Design and Modelling of PWM Based Interleaved Boost Converter for PEMFC(Proton Exchange Membrane Fuel Cell)

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Abstract**—** Fuel cells are a family of technologies that generate electricity through electrochemical process rather than combustion. Fuel cell is 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. Proton Exchange Membrane fuel cell (PEMFC) is one of the promising technologies for the distributed power generation. For designing high efficiency fuel cell power systems, a suitable DC-DC converter is required. Interleaved boost converter (IBC) is a better solution for fuel cell systems, due to improved electrical performance, reduced weight and size. Due to low temperature and use of precious metal based electrodes PEMFC cell must operate on pure hydrogen. In this paper, the electrochemical modelling of a Proton Exchange Membrane Fuel Cell (PEMFC) has been carried out. The type of the conversion structure is a boost, increasing the voltage delivered by the fuel cell and controlled by a PWM signal. After modelling the converter, it is connected to the fuel cell.

Keywords**—** *PEMFC* **(***Proton Exchange Membrane Fuel Cell), Modelling, IBC (Interleaved Boost Converter).*

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I. INTRODUCTION

Fuel cells are electro chemical devices that convert the chemical energy of a fuel directly to usable energy -electricity and heat - without combustion. This is quite different from most electric generating devices (e.g. steam turbines, gas turbines, and combustion engines) which first convert the chemical energy of a fuel cell to thermal energy, then to mechanical energy and finally to electricity.

PEMFC is a nonlinear, multiple-input and -output, strongly coupled, and large-delay dynamic system that convert chemical potential into electric power.

In past decades, fuel cells with many reasons such as excellent reliability, high efficiency, high power density, low operating temperature and their low emissions to the environment [1].

PEM fuel cell is one of the promising technologies for the distributed power generation [7]. Model is directly implemented under MATLAB/Simulink and connected to the static converter model which is regulated in voltage [2].This paper presents MATLAB/Simulink to design a PEMFC model and to study its performance. PEMFC model is based on BALLARD MARK V fuel cell parameters [3].

This paper uses for a relatively simple, physically motivated, dynamic electrical terminal model of a proton exchange membrane fuel cell [6].

A boost converter converts a lower DC voltage to a higher DC voltage. It can however inject current harmonics into the fuel cell which might otherwise damage the durability of the fuel cell. Therefore an interleaved boost converter was investigated to reduce current harmonics. Interleaved power converter topologies have received increasing attention in recent years for high power and high performance aerospace application. The advantages of interleaved boost converters are increased efficiency, reduced size, reduced electromagnetic emission, faster transient response and improved reliability.

II. BASIC OF PEM FUEL CELL

The PEMFC technology has many advantages as compared to other technologies, there are also some disadvantages of PEMFC technology such as high maintenance cost and high price per unit have made this technology difficult to commercialize. However, efforts are being made in order to produce low cost and high performance of fuel cells.

Generally, a PEMFC consists of a gas flow channel, an anode electrode, a catalyst, a polymer electrolyte membrane and a cathode electrode. The gas in the gas flow channel to the anode electrode is fuel gas which is pure hydrogen and the gas in the flow channel to the cathode electrode is air or oxygen gas. The anode and cathode electrode must be wet and having a porous electrode structure. This structure is necessary since it helps the reactant gases to dissolve inside the electrode. Therefore, it can increase the performance of fuel cell. The catalyst layers that exist between electrode polymer membranes are thin platinum plates. These catalyst layers are used to help the hydrogen element to split into proton and electron and to prevent the hydrogen and oxygen reacted directly through the membrane. At the cathode electrode, the reaction between hydrogen and oxygen is occurred. This reaction produces water and heat as by products[3].
The chemical reaction is shown below:

$$\text{Anode reaction: } H_2 \rightarrow 2H^+ + 2e^- \qquad (1)$$

Cathode reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O + Heat$ (2)

Overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Heat$ (3)

