# Design and Modeling of PEM Fuel Cell Using PWM Based Interleaved Boost Converter

M. Vijayalakshmi
*Department of Electrical and Electronics Engineering*
*Rajalakshmi Engineering college, Chennai, Tamil nadu, India*

A. Alice Hepzibah
*Department of Electrical and Electronics Engineering*
*Rajalakshmi Engineering College, Chennai, Tamil nadu, India*

**Abstract- Fuel cells are a family of technologies that generate electricity through electrochemical process rather than combustion. Unlike a battery, a fuel cell will continuously produce electricity as along as fuel is supplied and the catalyst remains active. Fuel cells provide major environmental, energy and economic benefits that advance critical national goals. Fuel cell generates electricity by an electrochemical reaction in which oxygen and a hydrogen rich fuel combines to form water. Fuel cell types are generally classified according to the nature of the electrolyte they use. This paper deals with the modeling of PEMFC which uses water-based, acidic polymer membrane as its electrolyte, with platinum-based electrodes. Due to relatively low temperatures and the use of precious metal based electrodes, this cell must operate on pure hydrogen. PEMFC are currently the leading technology for light duty vehicles and material handling vehicles. To reduce the current and voltage ripples, a simulation was done in MATLAB by modeling a fuel cell and then interfacing it with an PWM based interleaved boost converter. To design a high efficient fuel cell we require a suitable DC-DC converter. Among the leading topologies, PWM based interleaved boost converter (IBC) is taken as the best solution for high efficient fuel cells which increases the electrical performance and less bulky when compared to the other conventional boost converters. Simulation study for the PWM based IBC interfaced with PEM fuel cells has been studied using MATLAB /SIMULINK**

**Keywords – PEMFC, Design and Modeling, PWM based IBC and reduction of current and voltage ripples.**

## I. Introduction

GENERATING renewable electricity is an important way to reduce carbon dioxide ($CO_2$) emissions and many countries are installing wind and solar power plants to help meet targets for cutting $CO_2$. One drawback of these energy sources is their variability that the wind tends to blow intermittently and solar power is only available during the daytime. Hence renewable power plants either have to be over-engineered to take account of this lower capacity factor. Ideally, excess renewable energy generated times of plenty can be stored for use during periods when sufficient electricity is not available. But storing this energy is a difficult task that batteries and similar technologies perform well over short timescales, but over periods of week or months a different approach is necessary. Energy storage in the form of hydrogen is one such possibility in which excess electricity is fed into an electrolyser to split water into its constituent parts, oxygen and hydrogen. The hydrogen is then used in fuel stored energy back to the grid. Traditional solutions have included generators and batteries, but issues of maintenance, noise, pollution, size, insufficient runtime, remote monitoring difficulties and operation under extreme conditions all pose problems for these technologies. This has led to interest in fuel cell technology for this application, and fuel cell backup power units are now being installed in a number of countries. This paper discusses about PEM fuel cells which refers to proton exchange membrane or polymer electrolyte membrane where a proton conductive membrane is used as the electrolyte and at the same time as the separator in the electrochemical cell to separate the anode from the cathode. Because this type of fuel cell membrane electrolyte operates on protons, any oxidizable hydrogen rich fuel such as hydrogen gas, lower alcohols and acids can be used. In this paper the output voltage of PEM fuel cell is typically connected to a PWM based IBC to regulate the output voltage. The normal conventional boost converter however injects current and voltage ripples into the PEMFC. Such current and voltage ripples can cause a severe damage to the fuel cell. In order to reduce this ripple, several boost converters can be connected in parallel. Such parallel connections of various boost converters are called interleaving. This paper discusses the reduction of current and voltage ripple caused in the fuel cell by using the concept of interleaving. The comparison of result was made between interleaved boost converter using pulse generator and PWM generator and the results are shown.

