Design of a Fuel Cell–Based Battery Extender Auxiliary Power Unit for a Vehicular Microgrid

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Abstract—Fuel cell–based power units have increasingly become an attractive option to provide clean and efficient electricity in certain niche applications. This paper discusses the characteristics of a proton exchange membrane (PEM) fuel cell for a battery extender auxiliary power unit and explains the steps of the design process. A two-leg converter topology is proposed to control the fuel cell output, battery charge and discharge process, and the voltage of the DC link. Different operating modes of the system are analyzed and the functions of the energy management system are studied. Simulation case studies in both steady state and transient conditions are presented to validate the effectiveness of the presented fuel cell-based battery extender power unit and the proposed design process.

Index Terms—Battery management system, DC-DC power converters, energy management, fuel cells.

I. INTRODUCTION

Environmental concerns are an indispensable part of technology development. Different industries try to address this concern in their products by decreasing the produced emissions. In transportation industry, for example, an effort is to move away from conventional energy systems toward more electric energy systems [1]. Moreover, there is a growing need for electrical energy to supply electrical loads in vehicles. Supplying all the loads by the conventional energy systems results in increased size of the internal combustion engine and the main generator of the vehicles. An improvement can be made by providing a portion of demanded electrical energy from renewable energy resources to decrease the size of main generator.

Fuel cell technology is an improving solution for transportation industry. The fuel cells are highly efficient, clean, and more sustainable compared to the conventional vehicular energy systems [2]–[4]. A fuel cell–based power unit can be used as a part of the main powertrain of a vehicle or as an auxiliary power unit to supply loads. An auxiliary power unit helps reduce load of the main generator of the vehicle. Therefore, the power rating of the generator and consumption of fossil fuel can decrease. This also leads to a cleaner transportation system.

A fuel cell–based power unit consists of a fuel cell, an energy storage device, and power electronic converters [5], [6]. The fuel cell is slow and can only provides constant power to support the average load demand. For fast load variations, the fuel cell is complemented with an energy storage device, i.e., battery. The power electronic converters act as interface of different components and control the power transfer between different segments of the system. An energy management system (EMS) maintains the output voltage of the unit within the specified limits and ensures that the fuel cell and the battery operate within their limits [7]. The set of interconnected loads and energy resources of the power unit can act as a single controllable entity or islanded microgrid.

In the literature, fuel cell–based power units are studied from the view point of energy management system, system design, power electronic converter, and control algorithms. A comprehensive review of the recent trend in fuel cell–powered systems, including different converter topologies and energy management systems, is presented in [8]. A comparative study of the different energy management schemes, including the experimental results are discussed in [7]. The model of fuel cell is addressed in [2], [9]. However, none of these articles present a detailed procedure for designing different elements of the system. Also, the existing system configurations include different power electronic converters, which necessitates a complex energy management system.

The objective of this paper is to provide an easy-to-follow, yet detailed design of a proton exchange membrane (PEM) fuel cell–based auxiliary power unit. The system is designed for applications in different vehicles ranging from automobiles to commercial aircrafts. First, the fundamentals of PEM fuel cells are studied and key considerations for employing them in a power unit are discussed. Then, the energy management system is discussed. To simplify the power unit, a two-leg converter topology is proposed to control the operating points of the fuel cell and battery and to keep the DC-link voltage constant. Since for cost and space saving only one converter is used, the energy management system is simpler than other reported works. Also, the design procedure for system components, that is, fuel cell, battery, controller, and the power electronic converter is presented.

This paper is organized as follows: Section II describes the PEM fuel cell characteristics and Section III deals with the configuration of the proposed system. Section IV presents the design process and gives the results for a case study. Section V validates the presented theories and proposed design process by dynamic simulations.
II. FUEL CELL CHARACTERISTICS

The operation of a PEM fuel cell is shown in Fig. 1. Hydrogen molecules are split in the anode; protons are allowed to pass through the membrane, and electrons are forced to pass through an electrical circuit. The cathode combines these protons, oxygen, and returning electrons to produce water. Fig. 2 shows the simplified electrical model of a fuel cell [10] and its steady-state polarization curve. Based on the model, there is a voltage drop in the fuel cell as the current increases.

