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Research paper

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

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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 gausses. 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 H_2 and O_2 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].

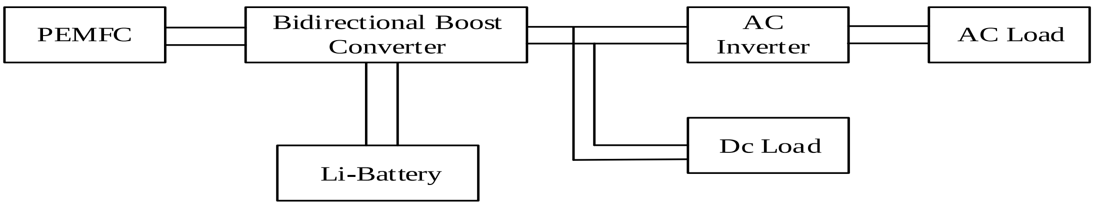


Figure 1: Block Diagram of Hybrid PEMFC-Battery System

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 passes 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].

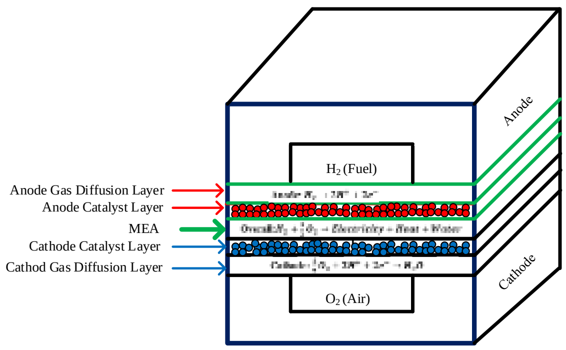


Figure 2.3D: Diagram of Polymer Exchange Membrane Fuel Cell (PEMFC) [3]

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

$$\text{Anode Cell Reaction:} \; H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

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

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

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,

$$W_{el} = -\Delta G \quad (4)$$

At high heating value ($\Delta H_{HHV} = -286.02\ kJ/mol$) 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;

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

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

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

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,

$$E_{LHV} = \frac{-\Delta G}{nF} = \frac{-\Delta G}{2F} = \frac{237{,}340\ \ J/mol}{2\times 96{,}485\ C/mol} = 1.23\ volts \quad (7)$$

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 call at vapor state is given by,

$$E_{HHV} = \frac{-\Delta H_{HHV}}{nF} = \frac{286.02\ \ KJ/mol}{2\times 96{,}485\ \ C/mol} = 1.48\ volts \quad (8)$$

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;
$P_{fc} = V_{Stack} I$ (9)
Where V_{Stack} is stack potential. Total stack potential is the product of number of cells (n) and the average cell voltagel, which is given by;

$$V_{Stack} = n \times E_{Cell} \quad (10)$$

$$E_{Cell} = E_{rev} - \eta_{act} - \eta_{ohm} - \eta V_{Con} \quad (11)$$

Where,

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

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 η. 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];

$$\eta_{act} = \frac{RT}{\alpha F} ln\left(\frac{i}{i_0}\right) \quad (13)$$

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];

$$\eta_{con} = \left(\frac{RT}{nF}\right) * \ln\left(\frac{i_L}{i_L - i}\right) \quad (14)$$

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

$$\eta_{Ohm} = i_{FC} * R_{Fc} = (R_{ele} + R_{ion}) * i_{FC} \quad (15)$$

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.

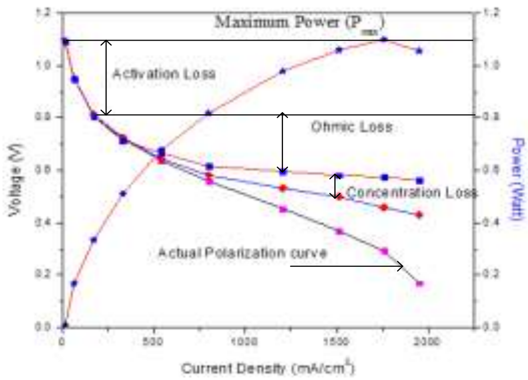


Figure 3: I-V Curve of PEM fuel cell for different losses

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.

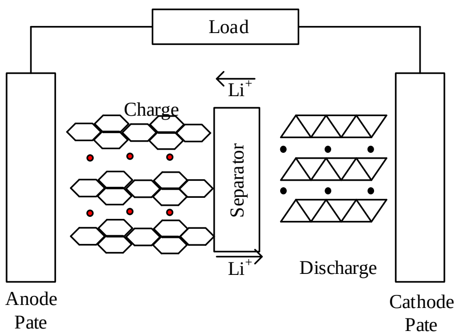


Figure 4: Schematic Diagram of Li-ion Battery

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.