## II. PROTON EXCHANGE MEMBRANE FUEL CELL

### *2.1 Principle of operation*

A proton exchange membrane fuel cell transforms the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy, as opposed to the direct combustion of hydrogen and oxygen gases to produce thermal energy. A stream of hydrogen is delivered to the anode side of the membrane electrode assembly (MEA). At the anode side it is catalytically split into protons and electrons. This oxidation half cell-reaction or hydrogen oxidation reaction (HOR) is represented by:

**At the Anode:**

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

The newly formed protons permeate through the polymer electrolyte membrane to the cathode side. The electrons travel along an external load circuit to the cathode side of the MEA, thus creating the current output of the fuel cell. Meanwhile, a stream of oxygen is delivered to the cathode side of the MEA [5]. At the cathode side oxygen molecules react with the protons permeating through the polymer electrolyte membrane and the electrons arriving through the external circuit to form water molecules. This reduction half-cell reaction or oxygen reduction reaction (ORR) is represented by:

**At the cathode:**

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

**Overall reaction:**

$$O_2 + 2H_2 \rightarrow 2H_2O + HEAT + ELECTRICITY \quad (3)$$

The reversible reaction is expressed in the equation and shows the reincorporation of the hydrogen protons and electrons together with the oxygen molecule and the formation of one water molecule.

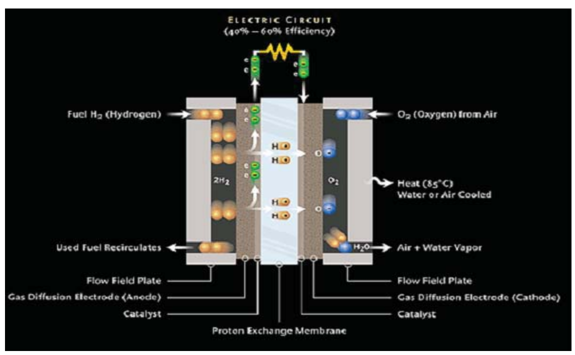


Figure1. Basic operation of PEMFC

### *2.2 Proton exchange membrane*

Proton exchange membrane (PEM) fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. This membrane is small and light, and it works at low temperatures (about 80 degrees C, or about 175 degrees F). Other electrolytes require temperatures as high as 1,000 degrees C.

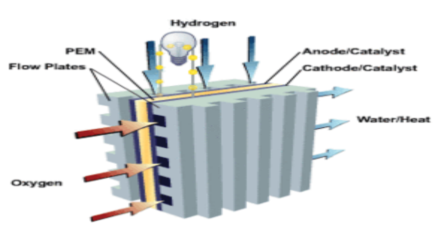


Figure2. Structure of proton exchange membrane

To function, the membrane must conduct hydrogen ions (protons) but not electrons as this would in effect “short circuit” the fuel cell. The membrane must also not allow either gas to pass to the other side of the cell, a problem known as **gas crossover**. Finally, the membrane must be resistant to the reducing environment at the cathode as well as the harsh oxidative environment at the anode. Efficiency for a PEM cell reaches about 40 to 50 percent. An external reformer is required to convert fuels such as methanol or gasoline to hydrogen. Currently, demonstration units of 50 kilowatt (kw) capacity are operating and units producing up to 250 kw are under development.

## III. ELECTROCHEMICAL MODELING OF PEM FUEL CELL

The modeling of the proton exchange membrane fuel cell is based upon the following design equations [1],

$$V_{fc}=E_{nerst}-V_{act}-V_{ohm}-V_{conc} \quad (4)$$

Here $V_{fc}$ represents the fuel cell voltage (V), $E_{nerst}$ represents the Nerst voltage (V), $V_{act}$ represents Actual voltage (V), $V_{ohm}$ represents Ohmic voltage drop (V) and $V_{conc}$ represents Concentration voltage (V). The reversible voltage of the cell, $E_{nerst}$ is calculated from the modified version of the equation [1].

$$E_{nerst}=1.229-0.85*10^{-3}(T-298.15)+4.31*10^{-5}*T[\ln(PH_2)+1/2(\ln(PO_2)] \quad (5)$$