The dynamic component of the model is the capacitor that acts as an energy buffer. Since the model is a capacitive circuit, to have a fast response, the current of the fuel cell should be controlled rather than its voltage. The current control circuit is able to quickly track the current command, and the fuel cell voltage reaches the steady state value gradually. If the voltage is the control variable, the fuel cell voltage cannot track the voltage command quickly even in the case of maximum current. In the proposed battery extender power unit, the fuel cell current is selected as the control variable.

Fig. 3 shows the output power and efficiency curve of a PEM fuel cell. It can be observed that it is not possible to simultaneously maximize both the output power and the efficiency. In addition, the efficiency increases by decreasing the load. Therefore, the minimum possible output power of the fuel cell is considered as the operating point to increase the efficiency of the proposed battery extender power unit. This operating point is derived in Section IV.

One of the important factors that inversely affect the lifetime and durability of a fuel cell is the current ripple [12]. In the proposed battery extender power unit, fuel cell feeds a boost (step-up) converter because this converter introduces low current ripple due to the input inductor.

III. CONFIGURATION AND DESCRIPTION OF THE PROPOSED SYSTEM

The proposed fuel cell–based power unit can be considered as an islanded microgrid. The primary energy source in a fuel cell–based battery extender power unit is the fuel cell. However, since the load power fluctuates, a battery storage system is needed. When the power generated by the fuel cell is more than the load demand and the battery is not fully charged, the excess charges the battery. On the other hand, when the generated power is less than the load demand, the battery storage system provides the difference. Therefore, the fuel cell provides the average power demand and the battery tracks the load fluctuations.

The topology of the proposed battery extender power unit is shown in Fig. 4. The role of fuel cell converter is to regulate the output power of the fuel cell. The bidirectional converter is used to regulate the battery charge or discharge rate by adjusting its duty ratio \( D_{Bi} \). This rate is determined based on the DC link voltage. When the DC link voltage decreases, the bidirectional converter acts as a battery discharger circuit to increase the voltage; otherwise, it acts as a charger circuit.

Fig. 5 shows the flowchart of energy management system of the proposed battery extender power unit. The output power of the fuel cell is usually constant and equal to \( P_{FC_{spec}} \) calculated in Section IV. However, the operating point of fuel cell is changed at the end of the charging interval to prevent the battery from being overcharged. Using a controller, the output power of fuel cell decreases when the battery is charged and there is excess generated power. When the battery voltage decreases in the discharge process, the fuel cell power returns to \( P_{FC_{spec}} \). When the battery voltage is less than the minimum value and the fuel cell power is less than the load power, the load is disconnected to prevent the battery overdischarge.

Based on Section IV, the nominal voltages of DC link, fuel
cell, and battery are 270 V, 145 V, and 144 V, respectively. Therefore, the bidirectional converter in discharging mode and the fuel cell converter are step-up converters. Moreover, the bidirectional converter in charging mode is a step-down converter. It is proposed to use a two-leg converter to implement both the fuel cell and the bidirectional converters. The proposed converter topology and different involved components are shown in Figs. 6 and 7, respectively.

Fig. 7(a) shows the fuel cell converter. This converter regulates the output power of the fuel cell by adjusting its duty ratio. This converter has a relatively slow controller whose input is the battery voltage. In normal conditions, this converter has a fixed operating point; however, at the end of the charge process, the fuel cell output power is gradually decreased to keep the battery voltage equal to the maximum value. In this converter, the top switch may be kept ON to decrease the diode losses. Figs. 7(b) and 7(c) show the bidirectional converter in discharging and charging modes. This converter tracks load variations and keeps the DC link voltage constant using a relatively fast controller. The difference between fuel cell and load powers determines the converter operating mode. The command of the bottom switch is complement of that of the top switch and the converter enters charging mode by increasing the duty ratio of the top switch.