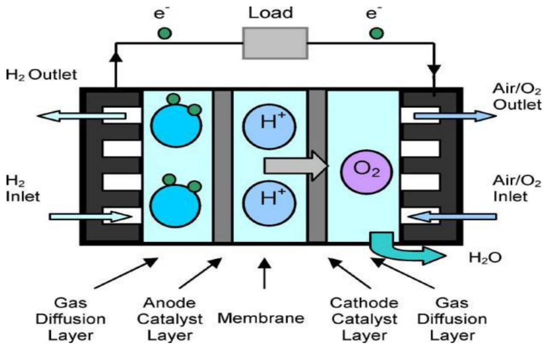

Figure 1. Basic Operation of PEMFC [1]

The chemical process inside PEMFC is explained below [3]:

1. Hydrogen molecules enter the anode.
2. Hydrogen elements react with the catalyst and split into protons and electrons.
3. The electrolytes allow the protons to pass through to the cathode.
4. The electrons are directed to external circuit to create electrical current.
5. Oxygen molecules enter the cathode.
6. Oxygen and protons will combine with electrons producing water and heat.

III. PEMFC PERFORMANCE

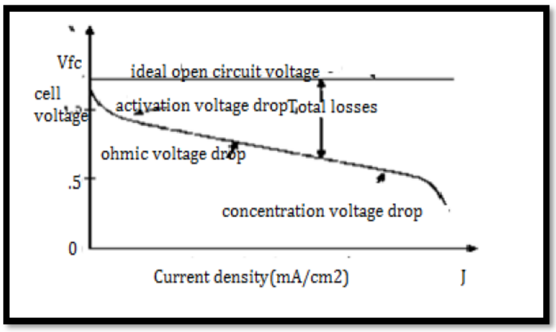

Figure 2. Voltage- Current Curve [3]

Figure 2. indicates the characteristic of voltage produced by a single cell of PEMFC against current density J . The ideal open-circuit voltage is the potential difference between anode and cathode. When there is no current flowing through the external circuit [3].

Theoretically, the ideal open-circuit voltage is defined as Nernst potential or E_{nernst} reversible voltage of cell. When the current flowing through the external circuit there are three voltage drops involved in fuel cell's output voltage. It is known as activation voltage drop, ohmic voltage drop and concentration voltage drop. The relation between the ideal open-circuit voltage and the voltage losses is describe as below [3]:

$$V = E_{nernst} - V_{act} - V_{con} - V_{ohm} \quad (4)$$

Where, V is the output voltage produced by a single cell, E_{nernst} is the reversible voltage between anode and cathode, V_{act} is the activation voltage drop ,V_{ohm} is the ohmic voltage drop and V_{con} is the concentration voltage drop.

A. *The Reversible Potential, E_{nernst} :*

The open circuit voltage (E) is calculated from the energy balance between the products, reactants and Faraday's Constant is given by the Nernst equation:

$$E_{nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F} \times (\ln PH_2 + 0.5\ln PO_2) \quad (5)$$

Where, ΔG is variation of Gibbs energy, F is Faraday's constant, ΔS is the entropy variation. R is the gases universal constant, PH_2 and PO_2 are respectively, partial pressure of hydrogen and oxygen, T and Tref are respectively the working and reference temperature of the cell .

Further this equation can be modified as:

$$E_{nernst} = 1.229 - 0.85 \times 10^{-4}(T - 298.15) + 4.308 \times 10{-}5T\ln PH2{+}0.5\ln PO2 \quad (6)$$

The partial pressure of hydrogen and Oxygen is given by:

$$PH_2 = 0.5P^{sat}H_2O[\exp\left(-\frac{\frac{1.635I}{A}}{T^{1.334}}\right)\frac{P_a}{P^{sat}\,H_2O} - 1] \quad (7)$$

$$PO_2 = P^{sat}H_2O[\exp\left(-\frac{\frac{4.192I}{A}}{T^{1.334}}\right)\frac{P_C}{P^{sat}\,H_2O} - 1] \quad (8)$$

Where, $P^{sat}\ H_2O$ is the saturated vapour pressure at absolute temperature, P_C is the partial pressure of cathode and Pa is the partial pressure of anode. The saturated vapour pressure P^{sat} H_2O is the function of the operating temperature of the PEMFC and it is defined as:

$$\log 10P^{sat}H_2O = -2.18 + 2.95 \times 10^{-2}T_C - 9.18 \times 10^{-5} + T_C^2 + 1.44 \times 10^{-7}T_C^3 \quad (9)$$

Where,

T_C = T-273.15

T is the absolute temperature.

