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An actively controlled fuel cell/battery hybrid to meet pulsed power demands

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Abstract

This paper presents the experimental results of an actively controlled fuel cell/battery hybrid power source topology that can be widely used in many applications, such as portable electronic devices, communication equipment, spacecraft power systems, and electric vehicles, in which the power demand is impulsive rather than constant. A step-down DC/DC power converter is incorporated to actively control the power flow between the fuel cell and the battery to achieve both high power and high energy densities. The results show that the hybrid power source can achieve much greater specific power and power density than the fuel cell alone. This paper first demonstrates that an actively controlled hybrid with a 35 W hydrogen-fueled polymer electrolyte membrane fuel cell and a lithium-ion battery pack of six cells yielded a peak power of 100 W, about three times as high as the fuel cell alone can supply, while causing a very limited (10%) weight increase to the whole system. After that, another hybrid source using a different battery array (eight cells) was investigated to further validate the control strategy and to show the flexibility and generality of the hybrid source design. The experimental data show that the hybrid source using an eight-cell battery supplied a peak power of 135 W, about four times that of the fuel cell alone. Finally, three power sources including the fuel cell alone and the two hybrids studied were compared in terms of specific power, power density, volume, weight, etc. The design presented here can be scaled to larger or smaller power capacities for a variety of applications.

Keywords: Hybrid power source; Lithium-ion battery; Polymer electrolyte membrane fuel cell; Power converter

1. Introduction

Many applications, such as portable electronic devices, communication equipment, spacecraft power systems, and electric vehicles, have a common characteristic in their load profiles. That is, they have a high ratio of peak power to average power. Fuel cells (e.g. PEM fuel cells) are considered to be the most promising alternatives among next generation energy devices due to their high energy density and clean energy [1,2]. However, limited by their inherent characteristics, fuel cells have a long start-up time (usually several minutes) and poor response to instantaneous power demands. Compared with fuel cells, lithium rechargeable batteries have a rapid transient response without any warm up or start up time, and their specific power capability is also much higher than that of fuel cells. Combining fuel cells with batteries yields hybrid power sources that make the best use of the advantages of each individual device and may meet the requirements for the above mentioned applications regarding both high power and high energy densities [3,4]. In such a hybrid fuel cell/battery power source, the fuel cell is controlled to satisfy load average power requirements over a long term; the battery, on the other hand, is used to serve high pulse power requirements in short intervals. Clearly, the load time-averaged power should be less than or equal to the fuel cell rated power capability, otherwise the battery will eventually become exhausted.

This paper mainly presents the experimental study of an actively controlled fuel cell/battery hybrid serving a pulse load. In contrast to a passive hybrid, where the fuel cell is connected directly in parallel with the battery, an active hybrid has several potential advantages. Consider the structure of the active hybrid shown in Fig. 1, a DC/DC power converter is incorporated between the fuel cell and the battery so that the power flow can be actively managed. In this configuration, the fuel cell is isolated from the pulse load through the power converter, while the battery is not. By controlling the power converter, the fuel cell output current, the battery current and the battery voltage all can be regulated.

The operating principle of the hybrid power source that is the focus of this study is described as follows: during periods of low power demand, the fuel cell will be controlled to

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generate an average power that is sufficient to serve the load and at the same time to charge the battery; during periods of high power demand, the fuel cell will generate the rated power and the battery will be discharged at any rate (up to the safe limit) necessary to satisfy the high power requirements.

Two configurations of hybrid power sources were tested in this study. Both configurations used the same fuel cell, power converter and control algorithm; the only difference between them was the battery array size. The study results show that such fuel cell/battery hybrid power sources achieved much greater specific power than the fuel cell alone. The first hybrid power source studied, which used a six-cell battery, demonstrated a 100 W peak power capability, which is three times that of the fuel cell alone. The second hybrid power source studied, which used an eight-cell battery, achieved a higher peak power of 135 W. Besides the advantage of providing higher specific power, the active hybrids offered advantages of a broader range and better regulation of the output voltage, a smaller fuel cell stress, a smaller weight and volume (for a fixed peak power capability) of the system, and faster response at startup and during step changes of power demand.

