ELSEVIER

Journal of Power Sources 80 (1999) 242–247

JOURNAL OF POWER SOURCES

A hybrid power source for pulse power applications

Peter B. Jones [a], J. Barry Lakeman [a], Gary O. Mepsted [a,*], Jon M. Moore [b]

[a] Defence Evaluation and Research Agency, Haslar, Gosport, Hants PO12 2AG, UK
[b] Loughborough University, Loughborough, Leics LE11 3TU, UK

Received 2 December 1998; accepted 20 December 1998

Abstract

Portable 12 V power supplies are used extensively for communications and power tool applications. These devices demand fast response times of the power supply. Fuel cells are generally best suited to continuous power applications and require an initial warm-up period, although they offer the prospect of increased operational duration over a battery for a given weight of portable system. This paper investigates the combination of specific energy performance from the fuel cell system with the specific power and response time of the battery. Two separate hybrid systems have been developed and tested; a planar, 20-cell, polymer electrolyte membrane fuel cell (PEMFC) stack together with either a lead–acid or nickel/cadmium battery; and a conventional 20-cell, bipolar, PEMFC stack. Both systems have been tested under pulse-load conditions at temperatures between −20°C and +40°C, and for comparison, the individual components have undergone similar tests. The hybrid systems have successfully operated continuously for several weeks under load profiles that the fuel cell alone could not sustain. Crown Copyright © 1999 Published by Elsevier Science S.A. All rights reserved.

Keywords: Fuel cells/polymer electrolyte membrane; Hybrid power sources

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFC) are being actively investigated for use in portable electronics and communications equipment as a result of their potentially high specific energy as a total system of fuel cell and portable fuel source. While the continuous power output of a PEMFC is good, its response to instantaneous loads, especially from a cold-start, is relatively poor. From start-up, a PEMFC requires a few minutes to heat up and to humidify the polymer electrolyte membrane before optimum performance can be achieved.

During this time, the fuel cell becomes highly polarised, which leads to loss of voltage and power output, wasted fuel, and the increased possibility of permanent damage to the polymer electrolyte membrane. In applications with extended periods of inactivity (e.g., the equipment is in stand-by mode) followed by instant high-power demands, this problem is compounded and it becomes necessary to waste fuel and power to keep the fuel cell in a state of readiness.

Military electronic equipment must be able to operate in a variety of environmental conditions and temperatures. To ensure this requirement is satisfied, batteries are subjected to a number of standard tests with which they must comply, including designated temperature ranges for storage and operation.

Fuel cell systems will also have to satisfy these standards if they are to be used by the military, and the low temperature requirements would be difficult to achieve unless the fuel cell was significantly over-sized (and over-rated).

A fuel cell/battery hybrid system could have a number of advantages over either stand-alone component. Providing that the temperature was not too low, the battery would enable instant cold-start operation since it would provide the majority of the load requirement whilst the fuel cell was warming up. It would condition the power output from the fuel cell to provide a voltage range that would be acceptable to the equipment since most devices are already designed to withstand the load characteristics of a battery. A hybrid system would allow both components to be of smaller dimensions and operate with higher efficiency since neither would have to provide full load and capacity. The fuel cell would provide enhanced capacity and recharge capability.

Some initial studies with hybrid systems have been published on low-power units with 4 V outputs at 5 A,

---

[*] Corresponding author

PII: S0378-7753(99)00074-9

incorporating both a fuel cell and capacitor assembly, or a fuel cell and lead–acid battery [1]. The aim of this paper is to describe the construction and testing of a 12 V, 60 W hybrid power source which could be used in a range of military equipments and would also be applicable for civilian uses, such as in power tools.

2. Experimental

All load-cycle testing was conducted with Bitrode automated battery cycling units, which also recorded temperature, current and voltage of the system. Low temperature experiments were housed in an Heraeus environmental chamber (−40°C to +140°C). Shunt resistors were employed to measure the contribution of currents from the battery and the fuel cell stack to the overall power output and an Anville 420 data logger was used independently of the Bitrode to separately record voltage and current for each component.