B. *The Activation Voltage Drop, Vact:*

The activation over potential is increases with increase in current density and can be expressed as shown below:

$$V_{act} = -0.9514 + 3.12 \times 10^{-3}T - 1.87 \times 10^{-4}T\ln I + 7.4 \times 10^{-5}T\ln Co_2 \quad (10)$$

Where, T is the absolute temperature (K), C_{O2} is the concentration of Oxygen on the catalyst surface, I is the fuel cell current (Amp). The concentration of Oxygen is obtained by Henry's Law and is measured in mol/Liter.

$$C_{O2} = \frac{P_{o2}}{5.08\times10^6}\exp(-\frac{498}{T}) \quad (11)$$

C. *The Ohmic Voltage Drop,Vohm:*

The Ohmic voltage drop is mainly due to the electronic losses between the bipolar plates, cooling plates, contact plates and ionic charge losses occur in the membrane. When hydrogen ions travel through the electrolyte. The voltage loss due to electron transport in the fuel cell is ignored because it contributes little overall fuel cell polarization (the number of charge carriers in an electronic conductor is much higher than an ionic conductor).

The Ohmic voltage loss is calculated by:

$$V_{ohm} = -IR_{int} \tag{12}$$

Where,

$$R_{int} = 1.605 \times 10^{-2} - 3.5 \times 10^{-5}T + 8 \times 10^{-5}I$$

D. *Concentration voltage drop, Vcon:*

The concentration voltage drop is caused by limited mass transport of reactants to the electrode. Mass transport in fuel cell is mainly divided into convection transport in channels and diffusive transport in electrodes. The fuel cell is producing current, the electrochemical reactions lead to depletion of reactants and accumulation of products at the catalyst layer. The concentration voltage drop in the fuel cell is defined as follows:

$$V_{con} = \frac{RT}{ZF}\ln\frac{C_S}{C_B} \tag{13}$$

Where, C_S is the surface concentration at the reaction sites, C_B is the bulk concentration in gas channels and z is the number of participating electrons. According to Flick's first law and Faraday's law, the above equation can be rewritten as follow:

$$V_{con} = B\ln(1 - \frac{I}{I_{lim}}) \tag{14}$$

Where, I_{lim} is the limit current of fuel cell and B is the parametric coefficient and its value depends on cell and its operation state.

E. *Dynamic response :*

The dynamic response in fuel cell's performance is due to the double-layer charging effect. The existence of two different surface charge layers at both electrodes and the electrolyte which acts for storage of electrical charge affect the activation and concentration voltage drop. This situation can be considered as capacitive effect. The dynamic response relationship can be obtained as:

$$\frac{dV_{act}}{dt} = \frac{I}{C} - \frac{V_{act}}{R_a * C} \tag{15}$$

Where,

$$R_{act} = \frac{V_{act\,0} + Vcon}{I}$$

Where, Vacto is the steady state activation loss.

F. *Thermodynamic response:*

The operating temperature of fuel cell is to calculate the reactant gas diffusion, the Nernst equation and all the voltage drops. The operating temperature is directly proportional to the cell current. The differential equation of transient temperature is given as:

$$C_t\frac{dT}{dt} = I(E - V_{cell}) \tag{16}$$

Where, C_t is the thermal capacitance of all the volume or mass of fuel cell, J/K. and H is total heat transfer coefficient of fuel cell, W/K.

IV. INTERLEAVED BOOST CONVERTER

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. All the channels of an interleaved boost converter design include both the inductors and diodes should be identical [7]. In order to select these components, it is necessary to know the duty cycle range and peak currents.