Where T represents the temperature (K), $PH_2$ represents the partial pressure of hydrogen ($N/m^2$) and $PO_2$ represents the partial pressure of the oxygen ($N/m^2$). The activation over potential, $V_{act}$ including anode and cathode can be calculated by the equation [1],

$$V_{act}= -[\xi_1 + \xi_2.T + \xi_3.T.\ \ln(Co_2) + \xi_4 \ln(I_{stack})] \quad (6)$$

Where $I_{stack}$ represents the cell operating current (A) and $\xi_i$'s represent parametric co-efficient for each cell model, whose values are based on equations with kinetic, thermodynamic and electrochemical foundations.
The ohmic loss is given by the equation [1],

$$V_{ohmic}=I_{stack}\,(R_m + R_c) \quad (7)$$

Where Rc represents resistance to the transfer of protons through the membrane. Rm represents resistance of the membrane to the electron flow. The voltage drop due to mass transport can be determined by [1],

$$Vconc=-B.\ln\,(1-J/J_{max}) \quad (8)$$

Where B (V) is a parametric coefficient which depends on the cell and its operation state and represents the actual current density of the cell (A/cm) [4]. The electrochemical model of fuel cell simulated using MATLAB is given below in Fig. 2. The parameters used for the equations are given in TABLE-I.

TABLE-I Mathematical circuit parameters

| Parameters | Values |
|---|---|
| Temperatures( T[K]) | 323 |
| Concentration resistance( $R_c[\Omega]$) | 0.0003 |
| Membrane resistance ($R_m[\Omega]$) | $6.29*10^{-6}$ |
| Current density ($J[A/m^2]$) | 500 |
| Maximum current density ($J_{max}[A/m^2]$ | 1500 |
| Parametric co-efficient (B[V]) | 0.016 |

## IV. INTERLEAVED BOOST CONVERTER

The recent research in the renewable resources proposed a new topology of high efficient boost DC-DC converter with interleaved and cascaded technology for fuel cell applications. This paper deals with the emerging techniques of interleaved boost converter which has been designed and developed with PWM generator. Generally, the output voltage of fuel cell is rather low, while the motors and other recent electrical equipments are driven at higher voltage for acquiring high power at a short period of time. Hence the combination of a fuel cell with an efficient boost DC-

DC converter is required as interface to convert the low DC voltage of the fuel cell into a high voltage. However, when a normal conventional boost converter is interfaced with a fuel cell would possibly introduce current and voltage ripples when operated at higher switching frequencies which can eventually damage the fuel cells. Hence this paper deals on the use of interleaved boost converter (IBC) with PWM based technology which further can reduce the ripple content when compared to IBC operating with pulse generator.

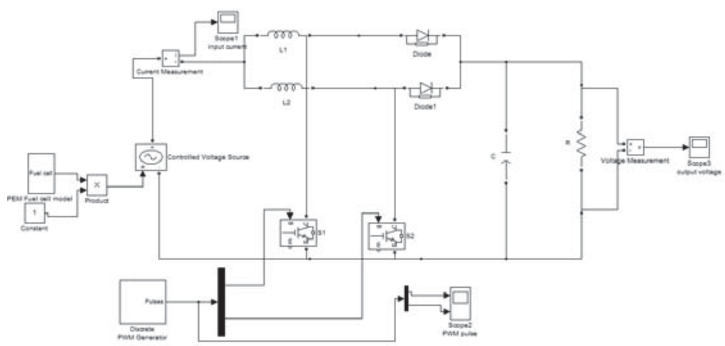


Figure3. Simulink model

## V. DESIGN CONSIDERATIONS OF IBC

The interleaved boost converter design involves the selection of the number of phases, the inductors, the output capacitor, the power switches and the output diodes. In all the channels of an interleaved boost converter design both the inductors and diodes should be identical. In order to select these components, it is necessary to know the duty cycle range and peak currents. Since the output power is channeled through ‘n’ power paths where n is the number of phases, a good starting point is to design the power path components using 1/n times the output power. Basically, the design starts with a single boost converter operating at 1/n times the power.