To simulate an averaged, typical pulse-load profile, as would be required by a number of equipments, a load cycle consisting of a background current of 210 mA for 15 min followed by a pulse load of 4.8 A for 30 s (a time-averaged current of 0.36 A) was used. This type of load profile demonstrates the power source's ability to cope with prolonged periods of inactivity together with demanding peak currents.

In additional experiments (to simulate the use of these power sources in other applications where continuous current may be required) the systems were subjected to a constant 2 A load.

Two PEMFC stacks were used in this investigation: The first consisted of twenty circular cells externally connected in series. The membrane/electrode assemblies used were manufactured with Nafion-112 electrolyte and E-tek electrodes, with an active area of 26 cm^2. Hydrogen was regulated to 0.7 bar (10 psi(g)) and fed in parallel, through an external manifold, to each cell. The second was a 20-cell bipolar stack (utilising 30 μm thick Gore-Select series 5510 membrane with 0.3 mg cm^{-2} of platinum catalyst and an active area of 40 cm^2) constructed from stainless steel. For each stack, a switch-operated solenoid valve was connected in-line to the exhaust to allow for periodic, manual, purging of water from the hydrogen flow field. Both stacks were designed to operate on ambient air without forced convection, provided the air supply was unrestricted.

The hybrid system employed either a Yuasa sealed lead–acid (12 V, 1.2 A h) or a nickel/cadmium (12 V, 0.7 A h) battery pack. The battery was connected in parallel with the fuel cell, and with a solid state voltage limiter in order to prevent the voltage fed to the battery from exceeding its recommended charging voltage.

Both the fuel cell and battery, together with the regulator circuit board, were housed in a Perspex box with an air inlet hole on the side and exhaust on the top. A miniature printed circuit board fan was used to assist the circulation of air through the enclosure.

3. Results and discussion

3.1. Performance of the circular fuel cell stack alone

The circular fuel cell stack was able to sustain the pulsed load profile (Fig. 1) provided that it was regularly purged and the environment temperature remained at or

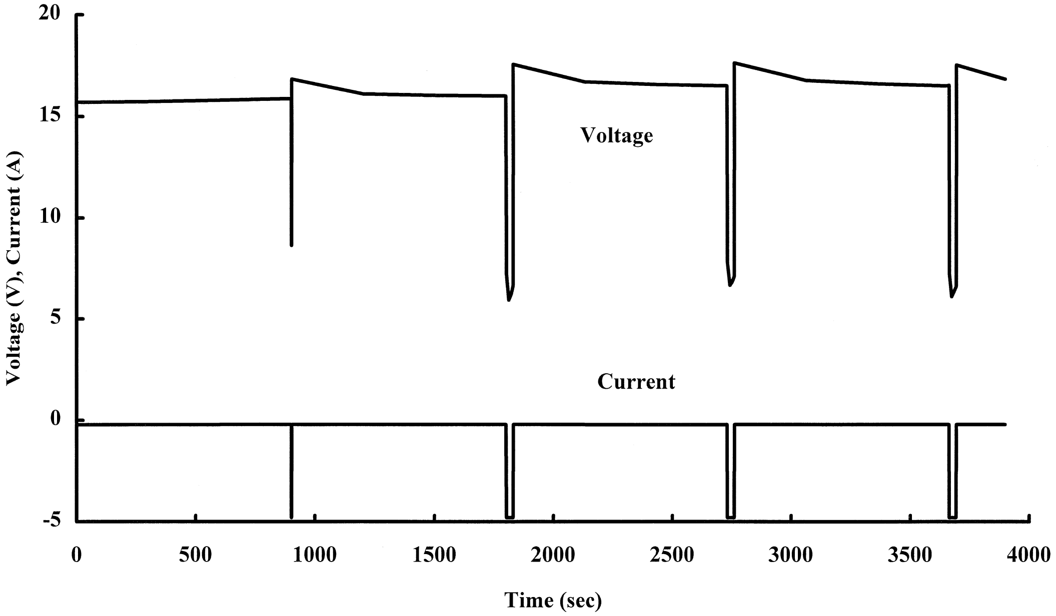

Fig. 1. Performance of a circular fuel cell stack under pulse-loads of 4.8 A for 30 s every 15 min plus a base load of 210 mA.

