Hybrid System of Proton Exchange Membrane Fuel Cell (PEMFC) with Battery for Portable Power Supply

Prakash Thapa¹ Sung Gi Kwon², Jin Lee³ and Gye Choon Park⁴*

¹, ², ³, ⁴ Electrical Eng. Department, Mokpo National University, Mokpo, South Korea
*Corresponding author E-mail: pgccgp@mokpo.ac

Abstract

Background/Objectives: The combustion of fossil fuels and increased number of advanced technology leads to the global warming and climate change. So, to reduce the greenhouse gas emission and conserve the energy we need to use green energy like fuel cell and Li-ion battery system. This hybrid system consists of PEM fuel cell stack, Li-ion battery and bidirectional step up converter and can be used stationary as well as mobile equipment like vehicles.

Methods/Statistical analysis: For the analysis of hybrid PEMFC/ Li-ion battery power supply system, portable embedded motor is proposed in this paper. The modeling, design, implementation and performance of hybrid system are demonstrate by using experimental results as well as MATLAB/Simulink.

Findings: The simulation results shows that hybrid fuel cell-battery system could provide the continuous power to the sudden changing load and protect the devices. The results also shows that, bidirectional controller can successfully control the fuel cell output and maintain the state of charge of battery at a constant level which provides the significant efficiency of the hybrid power supply system and increased the life-cycle of the system more than 35%.

Improvements/Applications: To improve the fuel cell system performance we need to provide the favorable conditions of temperature, pressure, humidity and control the flow rate of reactant gas. Similarly, due to internal resistance, temperature, material used in manufacturing process, charging and discharging strategy reduces the efficiency as well as life of the battery pack. By using proper voltage balancing methodology we can maintain the similar voltage and prevent from irregular charging.

Keywords: Bidirectional Boost Converter, Efficiency Curve, Li-ion Battery, SOC, Proton Exchange Membrane Fuel Cell (PEMFC)

1. Introduction

A fuel cell is an electrochemical device that directly generates electricity through the chemical reaction of hydrogen and oxygen. To produce electricity, fuel cell requires constant inputs supply of pure H₂ and O₂ gas. There are mainly five types of fuel cell. They are Alkaline Fuel Cell (AFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). Among these fuel cell, PEM fuel cell are lighter smaller and more efficient than other types of fuel cell. Also, it has high power density, low operating temperature, and fast start-up characteristics [1].

PEM fuel cell has high power density so it can supports variable loads but due to the variable parameters effect, the output of PEM fuel cell is not stable. So, a standalone PEM fuel cell system may not be satisfy the transient state and peak load demand condition. Thus, PEM fuel cell is combined with Li-ion battery to provide the steady state power for variable load conditions.

In this paper, a commercial PEM fuel cell is combined with Li-ion battery and operates the portable motor and then measure the performance theoretically as well as practically with variable load conditions. A Li-ion battery can supply a large amount of power but due to irregular charging technique it can’t provide the constant energy to the load. By the use of bidirectional converter, series connected multi battery’s voltage will be balanced and the life of also increased in a certain limit. The proposed hybrid Fuel Cell and Li-ion battery can create maximum power with fast dynamic response and meet the transient as well as peak load demand. The block diagram of hybrid FC/Battery with bidirectional controller is shown in [Figure 1].

![Figure 1: Block Diagram of Hybrid PEMFC-Battery System](image-url)
2. Polymer Exchange Membrane Fuel Cell (PEMFC)

It PEM fuel cell is also called proton exchange membrane fuel cells (PEMFC). It contains mainly 4 parts such as positive plate, negative plate, electrolyte and separator. The catalyst is typically platinum supported on carbon with loadings of about 0.3mg/cm². In PEM fuel cell hydrogen side is positive and is called anode while the oxygen side is negative and is called cathode. Hydrogen fuel is passed through anode where electrons are separated from protons on the surface of a platinum based catalyst. The protons pass through the membrane to the cathode side of the cell while the electrons travel in an external circuit by generating the electrical output of the cell. During this process, water and heat is produced as byproduct. A 3D structure of PEM fuel which depict internal parts of fuel cell is shown in [Figure 2].

