PEM-Proton Exchange Membrane Fuel Cell Emulator Based on Buck Converter

Bhatt Devangi Janakbhai, Hardik P. Desai
Department of Electrical Engineering, SCET college, Surat, India.

ABSTRACT:
PEMFC (proton Exchange Membrane Fuel Cell) seem to be a good solution because of their high power density, solid electrolyte, low corrosion and low temperature. Feature of this mathematical model is integration of all possible dynamic equations like dynamics of the charge equations, dynamics of the molar flow of hydrogen and oxygen pressure, temperature, stack current etc. The V-I characteristic of PEMFC is obtained for this dynamic model. This paper discusses a possible solution to emulate a PEMFC system by using a DC-DC buck converter. The emulator can easily applied to other fuel cell systems if the polarization curve has the same current rate and maximum power. In this way it is possible to utilize the converter and perform the necessary tests to optimize a fuel cell system by avoiding the waste of hydrogen and the purchases of cells as well as any cell damage. A mathematical model of 1.1KW proton exchange membrane fuel cell (PEMFC) is developed and FC emulator using buck converter is emulated for 500W.

Keywords: PEM Fuel Cell, Mathematical modelling, emulator, DC-DC converter, Buck converter.

I. INTRODUCTION
Increased awareness over increasing environment pollution, depleting fossil fuel reserves and the ongoing energy critical situation have led to tremendous research efforts on renewable and nonconventional energy source. With current high gas price and elevated level of air pollution, Fuel cell system (FCS) of PEMFC (proton Exchange Membrane Fuel Cell) seem to be a good solution for ground vehicle application, because of their high power density, solid electrolyte, low corrosion and low temperature. For emulator to work properly, a fuel cell stack needs several auxiliary components namely the hydrogen supply system for the anode, the air management system for the cathode, the cooling system, the humidifier system. All of the components in these auxiliary subsystems should be analyzed, designed and optimized to improve the FCS performance, so that not only FC stack output can be improved but also that the strong nonlinear interactions among the different auxiliaries can be optimized.[1]

All these issues make the control of FCS quite a complex task, especially for the experimentation part. With this regard the present price of FC stacks, the cost of the hydrogen and the fact that the life of a fuel cell stack is determined by the number of hours of use and off/on cycles limit their employment in experimentation. Moreover the size of the auxiliary equipment can have too great a size according to the size of the FC and this can result in too high associated costs and space. Therefore, a solution that can be used for developing experimentation without the need of a real FCS would be important for the first stage of experimentation. All these considerations suggest that the FC stack should be replaced by a hardware system capable of copying its behavior accurately. This hardware system is called “emulator”. This emulator permits then the real FC stacks to be replaced resulting in the possibility of studying and setting up the rest of the FCS. Once the system has been globally analyzed and verified then the emulator can be replaced by the real FC stack. As a consequence all the risks of damage are decreased, along with the limited use of the FC stack and the reduction of hydrogen consumption.

II. SYSTEM DESCRIPTION
To build a fuel cell emulator is necessary to obtain an accurate model of FC system. Many mathematical models for PEM-FC have described in the literature [2-4]. Figure 1 show the block diagram of the FCS emulator. The dynamic model block of the entire FCS systems with its auxiliaries [5-7] are modeled in Matlab. The two inputs of the model are the stack temperature T and the electrical load current required by the load I_{FC}. The output is V_{ref} the reference value of the stack voltage. The controller which process the signal V_{ref} and V_c and gives the corrected value of the duty cycle δ to the DC-DC converter in order to have chopper voltage V_c track the model fuel cell V_{ref}. The 500 Watt DC-DC buck converter is chosen to work in continuous-current conduction mode with low output voltage ripples.
III. THEORY OF PEMFC

A fuel cell is an electrochemical device that converts chemical energy of a reaction directly into the electrical energy. It has two one positive and one negative porous carbon electrodes called anode and cathode respectively, separated by a polymer electrolyte membrane. Fuel Cell (FC) produces electricity, water and heat from an electrochemical reaction between hydrogen and oxygen [2]. 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.