IV. SYSTEM DESIGN PROCESS

In this section, first, the sizes of battery, fuel cell and power electronic converter are calculated. Then, based on the system requirements, passive components of the converter are designed. Finally, the design process for power electronic controllers is discussed.

A. Size of Fuel Cell, Battery, and Converters

To determine the size of fuel cell, battery, and converters, the load profile and a simple efficiency model of the system are needed. Fig. 8 shows this model and the efficiencies of different components of this model. It is assumed that the efficiencies are constant. Fig. 9 shows the load profile in each period. Based on the load profile, the period of system operation is 30 minutes ($T = 30\text{ m}$) and the average power consumption is

$$ P_{L_{avg}} = \frac{P_{t1}t_1 + P_{t2}t_2 + P_{t3}t_3 + P_{t4}t_4}{T}. $$  

(1)

Thus, the average power delivered to the input of inverter is

$$ P_{INV_{avg}} = \frac{P_{t1}t_1 + P_{t2}t_2 + P_{t3}t_3 + P_{t4}t_4}{\eta_3T}. $$  

(2)

As mentioned in Section II, it is preferable to adjust the fuel cell output power at a fixed and minimum possible value. From Figs. 8 and 9, to meet the load demand, the specified value of fuel cell power is

$$ P_{FC_{spec}}\eta_1[(1-A)\eta_2^2\eta_{bat} + A] = P_{INV_{avg}}, $$  

(3)

where $A$ is the ratio of the fuel cell generated energy transferred directly to the load and $(1-A)$ is the ratio of the fuel cell generated energy transferred to the battery to
supply the load later. In the first three intervals of Fig. 9, the fuel cell output energy is transferred to the load, while in the last interval, the fuel cell supplies the load and the extra power charges the battery. Thus, \( A \) is

\[ A = \frac{P_{FC_{spec}}(t_1 + t_2 + t_3)}{P_{FC_{spec}}} T. \] (4)

From (3) and (4), \( P_{FC_{spec}} \) (or in short \( P_{FC} \)) is

\[ P_{FC_{spec}} = \frac{P_{INV} - P_1(1 - \eta_2^2 \eta_{batt})}{\eta_1(\eta_2^2 \eta_{batt} - 1) t_4/T + \eta_1}. \] (5)

The fuel cell can be selected based on the needed power and the required voltage. The nominal operating point of fuel cell can be determined using (5) and the polarization curve of the selected fuel cell.

To determine the battery size, the energy consumed by the load during the first three intervals of Fig. 9 should be studied. This energy in terms of kWh is

\[ E_L = \frac{P_1 t_1 + P_2 t_2 + P_3 t_3}{60}. \] (6)

A part of this energy is provided directly by the fuel cell and the other part by the battery. By calculating the fuel cell contribution, the battery contribution can be calculated as

\[ E_{batt} = \frac{P_1 t_1 + P_2 t_2 + P_3 t_3 - P_{FC} \eta_1 \eta_3 (t_1 + t_2 + t_3)}{60 \eta_2 \eta_3} \] (7)

Therefore, using the voltage and depth of discharge (DOD) of the battery, the battery capacity in terms of \( Ah \) is

\[ \text{BAT}_{Ah} = \frac{P_1 t_1 + P_2 t_2 + P_3 t_3 - P_{FC} \eta_1 \eta_3 (t_1 + t_2 + t_3)}{60 \text{DOD} \eta_2 \eta_3 V_{batt}}. \] (8)

Moreover, the maximum charging and discharging current of the battery can be calculated as

\[ I_{CH} = \frac{(P_{FC} - P_4)}{V_{batt}} \frac{1}{\eta_1 \eta_2}; \] (9) \[ I_{DIS-CH} = \frac{P_1 - P_{FC} \eta_1 \eta_3}{V_{bat} \eta_2 \eta_3}. \] (10)

In the design process, it is assumed that \( \eta_1 = \eta_2 = \eta_3 = 0.85, \eta_{batt} = 0.97, \) and DOD = 0.2. Consequently, the design process leads to the results summarized in Table I.

