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Fuel cell/electrochemical capacitor hybrid for intermittent high power applications

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Abstract

A hybrid power source was demonstrated to successfully power a simulated power load encountered in portable military electronics and communications equipment. The hybrid system consisted of a 25 W proton exchange membrane fuel cell (PEMFC) stack connected in parallel with a 70 F capacitor bank. The cyclic regime of 18.0 W for 2 min followed by 2.5 W for 18 min was chosen as the baseline for the simulation of power load. The operating potential cut-off voltage for pass/failure was set to 3.0 V. At room temperature (23–25°C), the PEMFC alone could not handle the described baseline regime with the PEMFC operating potential dropping below the cut-off voltage within 10 s. The hybrid, however, continuously powered the same regime for 25 h. Its operating potential never reached the voltage cut-off point, not even during the high load of 18.0 W. The tests with hybrid configuration were aborted after 25 h of operation with no signs of output degradation, suggesting that further extended operation was possible.

Keywords: Fuel cell/electrochemical capacitor hybrid; Proton exchange membrane fuel cell; Power source

1. Introduction

Because of their high-energy density, fuel cells are being actively investigated for use in portable electronics and communications equipment. For these specific applications, in addition to the high-energy density, the power capabilities of fuel cells are of interest. In general, fuel cells demonstrate good power capability during continuous operation; however, the response of fuel cells to instantaneous power demands is relatively poor. For example, PEMFC's often require up to 5 min to reach an operational steady state at a constant power load, during which individual cells of the stack become highly polarized. This polarized state is detrimental to the PEMFC stack and in many instances involving instantaneous power increases, the PEMFC's operating potential does not recover. This translates into fuel cells alone having great difficulty handling periods of high power pulses. The development of power assistance for PEM fuel cell is, therefore, of great interest.

Past effort [1] demonstrated the successful implementation of a PEMFC stack together with a lead/acid battery to form a hybrid. Such hybrid successfully powered the baseline described previously. Electrochemical capacitors are also of interest for this kind of applications because of their high power density. Fully packaged electrochemical capacitors have shown specific power densities of up to 2000 W/kg and specific energy density of up to 4.5 Wh/kg [2,3]. The utilization of such electrochemical capacitors in the power assistance of fuel cell stacks could allow for a system that has the energy density advantage of fuel cells and the high power output capability of electrochemical capacitors.

2. Experimental

For this effort a 6-cell proton exchange membrane (PEM) fuel stack was used. The fuel cell had a nominal rating of 4.0 V at 25-W load and open circuit voltage as high as 6.0 V. The stack used ambient air for both the reactant oxygen and for coolant air across a heat sink. The coolant air removed the heat energy produced by the electrochemical reaction. Zero grade (99.999%) com-

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pressed hydrogen, regulated to 1 psig, was used as fuel. The dead-ended design cell stack was fitted with a purge, which was activated for 1 s every 5 min. This purging of the system prevented the build-up of contaminants that eventually would reduce stack's performance.

Commercially available electrochemical capacitors with carbon electrodes and organic electrolyte were used for this effort. Panasonic 'Gold' power series capacitors; rated at 2.5 V and 10 F capacitance were selected. These capacitors are characterized by low leakage current (80 μA—measured following 5 h of charging), stable open circuit voltage (after 48 h from the initial 2.5 V the potential dropped to 2.27 V), and relatively low equivalent series resistance (72 mΩ—measured at 1 kHz). The capacitance measured from the discharge of a single capacitor at 100 mA was 14.2 F with a 95% charge to discharge efficiency.

Twenty-eight capacitors were connected in a series/parallel configuration to form a 2×12 bank of capacitors. This capacitor bank had a nominal capacitance of 70 F at 5.0 V. The total capacitance of the bank, as measured during continuous 1.0 A charge/discharge cycles at 5.0 V, was 114.5/107.3 F. The internal resistance of the capacitor bank, measured from the voltage drop during charge and discharge cycles, was 25 mΩ.

All testing was conducted with a Techware Automated Battery Cycler (ABC). The ABC is capable of constant power cycling to a maximum of 5.0 A. During testing, the operating voltage and current were monitored continuously and the test temperature was maintained in a Tenney Jr. environmental chamber.

Initial 18.0 W continuous power tests were conducted at 4.4°C, room temperature (23–25°C), and 37.7°C. These test were designed to determine the limits of the PEMFC alone at 18.0 W continuous power. Performance of the PEMFC alone and hybrid was determined at various radio simulations. These simulations represent typical transmit and receive duration and power for communications electronic devices. The tests that were performed at 4.4°C and room temperature (RT) were designed to last for 25.0 h of continuous operation. Operating voltage, current and internal stack temperatures were monitored and recorded.