### *5.1. Choosing the number of phases*

This paper utilizes two phases since the ripple content reduces with increase in the number of phases. If the number of the phases is increased further, without much decrease in the ripple content, the complexity of the circuit increases very much, thereby increasing the cost of implementation. Hence, as a tradeoff between the ripple content and the cost and complexity, number of phases is chosen as two. The number of inductors, switches and diodes are same as the number of phases and switching frequency is same for all the phases [1].

### *5.2. Selection of duty ratio*

Duty ratio is the proportion of time during which a component, devices, or system is operated. The duty ratio can be expressed as a ratio or as percentage. The selection of the duty cycle is based on the number of phases. This is because depending upon the number of phases, the ripple is minimum at a certain duty ratio. For two phase interleaved boost converter, the ripple is minimum at duty ratio, D = 0.45. Hence, the design value of the duty ratio is chosen as 0.45 [7].

### *5.3 Selection of capacitance and inductance*

The selection of capacitance and inductance is calculated using the following formulae [1],

$$C = V_0 DF / R\Delta V_0$$

Where $V_0$ represents the output voltage (V), D represents the duty ratio, F represents frequency (Hz), R represents resistance (Ω) and ΔVo represents the change in the output voltage (V).

$$L = V_S D / \Delta I_L F$$

Where Vs represents the source voltage and $\Delta I_L$ represents the inductor current ripple.

An interleaved boost converter with fuel cell as power source is simulated in MATLAB with the parameters as shown in table-II

TABLE –II IBC design parameters

| Parameters | Value |
|---|---|
| $V_{in}$[V]- Fuel cell source | 26 - 43 |
| L[mH] | 3.3mH |
| C[µF] | 2500µF |
| F[KHz] | 10 |
| Duty ratio | 0.63 |
| Output voltage | 64V |

*5.4* Selection of power devices–

Power diodes are used for lower cut-in voltage, higher reverse leakage current, higher operating frequency. IGBT is used as a switching device since it is a voltage controlled device, having high input impedance. With rise in temperature, the increase in on-state resistance in IGBT is not much pronounced; so on-state voltage drop and losses do not rise rapidly.

## VI. PULSE WIDTH MODULATION

Pulse Width Modulation refers to a method of carrying information on a train of pulses, the information being encoded in the width of the pulses. The pulses have constant amplitude but their duration varies in direct proportion to the amplitude of analog signal.

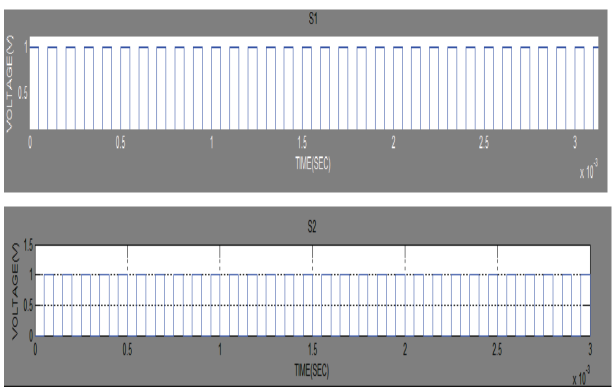


Figure4. PWM pulses for switches

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a commonly used technique for controlling power to inertial electrical devices, made practical by modern electronic power switches. The average value of voltage and current fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher will be the power supplied to the load.

## VII. SIMULATION RESULTS

The input current ripple, and output voltage ripple obtained from PEMFC connected to interleaved boost converter with PWM generator are shown in Figure5, Figure6. The following figure depicts the input current ripple waveform across the controlled voltage source and the converter. When the fuel cell voltage is applied to the converter circuit terminal we obtain the current ripple waveform as shown below.

