

A Fuel-Cell-Battery Hybrid Platform for Portable Embedded Systems^{*}

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Abstract: A portable proton exchange membrane (PEM) fuel cell operates at room temperature, has an energy density which is 4 to 6 times larger than that of a Li-ion battery, and thus is a promising next generation power source for power-hungry portable devices. However, in spite of the high energy density, fuel cells have limited power capacity and cannot respond to sudden changes in the load. Thus, a system powered solely by the fuel cell should be over-designed and not economical. Thus, fuel cells are commonly used with a battery to utilize both the high energy density of the fuel cell and the high power capacity of the battery.

Since power consumption of embedded systems dynamically changes over time, the control of a fuel cell and the charge management in the battery is sophisticated. Ultimate fuel-optimal configuration is achievable only when the control of the fuel cell, charge management of the battery, and the power management of the embedded system are jointly optimized. Since this is certainly a new problem, we first need an evaluation platform for the measurement and characterization. Nevertheless, there has been no existing platform to tackle such a problem.

In this paper, we demonstrate the design and implementation of a 20W average, 80W peak power fuel cell and dual Li-ion battery hybrid power source platform. This platform is designed to characterize the performance of hybrid power source, and also to explore new energy management strategies for embedded systems powered by a hybrid source. We devise a new hybrid power supply scheme named DTC (Dynamic duTy cycle Control) so that we may fully control the proportion of the fuel cell current and the battery current.

1. INTRODUCTION

One of the most important resources in portable electronics systems is a battery, which is a source of energy for a finite duration. The capacity of a battery depends on its size, and portability places very stringent constraints on its size, weight, and form factor. Improvements in the energy density of batteries have lagged far behind the increasing energy demand of many portable microelectronic systems. This widening gap between the capabilities of batteries and the demands of the microprocessor and peripherals is one of the main challenges in the design of portable systems.

As a result of more than a decade of research, a large body of previous contribution exists on improving the efficiency of the energy consumers, i.e., microprocessors and peripherals. However, power consumption still continues to plague the industry due to the continuing increase in leakage current. The alternative is to improve the energy density of the producer. An excellent alternative to a battery, and one which can provide the energy density required by portable computing and communication devices of the future, is a fuel cell.

A fuel cell is an electrochemical device that uses hydrogen (H_2) and oxygen (O_2) to generate electrical power. Fuel

cells are environmentally clean and safe. They provide instant power without a time consuming recharge process and very high energy densities as compared to batteries. For instance, a Li-ion battery pack used in cellular phones has a typical volumetric energy density of 250 Watt-hours per liter (Wh/l), with a theoretical upper limit of 480 Wh/l [1]. Even assuming 20% efficiency when converting chemical to electrical energy, these fuel cells have energy densities ranging from 1,000 to 1,500 Wh/l - more than 4X of the energy density of today's Li-ion batteries. Small-size room temperature fuel cells such as a PEM fuel cell (proton exchange membrane fuel cells) powered by H_2 are under development for portable applications where the power range is the order of 1 to 100 W [1, 2].

Although fuel cells are certainly more controllable power sources in comparison with other alternative power sources such as solar panels, windmills, etc., whose energy sources (sunlight and wind) are not controllable to track the load variation. However, still fuel cell system dynamics are orders of magnitude slower than the dynamics of embedded systems. Although fuel cells have high energy density, their power capacity is limited to the area of the membrane, and thus if an embedded system is powered by a fuel cell only, the area of the membrane should be determined by the maximum power demand, which is very pessimistic. As a result, a small-size battery is often used together with a fuel cell, which is a fuel cell and battery hybrid.

^{*} This work was supported in part by the Institute of Computer Technology (ICT) at SNU, the Brain Korea 21 Project, and LG Yonam Foundation in Korea.

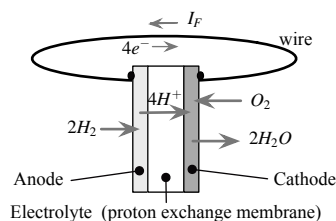


Fig. 1. The basic reaction in a fuel cell.

