Fuel Cell/Battery Powered Electric Vehicle System

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Abstract

This paper studies a fuel cell/battery hybrid power source for electric vehicle applications. The fuel cell is connected to a DC bus by a classical boost converter, and the battery bank is directly connected to the DC bus. It presents a control strategy used to control power from the fuel cell, power to the motor, and state-of-charge of the battery. A hardware system is realized by analogical circuits for the fuel cell current loop and numerical calculation in dSPACE for battery current and state-of-charge loops. Experimental results with a 500 W, 40 A PEM fuel cell and 33 Ah, 48 V lead-acid battery bank point out that the fuel cell/battery hybrid source can effectively function to meet the electric vehicle demand. The proposed system has achieved an excellent performance.

Keywords: Batteries, converters, energy storage, fuel cells, electric vehicles, state-of-charge.

1. Introduction

Currently, fuel cells (FCs) are acknowledged as one of the most promising technologies to meet the future power generation requirements. Since fuel cells directly convert fuel and an oxidant into electricity through an electrochemical process without pollution (CO_2), they can achieve operating efficiencies 50% - nearly three times of the efficiency of conventional internal combustion engines [1]. There are several types of fuel cells characterized by their electrolytes. As already presented in [2], Polymer Electrolyte Membrane Fuel Cell (PEMFC) is important as the main source for vehicle applications because of their low operating temperature, high power density, and high efficiency.

Nonetheless, there are some well-known technical limitations of a fuel cell system as follows:

- it does not allow bidirectional energy (current) flow, thus, prohibiting braking energy regeneration in electric vehicle applications,
- a current slope of fuel cell must be limited in order to prevent a fuel starvation phenomenon [3],
- and, it has a warm up time of 5-10 minutes.

In addition, for vehicle applications, the traction drive demands high power in a short time (for example, vehicle acceleration and deceleration), around two times of average power during drive cycle [4]. For these reasons, some kind of hybridization of FC with other energy storage devices such as batteries or supercapacitors will be advantageous (Figs. 1 and 2).

This paper presents method on how to function a main source (fuel cell) and a storage device (battery bank) for distributed generation system. After presenting the proposed structure and control algorithm in section 2, it will illustrate experimental results obtained with a small-scale test bench based on a PEM fuel cell, a lead-acid battery bank, and a DC motor with converter drive as a traction drive in electric vehicle in section 3.

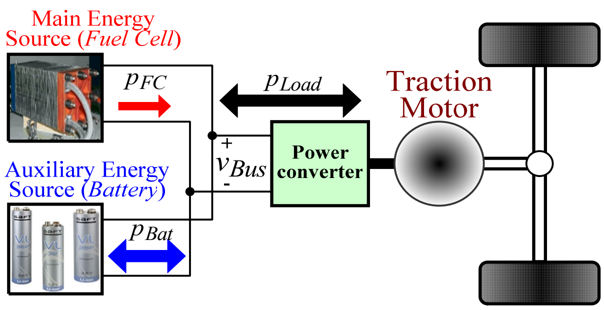

Fig. 1: Fuel cell hybrid power source for distributed generation system. (p_{Load}, p_{FC} and p_{Bat} are the load, fuel cell, and battery powers and v_{Bus} is the DC bus voltage.)

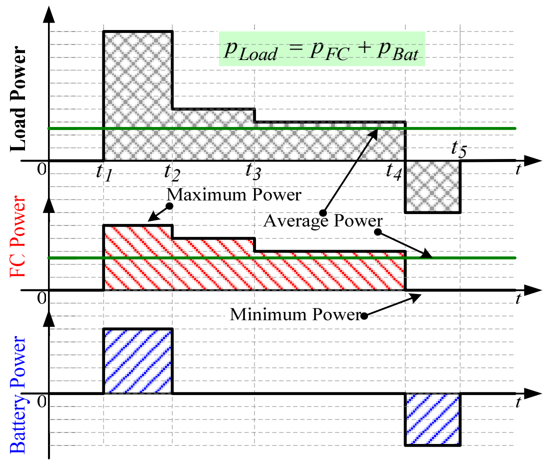

Fig. 2: Power profile of fuel cell hybrid source.

2. Fuel Cell/Battery Hybrid Power Source

2.1 Configuration of Hybrid Power Source

FC voltage v_{FC} is highest when no current is flowing and drops with increasing current because of losses in the stack. At rated current $I_{FCRated}$, v_{FC} drops to around half of the no-load voltage [5]. On the other hand, battery voltage curve, for example in a lead-acid battery, is linear over most of its operating range, however, at the end-of-discharge, the voltage decreases very rapidly toward to zero [6]. Many previous works with a battery bank as an energy storage device have operated by connecting batteries directly to a DC bus (for example, a DC bus voltage (battery voltage) of the Honda Hybrid Insight is 144 V [4]).