Figure 2 shows Structure of a PEMFC. A fuel cell is provided with a simultaneous supply of the hydrogen in form of molecules \( H_2 \) on the anode side and oxygen in form of molecules \( O_2 \) or air on the cathode side. The contact of \( H_2 \) hydrogen molecules with the (pt) platinum catalyst induces reaction on the surface of proton membrane, whereas the hydrogen molecules decompose to \( H^+ \) protons and \( e^- \) electrons. The electrons are subject to the external electric load and they are received by the oxygen atoms on the cathode side to form the \( O^{2-} \) ion, which has been formed upon degradation of the \( O_2 \) molecules using (pt) platinum catalyst. PEM type fuel cell provide for the chemical reaction listed below: [3]

\[
\begin{align*}
\text{Anode} & : 2H_2 \rightarrow 4H^+ + 4e^- \\
\text{Cathode} & : O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \\
\text{Overall} & : 2H_2 + O_2 \rightarrow 2H_2O
\end{align*}
\]

A. Polarisation curve of a PEM Fuel Cell (volt-ampere characteristic)

In the ideal situation theoretically the electric output voltage of a fuel cell would determine of 1.187 V under any operating current. The fuel cells actually achieve their highest output voltage during off-load periods. The cell voltage will decrease with the increasing current passing through. This phenomenon is generally known as the “cell polarisation” and it is represented by the Polarisation curve (the Volt-Ampere characteristics) shown in the Figure 3. The magnitude of current depends on the volume of electric load connected to a fuel cell [2]. Polarisation is caused by chemical and physical agents produced due to various characteristics of a fuel cell. These agents limit the process of reaction with the flow of current through the cell.

There are three basic fields of action affecting the overall polarisation: [2]

- Activation polarisation
- Ohmic polarisation (resistance polarisation)
- Concentration polarization

The deviation of fuel cell voltage from the ideal voltage level is the direct consequence of action of all these factors together.
IV. MATHEMATICAL MODEL OF PEMFC

A. Dynamic Model of PEMFC

The actual voltage of the PEM fuel cell is lower than the theoretical voltage due to various irreversible loss mechanisms, which are often called over-voltage or losses.

These losses are:
- Activation over-voltage ($E_{act}$), which arises from the kinetics of charge transfer reaction.
- Concentration over-voltage ($E_{conc}$), which arises from the limited rate of mass transfer.
- Resistive or ohmic over-voltage ($E_{ohm}$), which arises from component resistances.

The output voltage of the single cell is given by equation (1) according to the PEMFC output characteristics empirical equation [4].

$$V_{cell} = E_{nernst} - E_{act} - E_{conc} - E_{ohm} \quad (1)$$

Where $V_{cell}$ is the fuel cell output voltage, $E_{nernst}$ open circuit voltage, $E_{act}$, $E_{conc}$, $E_{ohm}$ are the activation, concentration and the ohmic fuel cell overvoltage respectively.

$E_{nernst}$ is the electrochemical thermodynamic potential of the cell and it represents its reversible voltage, which is an ideal output voltage. Using the standard pressure and temperature (SPT) values, the Nernst equation-(2) for the hydrogen/oxygen fuel cell for the above reaction is [4]:

$$E_{nernst} = \frac{\Delta G}{nF} + \frac{\Delta s}{nF}(T - T_{ref}) + \frac{RT}{2F} \ln \left( \sqrt{P_{O2}P_{H2}} \right) \quad (2)$$

Where, $\Delta G$ is Gibbs free energy change $\Delta s$ is Standard mole entropy change, $T$ is Temperature in Kelvin, $T_{ref}$ is Reference temperature, $R$ is Gaseous constant, $P_{O2}$ is Effective partial pressure of oxygen, $P_{H2}$ is Effective partial pressure of hydrogen, $n$ is Number of atom, F is Faraday constant.

The activation loss in equation-(3) is related with the battery energy, which must be exceeded to trigger the chemical reaction between reactants. The speed of electrons is low at a low current and some of the electrons are lost due to the need for compensation of lacking electro-catalytic operation. Where, $I_{FC}$ : Fuel cell current

$$V_{act} = a_1 + a_2T + a_3T \ln(C_{O2}) + a_4T \ln(I_{FC}) \quad (3)$$

Concentration of $O_2 - C_{O2}$ can be evaluated from Henry’s law in equation-(4).

$$\text{Concentration of } O_2 - C_{O2} = \frac{P_{O2}}{5.08 \times 10^6 e^{(-0.08/T)}} \quad (4)$$