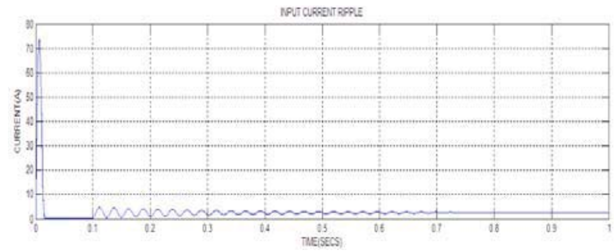

Figure5. Input current ripple waveform

The following figure depicts the output voltage ripple waveform. The input voltage given to the proposed converter is 30.7V and the frequency given is 10 kHz. Maximum output voltage obtained is 64V.

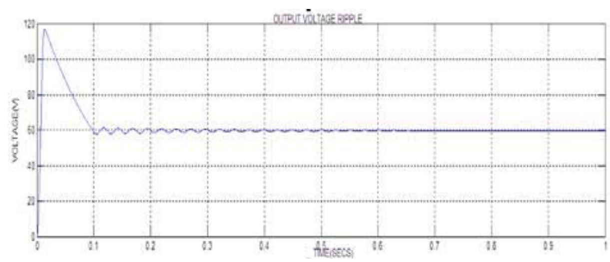

Figure6. Output voltage ripple waveform

The input current ripple, and output voltage ripple obtained from PEMFC connected to interleaved boost converter with pulse generator are shown in Figure7, Figure 8.

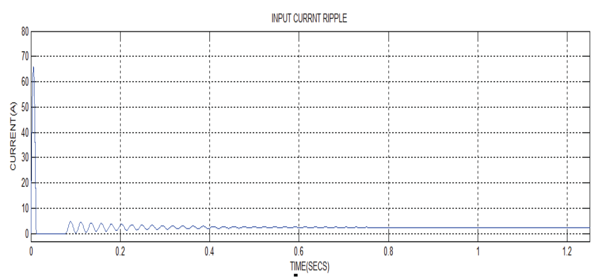


Figure7. Input voltage ripple waveform

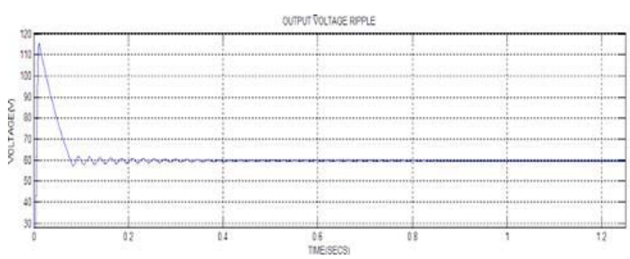


Figure8. Output voltage ripple waveform

The benefit in the ripple cancellation or the reductions in THD are better efficiency, better thermal performance, and high power density. The current ripple reduction can also reduce the input filter capacitor size or prolog the input capacitor life time by reducing the power loss of the capacitor. However by reducing the ripple not only reduces the ripple magnitude but also increases ripple frequency four times the normal boost converter

The total harmonic distortion (THD) is calculated using FFT analysis tool which is provided in simulink model in the form of powergui is shown in Figure9.

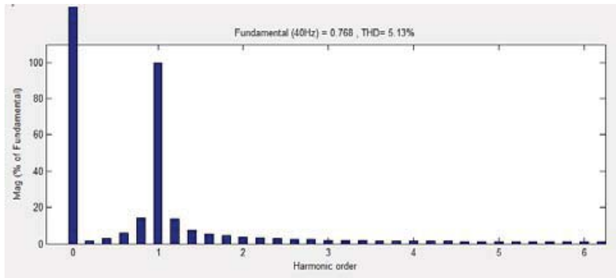


Figure9. FFT Analysis of current ripple

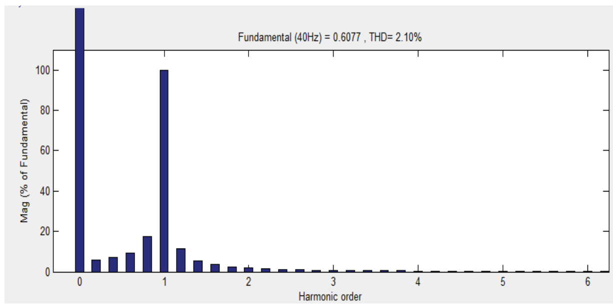


Figure10. FFT Analysis of voltage ripple

Generally the best cases for the THD are from below 10%. Here in this paper comparison of results have been shown for both IBC using PWM generator and IBC using pulse generator which is shown in TABLE-III.