In the following section, the system experimental setup is detailed. Section 3 then describes the experimental tests of two configurations of active hybrids, and compares the hybrid power sources to the fuel cell alone with attention to the specific power, power density, and power source volume and weight. Finally, the conclusions are given in Section 4.

2. System setup

The experimental system of the active fuel cell/ battery hybrid, illustrated above in Fig. 1, was built using a hydrogen-fueled polymer electrolyte membrane fuel cell manufactured by H-Power with a nominal power capacity of 35 W and nominal 24 V open-circuit voltage, and Sony US18650 lithium-ion batteries with a nominal capacity of 1400 mAh per cell. A step-down DC/DC power converter was constructed using a synchronous rectifier, as shown in Fig. 2. Two MOSFETs were adopted in this construction and were operated synchronously and complementarily. Using an active switch instead of a passive diode decreases the conductance loss dramatically and thus improves the converter efficiency; therefore, this topology is more and more commonly adopted in low-voltage power supplies.

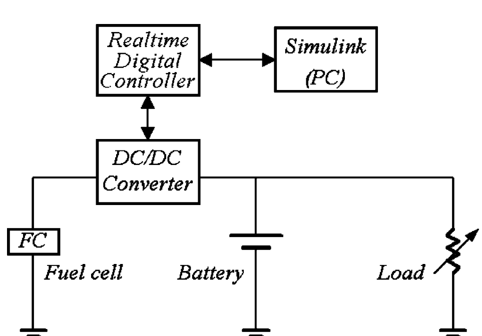

Fig. 1. The active fuel cell/battery hybrid.

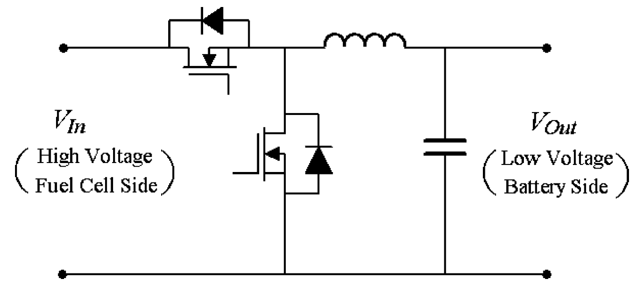

Fig. 2. Circuit of the DC/DC converter.

A real-time digital controller (dSPACE DC1103PPC controller board) was used to control the DC/DC converter. In the experiment, the control algorithm was first developed in Matlab/ Simulink and then compiled and downloaded to the dSPACE hardware. The battery current and voltage and the fuel cell current were monitored and input into the dSPACE controller board through its A/D converters. The real-time controller provided the switch duty commands to the power converter.

Fig. 3 shows a photograph of the hybrid system. Note that the power converter was constructed for general testing purpose and its volume can be decreased dramatically in industrial production. A programmable electronic load (not shown in the picture) was used to generate a pulse current load profile. Some specifications of the experimental system are listed in Table 1. Two different battery packs were adopted in this study: one had a total of six cells with three cells in series and two such strings in parallel; the other used eight cells with four cells in series and two strings in parallel.

By adjusting the duty cycle of the power converter, the fuel cell output current, the battery current and the voltage can be regulated. For such a system, the following are primary considerations: the battery voltage should be regulated to prevent battery pack over charging or over discharging; the battery charging current should be limited to less than the safe maximum; and the fuel cell current should be adjusted to supply appropriate power to the load or to charge the battery as well as be limited to its safe maximum. Therefore, these three parameters including the fuel cell current, the battery voltage and the battery current can be sampled

Table 1
Specifications of the active power source

Battery pack (SonyUS18650)	1400 (mAh) 42 (g/cell), 16.6 (cm^3/cell)
Fuel cell (H-Power D35)	35 W hydrogen-fueled PEM, 25 cells in series, 2900 g including all of the peripherals, 5092 cm^3
Pulse load	Chroma 6310 electronic load
DSPACE	dSPACE DS1103 PPC controller board
DC/DC converter	Buck converter using a synchronous rectifier, about 30 cm^3, 30 g