### Table I: Summary of the Design of Different Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell</td>
<td>( P_{FC} = 3.18 \text{ kW}, V_{FC} = 145 \text{ V}, I_{FC} = 21.9 \text{ A} )</td>
</tr>
<tr>
<td>Battery</td>
<td>( \text{BAT}<em>{Ah} = 28 \text{ Ah}, I</em>{CH} = 14.6 \text{ A}, I_{DIS-CH} = 82.1 \text{ A} )</td>
</tr>
<tr>
<td>Fuel cell converter</td>
<td>( P_{in} = 3.18 \text{ kW}, V_{in} = 145 \text{ V}, V_{out} = 270 \text{ V}, I_{out} = 144 \text{ A} )</td>
</tr>
<tr>
<td>Bidirectional converter</td>
<td>( P_{in} = 2.70 \text{ kW}, V_{in} = 270 \text{ V}, V_{out} = 144 \text{ V}, I_{out} = 144 \text{ A} )</td>
</tr>
</tbody>
</table>

### B. Design of Passive Component of Converters

The fuel cell converter is a step-up converter. The bidirectional converter is a step-up converter in one mode and a step-down converter in the other mode. The inductors of step-up and down converters are designed based on the maximum allowed increase in the inductor currents when the corresponding switch is on. Thus, the needed inductances are

\[ L_{\text{step-up}} = \frac{D V_{in}}{f_{sw} \Delta I_{in}}, \] (11) \[ L_{\text{step-down}} = \frac{D (V_{in} - V_{out})}{f_{sw} \Delta I_{out}}, \] (12)

where \( V_{in}, V_{out}, \Delta I_{in}, \Delta I_{out}, D, \) and \( f_{sw} \) are input voltage, output voltage, input current variation, output current variation, duty ratio, and switching frequency of a converter.

To design the capacitors, the voltage drops due to equivalent series resistance (ESR) and capacitance of capacitors are taken into account. The product of the ESR and capacitance of a capacitor is considered as \( 65 \times 10^{-6} \) [13]. Thus, the output capacitor of the step-up and step-down converters are

\[ C_{\text{step-up}} = \frac{65 \times 10^{-6} I_{in}}{V_r} + \frac{(I_{in} - I_{out})(1 - D)}{V_r f_{sw}} \] (13) \[ C_{\text{step-down}} = \frac{65 \times 10^{-6} \Delta I_{out}}{V_r} + \frac{\Delta I_{out}}{8 V_r f_{sw}}, \] (14)

where \( V_r, I_{in}, \) and \( I_{out} \) are the output voltage ripple, the input current, and the output current of the converter. In these equations, the first term is due to the ESR and the second term is due to the capacitance of the capacitor. From Fig. 7, the DC link capacitor is the output capacitor of the fuel cell converter and bidirectional converter in discharging mode. Therefore, the calculated capacitance for these two converters should be added to meet the limit.
for DC link voltage ripple. Moreover, a single inductor is employed in the bidirectional converter for both operating modes. Therefore, the maximum value calculated for the two operating modes should be used.

Based on the design requirements, the current ripple of the inductor in step-up and step-down converters should be less than 10% and 40%, respectively. The voltage ripples should be less than 0.5%. From (11)–(14) and Table I, the inductor of the fuel cell converter, the inductor of the bidirectional converter, the capacitor of the DC link, and the output capacitor of the bidirectional converter in charging mode are 1.62 mH, 0.56 mH, 0.4 mH, 3.5 mF, and 0.64 mF, respectively. Since the bidirectional converter employs a single inductor and due to practical limitations, the selected inductance for this converter is 0.56 mH. Also, practical limitations on the size and weight make the inductor of the fuel cell converter and the capacitor of the bidirectional converter in charging mode equal to 1.85 mH and 0.68 mF.