![Diagram of Polymer Exchange Membrane Fuel Cell (PEMFC)](image)

The electrochemical reactions occurs in PEM fuel cell are [2]

**Anode Cell Reaction:** \( H_2 \rightarrow 2H^+ + 2e^- \) (1)

**Cathode Cell Reaction:** \( \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \) (2)

**Overall Cell Reaction:** \( H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} + \text{electricity} \) (3)

The electrical energy \( (W_{el}) \) generated in PEM fuel cell is resemble with Gibbs free energy, \( \Delta G = -237.34kJ/mol \). Which is given by,

\[ W_{el} = -\Delta G \] (4)

At high heating value \( (\Delta H_{HHV} = -286.02 \text{kJ/mol}) \) and lower heating value \( (\Delta H_{LHV} = -241.98kJ/mol) \), Gibbs free energy of hydrogen gas can be converted into electrical energy. Thus, theoretical efficiency of fuel cell at HHV condition is given by:

\[ \eta_{HHV} = \frac{\Delta G}{\Delta H_{HHV}} = \frac{237.34kJ/mol}{286.02 \text{kJ/mol}} = 83\% \] (5)

Similarly, theoretical efficiency of fuel cell at LHV condition is given by:

\[ \eta_{LHV} = \frac{\Delta G}{\Delta H_{LHV}} = \frac{237.34kJ/mol}{241.98kJ/mol} = 94.5\% \] (6)

When \( n \) is number of electrons, \( F \) is the Faraday’s constant (96,485 Column/electron-mole). The potential energy \( (E) \) of fuel cell at LHV condition (liquid state) is given by:

\[ E_{LHV} = \frac{-\Delta G}{nF} = \frac{-237.34kJ/mol}{286.02 \text{kJ/mol}} = 1.23 \text{volts} \] (7)

Where \( n \) and \( F \) are number of electrons and Faraday’s constant (96,485 Column/electron-mole) respectively. At standard room temperature, theoretical output potential of PEM fuel cell at vapor state is given by:

\[ E_{HHV} = \frac{-\Delta H_{HHV}}{nF} = \frac{286.02 kJ/mol}{286.478 C/mol} = 1.48 \text{volts} \] (8)

3. Power Model of Proton Exchange Membrane Fuel Cell

The product of stack voltage and stack current is called output power of PEM fuel cell, which is given by,

\[ P_FC = V_{Stack} \] (9)

Where \( V_{Stack} \) is stack potential. Total stack potential is the product of number of cells \( (n) \) and the average cell voltage, which is given by:

\[ V_{Stack} = n \times E_{Cell} \] (10)

\[ E_{Cell} = E_{rev} - \eta_{act} - \eta_{ohm} - \eta_V \] (11)

Where,

\[ E_{rev} = 1.229 - 0.85 \times 10^{-3}(T_r - 298.15) + 4.31 \times 10^{-5}T \ln(P_{H2}) + \frac{1}{2} \ln(P_{O2}) \] (12)

Where \( P \) and \( T_r \) represent the effective pressure and room temperature respectively. Due to the irreversible losses in thermodynamic potential \( (E_{rev}) \), the actual potential \( (E_{Cell}) \) is decreased.

The deviation in output voltage from the equilibrium value is called polarization loss and is denoted by \( \eta \). There are mainly three types of losses in the PEM fuel cell. These are active potential loss, ohmic potential loss and concentration potential loss.

According to Sluggish electrode kinetics some voltage difference is required to get electrochemical reaction running properly. At higher the exchange current density, lower activation polarization losses occur. If anode polarization is neglected then it will be similar to Tafel Equation which is given by [3]:

\[ \eta_{act} = \frac{RT}{nF} \ln\left(\frac{i}{i_0}\right) \] (13)

Due to the change in concentration of reactants at the surface of the electrodes, the partial pressure of reactants will be reduce, at this condition output voltage of the system will be reduced. The voltage at this condition is known as concentration over potential and given by [4],

\[ \eta_{con} = \frac{RT}{nF} \ln\left(\frac{i}{i_{i0}}\right) \] (14)

Ohmic potential loss is the product of current and internal resistance (electrical resistance and ionic resistance) of fuel cell which is given by [5]:

\[ \eta_{ohm} = i_{FC} \times R_{FC} = (R_{ele} + R_{ion}) \times i_{FC} \] (15)

4. I-V Characteristics Curve of Proton Exchange Membrane Fuel Cell

[Figure 3] shows the typical polarization characteristics curve.
with voltage, current density and the resulting power of fuel cell. The performance of fuel cell depend upon the different operating condition such as temperature, pressure, humidity, flow rate and concentration of reactant gases. At room temperature, ideal voltage of PEM Fuel Cell at liquid state is 1.229V whereas 1.48V at vapor state. However the actual voltage of PEMFC is less than the theoretical potential due to irreversible losses even no external load is connected in fuel cell. Figure 3 shows that, as the current density increases voltage drops due to its internal resistance increased. So there is a region exists, which is called ohmic polarization region. It is also called ohmic loss. At low current density level, the ohmic loss become less significant. But due to its internal chemical reactions, the output voltage starts to increases and a region is formed which called active polarization region which is also is called activation loss. At higher value of current density voltage decreases significantly due to the flooding of waters in catalyst layer occur and the region is formed which is called concentration polarization region. This region is also called concentration polarization loss.