The control of a fuel cell and battery hybrid is not trivial. A study of the characteristics of the fuel cell and battery hybrid system brought to light several significant differences with battery powered systems. First, the efficiency of the fuel cell is a function of the load current and is independent to the amount of remaining fuel, in contrast to batteries whose performance is primarily affected by the remaining energy. Second, the limited power capacity of the fuel cell restricts the range in which the fuel cell can track the load. Even in this restricted range, the *load following* is not automatic, and has to be controlled by explicit fuel flow rate control.

The ultimate fuel saving can be achieved only when a joint optimization of the fuel cell control, change management of the battery, and the power management of the embedded system, is applied. This implies that existing range of power management schemes for embedded systems that assumed battery power sources, should be rearranged for the application of embedded systems powered by fuel cell and battery hybrids. Such a power management scheme cannot be developed without precise characterization of the portable fuel cell and battery hybrid power source. Since this is a new problem than has not been addressed yet, there is no commercially available fuel cell and battery hybrid platform which is optimized for detailed characterization.

This paper is the first attempt to develop a fuel cell and battery hybrid platform, which is highly flexible to accommodate various control policies, and fully observable with complete measurement of current, voltage, temperature, pressure, etc. The proposed platform enables us to come up with complete observation of its behavior, and inspires many new attempts for the globally fuel-optimal control schemes. As a result, we have developed new DVS schemes, DPM schemes, and a combination of DPM and DVS that are fully aware of the fuel cell and battery hybrid system characteristics.

2. FUEL CELL AND BATTERY HYBRID

2.1 Fuel cell and battery

Fuel cells are typically classified based on the type of electrolyte [3]. We focus on PEM fuel cells since it has high performance and is also cost effective. In fact, a PEM fuel cell requires only 0.2 mg/cm² of platinum catalyst [4] compared to a DMFC (direct methanol fuel cell) which requires significantly large amounts, usually 4 to 8 mg/cm² [5].

In its simplest form, a PEM fuel cell has two electrodes (anode and cathode) separated by an ion conducting

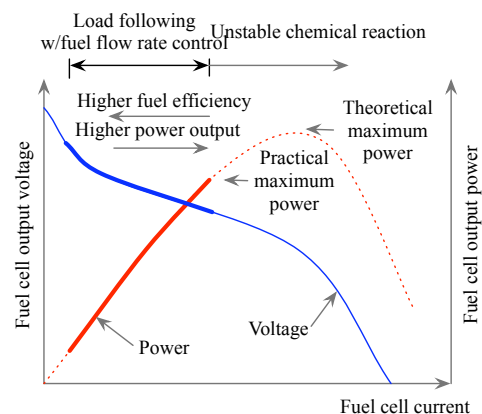
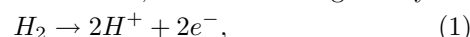
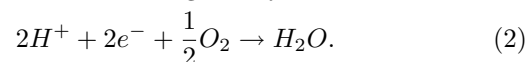


Fig. 2. Polarization curves for a PEM fuel cell.

membrane. The fuel is fed to the anode and O_2 is fed to the cathode. At the anode, the reaction is given by



i.e., a H_2 molecule splits into H^+ ions and e^- electrons. The H^+ ions move towards the cathode through the ion conducting electrolyte (membrane). The e^- electrons find a different path to the cathode, namely, through the external wire that connects the anode and the cathode. At the cathode, the reaction is given by



A complete fuel cell system thus requires a thermal and hydration management system to maintain the required temperature and hydrating condition, and also the capability to remove excessive heat and water. Also, many fuel cell systems use air to provide O_2 to the cathode, and so require an air management system to ensure that the O_2 supply is in abundance.

Figure 2 shows a plot of the voltage and power versus current of a PEM fuel cell. As the current density increases, the open circuit voltage (about 1.2 V per cell) reduces. The maximum fuel cell output current is determined by the current density of the membrane times the area of the membrane. The fuel cell output voltage is determined by the single cell voltage times the number of stacked cells. The fuel cell power output can be varied with a given range, referred to as the *load following* region, by controlling the fuel flow rate. In summary, the fuel cell output power depends on temperature, pressure and humidity, and these need to be dynamically controlled for maximum efficiency [6].