C. Design of Controllers

1) Controller of the fuel cell converter: The fuel cell converter is controlled by a single-loop current controller. For control purpose, the averaged model of the converter is derived. Fig. 10 shows the averaged and simplified average models of the fuel cell converter. It is assumed that the variation of the DC-link voltage is small; therefore, this voltage is considered constant in the design process. In the simplified averaged model, $V_1$ is equal to

$$V_1 = V_{FC} - (1 - D_{FC})V_{DC}, \quad (15)$$

where, $D_{FC}$ is the duty ratio of the bottom switch of the fuel cell converter. The transfer function of this converter is

$$\frac{I_{LFC}(s)}{V_1(s)} = \frac{1}{L_{FC}s}. \quad (16)$$

From (16), a closed-loop control algorithm with a $P$-controller can effectively control the inductor current. Consequently, the closed-loop transfer function of the converter and its controller is

$$\frac{I_{LFC}(s)}{I_{LFC}^*} = \frac{K_{PFC}}{L_{FC}s} = \frac{K_{PFC}}{s + \frac{K_{PFC}}{L_{FC}}}. \quad (17)$$

where $K_{PFC}$ is the gain of the $P$-controller. The time constant of this first-order transfer function is

$$T_{FC} = \frac{L_{FC}}{K_{PFC}}. \quad (18)$$

A larger gain results in smaller time constant but higher sensitivity to noise and stability issues. The controller gives the duty cycle ($D_{FC}$) of the switch

$$D_{FC} = \frac{V_1 + V_{DC} - V_{FC}}{V_{DC}}. \quad (19)$$

Fig. 11 shows the block diagram of the control system. To avoid division by zero during start-up, the minimum value of the DC-link voltage is limited.

2) Controller of the bidirectional converter: As shown in Fig. 12, the bidirectional converter employs a dual-loop controller. The inner loop controls the inductor current while the outer loop controls the DC-link voltage. The duty ratio of the top switch of the bidirectional converter is $D_{Bi}$. Fig. 13 shows the averaged and the simplified average model of the bidirectional converter. This model is used to design the inner loop controller. The transfer function of the circuit shown in Fig. 13 is

$$\frac{I_{L_{Bi}}(s)}{V_2(s)} = \frac{1}{L_{Bi}s}. \quad (20)$$

where,

$$V_2 = V_{BT} - D_{Bi}V_{DC}. \quad (21)$$

A $P$-controller results in a first-order closed-loop transfer function, thus it can effectively control the inductor current. The outer controller should be slower than the inner controller. In the design of the outer controller, it is assumed
that the inner controller instantaneously adjusts the inductor current. Fig. 14 shows the averaged model of the outer control loop. The transfer function of this circuit is

\[
\frac{V_{DC}(s)}{I_L^*(s)} = \frac{R_L D_{Bi}}{1 + R_L C_L s}. \tag{22}
\]

Thus, the transfer function of the closed-loop control system considering a controller in the forward loop is

\[
\frac{V_{DC}^*}{V_{DC}} = \frac{G(s)\left(\frac{R_L D_{Bi}}{1 + R_L C_L s}\right)}{1 + G(s)\left(\frac{R_L D_{Bi}}{1 + R_L C_L s}\right)} \tag{23}
\]

where, \(G(s)\) represents the outer controller. A PI-controller is designed for controlling the DC-link voltage. Thus, the transfer function of the controller is \(G(s) = \frac{K_{P_o} + K_{I_o}}{s}\), where \(K_{P_o}\) and \(K_{I_o}\) are the proportional and integral gains of the outer controller. Consequently, (23) gives

\[
\frac{V_{DC}^*}{V_{DC}} = \frac{(K_{I_o} + K_{P_o}) R_L D_{Bi}}{s(1 + R_L C_L s)} \tag{24}
\]

