of a PWM inverter employing IGBTs using a relatively simple method from manufacturer’s catalogue parameters. The losses have been calculated for different modulation methods. Maswood (2008) has discussed an exact mathematical approach for calculating the IGBT turn-on, turn-off and on-state energy losses. Instantaneous voltage and current values are studied, linearized and employed to formulate the equations needed to calculate the IGBT switching losses.

1.2.5 Controller for Fuel Cell based HCMLI

Georgakis et al (2005) have presented the fuel cell model and control concepts for grid connected operation. The physical model of the fuel cell stack is described to properly represent the slow dynamics associated with the gas flows and the fuel processor operation. Suitable control architecture is presented for the overall system, whose objective is to regulate the input fuel flow in order to meet a desirable output power demand, achieving at the same time a near optimal operation of the fuel cells. Mohamed et al (2008) have analyzed the performance of a Sugeno-type Fuzzy Logic Controller (SFLC) applied to a Modular Structured Multilevel Inverter (MSMI) to regulate its output voltage at a specified frequency. The proposed SFLC has shown good performance for closed-loop control of an MSMI during simulation using MATLAB/SIMULINK with higher execution speed compared to the mamdani FLC. Wang et al (2006) have proposed a detailed design for PEMFC based distribution system. In this paper, the overall configuration of the PEMFC distributed generation system is given and dynamic models for the PEMFC plant and its power electronic interfacing have been briefly described. Controller design methodologies for the power
conditioning units to control the power flow from the fuel cell plant to the utility grid are also presented. Blaabjerg et al (2004) have analyzed the various power converter topologies for renewable energy sources. This work reviews the applications of power electronics in the integration of distributed generation units, in particular, wind power, fuel cells and PV generators. Ozpineci et al (2004) have developed a level reduction modulation strategy for a cascaded MLI interfaced with fuel cells. Level reduction is done by inhibiting a certain number of fuel cells when the load current decreases. The inhibited fuel cells can be used in other applications such as charging batteries to further increase their utilization and the efficiency of the system.

1.3 OBJECTIVES OF THE THESIS

In this thesis, the performance of PEMFC powered HCMLI for power generation is analyzed. In order to achieve the desired performance of the fuel cell based system, suitable control techniques are designed for each power converter unit in the system. An outline of the research objectives proposed in this thesis is given below:

1. Mathematical modeling of PEM fuel cell
2. Design of IBC
3. Development of HCMLI using SiC BJT and to study its performance with various loads
4. Implementation of a novel hybrid modulation technique using VFISPWM
5. Design of a fuzzy logic controller for fuel cell based HCMLI
1.4 ORGANIZATION OF THEESIS

Chapter 1 gives a brief introduction to PEMFC based HCMLI. A detailed survey of literature is carried out. The organization of the thesis is also presented.

In chapter 2, the mathematical model of a 750W PEMFC has been developed. This model depicts its behavior under static and dynamic load conditions. The static model is useful in sizing the components whereas the dynamic model is used to study the response time on load changes. Novel feature of this work is the integration of all possible dynamic equations like dynamics of the charge double-layer capacitance, lumped fuel cell body dynamics and anode and cathode channel dynamics into a single model developed and presented. This enables simultaneous capture of transients in cell voltage, temperature of the cell, hydrogen/oxygen inflow and outflow rates and cathode and anode channel temperatures and the corresponding pressures due to sudden change in load current. The PEMFC model is simulated in MATLAB/SIMULINK. The polarization curves (V-I characteristics of the PEMFC) are obtained for different values of input variables (Mammar and Chaker 2009). The transient response of the chosen PEMFC over short and long-time periods is analyzed with a resistive load.