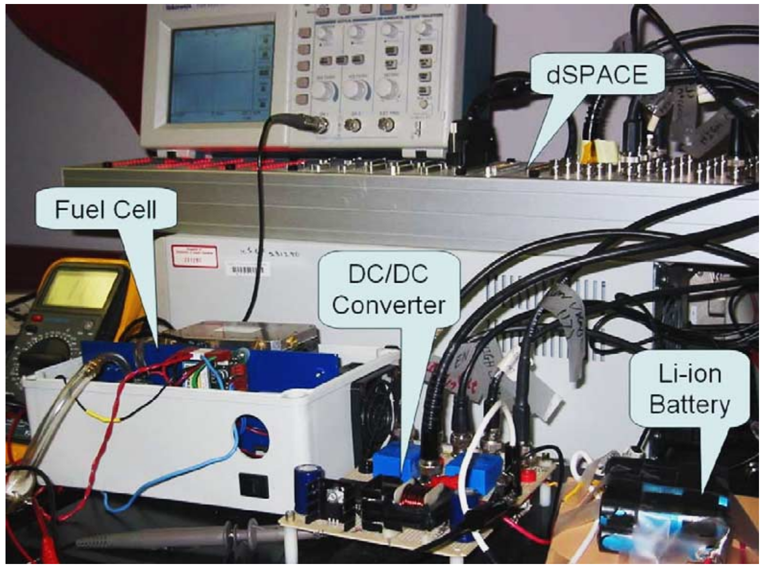

Fig. 3. Experiment setup of active controlled fuel cell/battery hybrids.

and used as the system regulation indices. As a result three system regulation modes are defined: constant battery voltage (CBV), constant battery current (CBC), and constant fuel cell current (CFCC). If the battery voltage exceeds the reference voltage, which may correspond to the condition of no load or light load as well as high battery state of charge, CBV mode applies. Under this mode, the output current of the fuel cell and the charging current of the battery should be below the rated currents. If the battery voltage is below the reference voltage, which may correspond to the condition of heavy load or light load as well as low battery state of charge, CFCC mode or CBC mode may apply depending on the load. If the current demand is lower than the rated output current of the fuel cell, the charging current of the battery may need to be regulated in order to protect the battery, i.e. CBC mode applies. In this case, the fuel cell current is unregulated but is always below the rated current. If the current demand is very high, CFCC mode applies. In this case, the battery may be discharged or charged at a lower rate.

The control strategy was implemented in Matlab/Simulink and tested under the pulsed-current load condition. In the experiments, the Simulink code of the control algorithm was compiled and downloaded to the dSPACE platform to control the real hardware. More details on the control design and implementation are described in [5].

3. Experimental results and discussion

3.1. Power enhancement of active hybrid

The following experimental study demonstrates the power enhancement capability of an actively controlled hybrid compared to a fuel cell alone. In this experiment, the actively controlled hybrid power source used a six-cell lithium-ion battery with three cells in series and two strings in parallel. The battery pack initial voltage was 11.5 V and the charging current was limited to 2.0 A for battery safety considerations (roughly a 1 C charge rate for each cell). The maximum battery pack discharge current, which is mainly determined by the battery cell internal construction, was set at 8.0 A here, corresponding to 4.0 A per cell. A pulse current load was specified with the current profile shown in Fig. 4. The period of the load was 20 s with 3 s high pulse current at 12 A and 17 s low current demand at 0.5 A. The rated power of the fuel cell is 35 W, which corresponds to 2.0 A current with the fuel cell terminal voltage about 17.5 V.

In the experiment, during periods of low power demand, the fuel cell was controlled to generate an average power that was sufficient to serve the load and at the same time to charge the battery; during periods of high power demand, the fuel cell was controlled to generate the rated power and the battery was discharged to satisfy the extra power requirements that exceeded the fuel cell capability.