Setting the PI-controller such that \(K_{P_o} = K_{I_o} R_L C_L\) yields

\[
\frac{V_{DC}^*}{V_{DC}} = \frac{K_{I_o} R_L D_{Bi}}{s + K_{I_o} R_L D_{Bi}} \tag{25}
\]

which is a first-order transfer function. The time constant of the transfer function is given by

\[
T = \frac{1}{K_{I_o} R_L D_{Bi}} = \frac{C_L}{K_{P_o} D_{Bi}}. \tag{26}
\]

Fig. 15 shows the block diagram of the controller of the bidirectional converter.

V. SIMULATION RESULTS

The fuel cell-based battery extender power unit is simulated in MATLAB/Simulink to validate the proposed topology and presented theories. In the first case study, the system performance in the steady-state conditions is investigated. Fig. 16 shows the steady-state waveforms of the inductor current in bidirectional converter, DC-link voltage, inductor current in fuel cell converter, and the fuel cell voltage in the presence of maximum load. Table II compares the voltage and current ripples derived from the simulation results and the design process. There is good agreement between the results of design process and simulation results.

In the second case study, the performance of the battery extender power unit in the presence of load variation is evaluated. Fig. 17 shows the load profile and the corresponding transient waveforms. The controller of the bidirectional converter effectively controls the inductor current in a way that the ripple of DC link voltage is always less than 2%. Also, the fuel cell controller can effectively control the fuel cell operating point in the presence of the load variation.

In the third case study, the performance of the battery extender power unit in the presence of a change in the reference value of fuel cell current is studied. At \(t = 0.1\) s, the reference value of the fuel cell current changes from zero to the nominal value. Fig. 18 shows the current and voltage of the fuel cell and the response of DC link voltage to this change. The fuel cell controller can effectively track the reference value of the fuel cell current. Also, the bidirectional controller can quickly return the DC-link voltage to its rated value and keeps the transient ripple equal to 1.2%. Based on the simulation results in different case studies, the system behavior in steady-state and transient conditions satisfies the expectations of the design process.

VI. CONCLUSION

This paper addresses important factors in the design of a fuel cell–based battery extender power unit which has application in transportation systems as an auxiliary power unit. To have an efficient, durable, and fast power unit, a fixed operating point fuel cell is suggested. A two-leg converter is employed to control the fuel cell output power, battery charge and discharge process, and the voltage of
TABLE II
VOLTAGE AND CURRENT RIPPLE IN SIMULATION AND DESIGN PROCESS

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Design DC ripple (V)</th>
<th>Simulation DC ripple (V)</th>
<th>Fuel cell voltage (V)</th>
<th>Bidirectional converter voltage (V)</th>
<th>Bidirectional converter current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
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<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
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<tr>
<td>7</td>
<td>2.50</td>
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<tr>
<td>8</td>
<td>2.50</td>
<td>2.45</td>
<td>2.40</td>
<td>7.60</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Fig. 17. Simulation results in transient condition: (a) the load profile, (b) inductor current in bidirectional converter, (c) DC-link voltage, (d) fuel cell current, and (e) fuel cell voltage.

Fig. 18. Simulation results in the presence of a change in the fuel cell set point: (a) fuel cell current, (b) fuel cell voltage, and (c) DC-link voltage.

DC link. The two-leg converter consists of a step-up and bidirectional converters. The step-up converter controls the output power of the fuel cell and prevents the battery from overcharging, and the bidirectional converter keeps the voltage of the DC link constant. The design process for the size of different components of the system is proposed and the result for a case study is presented. Simulation results validate the proposed topology and presented design process.

REFERENCES