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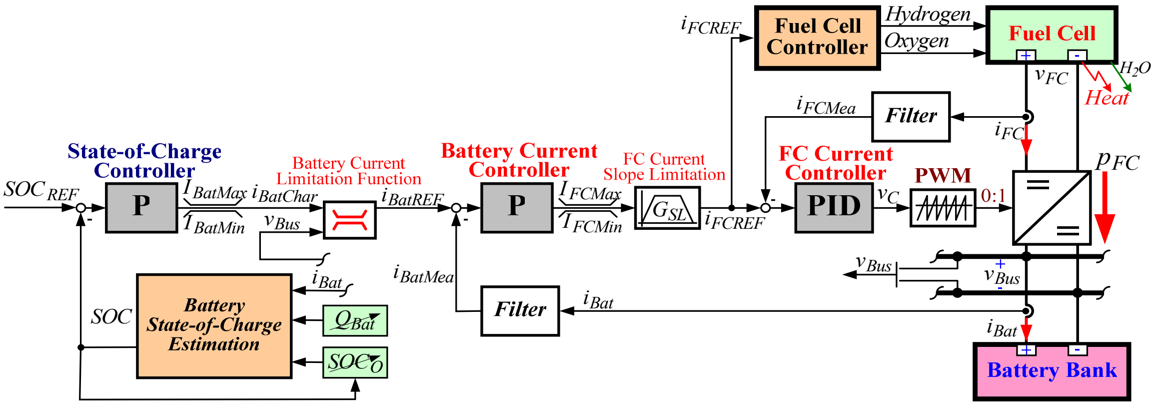

Fig. 3: Proposed control structure of fuel cell/battery hybrid power source.

For these reasons, the proposed configuration of fuel cell/battery hybrid source (Fig. 3) is that the fuel cell is connected to the DC bus by a boost converter (Fig. 4) and the battery bank is directly connected to the DC bus.

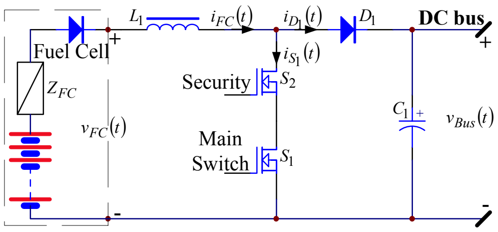

Fig. 4: FC power conditioning (FC converter) [3].

2.2 Fuel Cell Current Regulation

When a fuel cell system is operated, its fuel flows are controlled by a "Fuel Cell Controller" (Fig. 3), which receives a fuel cell current demand (reference) i_{FCREF} from the hybrid control algorithm (automatic operation in this work). The fuel flows must be adjusted to match the reactant delivery rate to the usage rate. Then, the inner fuel cell current control loop is compulsory and the control algorithm demands energy from the fuel cell to the DC bus by generating i_{FCREF} (Fig. 3) [5], which is sent to the "Fuel Cell Controller" synchronously. One can take advantage of safety and high dynamics of this loop as well; thus, it must be realized by analogical circuits to function at high bandwidth.

2.3 Proposed Control Algorithm

To manage energy exchanges between the DC bus, the main source and the storage device, one may define three operating modes (or states), refer to Fig. 2:

- **charge mode**, in which the main source supplies energy to the storage device and/or to the load (t_2 to t_4),
- **discharge mode**, in which both main source and storage device supply energy to the load (t_1 to t_2),
- **recovery mode**, in which the load supplies energy to the storage device (t_4 to t_5).

The proposed control scheme is that one takes advantage of a battery bank, which is directly connected to the DC bus for supplying transient energy demand and peak loads required during motor acceleration and deceleration, as if this device is a standard source. Besides, the fuel cell as a slow dynamic device functions to supply energy to a battery bank to keep them charged.

The control strategy is a cascade control structure composed of three loops. The outer loop is a battery state-of-charge (SOC) control loop composed of SOC_{REF} as a reference of SOC and i_{BatREF} as a control variable output demanding a battery charging current. The middle loop is the battery current control composed of i_{BatREF} as a battery current reference coming from the outer loop and i_{FCREF} as a control variable output demanding a fuel cell current. The inner loop is the fuel cell current control loop as already explained in the previous section.

2.3.1 Battery State-of-Charge Control Loop

The well-known SOC estimation is defined as,

$$SOC(t) = SOC_o + \frac{1}{Q_{Bat}} \int_{t_o}^{t} i_{Bat}(\tau)\,d\tau \qquad (1)$$

where SOC_o is the known battery SOC [%] at the time t_o and Q_{Bat} is the rated capacity [Ah]. The simple method to charge the battery is a constant current (maximum current I_{BatMax} is set around $Q_{Bat}/2$ - $Q_{Bat}/5$) when SOC is far from a SOC_{REF} [7] and reduced current when SOC is near SOC_{REF} and zero when SOC is equal to SOC_{REF} (Fig. 5). More importantly, in automotive applications, battery monitoring is obligatory in order to replace an aged battery [6]. Note here that it is beyond the scope of this paper to observe the potential capacity of the battery. It is assumed that Q_{Bat} is constant. And in a real system of applications, SOC_o can be retained in a storage device.