above 20°C. However, the wide voltage range output from the fuel cell under this load profile would be unacceptable for most electronic equipment and its ability to operate successfully after a prolonged period of inactivity or at lower ambient temperatures was severely limited. This profile is particularly difficult for fuel cells to follow since the time spent at the background current is sufficient to allow them to cool to ambient temperature. At this low current, the membrane has a tendency to dry out as air is drawn over the cathode, increasing the internal resistance which is disadvantageous for the high current phase of the duty-cycle. To operate a fuel cell successfully on this load profile it would be necessary to size it such that the high current load could be drawn at a lower current density, nearer to its open-circuit potential. A fuel cell of this size would not need to warm up to achieve the power output and any loss of efficiency from a dry membrane would be counteracted by the excess capacity in the stack. This approach, however, has several disadvantages including the physical size, weight and cost of the fuel cell stack, and the increased loss of hydrogen fuel (and so A h capacity) through the larger membrane surface.

The bipolar stack was unable to sustain the load profile, as the first pulse reduced the voltage to below the safety cut-out (8 V) which was initially surprising as it has a larger active area than the circular stack. However, it had a very high internal resistance as the bipolar plates were of an older design, with minimal contact area between the membrane electrode assembly (MEA) and the stainless steel bipolar plate, which had not been treated to prevent an insulating passive layer from forming on its surface. These factors ensured that the fuel cell operated rather inefficiently; the voltage drop on load was excessive and it was prone to over-heating and, therefore, it dehydrated.

3.2. Performance of the battery alone

To investigate the voltage characteristics of the battery on this load profile, the battery cycling unit was made to simulate the fuel cell for charging purposes. The lead–acid battery (1.2 A h) operated between 13.8 and 11.4 V at 20°C (Fig. 2). Without charging, the battery would have lasted a maximum of 3 h 20 min.

3.3. Performance of the circular stack fuel cell / lead–acid battery hybrid on a pulsed load

Fig. 3 shows this hybrid system following the load profile for six days continuously in one test. During this period, the fuel cell required no purging since the battery allowed the fuel cell to operate at its optimum design point, so enabling water to be naturally evaporated without any significant build-up on the anode side. Loss of hydrogen from purging the fuel cell can result in a major reduction in the available capacity of the system, and minimising this parasitic loss is of primary importance if