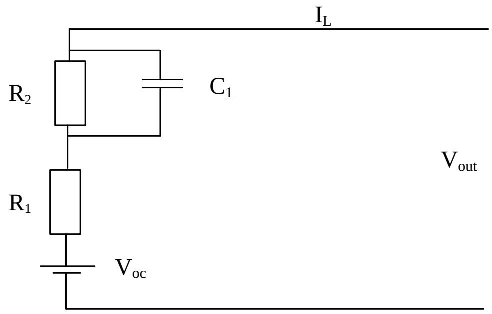


Figure 5: Equivalent Circuit diagram of Li-ion Battery

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];

$$V_{OC} = F(z) = \sum_{i=0}^{n} C_i Z^i \quad (16)$$

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;

$$C_1 \frac{dV_C}{dt} + \frac{V_C}{R_2} = I_L \quad (17)$$

$$V_{out} = V_{OC} - I_L R_1 \quad (18)$$

.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_W) is closed, the series connected inductor stores certain energy and capacitor releases energy. Similarly, when switch (S_W) 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 gets supply voltage from the input 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].

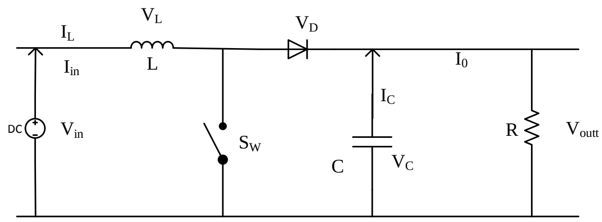


Figure 6: Circuit Diagram of Bidirectional Boost Converter

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].

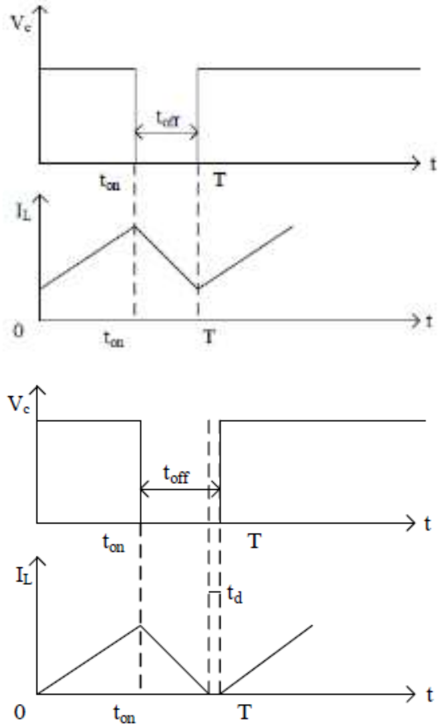


Figure 7: Continuous/ Discontinuous Current Mode

For the voltage balancing mode of operation of bidirectional converter, inductor current can be calculated by [11];

$$I_{L_n} = \begin{cases} \dfrac{V_{B_n}}{L_n}\alpha & ,0 \le \alpha < dT_n \\ \dfrac{V_{B_n}}{L_n}.dT_n - \dfrac{V_{0_n}}{L_n}(T_n - d_cT_n) & ,dT_n \le \alpha \le T_m \\ 0 & ,T_m \le \alpha \le T_n \end{cases}$$

Where, T_n and T_m are the switching period. When α equal toT_m, then inductor current falls to zero. So,

$\frac{V_{B_n}}{L_n}.d_cT_n - \frac{V_{0_n}}{L_n}(T_n - d_cT_n) < 0$Or,$d_c < \frac{V_{0_n}}{V_{B_n}+V_{0_n}} = \frac{1}{\frac{V_{B_n}}{V_{0_n}}+1}$

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, $d_c < \frac{1}{\frac{V_{B_1}}{V_{B_2}+V_{B_3}+V_{B_4}+1}}$