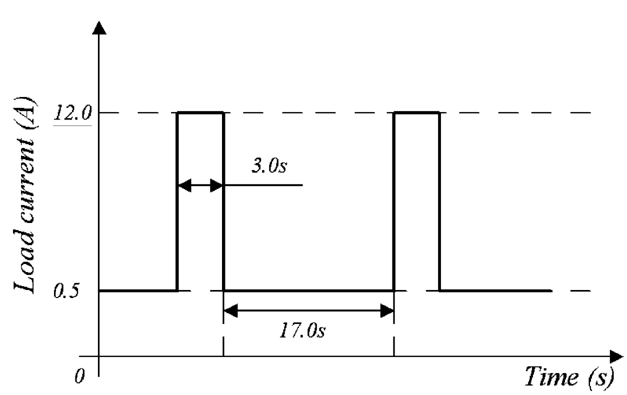

Fig. 4. Pulse current load profile.

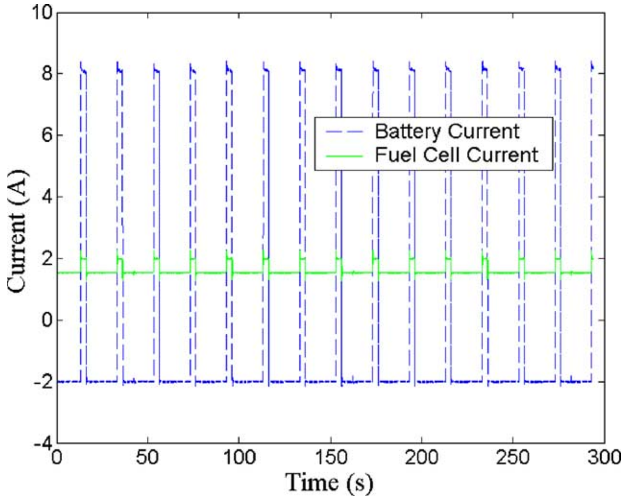

Fig. 5. Current waveforms of the fuel cell and the battery.

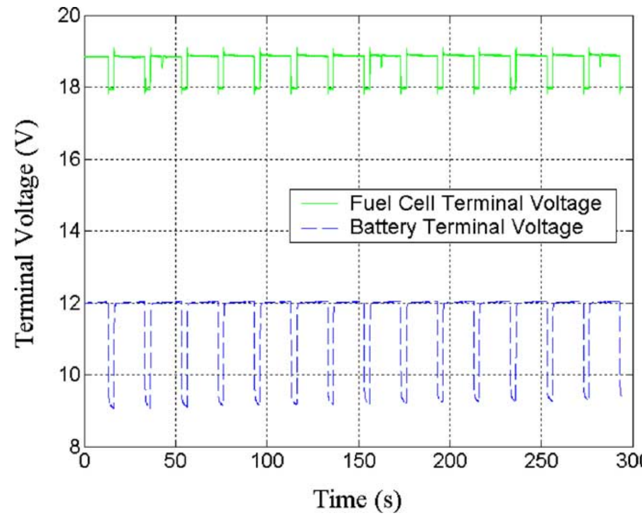

Fig. 6. Terminal voltage waveforms of the fuel cell and the battery.

Eq. (1) describes power conservation in the hybrid system: the net power generated by the fuel cell equals the battery charging/discharging power plus the load consumption.

$$v_{FC} i_{FC} \eta_{Conv} = v_{Batt} i_{Batt} + v_{Batt} i_{Load} \quad (1)$$

where v_{FC} and i_{FC} are the fuel cell terminal voltage and the output current, η_{Conv} is the power converter efficiency which is estimated here at a constant value of 92% to simplify the analysis, v_{Batt} and i_{Batt} are the battery pack terminal voltage and the input current, and i_{Load} is the load current.

When the pulse load requirement is low (0.2 A), the total power requirement of the load and the battery charging is estimated in Eq. (2) in which the load power is about 2.4 W and battery charging power is about 24 W. The maximum net power that can be supplied by the fuel cell and the power converter pair is calculated in Eq. (3), and it is larger than the total power requirements of the load and the battery. Therefore, the hybrid system will operate in CBC mode.

$$P_{Low} = v_{Batt} i_{Batt} + v_{Batt} i_{load} = 12 \times 2 + 12 \times 0.2 = 26.4\,(W) \quad (2)$$

$$P_{MFC} = 35 \times 0.92 = 32.2\,(W) \quad (3)$$

where P_{Low} is the total power requirement during the low level of load profile, and P_{MFC} is the maximum net power of the fuel cell and the power converter pair.