In chapter 3, a three-phase directly coupled IBC has been proposed as a suitable interface for fuel cells to convert low voltage high current input into a high voltage low current output. The advantages of interleaved boost converter are minimized current ripple, increased efficiency, faster transient response, reduced electromagnetic emission and improved reliability. Based on the tradeoff between the ripple content, cost and complexity, the number of phases is chosen as three. The variation of inductor current ripple and input current ripple for various duty ratios and coupling coefficients is analyzed.
The design equations for IBC have been presented. The performances of IBC for uncoupled and directly coupled inductors have been studied. Hardware prototypes have also been developed to validate the results.

In chapter 4, a seven-level HCMLI with fuel cell as a main DC source has been developed. The HCMLI has two H-bridges. One H-bridge is connected to the output of IBC whose voltage is held at \( V_{dc} \) and another is connected to a capacitor whose voltage is held at \( 0.5V_{dc} \). The existence of redundancy in the switching states of HCMLI has been utilized for capacitor voltage regulation. Novel feature of the HCMLI employed in this work is the higher voltage levels (\( \pm 100V \)) are synthesized using Si IGBT inverter switched at 50 Hz while the lower voltage levels (\( \pm 50V \)) are synthesized using SiC BJT inverter switched at 39.5 kHz. The SiC BJT is modeled in PSPICE using Ebers-Moll equations. The most important Ebers-Moll parameters which differentiates Si and SiC BJT devices are: parasitic capacitances (\( C_{BC} \) and \( C_{BE} \)), the forward current gain (\( \beta_F \)), the early voltage (\( V_F \)) and the saturation current (\( I_s \)). Using these parameters, the output characteristics of SiC BJT are obtained for different junction temperatures. Simulation of the chosen single-phase seven-level HCMLI is performed using MATLAB/SIMULINK.

Chapter 5 analyzes the impact of the proposed hybrid modulation on the semiconductor devices power losses and harmonics of HCMLI (Liao et al. 2008). The proposed technique combines the fundamental frequency switching scheme and variable frequency inverted sine pulse width modulation. Fundamental frequency switching is employed for Si IGBT inverter bridge where the switches turn on and off once per cycle. This strategy makes this bridge to operate with the lowest possible switching loss. For SiC BJT inverter bridge, VFISPWM is applied which replaces the
conventional fixed frequency carrier waveform by variable frequency inverted sine carrier. The VFISPWM is found to provide an enhanced fundamental output voltage, lower THD and minimal switch utilization among the various bridges in inverter. In this work, the control signals have been generated by comparing sinusoidal reference signal with a high frequency inverted sine carrier. The modulating sine wave is broken into three vertical components. The first band is between 0 and 0.33 pu, second band is between 0.33 pu and 0.66 pu and the remaining 0.66 pu to 1 pu is the third band. The frequency ratio for each band has been set properly for balancing the switching action for all levels. The reference carrier frequency has been chosen as 39.50 kHz in this work as the switching losses and THD are found to be low at this frequency only. The voltage and current waveforms of HCMLI are obtained for different loading conditions (linear and non-linear loads) by employing hybrid modulation technique. Comparison is made between HCMLI and asymmetrical topology in terms of switching losses and THD.

Chapter 6 describes the design and construction of a single-phase seven-level HCMLI prototype to verify the hybrid modulation PWM scheme proposed in chapter 5. The gating signals are generated using FPGA.

In chapter 7, Fuzzy Logic Controller (FLC) architecture for fuel cell based HCMLI is discussed. A simulation model of FLC to regulate the flow rate of hydrogen in PEMFC, to regulate the output voltage of IBC and to control the output of HCMLI has been presented. The fuel cell stack is controlled by operating the cell at an optimum fuel utilization point (Georgakis et al. 2005). The fuel cell control problem is translated into an output current control requirement to be realized by the power conditioning unit in order to ensure optimal operation for a given fuel flow rate. The system is tested with a voltage disturbance and this effect is observed in all
parameters like fuel cell voltage, PEMFC power, hydrogen flow rate, multilevel inverter output voltage and output AC power. The performance of FLC is compared with that of PI controller.

Chapter 8 gives the conclusion highlighting the benefits of HCMLI for fuel cell powered system and also suggests about the future work that can be carried out.