n=2, $d_c < \frac{1}{\frac{V_{B_2}}{V_{B_1}+1}}$

n=3, $d_c < \frac{1}{\frac{V_{B_3}}{V_{B_1}+V_{B_2}+1}}$

n=4, $d_c < \frac{1}{\frac{V_{B_4}}{V_{B_1}+V_{B_2}+V_{B_3}+1}}$

Table1: Cell Voltage Measurement

Total Cells	24	No	Cell No.	Cell Voltage (V)	Cell Temp (T_{cell}), ^{0}C	Internal Res (R_{in}), Ω	Cell No.	Cell Voltage (V)	Cell Temp (T_{cell}), ^{0}C	Internal Res (R_{in}), Ω
Series	24	No	1	3.635	21.31	4.912	13	3.636	21.5	4.914
Parallel	1	No	2	3.625	21.35	4.899	14	3.335	21.31	4.507
Temp	21.54	^{0}C	3	3.649	21.31	4.931	15	3.439	21.38	4.647
Min	21.35	^{0}C	4	3.89	21.31	5.257	16	3.534	21.38	4.776
Max	22.15	^{0}C	5	3.532	21.31	4.773	17	3.628	21.38	4.903
Voltage	86.88		6	3.423	21.64	4.626	18	3.638	21.31	4.916
Min	3.329	Volt	7	3.329	21.64	4.499	19	3.631	22.15	4.907
Max	3.926	Volt	8	3.636	21.64	4.914	20	3.636	21.88	4.914
Avg	3.62	Volt	9	3.495	21.64	4.723	21	3.773	21.64	5.099
Current	0.74	A	10	3.737	21.64	5.050	22	3.926	21.7	5.305
SOC	95	%	11	3.546	21.5	4.792	23	3.69	21.95	4.986
DOD	45	%	12	3.631	21.5	4.907	24	3.918	21.47	5.295

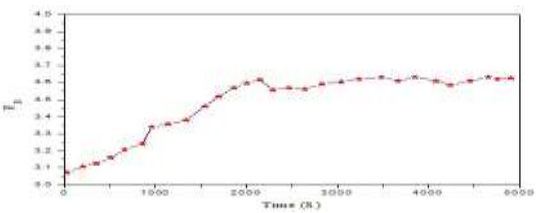
By using these data from the experimental value of [Table 1], the duty cycle (d) must be used 0.458 for discontinuous mode.

$V_{max} = 3.926,\ V_{min} = 3.329,\ \ V_{avg} = 3.62$

$$\mathrm{d} = \frac{1}{\frac{V_{max}}{V_{min}}+1} = \frac{1}{\frac{3.926}{3.329}+1} = \frac{1}{2.179} = 0.458$$

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.



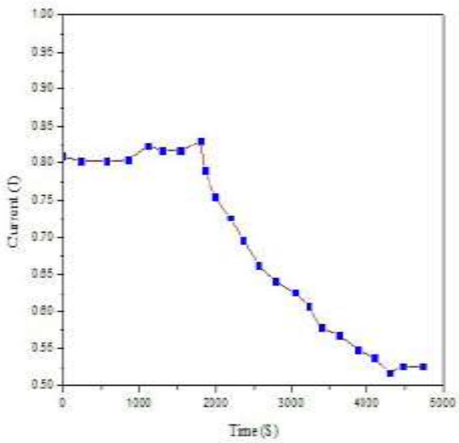


Figure 8: Battery Voltage and Current without Bidirectional Converter

The [Figure 9] shows balance output voltage of 24 Li-ion series connected battery package after 40 second. In this case we used duty cycle of controller is equal to 0.45.

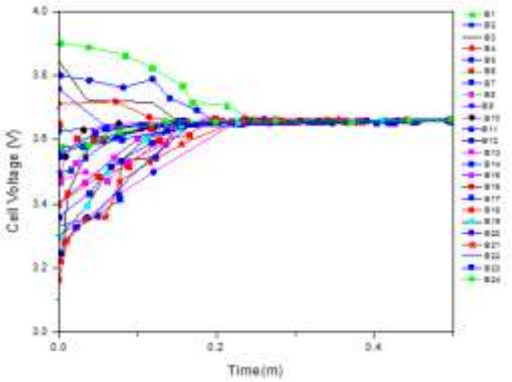


Figure 9: Voltage Balancing By Using Bidirectional Converter

The [Figure 10] shows an effect of hybrid system on load system. When the load increased, the battery power gradually decreased where as 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.

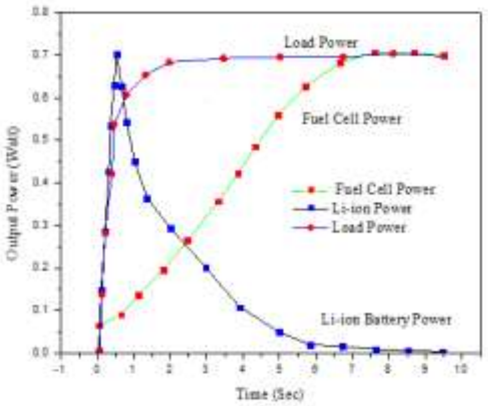


Figure 10: Load Balancing By Hybrid System

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.

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