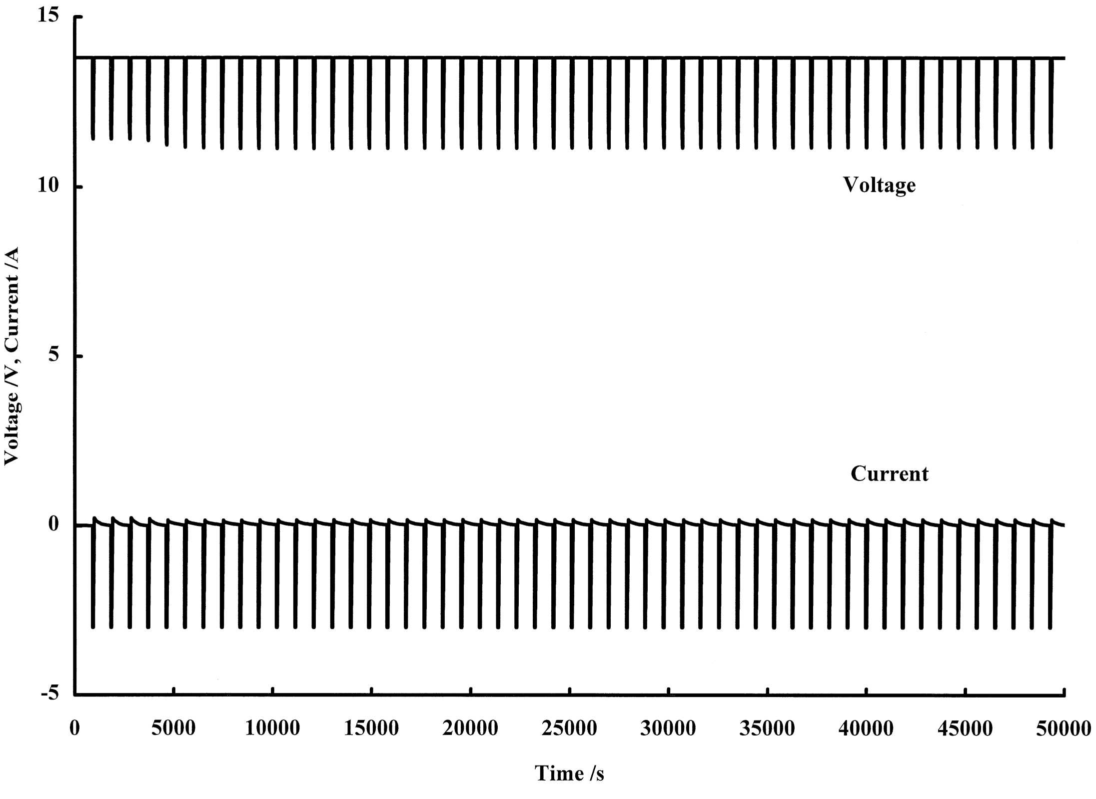

Fig. 2. Performance of a 1.2 A h lead–acid battery discharging continuously for 14 h under pulse-loads of 4.8 A for 30 s every 15 min plus a base load of 210 mA, whilst being float charged from a cycling unit.

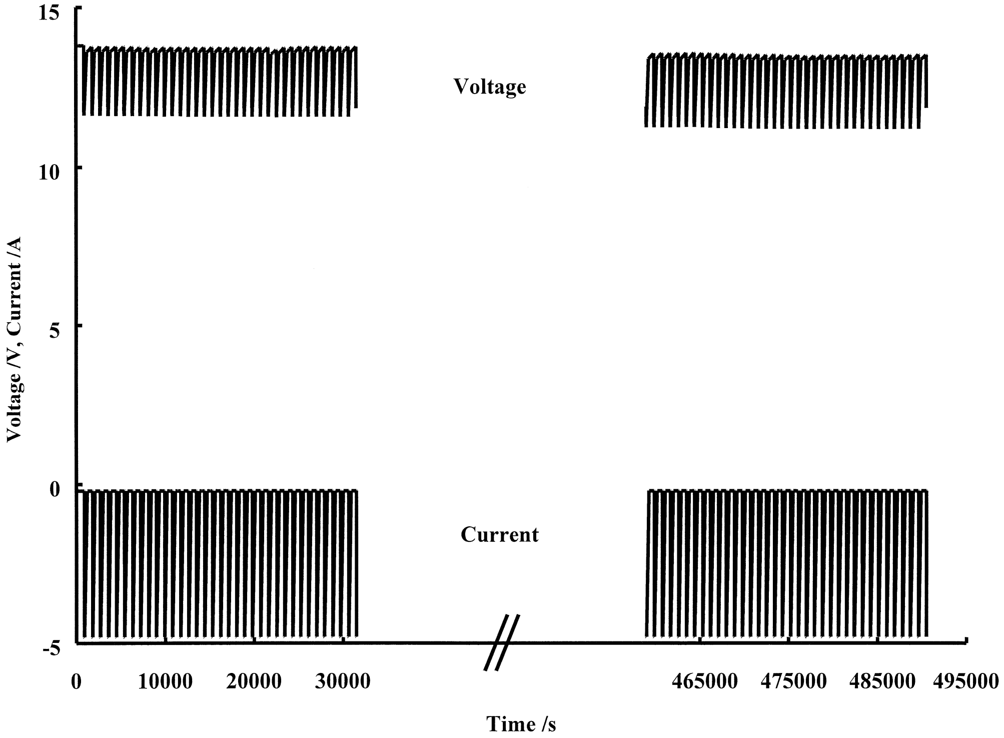

Fig. 3. Performance of a circular fuel cell stack/lead–acid battery hybrid discharging continuously for 6 days under pulse-loads of 4.8 A for 30 s every 15 min plus a base load of 210 mA.

the system is ever to compete with high-capacity batteries. The presence of the battery allowed the system to provide instant start-up capability whilst the fuel cell temperature rose to operating levels. The slight lowering of overall system voltage, observed after a few days of operation, occurred as a consequence of the build-up of water at the anode. After several days of operation this had reached an equilibrium position and the voltage stabilised. Purging the cell quickly returned the voltage to its original value (not shown in Fig. 3).