When the pulse load requirement is high (12 A), clearly the load power requirement is much higher than the fuel cell rated power; therefore, the fuel cell is controlled to supply the rated power and the battery then supplies the extra power requirement. At this time, the battery pack discharge current is very high and the battery terminal voltage drops heavily. During this time period, the hybrid system will operate in CFCC mode.

Figs. 5 and 6 show current and voltage waveforms of the fuel cell and the battery during a 300 s experiment. From Fig. 5, it can be seen that, when the load drew low power, the fuel cell current was about 1.55 A, supplying 0.2 A current to the load and at the same time charging the battery at 2.0 A; therefore, the hybrid system worked in CBC mode. When the load drew high power, the fuel cell current was raised to 2.0 A, corresponding to its rated power capability. At the same time, the battery was discharged and its current jumped to about 8.2 A. During the high power demand periods, the system worked in CFCC mode. In Fig. 6, the fuel cell voltage was at about 18.8 V during periods of low power demand, and dropped to 18.0 V during periods of high power demand. The battery pack voltage was held at about 12 V when the load was light, and decreased to about 9 V when the load was heavy.

From the experimental results, it can be seen that the designed control algorithm worked well, and such a hybrid source, using a 35 W PEM fuel cell and a lithium-ion battery pack of six Sony US18650 cells, yielded a peak power of 100 W, about three times as high as the fuel cell alone can supply.

3.2. *Design flexibility and control generality*

In this part, another hybrid source using an eight-cell lithium ion battery was tested to further validate the system control and to demonstrate the flexibility and generality of the hybrid power source design.

One important advantage of incorporating a power converter between the fuel cell and the battery pack is that the battery pack voltage can be different from the fuel cell voltage; therefore, it allows a broader range of the output voltage and provides more flexibility for power source design. After the study of the hybrid source using six cells of battery in the previous section, we increased the battery cells to eight and repeated the pulse current test using the same fuel cell, power converter, and control strategy. The previous specified pulse current profile was also adopted, except that the high current demand value was changed

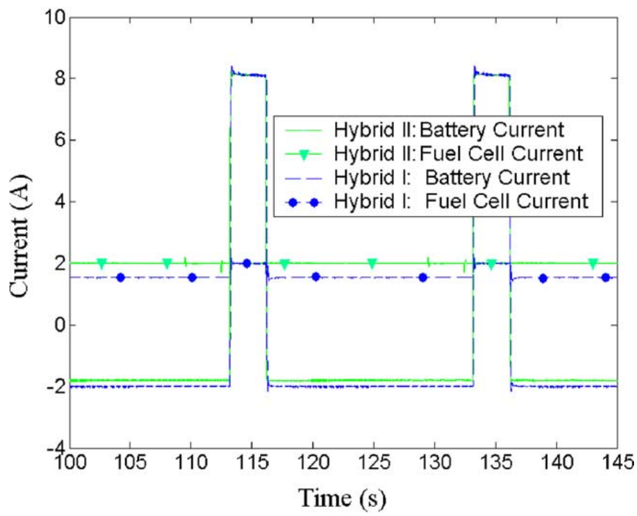

Fig. 7. Fuel cell and battery currents in Hybrids I and II.

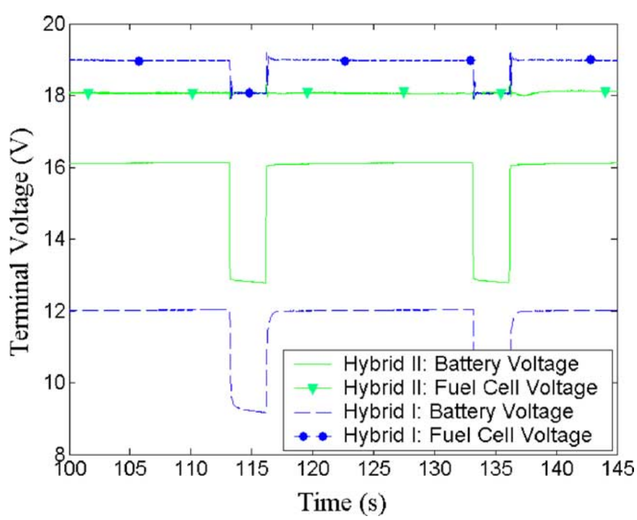

Fig. 8. Fuel cell and battery voltages in Hybrids I and II.

to 10.5 A to make the battery discharge at the maximum current.