TABLE – III Comparison of results

| PARAMETER | IBC USING PWM GENERATOR | IBC USING PULSE GENERATOR |
|---|---|---|
| Input current ripple (%) | 0.05 | 0.08 |
| Output voltage ripple (%) | 0.02 | 0.07 |

## VIII. CONCLUSION

In this fast moving world, as people are much concerned with the fossil fuel exhaustion and the environmental problems caused by the conventional power generation, renewable energy sources and among them fuel cells are now widely used. PEM fuel cells operate at relatively low temperatures, have high power density, and can vary output quickly to meet shifts in power demand. As power densities continue to rise, interleaved boost designs become a powerful tool to keep input currents manageable and increase efficiency, while still maintaining good power density. With mandates on energy savings more common, interleaved construction may be the only way to achieve design objectives. The simulation of the module layout was successfully carried out using MATLAB simulink software and the obtained waveforms were observed.The output responses of the interleaved boost converter are analyzed. Firstly, the PEM fuel cell was modeled using MATLAB. The interleaved boost converter using PWM generator was designed and interfaced with the PEM fuel cell. The input current ripple and output voltage ripple values were found out and compared with the result of an interleaved boost converter using normal pulse generator and concluded that an interleaved boost converter using PWM generator is a better option for PEM fuel cell as the ripple content is lesser.

## REFERENCES


[1] Harinee M., Nagarajan V.S., Seyezhai R. and Mathur B.L. “Modeling and Design of Fuel Cell Based Two Phase Interleaved Boost Converter” International Conference on Electrical Energy Systems, pp.72-77, 2011.

[2] Beer C. D., Barendse P. and Khan M. A. “Development of a HT PEM Fuel Cell Emulator Using a Multiphase Interleaved DC-DC Converter Topology" IEEE Transactions on Power Electronics, vol.28, Issue 3, pp.1120-1131, 2011.

[3] Changrong Liu and Jih-Sheng Lai “Low Frequency Current Ripple Reduction Technique With Active Control in a Fuel Cell Power System With Inverter Load” IEEE Transactions on Power Electronics, vol. 22, Issue 4, pp.1429-1436, 2007.

[4] Dong-Jing Lee and Li Wang “*Dynamic* and Steady-State Performance of PEM Fuel Cells under Various Loading Conditions” Power Engineering Society General Meeting, pp.1-8, 2007.

[5] Jia J., Li Q., Y.Wang., Cham Y.T. and Han M. “Modeling and Dynamic Characteristic Simulation of a Proton Exchange Membrane Fuel Cell” IEEE Transactions on Energy Conversion, vol. 24, Issue 1, pp.283-291, 2009.

[6] Sandip Pasricha and Steven Shaw R. “Dynamic PEM Fuel Cell Model” IEEE Transactions on Energy Conversion, vol. 21, Issue 2, pp.484-49, 2006.

[7] Seyezhai R. “Design Consideration of Interleaved Boost Converter for Fuel Cell Systems" (IJAEST) International Journal of Advanced Engineering Sciences and Technologies, Vol. 7, Issue 2, pp. 323 – 329, 2011.

[8] Shih-Jen Cheng, Yu-Kang Lo and Huang-Jen Chiu “ High efficiency digital Controlled interleaved power converter for high power PEM fuel cell applications” IEEE Transactions on Industrial Electronics, vol.60, Issue 3, pp.194-002, 2011.