At ambient temperature, the circular fuel cell stack/lead–acid battery hybrid, operated between 11.2 V (54 W) on the pulse load and 13.8 V (3 W) on background load, which compares favourably with the fuel cell alone. During this test, the fuel cell temperature fluctuated by 2°C from its steady-state of 32°C, which was within design limits.

As the environment chamber temperature was progressively lowered, the output voltage range of the hybrid system was altered (Table 1). In particular, the power output during the pulse loads was reduced as the temperature of the system dropped, primarily due to temperature characteristics of the lead–acid battery which had a recommended operating temperature between +5°C and +35°C. In fact, the failure of the system at −10°C was due to the battery. Replacement of the lead–acid battery with a nickel/cadmium 12 V pack (0.7 A h) enabled the system to operate down to −20°C prior to failure.

At low temperature, a fuel cell operates less efficiently as a result of reduced proton conduction through the membrane. This would lower the overall capacity of the hybrid for a given amount of fuel storage. However, separate tests conducted in the environment chamber with single cells, using the same technology as the circular

Table 1
Output from the fuel cell/battery hybrid with varying temperature

Temperature (°C)	Volts at 0.21 A (V)	Power at 0.21 A (W)	Volts at 4.8 A (V)	Power at 4.8 A (W)
20	13.8	2.9	11.6	55.7
10	13.8	2.9	11.4	54.7
5	13.8	2.9	11.4	54.7
0	13.8	2.9	11.1	53.3
−5	13.8	2.9	10.8	51.9

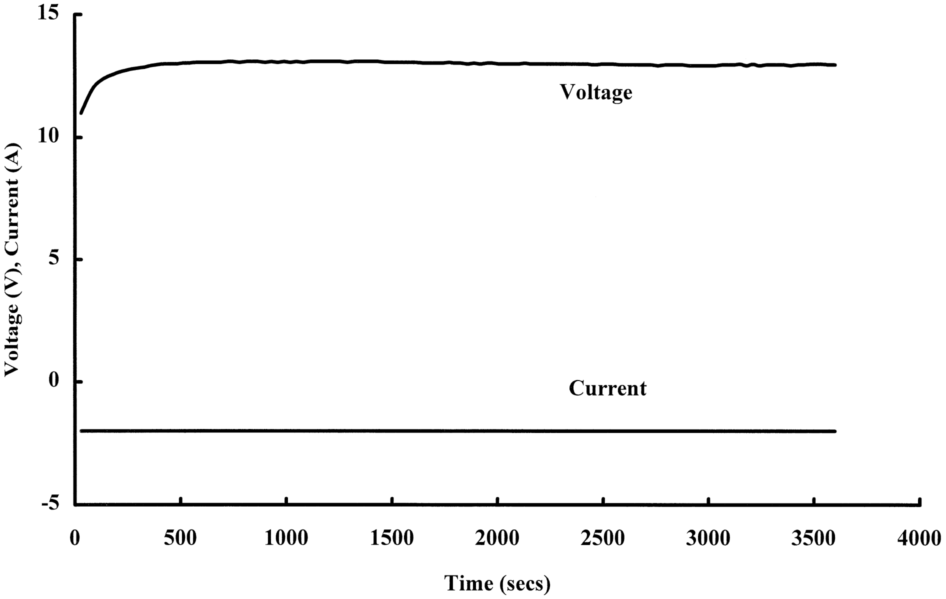

Fig. 4. Performance during the first hour of a circular fuel cell stack/lead–acid battery hybrid discharging continuously at 2 A.

cells, have shown that the fuel cell was able to operate down to −20°C, beyond which the formation of ice on the cathode access holes starved the cell of oxidant. The single cell was not insulated or packaged, so the surrounding temperature would have had a greater effect than it would on an integrated stack within an enclosure. It seems likely that low temperature operation will be possible with a suitable battery, but to maintain the system it may be necessary to operate it with a higher background current to keep the fuel cell stack warm. This would have the effect of depleting the fuel store, with a concomitant reduction in capacity.