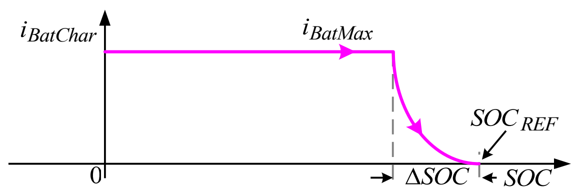

Fig. 5: Charging battery algorithm.

By this SOC algorithm, a proportional (P) controller is enough to generate a battery charging current $i_{BatChar}$. And the charging current must be limited at I_{BatMax}. So the P-controller gain (G_{SOC}) can be sized as,

$$G_{SOC} = \frac{I_{BatMax}}{\Delta SOC} \tag{2}$$

where ΔSOC is the defined band of a battery SOC.

To avoid over-voltage at the DC bus in case of an erroneous SOC estimation, v_{Bus} must be monitored to limit charging current. The battery current limitation function consists of limiting i_{BatREF} versus v_{Bus} as [8],

$$i_{BatREF}(t) = i_{BatChar}(t) \times min\left(1, \frac{V_{BusMax} - v_{Bus}(t)}{\Delta V_{Bus}}\right) \tag{3}$$

where V_{BusMax} is the defined maximum DC bus voltage and ΔV_{Bus} is the defined voltage band.

2.3.2 Battery Current Control Loop

The battery current control loop received i_{BatREF} from a SOC regulation loop. A P-controller is sufficient to generate i_{FCREF}, which must be limited in level, within an interval maximum current I_{FCMax} (corresponding to a fuel cell rated current) and minimum I_{FCMin} (set to 0 A) and limited in slope to a maximum absolute value G_{SL} of some amperes per second, which enables the safe operation of the fuel cell to respect constraints associated with the fuel cell, as far as the proportional gain G_{iBat} is high enough to introduce a small static error.

To obtain the open loop transfer function associated with the battery current control loop, one can write power conservation (without losses) as:

$$v_{FC}(t) \cdot i_{FC}(t) = v_{Bus}(t) \cdot i_{Bat}(t) + p_L(t) \tag{4}$$

If variations are introduced and the load power is considered as a disturbance of the system, (4) becomes,

$$\tilde{i}_{FC}(t) = \frac{V_{Bus}}{V_{FC}} \tilde{i}_{Bat}(t) \tag{5}$$

where V_{Bus} and V_{FC} are the nominal DC bus and fuel cell voltage, respectively.

Therefore, the open loop transfer function can be written with a gain depending on the operating point as,

$$\left.\frac{\tilde{i}_{BatMea}(s)}{\tilde{i}_{BatREF}(s)}\right|_{OL} = \overbrace{G_{iBat}}^{P\,controller} \cdot \overbrace{\frac{V_{FC}}{V_{Bus}}}^{\tilde{i}_{Bat}(s)/\tilde{i}_{FC}(s)} \cdot \overbrace{\frac{G_{Bat}}{T_{Bat}s+1}}^{filter} \tag{6}$$

A first-order low pass filter is used for the battery current measurement in order to reduce current ripples caused by the switching frequency of the fuel cell and electric load (motor drive) converters.

3. Experimental Results

The small-scale test bench is presented in Fig. 6. The storage device is four aged lead-acid batteries of 7.78 Ah (33 Ah at name plate), 12 V connected in series. The 500 W, 13 V PEM fuel cell system was constructed by the ZSW Company, Germany [9].

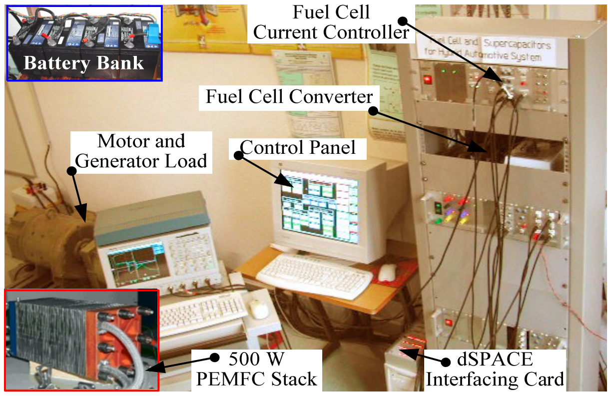

Fig. 6: Hybrid source test bench.