![Figure 3: I-V Curve of PEM fuel cell for different losses](image)

**5. Lithium-ion (Li-ion) Battery Model**

Li-ion battery is an electrochemical device which is used to stored electrical energy and used as per our requirement. There are mainly three components of li-ion cell, which are negative plate, positive plate and separator [6]. Generally, graphite is used as negative plate which is connected to the negative terminal whereas positive plate is connected to the positive terminal of the cell and is made from a mixture of LixMn2O4 and LixCoO2 [7]. The electrolytic solution of li-ion with a high concentration is used as separator. It helps in the flow of electrons between negative and positive plates. [Figure 4] shows the schematic diagram of Li-ion cell which depict the individual parts.

![Figure 4: Schematic Diagram of Li-ion Battery](image)

The equivalent first order RC model of li-ion battery is shown is [Figure 5]. Voltage source $V_{oc}$ stands for open circuit voltage, $V_{out}$ is the terminal output voltage and $R1$ is internal ohmic resistance of battery.

![Figure 5: Equivalent Circuit diagram of Li-ion Battery](image)

The open circuit voltage ($V_{oc}$) of li-ion battery can be expressed in terms of state of Charge (SOC) which is given by the following equation [8]:

$$V_{oc} = F(z) = \sum_{i=0}^{n} C_i z^i$$

Where, $Z$=State of Charge, $n$= number or order of polynomial curve, $C_i$ = coefficient of polynomial coefficient

The mathematical form of RC model can be expressed by the following equation:

$$C_1 \frac{dV}{dt} + \frac{V}{R_1} = I_L$$

$$V_{out} = V_{oc} - I_L R_1$$

Where, $I_L$=load current, $V_{out}$=output voltage of battery, $V_C$= capacitive voltage

**6. Bidirectional Converter**

Boost converter is used to convert lower input voltage to higher output voltage. When switch ($S_{sw}$) is closed, the series connected inductor stores certain energy and capacitor releases energy. Similarly, when switch ($S_{sw}$) is open, the inductor release energy and capacitor stores energy [10]. Thus, when switch is OFF, the load gets voltage supply form the capacitor and when the switch is ON, the load get voltage supply from the inductor and inductor. The bidirectional converter has mainly three tasks. First of all, it converts the unregulated output of fuel cell into regulated dc voltage. Secondly, it constantly charges the multiple number of series connected battery and equalize the voltage. Finally, it provides the constant supply for transient and peak load and increase the efficiency and life of the system. The dc-dc bidirectional boost converter circuit diagram is shown in [Figure 6].

![Figure 6: Circuit Diagram of Bidirectional Boost Converter](image)

In bidirectional controller, micro control unit (MCU) monitors the individual cell voltage and commands the field programmable gate array (FPGA) to provide the required energy for equalization of series connected battery system [9]. Generally, controller operates in continuous current and discontinuous current mode. But, to control the converter by using duty cycle we need to operate in discontinuous current mode. The graph for both modes is shown in [Figure 7].
For the voltage balancing mode of operation of bidirectional converter, inductor current can be calculated by [11]:

\[
I_{Lm} = \left\{ \begin{array}{ll}
\frac{V_{Bn}}{L_n} & 0 \leq \alpha < dT_n \\
\frac{V_{Bn}}{L_n} - \frac{V_{Bn}}{L_n}d_cT_n & dT_n \leq \alpha \leq T_m \\
0 & T_m \leq \alpha \leq T_n 
\end{array} \right.
\]

Where, \(T_n\) and \(T_m\) are the switching period. When \(\alpha\) equal to \(T_m\), then inductor current falls to zero. So,

\[
\frac{V_{Bn}}{L_n}d_cT_n = \frac{V_{Bn}}{L_n}(T_n - d_cT_n) < 0 \Rightarrow d_c < \frac{V_{Bn}}{V_{Bn}+\frac{1}{R_m}}
\]

To find the duty cycle \(d_c\), we need to put the different value of \(n\) and then calculate. As a result we can find the following type of equations.