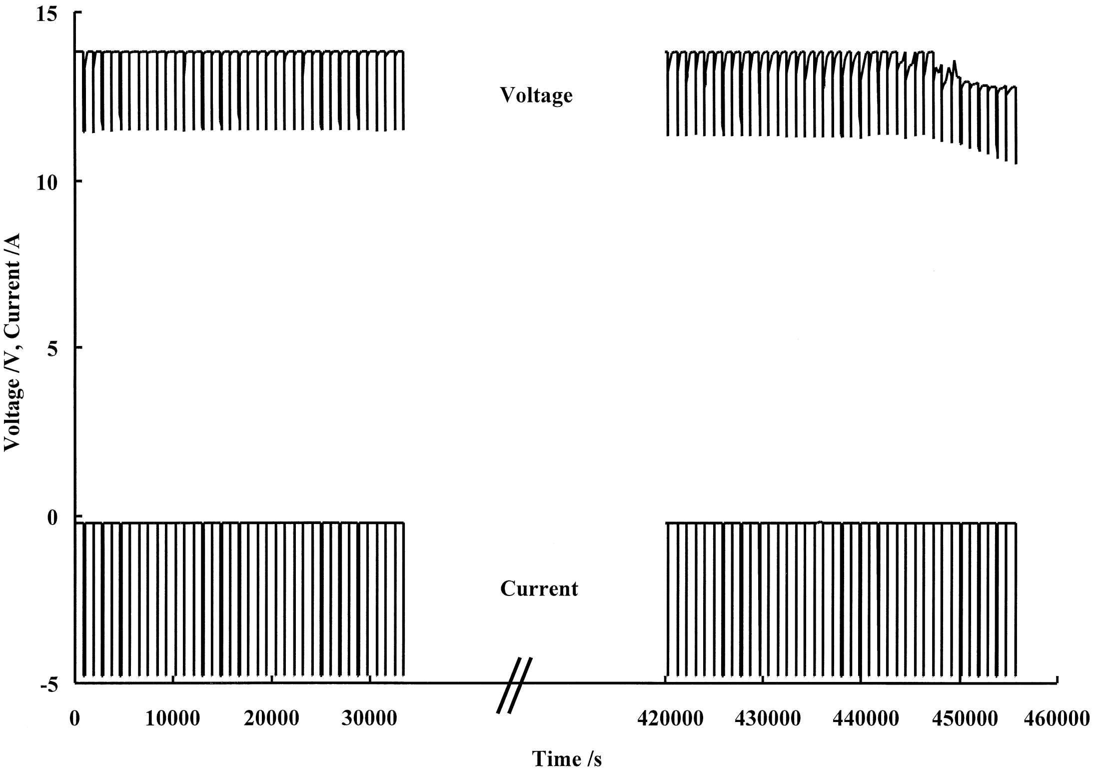

Fig. 5. Performance of a bipolar fuel cell stack/lead–acid battery hybrid discharging continuously for over 5 days under pulse-loads of 4.8 A for 30 s every 15 min plus a base load of 210 mA.