Ohmic loss occurs due to resistance losses within a cell. $V$-ohmic is consists of voltage drop that is caused by $R_M$ Equivalent membrane resistance & $R_c$ the contact resistance between membrane & electrode, electrodes & bipolar plates. Lambda is water content at membrane, which is an adjustable Parameter & a function of the relative humidity on the gas in anode.14 to 23 range. The ohmic losses can be formulated using equation-(5) [4]:

$$V_{ohm} = I_{FC}(R_M + R_C) \quad (5)$$

The concentration losses occur at the moment, when the electrode reactions are inhibited due to the effect of mass transmitted. This field is associated consumption of reactants exceeding their possible supply, while the reaction product water accumulates faster that it can be discharged. These effects result in moderation of further reaction and the cell voltage is decreasing towards zero level. At high current density, the concentration of hydrogen & oxygen affected.
\[ V_{\text{conc}} = B \ln \left( 1 - \frac{J}{J_{\text{max}}} \right) \]  
(6)

In equation-(6) B is parametric co-efficient in volts depending on cell & its operating state, \( J \) is actual current density and \( J_{\text{max}} \) is current density

In a PEM fuel cell, the two electrodes are separated by a solid membrane which only allows the \( H^+ \) ions to pass, but prevents the motion of electrons. The electrons at the anode will flow through the external load and comes to the surface of the cathode, to which the protons of hydrogen will attracted at the same time. Thus, two charged layers of opposite polarity are formed across the boundary between the porous cathode and the membrane [4-5]. Circuit model of fuel cell by considering all the effect discussed above is shown in Figure 4, where the resistances are the equivalent resistance for different types of fuel cell losses. This loss is due to the double layer capacitance and can be described by the equation-(7) [5-7];

\[ V_{\text{dynamic}} = \int \frac{V_{\text{FC}}}{C} \frac{dV_{\text{dynamic}}}{\tau} \]  
(7)

Where, \( V_{\text{dynamic}} \) represents the dynamic voltage across the equivalent capacitor (associated with \( V_{\text{act}} \) and \( V_{\text{conc}} \)), \( C \) is the equivalent electrical capacitance and \( \tau \) is the fuel cell electrical time constant dependant of the cell temperature given by the equation-(8):

\[ \tau = \frac{C(V_{\text{act}} + V_{\text{conc}})}{I_{\text{FC}} - I_{\text{C}}} \]  
(8)

Figure 4 Equivalent electrical circuit of PEM fuel cell [4]

Including this electrical dynamic behavior term, The equation-(9) the resulting FC voltage is then define by,

\[ V_{\text{cell}} = E_{\text{nernst}} - V_{\text{ohm}} - V_{\text{dynamic}} \]  
(9)

This effect is incorporated in the output voltage of the PEM fuel cell. If the stack is fabricated in series by \( N \) identical single cells, the output voltage of the stack is

\[ V_{\text{stack}} = NV_{\text{cell}} \]  
(10)

B. Model of the stack with molar flow gas and its partial pressure

The Time constant, FC current and number of cells in each module affect on oxygen and hydrogen pressure. The relationship between the molar flow of any gas (hydrogen and oxygen) through the valve and its partial pressure inside the channel can be expressed as [8];

\[ \frac{dP_{H_2}}{dt} = \frac{RT}{V_{\text{an}}} (Q_{H_2}^{\text{in}} - Q_{H_2}^{\text{out}} - Q_{H_2}^r) \]  
(11)

Where, \( R \) is the universal gas constant (atm\( K \)\( \text{mol} \)); \( T \) is the absolute temperature (K); \( V_{\text{an}} \) is the volume of the anode; \( P_{H_2} \) hydrogen partial pressure (atm); \( Q_{H_2}^{\text{in}} \) is the hydrogen input flow(\( \text{kmol/s} \)); \( Q_{H_2}^r \) is the hydrogen flow that reacts inside the stack(\( \text{kmol/s} \)) and \( Q_{H_2}^{\text{out}} \) is the hydrogen output flow(\( \text{kmol/s} \)).