Experimental results are shown in Figs. 7 and 8. For convenience, we refer to the hybrid using a six-cell battery as Hybrid I and the hybrid using an eight-cell battery as Hybrid II. Fig. 7 illustrates the current waveforms of both hybrids. It can be seen that the fuel cell current of Hybrid II always kept constant at 2.0 A, corresponding to the fuel cell rated power generation, while the fuel cell current of Hybrid I showed square wave variation and only reached 2.0 A during periods of high power demand. During periods of low power demand, the battery pack in Hybrid II was discharged and the current was about 1.8 A, which was lower than the reference value (2.0 A). This was because the total requirement of the load demand plus the battery charging power was higher than the rated power of the fuel cell. While in Hybrid I, the battery charging current reached its maximum value. When the load power demand was high, the battery pack in Hybrid II was discharged with a high discharging current at about 8.1 A. Fig. 8 shows voltage waveforms of the fuel cell and the battery. The fuel cell terminal voltage in Hybrid II stayed constant at about 18.1 V except for small transient spikes when the load changed power demands. The battery voltage was about 16.1 V when the load was light and about 12.8 V when the load was heavy.

It can be seen that Hybrid II worked only in CFCC mode while Hybrid I switched between CFCC mode and CBC mode. The load drew about 135 W (12.8 V × 10.5 A) during periods of high power demand, which was about 4 times as much as the fuel cell alone can supply, and was also higher than the peak power capability of Hybrid I, because Hybrid II used two more cells of battery than Hybrid I.

3.3. Source comparison

Three power sources including the fuel cell alone and the two hybrid power sources studied are compared in terms of specific power, power density, volume, and weight.

Even though the battery pack and the converter contribute increase in both mass and volume, the specific power and power density are still dramatically increased for the active system due to its high power capacity. This is summarized in Table 2 in comparison to the fuel cell alone for the previously specified pulse current load conditions (a period of 20 s and a duty ratio of 15%). It can be seen that the specific power of the active hybrid using eight cells of battery is 1.2 times that of the active hybrid using six cells of battery and 3.4 times that of the fuel cell alone. The power density comparison gives a similar conclusion. Note that the volume of hybrid power sources is as the same as the fuel cell alone since

Table 2
Comparison of three power sources

	Fuel cell alone	FC/Batt Hybrid (I)	FC/Batt Hybrid (II)
Configuration	Fuel cell: D35	Fuel cell: D35 Battery: 3 × 2 US18650 DC/DC power converter	Fuel cell: D35 Battery: 4 × 2 US18650 DC/DC power converter
Weight (g)	2900	3182	3266
Volume (cm^3)	5092	5092	5092
Power capacity (W)	35	110	135
Specific power (W/kg)	12.1	34.6	41.3
Power density (W/cm^3)	6.9 e-3	2.16 e-2	2.65 e-2

the original fuel cell case is loose and the battery and the converter can be inserted into it. It is clear that the active system is superior in terms of specific power and power density. The weight increases of the active fuel cell/ battery hybrid power sources are only 9.7 and 12.6% of the weight of the fuel cell alone, respectively. Similar results can also be found in the volume comparison.

4. Conclusion

Experimental studies of two active hybrid fuel cell/battery power sources have been presented with attention to their power enhancement, system control design, specific power, and power density. A DC/DC power converter has been incorporated in the power sources to actively control the power flow between the fuel cell and the battery for achieving both high energy and high energy densities. Experimental results show that both the hybrid power sources using a six-cell battery and an eight-cell battery are effective, but the latter yields higher peak power capability. The hybrid source using a 35 W fuel cell and eight cells of lithium-ion battery yields 135 W peak power with only about 13% weight increase, and the corresponding specific power of the active hybrid is 3.4 times that of the fuel cell alone. The design can be scaled to larger or smaller power capacities for a variety of industry applications.

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