3. Results

The 25 W PEMFC stack by itself could not power the high load pulse of high/low power cyclic regimes. The baseline profile of 18.0 W for 2 min followed by 2.5 W for 18 min, for example, was a great strain on the stack alone. During the 18.0 W pulse the stack operating potential substantially dropped and became very erratic. Within 10 s , the stack voltage fell below the 3.0 V cut-off voltage.

A 70-F capacitor bank connected in parallel with the 25 W PEMFC successfully powered the baseline regime described above. Fig. 1 shows the system baseline curve at RT with and without the 70-F capacitor attached. It clearly shows that the PEMFC alone could not power the 18.0 W load. During the first ten cycles (200 min) the hybrid successfully powered the entire regime. The operating voltage never dropped below 3.0 V, even during the high 18.0 W load. Following the 2-min high load sequence of the 11th cycle, the capacitor was disconnected from the fuel cell. This is denoted by region A in Fig. 1. At this instance, the PEMFC alone was successfully powering the low load section of cycle 11. Following the 18 min of low load, it is shown that the PEMFC alone failed to power the 18.0 W pulse of cycle 12 (region B). The stack potential immediately fell below 3.0 V and never recovered. This demonstrated the inability of the fuel cell alone to maintain operating potential above 3.0 V during pulse power operation.

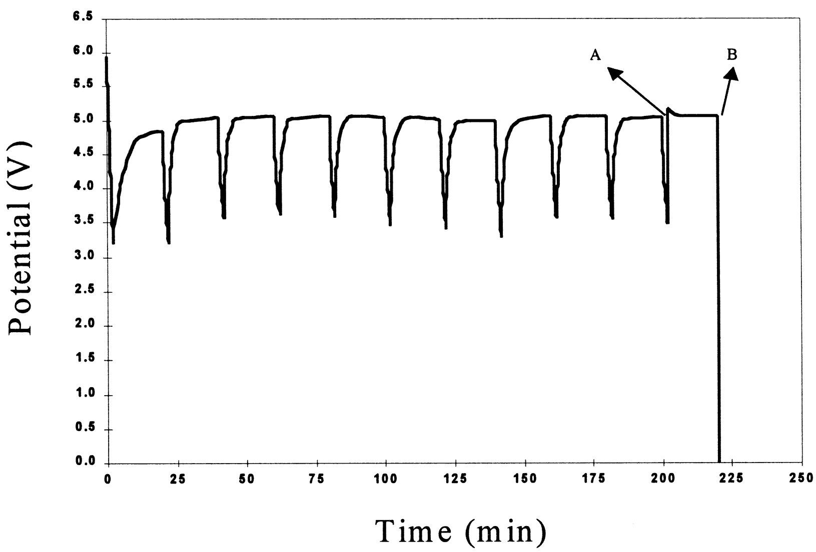

Fig. 1. System (25 W PEMFC and 70 F capacitor hybrid) baseline curve.

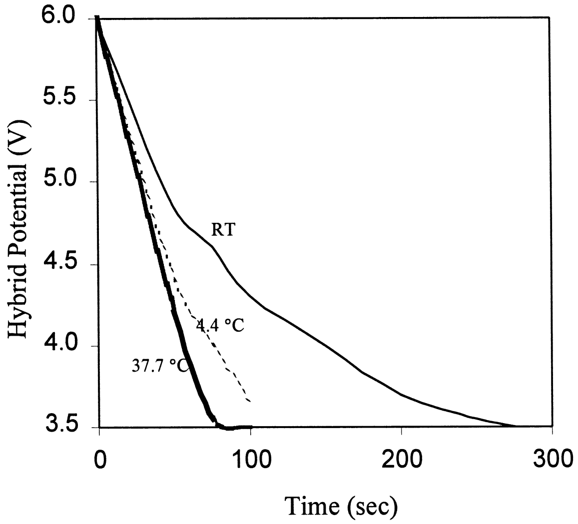

Fig. 2. Hybrid: 18 W continuous discharge.

Fig. 2 displays the hybrid limits at constant power discharge of 18.0 W (worst case scenario). Tests were run at 4.4°C, RT, and 37.7°C. At 4.4°C and RT, hybrid performance clearly followed the effects of ambient temperature on concentration polarization. Fig. 2 shows that up to 300 s continuous 18.0 W RT operation can be achieved utilizing the hybrid configuration. This data, combined with the fact that it often requires up to 5 min for a non-hybrid PEMFC to recover to an operational steady state when a power load is instantaneously applied, demonstrates the benefit of the hybrid configuration.

A PEMFC becomes excessively polarized when a power load is instantaneously applied. This is due mainly to mass transfer limitations within the membrane of the PEMFC. The hybrid configuration allows for a gradual increase in mass transfer within the membrane allowing for the establishment of steady state diffusion without subjecting the stack to deep polarization. This is a result of the capacitors assuming the initial load and the fuel cell gradually providing the required power as the capacitors' voltage drops. At cold temperatures the power-handling device of the hybrid requires higher capacity (capacitance) to overcome the additional transport resistance introduced with temperature.