Now, we describe a fuel cell and battery hybrid power source where the fuel cell is the primary power source and provides the average power, and the battery is the secondary source and supplies the additional power (peak power) to support the fluctuation. Figure 3 shows a situation where the maximum load current is 3X of the average current. If the power source was only a fuel cell, the fuel cell would be designed to accommodate the worst case load (the 3X fuel cell), requiring a larger and heavier unit. On the other hand, the fuel cell unit in a hybrid system can be designed for the average case, with a small battery providing the additional current when needed.

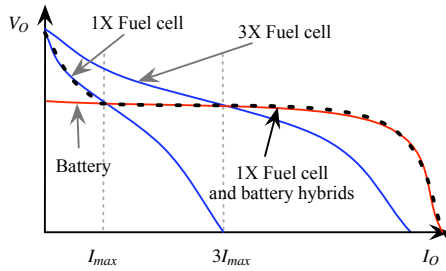


Fig. 3. Advantage of using a fuel cell and battery hybrid power source over a fuel-cell-only source.

2.2 Human-portable fuel cells (related work)

Most advances in fuel cells have come from stationary and automotive applications, where the power ranges are of the order of 1 to 10 MW and 1 to 10 KW, respectively. Fuel cell and battery hybrid is actively studied for automotive applications. However, in automotive systems, the load demand is generally a soft constraint. Failure to accurately follow the load results in lack of traction power which might be an inconvenience to the driver but does not result in a technical system failure. In contrast, the load demand of an embedded system is a hard constraint, and its violation is likely to result in a critical system failure. Secondly, the load dynamics in embedded systems is orders of magnitude faster; this makes the fuel flow control and the charge management quite complicated. Most importantly, the automotive systems are simply reactive and the required load current acts as a reference signal that the hybrid power system must track faithfully. In contrast, in embedded systems, as long as the task deadline is met, appropriate speed control can be applied to reduce its power consumption. So the best charge management policy for portable embedded systems does not only track the load profile, but also actively reshapes the load profile.

Recently, significant efforts are underway to design fuel cells for the portable consumer electronics market where the power range is the order of 1 to 100 W. Fuel cells for portable applications are being built by many companies, including Casio (Japan), Motorola (US), Nokia (Europe), Samsung (Korea), etc. Several operational prototypes based on DMFCs have been reported, including a sub-one W power unit by Motorola [1], a miniaturized PEM methanol-based fuel cell with 0.5 to 20 W of power for powering portable telecommunication and computing devices [7], and a 15 W unit that consists of a H_2 -generating fuel reformer coupled to a PEM fuel cell [2]. However, most of them are designed for functional demonstration, and no joint power optimization between the fuel cell and the embedded systems has been attempted.

3. DESIGN AND IMPLEMENTATION

3.1 The prototype

We use a room temperature, self-humidifiable, 20-cell, 20-W, 18-V open-circuit-voltage PEM fuel cell stack manufactured by BCS fuel cell Systems [8]. The structure of the hybrid system is shown in Figure 4. It consists of three subsystems: the fuel processor, the fuel cell stack

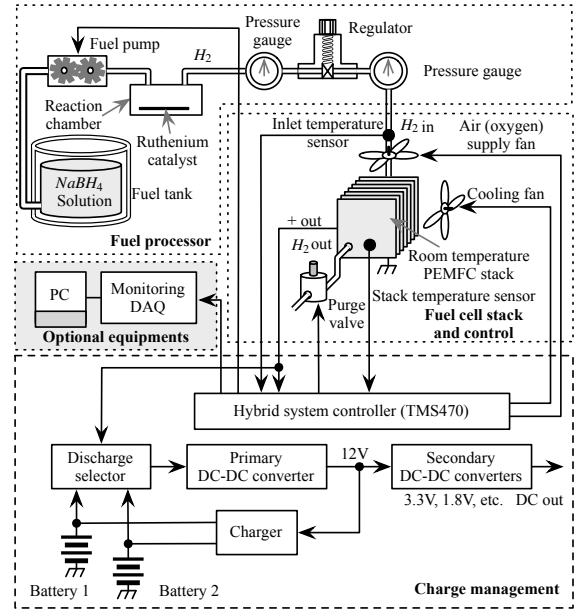


Fig. 4. Schematic diagram of the fuel cell and battery hybrid platform.