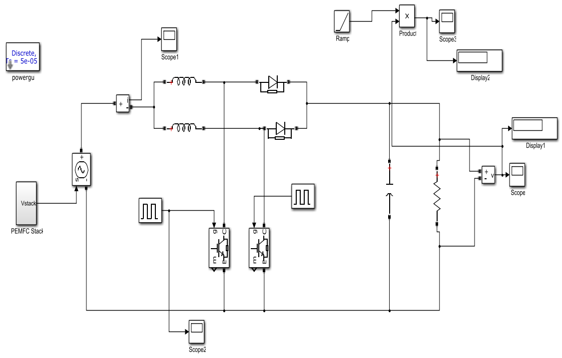

Figure 3. Simulink Model

1. *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 a percentage. The selection of the duty cycle is based on the number of phases. This is 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. The design value of the duty ratio is chosen as 0.45[7].

2. *Selection of Capacitance and Inductance:*

The Selection of Capacitance and Inductance is calculated using the following formula [7]:

$$C = V_0 DF/R\Delta V_0 \tag{17}$$

Where, V_0 represents the output voltage (V), D represents the duty ratio, F represents frequency (Hz), R represents resistance and ΔV_0 represents the change in the output voltage.

$$L = V_S D / \Delta I_L F \tag{18}$$

Where, Vs is the source voltage and ΔI_L is the inductor current ripple.

3. Selection of Power Device:

Power diodes are used for lower cut-in voltage, higher reverse leakage current and higher operating frequency. IGBT is used as a switching device. It is a voltage controlled device, having high input impedance [1]. 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.

4. 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. 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.

V. SIMULATION AND RESULTS

Here PEMFC stack is connected to interleaved boost converter for increasing the fuel cell output voltage and boost converter increases the output voltage from 25V to 65V.

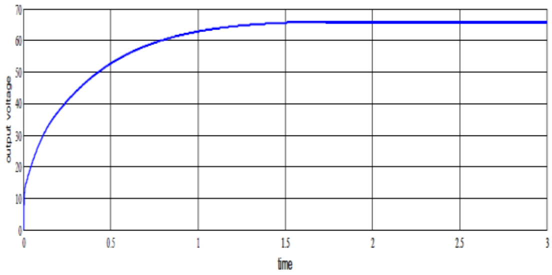

Figure 4. Output Voltage of Interleaved Boost Converter

Here is the mathematical modelling of PEMFC is simulated using Nernst equation, Ohmic and concentration voltage drops. The equations are derived in section III.

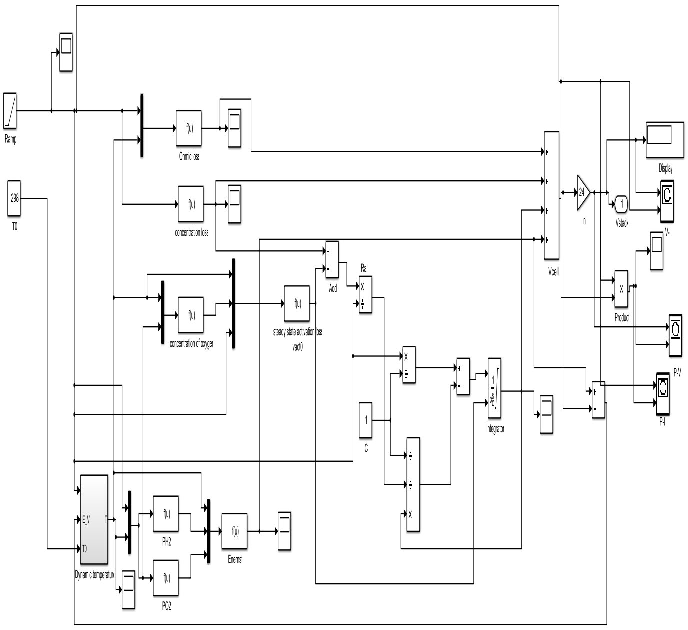

Figure 5. Simulink Block Diagram of PEMFC

Thermodynamic model of the PEMFC is simulated using below equation. The operating temperature is calculated using Nernst equation, and all the voltage drops.