Fig. 2 also shows the results at lower ambient temperatures, where chemical activity is reduced; therefore, increasing the internal resistance and reducing performance of both components. At 37.7°C; however, the six membrane electrode assemblies (MEAs) of the PEMFC stack quickly 'dried out' due to moisture loss. At this stage the proton conductivity was significantly reduced; thus, lowering fuel cell performance. The MEAs were rehydrated by 4.0 A continuous discharge for 12 h. Due to the unreliability at 37.7°C, evaluation at this temperature was discontinued.

At 4.4°C, the hybrid failed to successfully power any regime consisting of transmit load (18.0 W) durations of 2 min or longer. Fig. 2 shows this. At 4.4°C and 18.0 W continuous discharge, the hybrid 'lasted' for slightly more than 100 s. For up to 1 min transmit durations; the hybrid successfully powered regimes with the receive period as low as 3 min (2.5 W).

Table 1 tabulates the hybrid performance at the various temperatures and cyclic profiles. At each regime, the hybrid operating potentials at the transmit and receive loads is listed. The operating potential cut-off voltage for pass/failure is 3.0 V. At 4.4°C, the hybrid successfully powered the cyclic regime of 1-min high load (18.0 W) followed by 3 min low load (2.5 W) for 25 h continuous. This means that the PEMFC stack required only 3 min to recharge the 70-F capacitor assembly to a charge state sufficient to 'assist' the stack for the next high load pulse of 18.0 W.

At RT, the hybrid successfully powered cyclic scenarios consisting of transmit durations of up to 3 min. Fig. 2 demonstrates this. At RT and 18.0 W continuous discharge, the hybrid capacity was enough for approximately 250 s of operation down to 3.5 V. Transmit durations of 1, 2, and 3 min required receive lengths of as low as 1.5, 3, and 4.5 min, respectively. This means, for example, that for 3 min transmit (18.0 W) the PEMFC stack required 4.5 min of receive (2.5 W) period to recharge the capacitors for the next cycle. Note that the hybrid will run any cyclic scenario with transmit: receive ratio of 1:1.5 for up to 3 min transmit (18.0 W). This specific duty cycle provides sufficient charging time for the capacitor assembly. This allowed for continuous hybrid operation.

Testing of the hybrid performance at 37.7°C showed that dehydration of the fuel cell stack is the major limitation to its performance. Two individual runs were attempted with the fuel cell at 37.7°C. These experiments were conducted to determine if the hybrid configuration could overcome the conductivity limitation of the PEMFC due to 'dried out' conditions caused by high-temperature operation. Duty cycles of 1 min transmit followed by 9 min receive and 1 min transmit followed by 30 min receive were used. The result of the 1 and 9 test shows that the PEMFC did not have sufficient time to recharge the capacitor for the next pulse. When the 1 and 30 test was performed, the results were similar. The operating potential is significantly lower than at both 4.4°C and RT. The potential of the hybrid quickly fell below the 3.0 V cutoff

Table 1
Hybrid performance

Ambient temperature) (°C)	Cyclic regime (transmit/receive)	Transmit operating potential (V)	Receive operating potential (V)
4.4	1:3	3.7	5.0
RT	2:3	3.8	5.2
RT	3:4.5	3.9	5.3
37.7	1:9 to 1:30	[a]	4.5

[a] Load sustained by capacitors only.

at the start of the second cycle. This is all result of the MEAs of each cell of the PEMFC stack drying out, thus drastically affecting its performance.

4. Conclusions

A hybrid design of PEM fuel cell and a bank of electrochemical capacitors successfully powered an instantaneous power load of 18 watts that corresponds to the transmission cycle of a radio equipment under consideration. As it was shown, the PEM fuel cell with nominal power rating of 25 W alone could not handle such high power pulse load with the voltage dropping below the cut-off point. The hybrid configuration, however, powered this load for extended time and a variety of duty cycles, and also in certain range of temperatures. In doing so, the capacitor was responsible for improved performance of the system by assisting the fuel cell in handling the initial pulse load allowing slower and gradual transition of the fuel cell to the higher power level. During following receive or standby cycles, the fuel cell was able not only to drive the base load but also to recharge the capacitor bank to its operating voltage. This mechanism allows to view such a system as a high energy and high power density system and optimize its design for performance, size or weight.

References

[1] L.P. Jarvis, T.B. Atwater, E.J. Plichta, P.J. Cygan, Power assisted fuel cell, Journal of Power Sources 70 (1998) 253–257.
[2] US Department of Energy, Capacitor State-of-the-Art Overview, Proceedings IAPG Meeting, Newport, RI, 9–11 May 1995.
[3] T.C. Murphy, G.H. Cole, P.B. Davis, Temperature Effects on Ultracapacitor Performance: INEL Test Results, Proceedings of the 5th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Boca Raton, FL, 4–6 December 1995.