and control, and the charge management system (CMS). The fuel processor is responsible for supplying the H_2 . The fuel cell stack and control subsystem consists of a PEM fuel cell stack, a microprocessor, and balance of plants (BOP) such as sensors (current, voltage, temperature and pressure), fans, pumps, solenoid valves, etc. The CMS delivers the required power to the embedded system. Its functions include discharge scheduling (discharging the fuel cell, battery or both simultaneously), and battery charge scheduling.

The BCS PEM fuel cell stack requires 2 to 3 psig H_2 pressure in the anode. When $NaBH_4$ solution is supplied to the reaction chamber of the fuel processor, the chemical reaction is activated by Ru and H_2 is generated. The amount of $NaBH_4$ delivered, determines the amount of H_2 generation. Because of significant fluctuations in pressure, we use a pressure regulator to regulate the H_2 pressure in the anode, with 2 psig as the default value. Typically, a miniature gear-driven or cam-driven electric motor pump or piezoelectric pump is used for the fuel pump. We use a micro piezoelectric pump (25 mm \times 25 mm \times 4.8 mm) with the flow rate of 7 ml/min and the power consumption of 240 mW [9]. As 2 to 3 psig H_2 pressure is formed at the anode, a similar amount of O_2 pressure is required at the cathode. While a piston- or a diaphragm-type air compressor is used for high-pressure fuel cell stack operation (> 4 psig) that has an O_2 channel, here we use a blower fan to deliver O_2 since the cathode of the BCS PEM fuel cell stack is exposed to outside (convicting air type) without a channel.

The efficiency of the fuel cell stack is dependent on the temperature and so the stack temperature must be maintained at a particular (45°C for the BCS PEM fuel cell stack) value for maximum efficiency. Generally the fuel cell stack has less than 50% efficiency, since more than half of the chemical energy becomes heat. It is possible to cool down a fuel cell below 100 W purely with convective



Fig. 5. Photograph of the fuel cell and battery hybrid system demonstrated at ISLPED 2007 design contest.

air [3], but we use a cooling fan for robust operation against the ambient temperature variation. The maximum allowable temperature of the BCS 20 W fuel cell stack is 65 °C.

We operate the fuel cell stack with a dead-end anode configuration; i.e., the H_2 flows into the anode with nowhere to go except through the membrane. This creates a sufficient back pressure that provides an automatic regulation of the inflow of H_2 . While this is more efficient than an open-end configuration, it may generate excessive water that blocks the H_2 channel. Hence it is necessary to periodically flush (or purge) water by opening the purge valve, often implemented with a normal-closed type solenoid valve at the end of the H_2 channel. On the cathode side, we use two fans to control the air (O_2) flow into the cathode as well as maintain the stack temperature.

The main controller unit is equipped with TI TMS470. The main controller unit also has a constant-current and constant-voltage Li-ion battery charger with a maximum charging current of 1 A, and three PWM drivers with a frequency of operation of 20 KHz. The final output DC-DC converter can be selected depending on the voltage requirement of the target embedded system (Figure 4).

Our hybrid system control software has been designed to operate on a tiny real-time OS, called μ C-OS II. The μ C-OS II is small enough to be squeezed into 2KB of code space, and thus is suitable for TMS470 with small on-chip memory. The control program consists of five main threads for the system boot up, temperature control, water management, monitoring, and housekeeping. Figure 5 shows a photograph of the prototype that we built and demonstrated.