In a small size PEM fuel cell power modules \( Q_{H_2}^{\text{out}} \) can be set to zero, because the channel of the anode is usually a dead-end. According to the fundamental electrochemical relationship, the reacting hydrogen flow can be calculated as:

\[ Q_{H_2}^r = \frac{N_{\text{cells}}}{2F} = 2K_rI_{\text{FC}} \quad \text{and} \quad K_r = \frac{b}{4F} \]  
(12)

In equation-(12) \( F \) is Faraday’s constant (C/Kmol); \( K_r \) is the modeling constant (mol/S A) and \( N \) is the number of the cells connected in series in the stack. By isolating the hydrogen partial pressure and then taking the Laplace transform, the dynamic characteristics of the fuel cell can be written using equation-(13) to equation-(15).

\[ P_{H_2} = \frac{1/K_rH_2}{(1+\tau_{H_2})} \times \left( Q_{H_2}^{\text{in}} - 2K_rI_{\text{FC}} \right) \]  
(13)
\[ \tau_{H_2} = \frac{V_{an}}{R \times T \times K_{H_2}} \]  

(14)

\[ q_{in}^{H_2} = \frac{2K_r}{U_{opt}} \left( \frac{1}{1+\tau_f} \right) \]  

(15)

Where, \( K_{H_2} \) is the hydrogen valve molar constant (kmol/s.atm); \( \tau_{H_2} \) is the response time for hydrogen (s). Similarly, a specific relation can be derived between the partial pressure and the input flow rate of the fuel.

V. FUEL CELL EMULATOR

A FC emulator is power electronics converter that can be reproduce the desired output characteristics of the environment condition. A FC emulator is a DC-DC converter that follows the response of real FCS independent factor like temperature and fuel cell current for testing FC system equipment.

The main elements of PEMFC emulator are:

- Dynamic model block of the entire FC system with two inputs of the model are stack temperature (T) and the electric current required by the load \( I_{fc} \). The output is \( V_{ref} \) the reference value of the stack voltage.
- DC-DC buck converter.
- The Proportional and Integral (PI) controller which process the signals \( V_{ref} \) and \( V_C \) and gives the corrected value of the duty cycle to the DC-DC converter in order to have the voltage \( V_C \) chopper track the model fuel cell \( V_{ref} \).

VI. SIMULATION AND RESULTS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta G ) - Gibbs free energy Change</td>
<td>237180 J/mol</td>
<td>lenda-water content at membrane</td>
<td>20</td>
</tr>
<tr>
<td>( \Delta s ) - entropy change</td>
<td>-163.15 mol K</td>
<td>alpha1</td>
<td>-0.9514</td>
</tr>
<tr>
<td>n - No. of element</td>
<td>2</td>
<td>alpha2</td>
<td>0.00312</td>
</tr>
<tr>
<td>F - faraday constant</td>
<td>96486.7 c/mol</td>
<td>alpha3</td>
<td>7.4e-5</td>
</tr>
<tr>
<td>Tref</td>
<td>298.15 K</td>
<td>alpha4</td>
<td>-1.87e-4</td>
</tr>
<tr>
<td>T</td>
<td>323 K</td>
<td>L-length of membrane</td>
<td>51e-6 micrometer</td>
</tr>
<tr>
<td>R - ideal gas constant</td>
<td>8.314 J/mol k</td>
<td>A-area</td>
<td>150 cm2</td>
</tr>
<tr>
<td>PO2-pressure of O2</td>
<td>0.5 atm</td>
<td>Rp-resistance of proton</td>
<td>3e-4 ohm</td>
</tr>
<tr>
<td>pH2-pressure of H2</td>
<td>0.5 atm</td>
<td>Jfc_max</td>
<td>1.5 A/cm2</td>
</tr>
<tr>
<td>B - parametric co-efficient</td>
<td>0.016 v</td>
<td>N-No. of cell</td>
<td>20</td>
</tr>
<tr>
<td>KH2-hydrogen valve molar constant</td>
<td>4.22e-5 kmol/s.atm</td>
<td>Kr-parameter modeling Constant</td>
<td>1.0364e-5 kmol/s.A</td>
</tr>
<tr>
<td>KO2-oxygen valve molar Constant</td>
<td>2.11e-5 kmol/s.atm</td>
<td>Tau-O2- response time of Oxygen</td>
<td>6.74 s</td>
</tr>
<tr>
<td>tau-H2- response time of hydrogen</td>
<td>3.37s</td>
<td>tau-f- response time of fuel</td>
<td>0.8 s</td>
</tr>
<tr>
<td>Uopt</td>
<td>85</td>
<td>rH2O</td>
<td>1.168</td>
</tr>
</tbody>
</table>

Comparison between Dynamic Model & PEMFC system model with relationship between the molar flow of gas and its partial pressure