$$C_t \frac{dT}{dt} = I(E - V_{cell}) - H(T - T_f) \tag{19}$$

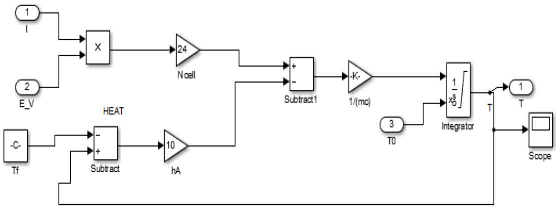

Figure 6. Thermodynamic model Subsystem

Graphical Results:

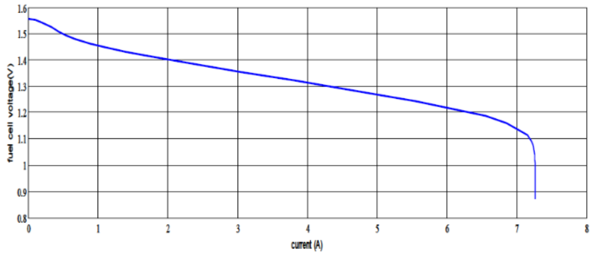

Figure 7.Voltage-Current Curve

Above figure 7. Indicates the Voltage-Current curve of PEM fuel cell , the voltage current graph characteristics are based on Ballard- mark- V parameters. From above curve we observed three losses first activation losses after that ohmic losses and after that concentration losses.

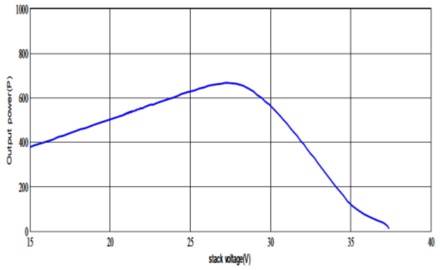

Figure 8. Power -Voltage Curve

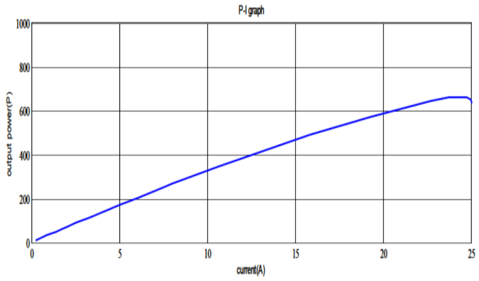

Figure 9.Power-Current Curve

From Figure 9.it is observed that power is increased gradually to the maximum power point. The maximum power produced by the PEM fuel cell is 680W when the current is 24A.

VI. CONCLUSION

This paper represents PWM based interleaved boost converter for PEMFC. The simulation of PEMFC stack is done using equation of Nernst voltage, ohmic activation losses and concentration losses. Interleaved Boost Converter is used for increasing the fuel cell stack voltage from 25V to 65V and less ripple in output voltage.

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APPENDIX

TABLE-I

Vin(V)	25-43
L(mH)	3.3mH
C(µF)	2500 µF
F(Hz)	10
Duty ratio	0.63
o/p Voltage	65

TABLE-II

Symbol	**Parameters**	**Value**	**Unit**
R	Gas Constant	8.3143	J/mol
∆G	Gibbs free Energy	237.1	KJ/mol
F	Faraday’s Constant	96,485	J
P_a	Pressure of Anode	1	Atm
P_c	Pressure of Cathode	1	Atm
T	Absolute Temperature	298.16	K
T_{ref}	Reference Temperature	273.15	K
A	Fuel cell active Area	54	Cm^2
B	Parametric Coefficient	0.016	V
I_{limit}	Limit Current	25.1	A
N	Number of cells	24	-
C	Double layer Capacitance	1	F
H	Total heat Transfer Coefficient	10	W/K