3.2 Proposed hybrid operation

In a fuel cell and battery hybrid system, the embedded system can be powered by the fuel cell or battery or both. An appropriate hybrid operation makes it possible to use a very small size battery in comparison with battery-only systems, and also to use a smaller size fuel cell in comparison with fuel-cell-only systems.

The ideal hybrid operation is to use the fuel cell to supply bulk of the power and to compensate the shortage (when the load current is larger than the maximum fuel cell current) with a battery. The maximum power capacity of such a structure is the sum of the fuel cell capacity

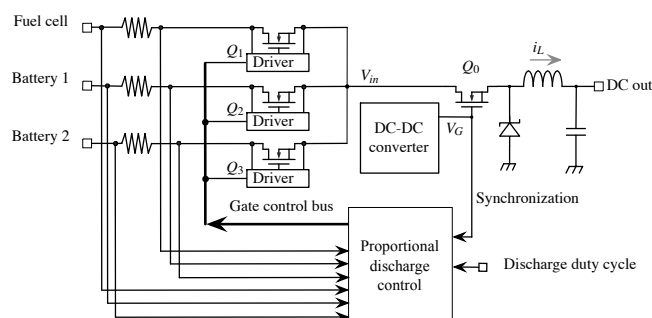


Fig. 6. Proposed dynamic duty cycle control (DTC).

and the battery capacity. Figure 6 illustrates the proposed circuit that gives the maximum degree of freedom for the hybrid operation. The DC-DC converter periodically draws current from the source by switching Q_0 . DTC steers one of the multiple input sources enabling one of Q_1 , Q_2 and Q_3 , and such an input selection is also synchronized with Q_0 gate control signal. This makes DTC avoid producing additional switching noise and efficiency degradation while the microprocessor arbitrary sets the proportion of the fuel cell current and the battery current.

3.3 Battery management

Li-ion batteries and super capacitors are commonly used as charge buffers for alternative power sources [10]. Super capacitors are not subjected to the cycle-life problem, but they have problems of leakage current. Also, their output voltage is linearly proportional to the amount of charge stored, which makes the design of the DC-DC converter and charger circuit particularly challenging. The proposed prototype can accommodate two Li-ion batteries, or a Li-ion battery and a super capacitor, at the same time.

The amount of charging current is controlled by a microcontroller using a digital potentiometer connected to a battery charger. The charging current is limited by 750 mA, slightly below the maximum allowed charging current (1 C). The battery output voltage level is recorded periodically by an analog-to-digital converter embedded in the microcontroller. If this parameter reaches 12 V, the microcontroller changes the charging method from constant current mode to constant voltage mode using a GPIO connected to the charger IC.

4. MEASUREMENT AND CHARACTERIZATION

The fuel cell stack efficiency is best described in terms of Gibbs free energy, unlike heat engines which are explained in terms of Carnot limit. The fuel cell stack efficiency is defined as the ratio of the electrical energy to the Gibbs free energy [3]. The amount of Gibbs free energy change is the fuel consumption, i.e., the number of H_2 molecules consumed. The number of H_2 molecules is exactly proportional to the number of electrons. Thus the fuel cell stack efficiency has the same trend as the stack output voltage.

The fuel cell system efficiency is a function of not only the fuel cell stack efficiency but also the power consumption of the BOP and the DC-DC converter efficiency. Among the

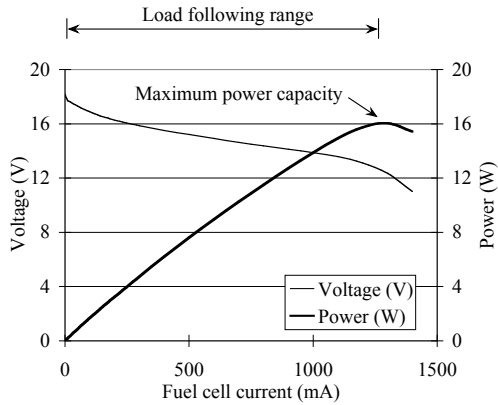


Fig. 7. Measured output voltage and power versus load current characteristics of the BCS 20 W, 20 stack, room-temperature PEM fuel cell (@2 psig H_2 pressure).