The parameters associated with the battery SOC and current regulation loop are detailed in Table I and II, respectively. The fuel cell current absolute slope limitation (G_{SL}) is set to 4 A/s. This value has been experimentally determined as the highest current slope of this fuel cell system, where no fuel starvation occurs [9]. The battery current control loop has been implemented in the real-time controller card dSPACE DS1104 with a sampling frequency of 25 kHz. The ControlDesk software enables changes in the parameters of the control loops.

Table I. BATTERY *SOC* REGULATION LOOP PARAMETERS.

SOC_{REF}	Q_{Bat}	I_{BatMax}	ΔSOC	V_{BusMax}	ΔV_{Bus}	G_{SOC}
100%	7.78 Ah	4.5 A	1.5%	61 V	2 V	3

Table II. BATTERY CURRENT REGULATION LOOP PARAMETERS.

G_{SL}	I_{FCMax}	I_{FCMin}	G_{iBat}	G_{Bat}	T_{Bat}
4 A/s	30 A	0 A	30	1	31.8 ms

The experimental tests have been carried out by connecting the DC bus to an active load composed of a 2-quadrant converter, loaded by a DC motor coupled with a DC generator. Fig. 7 presents waveforms obtained during a motor drive cycle. It shows the DC bus and FC voltages; motor speed; FC, battery, and load (motor) powers; FC, battery, and motor currents; and battery SOC curves. The initial state is zero for the motor, fuel cell, and battery powers and 100% SOC. First, the motor starts to 1,500 rpm at t = 4 s. One can observe that

- the battery supplies most of the 1800-W power required during motor acceleration,
- the fuel cell current increases with a limited slope of 4 A/s up to a limited maximum level of 30 A,
- simultaneously the battery current, after a sharp decreases (negative) during motor acceleration, increases slowly to -10 A, because the steady state load power (approximately 800 W) is greater than the maximum fuel cell power set at around 380 W.

Second, after that at t = 56 s the motor reduces speed to stop with the peak load power approximately -600 W; hence, the battery is deeply charged in which the battery recovers the energy supplied to the DC bus by the fuel cell (limited slope) and the motor. After the end of regenerative braking, the battery is charged at a constant current of around 4 A (I_{BatMax} = 4.5 A, a small error introduced by the battery current controller, P-controller) by the fuel cell current of 16 A. Finally, when battery *SOC* is 98.5% at t = 106 s, the battery charging current is reduced automatically because of ΔSOC = 1.5%, and G_{SOC} = 3, and the fuel cell current is synchronously reduced. After that both the fuel cell and battery current will reduce to zero at the 100% *SOC*.

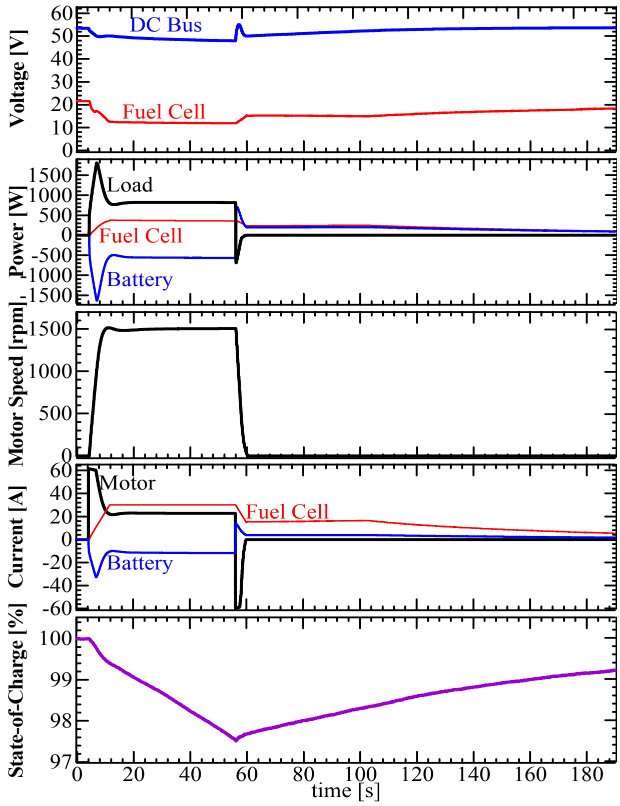

Fig. 7: Hybrid system response during motor drive cycle.

4. Conclusion

In this paper, an innovative method how to function a fuel cell/battery hybrid power source is explained in detail. The control strategy lies in using fuel cell to supply energy to load and to battery charged with respect to the fuel cell dynamics. This method is easier than normal state machines used for hybrid source regulation. It is also free of chattering problems.

An experiment was carried out by means of a hybrid test bench, which employs a storage device composed of four 33 Ah lead-acid batteries connected in series, a 500 W PEMFC, and the DC motor drive as a load at DC bus. The results have evidently shown the excellent performance during motor drive cycle.

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