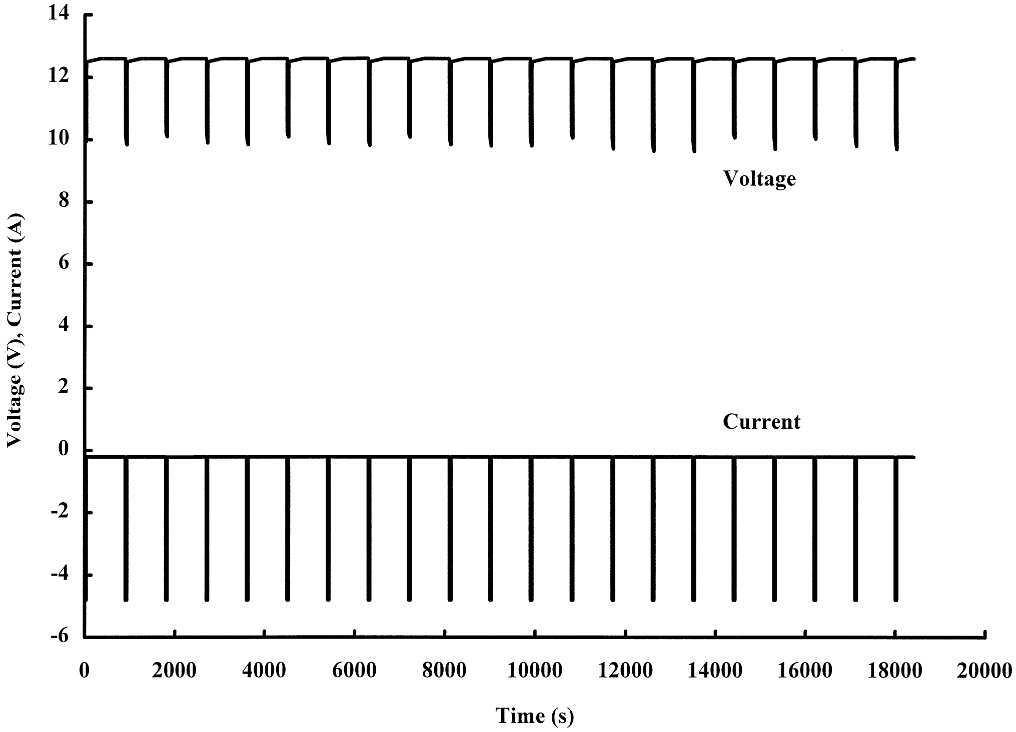

Fig. 6. Performance of a circular fuel cell stack/lithium-ion rechargeable battery hybrid discharging continuously for 5 days under pulse-loads of 4.8 A for 30 s every 15 min plus a base load of 210 mA.

3.4. Performance of the circular stack fuel cell / lead–acid battery hybrid on a steady load

Operation of the hybrid system on a continuous load of 2 A was conducted at ambient temperature (Fig. 4). While the fuel cell could sustain a continuous current for long periods, it is also required to deliver current at charge voltage to the battery to prevent this becoming discharged, as it is still needed in this scenario to provide instant start-up and allow the fuel cell time to reach operating temperature. This hybrid system was able to provide 2 A continuously, as the fuel cell voltage at this current was 14 V and during this time it reached an operating temperature of 42°C.

3.5. Performance of the bipolar fuel cell stack / battery hybrid on a pulsed load

Fig. 5 shows that, once a lead–acid battery had been connected to the bipolar fuel cell stack, it was able to sustain the cycle load in a similar manner to the circular system. However, this fuel cell did not operate as efficiently, which meant that it was prone to over-heating and it required periodic purging of the anode in order to maintain voltage. Low temperature operation established that the fuel cell voltage was quickly reduced to below the float-charge voltage of the battery, which caused the latter to slowly discharge. Since the float-charge voltage of the lead–acid was a little too high for this fuel cell, this battery was replaced with three Sony 26650 lithium-ion cells connected in series. This system had a float-charge requirement of 12.6 V and the hybrid followed the pulse load profile for 5 h at ambient temperature without any noticeable degradation in performance (Fig. 6).

4. Conclusions

Man–portable fuel cell systems, with a lightweight fuel store, are potentially longer lasting than batteries, but are not sufficiently optimised to meet every user's load profile. Additionally, compact fuel source technologies are, as yet, not sufficiently advanced for the whole system to be as compact as a battery.

Two fuel cell/battery hybrid power sources were constructed and successfully tested under pulse-load conditions. Comparisons with a battery or fuel cell stack alone showed that the hybrid arrangement enabled successful operation during cold start-up periods and was more capable of delivering high current pulses. A hybrid system allowed both components to be downsized with respect to what would be necessary if they were used individually and enabled the fuel cell to operate at optimum efficiency. Thus, hybrid systems combine the capacity of fuel cells (dependent on fuel storage only) with the instant start-up benefits of a battery.

References

[1] L.P. Jarvis, T.B. Atwater, P.J. Cygan, Proc. 2th Annual Battery Conf., Calif. State Univ., Long Beach, CA, USA, 1997, p. 37.