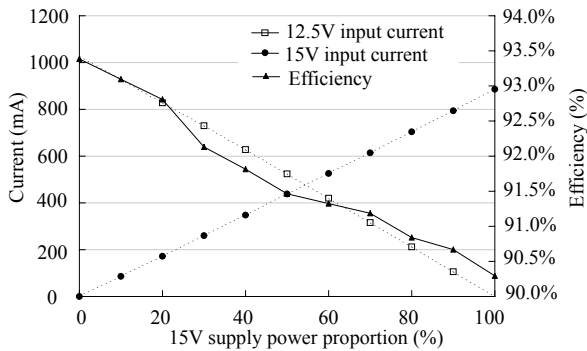


Fig. 8. Measured DC-DC converter efficiency with DTC (12.5 V and 15 V dual inputs) @12 V 1 A output.

BOP, the cathode air blower fan and the cooling fan consume significant power, and thus seriously affect the fuel cell system efficiency. Their power consumption is strongly dependent on the size and type (blower, diaphragm, piston, etc.) as well as the type of control method. In this paper, we compare two control methods. A constant-speed fan control, which is simple and suitable for low-cost systems, and a variable-speed fan control that performs speed control of the fan according to the O_2 consumption, or equivalently, the fuel cell current. Like the cathode fan, the power consumption of the cooling fan depends on the size and type of the fan as well as the control method. Note that the cooling fan power is also strongly dependent on the airflow design.

The proposed DTC switches the input between the fuel cell whose voltage ranges from 12 V to 18 V, and the 3 cell Li-ion battery whose voltage is around 12.3 V. The DC-DC converter efficiency is a function of the input voltage level. The DC-DC converter used in the platform shows better efficiency when the input voltage is 12.5 V than when the input voltage is 15 V. So, the DC-DC converter's efficiency varies according to the proportion setting of the DTC.

Figure 8 shows the efficiency variation of the DTC setting. As shown in Figure 8, the DC-DC converter efficiency with DTC ranges between the efficiency at 12.5 V input and the efficiency at 15 V input. In addition, it turns out

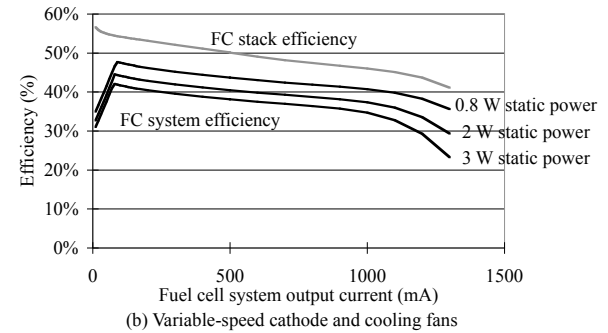
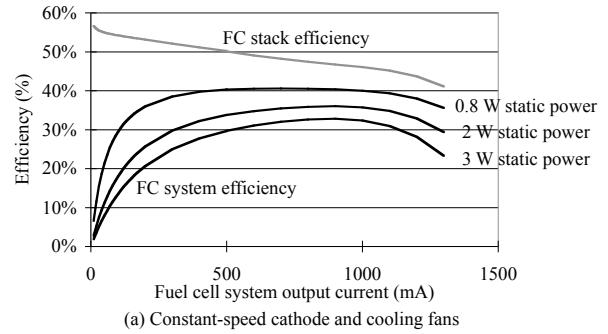


Fig. 9. Measured fuel cell stack efficiency and fuel cell system efficiency. Static power is the summation of the power consumption of all the controller components, where the cathode fan power and cooling fan power are dominant.

that DTC does not affect the DC-DC converter efficiency showing more than 90% DC-DC converter efficiency at 12 W output.