Using the equation (1) – (15) and the data in Table 1, the stack is composed of 20 unit cells and have a membrane active area of 150cm². Hydrogen and air are supplied at the same pressure 0.5 atm. For this test, the stack runs at a temperature...
of 25°C. The equivalent capacitor will basically change the stack electrical constant, then it will change the response time. By comparing the two systems as shown in Figure 5, if we change the molar flow of the reactant than the time constant and fuel cell current in each module affect the hydrogen and oxygen pressure. For these we can say that the gas reaction process requires a short time of delay to response. From Figure 5 we see that $E_{\text{ernst}}$ voltage increased from 1.194 to 1.3 V for the changing the supply of the reactant as per require at the load side. The polarization curve presented in Figure 6 was established for the 1.1 KW PEMFC stack. Also the polarization curve is shifted in upward direction. So we can say that we can able to get more output power at the load side.

![Figure 5 Comparison model between Dynamic Model & PEMFC system model with relationship between the molar flow of gas and its partial pressure](image)

![Figure 6 Comparison between Dynamic Model & PEMFC system model with relationship between the molar flow of gas and its partial pressure](image)

**Buck Converter**

Figure 7 shows the electrical scheme of Buck converter, where the value of parasitic resistance $r_L$ and $r_C$ are 0.509 and 1.2 ohm respectively. The switching frequency is 10 kHz. The value of inductor and capacitor are $10e^{-3}$H and $5000e^{-6}$ F.
respectively. The supply voltage is 55 V. Figure 8 and figure 9 show the V-I characteristic and P-I characteristic produced by the buck converter is similar to the FCS.

**Figure 7 Electric scheme of Buck converter**

**Figure 8 Voltage - Current of Buck converter**

**Figure 9 Power - Current of Buck converter**

**FC Emulator using Buck converter**

The goal of emulator is to reproduce the FCS model by considering the variation of the load current. A switching DC-DC buck converter has been chosen, operated at constant switching frequency and a constant input DC voltage, while the output DC voltage is obtained by varying the converter duty cycle. A 500W FCS emulator V-I (Voltage – Current) static characteristics has been obtained at a constant working temperature 348 K, area 348.8 m² and length 25e-2 m with the FCS auxiliaries as shown in Figure 5. In order to use the classical PI controller, the fuel cell system linear model has been obtained by linearizing the non linear model around the operating point at the FCS rated value. The PI controller has been put to get the output error less than 2% for different load current. Now, this error voltage compared with the reference voltage to get the corrected value of duty cycle in such way that the DC-DC converter output voltage $V_c$ track the reference voltage of FCS.

**Figure 10 MATLAB simulation of FC Emulator using buck converter**
In Figure 10, simulink model of FCS Emulator with Buck converter is shown. The entire model of the FCS system, including the FC stack and its auxiliaries, as well as the control system of the DC-DC converter has been simulated in MATLAB. Simulation results in Figure 11 shows the comparison of reference voltage FC and converter voltage, converter power and error voltage for variable load current. The waveform of FC emulator in which the load current is varied at some reference point $t=0$ ($I=20A$), $t=1$ ($I=25$), $t=2$ ($I=30$), $t=3$ ($I=35$), and $t=4$ ($I=40$). In this case, the measured voltage quickly follows its reference. Higher the load current, lower the corresponding voltage and higher the power. The Figure 11 shows the simulation results for FCS emulator.

VII. CONCLUSION

In this paper, the complete set of equation is used to developed the characterize effect of the dynamic and the molar flow of hydrogen and oxygen pressure in the anode and cathode channels features in the fuel cell body. Improved dynamic characteristic with change in molar flow relationship to its pressure of both the reactance is simulated and get $E_{\text{Nernst}}$ voltage increased from $1.194$ to $1.3$ V. The use of the buck converter allows the behavior of any fuel cells to be easily emulated since only the modification of the control law of the switch is necessary. The produced emulator can be applied easily to other fuel cell system if the polarization curve has the same current rate and maximum power. In this way it is possible to utilize the converter and perform the necessary tests to optimize a FCS by avoiding the waste of hydrogen and the purchase of cells as well as any cell damage.

ACKNOWLEDGMENT

This research is the results of many endless hours of the hard work. It would not have been possible to complete without the help and supervision of many people. With a sense of gratitude and respect, I would like to extend my heartiest thanks to all those who provided help and guidance. I would like to articulate my profound gratitude and
indebtedness to my guide Prof. Hardik Desai who has always been a source of constant motivation and guiding factor throughout the course of the project, in and out as well.

REFERENCES