\[n=1, \quad d_c < \frac{1}{V_{Bn}}\]

\[n=2, \quad d_c < \frac{1}{V_{Bn}+\frac{1}{R_m}}\]

\[n=3, \quad d_c < \frac{1}{V_{Bn}+\frac{3}{R_m}}\]

\[n=4, \quad d_c < \frac{1}{V_{Bn}+\frac{5}{R_m}}\]

**Table 1: Cell Voltage Measurement**

<table>
<thead>
<tr>
<th>Total Cells</th>
<th>No.</th>
<th>Cell No.</th>
<th>Cell Voltage (V)</th>
<th>Cell Temp ((T_{Cell})^°C)</th>
<th>Internal Res ((R_m)), (\Omega)</th>
<th>Cell No.</th>
<th>Cell Voltage (V)</th>
<th>Cell Temp ((T_{Cell})^°C)</th>
<th>Internal Res ((R_m)), (\Omega)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>1</td>
<td>2</td>
<td>3.625</td>
<td>21.35</td>
<td>4.899</td>
<td>14</td>
<td>3.335</td>
<td>21.31</td>
<td>4.507</td>
</tr>
<tr>
<td>Max</td>
<td>22.15</td>
<td>5</td>
<td>3.532</td>
<td>21.31</td>
<td>4.773</td>
<td>17</td>
<td>3.628</td>
<td>21.38</td>
<td>4.903</td>
</tr>
<tr>
<td>Voltage</td>
<td>86.88</td>
<td>6</td>
<td>3.423</td>
<td>21.64</td>
<td>4.626</td>
<td>18</td>
<td>3.638</td>
<td>21.31</td>
<td>4.916</td>
</tr>
<tr>
<td>Min</td>
<td>3.329</td>
<td>7</td>
<td>3.329</td>
<td>21.64</td>
<td>4.499</td>
<td>19</td>
<td>3.631</td>
<td>22.15</td>
<td>4.907</td>
</tr>
<tr>
<td>Max</td>
<td>3.926</td>
<td>8</td>
<td>3.636</td>
<td>21.64</td>
<td>4.914</td>
<td>20</td>
<td>3.636</td>
<td>21.88</td>
<td>4.914</td>
</tr>
<tr>
<td>Avg</td>
<td>3.62</td>
<td>9</td>
<td>3.495</td>
<td>21.64</td>
<td>4.723</td>
<td>21</td>
<td>3.773</td>
<td>21.64</td>
<td>5.099</td>
</tr>
<tr>
<td>Current</td>
<td>0.74</td>
<td>10</td>
<td>3.737</td>
<td>21.64</td>
<td>5.080</td>
<td>22</td>
<td>3.926</td>
<td>21.7</td>
<td>5.305</td>
</tr>
<tr>
<td>SOC</td>
<td>95</td>
<td>11</td>
<td>3.546</td>
<td>21.5</td>
<td>4.792</td>
<td>23</td>
<td>3.69</td>
<td>21.95</td>
<td>4.986</td>
</tr>
</tbody>
</table>

By using these data from the experimental value of [Table 1], the duty cycle \(d\) must be used 0.458 for discontinuous mode.

\[
V_{max} = 3.926, \quad V_{min} = 3.329, \quad V_{avg} = 3.62
\]

\[
d = \frac{V_{max} - V_{min}}{V_{max} + V_{min}} = \frac{3.926 - 3.329}{3.926 + 3.329} = 2.179 = 0.458
\]

### 7. Simulation Results

The [Figure 8] shows output voltage and current of Li-ion battery without voltage balancing circuit. It has upset output voltage which may damage the load system as well as decrease the life of own battery pack.
The [Figure 10] shows an effect of hybrid system on load system. When the load increased, the battery power gradually decreased whereas fuel cell power slightly increased but in the transient load and peak load condition both voltage is controlled by bidirectional converter and provides the constant power to the load. Thus to increase the performance as well as life of power supply system bidirectional controller plays an important role.

6. Conclusion

In this paper we are trying to describe the design and implementation of hybrid PEM FC/Li-ion Battery for the use in portable applications. Due to the unique power and efficiency characteristics of the hybrid system, the operational life time of the system will be increased. The bidirectional controller control the output voltage of fuel cell and maintain the balance individual cell voltage of battery. Thus, by the use of hybrid power supply system along with bidirectional controller in stationary as well as mobile vehicles, we can achieve higher efficiency with increased life of the power supply system. Also simulation results shows that, hybrid source performance are neither affected by the fuel cell transient response nor by the battery runtime.

Acknowledgement

This research work was prepared under the support of Korea Electric Power Corporation (R16DA11) and the Ministry Of Trade, Industry & ENERGY (MOTIE) through the fostering project of Energy valley Industry-University Convergence.

References