The rest of the BOP components consume very small power, and their contribution to the fuel cell system efficiency is minor. The fuel pump power is negligible even though we use a motorized pump. A piezoelectric pump consumes even less amount of power. The purge valve is a solenoid, which is supposed to consume 0.67 W to open it, but since it is operated for around 0.35 s every 5 min, its average power is quite small. Finally, the TI TMS470 is consuming around 30 mW. The charge loss in the charge storage elements is highly dependent on the manufacturer as well as the charging method.

Figure 9 shows the whole fuel cell system efficiency as a function of the output current. The overall system efficiency is worse than the fuel cell stack efficiency, as expected. We see that the constant speed fan control is good enough when the minimum load current is larger than 30% of the maximum as shown in Figure 9(a). However, if the fuel cell system frequently operates below 30% of the maximum current, variable-speed fans are more efficient as shown in Figure 9(b).

Embedded systems which implement DPM for energy management benefit by using a fuel cell and battery hybrid system with variable-speed fans. This is because DPM policies tend to aggregate the active periods (or idle periods), resulting in high load current variation. When the load current is small, the fuel cell and battery hybrid system has high efficiency (low power loss). In contrast, energy management policy such as dynamic voltage scaling (DVS) tends to flatten out the load current. For such

configurations, a constant-speed fan setup gives reasonable efficiency in spite of its simple structure and has been used in [11].

In the prototype, we use a PWM-PFM DC-DC converter and variable-speed fans, where the fan speed is proportional to the load current. The measured fuel cell system efficiency for this configuration is shown in Figure 9(b). The system efficiency is now a function of the load current. In the load following range under consideration, the system efficiency drops from 46% to 30%.

5. APPLICATIONS

Based on the prototype, we have developed a DVS schemes for an embedded system powered by a fuel cell and battery hybrid, when there is no fuel flow rate control capability [12] and when a task-by-task fuel flow rate readjustment is available [11]. The result in [12] exhibits 50% fuel saving than a baseline setup, which is not fuel-cell aware. The task-by-task fuel flow rate readjustment gives additional 11.5% more fuel saving.

We recently introduced a new DPM schemes for an embedded system powered by a fuel cell and battery hybrid considering the hybrid system efficiency [13], and will introduce a combination of DPM and DVS for such a system in ISLPED 2007 [14]. The result in [13] demonstrated 69.2% fuel saving over conventional DPM schemes that ignore the characteristics of the fuel-cell and battery hybrid. Our scheme even gives 24.4% more fuel saving over conventional fuel-cell control schemes that do not consider the embedded system characteristics. The combination of DPM and DVS, to be presented at ISLPED 2007, will give additional 5% and 8% fuel saving over DVS-only and DPM-only methods that are fuel-cell aware.

6. CONCLUSIONS

Fuel cells are one of the most promising next generation energy sources for human-portable applications providing much higher energy density than conventional batteries. However, due to their limited power capacity, they are inefficient as a stand-alone power source. A fuel cell and battery hybrid (fuel cell and battery hybrid) system is very efficient since it has the energy density of the fuel cell and power capacity of the battery. Such a system introduces nonlinearities and requires development of novel charge management policies and new power management policies. Nevertheless, there is no available portable fuel cell and battery hybrid platform for measurement and characterization.

To tackle such a problem, we have developed a prototype fuel cell and battery hybrid system for use in portable applications. The contribution of this platform is as follows. This is the first prototype to our knowledge aiming at high flexibility for the control policy development and full observability for precise characterization. The prototype is designed for the joint optimization of the fuel cell control and charge management together with the power management of embedded system. We have demonstrated the platform at SIGDA Ubooth 2006 and ISLPED 2007 design contest.

ACKNOWLEDGEMENTS

We give special thanks to Dr. Ken Han and his colleagues at Korean Institute of Industrial Technology, and Dr. Dominic Gervasio and his colleagues at Arizona State University, for their support in providing us with the PEM fuel cell stack and the H_2 generator, and Dr. Chaitali Chakrabarti, Dr. Sarma Vrudhula, and Jianli Zhuo at Arizona State University for the collaboration for the fuel-cell-aware power managements.

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