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Intelligent uninterruptible power supply system with back-up fuel cell/battery hybrid power source

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Abstract

This paper presents the development of an intelligent uninterruptible power supply (UPS) system with a hybrid power source that comprises a proton-exchange membrane fuel cell (PEMFC) and a battery. Attention is focused on the architecture of the UPS hybrid system and the data acquisition and control of the PEMFC. Specifically, the hybrid UPS system consists of a low-cost 60-cell 300 W PEMFC stack, a 3-cell lead–acid battery, an active power factor correction ac–dc rectifier, a half-bridge dc–ac inverter, a dc–dc converter, an ac–dc charger and their control units based on a digital signal processor TMS320F240, other integrated circuit chips, and a simple network management protocol adapter. Experimental tests and theoretical studies are conducted. First, the major parameters of the PEMFC are experimentally obtained and evaluated. Then an intelligent control strategy for the PEMFC stack is proposed and implemented. Finally, the performance of the hybrid UPS system is measured and analyzed.

Keywords: Uninterruptible power supply; Proton-exchange membrane fuel cell; Lead–acid battery; Hybrid power source; Back-up and emergency power; Intelligent control

1. Introduction

Uninterruptible power supply (UPS) systems play a very important role as back-up and emergency power supplies for important applications such as computers, medical/life support systems, communication systems, office equipment, hospital instruments, industrial controls and integrated data centre. The UPS systems provide reliable constant voltage and constant frequency power in case of mains failure [1,2]. An ideal high-performance UPS system should provide a clean and regulated sinusoidal output voltage with low total harmonic distortion (THD) for both linear and non-linear loads, a fast transient response to sudden changes of the input voltage or load, on-line operation with zero switching time from normal to back-up mode and vice versa, a low THD sinusoidal input current and unity power factor, high power density, high reliability, high efficiency, low electromagnetic interference (EMI) and acoustic noise, electric isolation, low maintenance, low cost and weight, and small size. With the fast development of personal computers, information technology and network communications technology, UPS products will take an increasing share of industrial and domestic markets. Modern UPS power source technologies are being developed in terms of high switching frequency, miniaturization, redundancy, digitalization, intelligence and networking. The key embodiment of the intelligent UPS system is the monitoring functions of abundant hardware and software.

A UPS system based solely on the use of batteries finds difficulty in providing sufficient back-up power to critical loads, especially when a supply for a relatively long duration is required [3]. Hence, other energy sources and storage technologies, such as the fuel cell, have been investigated to replace the batteries. Since fuel cells can provide electrical power with high specific energy, high efficiency and no pollution, they are considered as a promising technology for UPS products. The proton-exchange membrane fuel cell (PEMFC) and direct methanol fuel cell (DMFC) are considered to be promising technologies due to their excellent dynamic characteristics. The present lifetime capabilities of PEMFC are suitable for back-up UPS applica-

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tions. Furthermore, the PEMFC complies with the demand for a fast cold start (a few seconds) [4,5].

A UPS system with a PEMFC and battery hybrid power source should ensure that there is sufficient fuel and battery capacity to provide the power needed by the external load. When power from the utility grid is interrupted, hydrogen will be supplied to the PEMFC stack. During start-up of the PEMFC stack or a sudden change of external load, however, hydrogen cannot be fed fast enough and the fuel cell stack may take a few seconds to reach the required output voltage. To overcome this problem, a rechargeable battery or supercapacitor can be employed to respond quickly to the external load and thereby protect the PEMFC from excessive use.

In this study, an intelligent hybrid UPS system with a PEMFC/battery hybrid power source has been developed for back-up and emergency power applications. Fig. 1 shows the schematic diagram of the system, which includes a 300 W PEMFC stack, a 3-cell lead–acid battery, a single-phase high-frequency UPS, and intelligent control and communication units. The UPS is composed of an ac–dc rectifier, an ac–dc charger, a dc–ac inverter and a dc–dc converter, and can supply linear and non-linear loads with uninterruptible ac power. The PEMFC stack operates on hydrogen and air. Because of the slow dynamic performance of the PEMFC stack, a small capacity battery is employed to improve the response time to sudden changes in load. The intelligent controller enables automatic operation of the whole system that, when there is a power failure, includes disconnecting the system from the utility grid supply, connecting the battery to the dc–dc converter and dc–ac inverter to maintain the uninterrupted ac power supply to the load, starting the PEMFC to provide power for longer periods, and switching the power supply back to the grid when utility power is restored. Through an RS-232 or USB interface, a simple network management protocol (SNMP) adapter and specially designed software, the UPS hybrid system can realize the functions of telecommunications, control and power management.

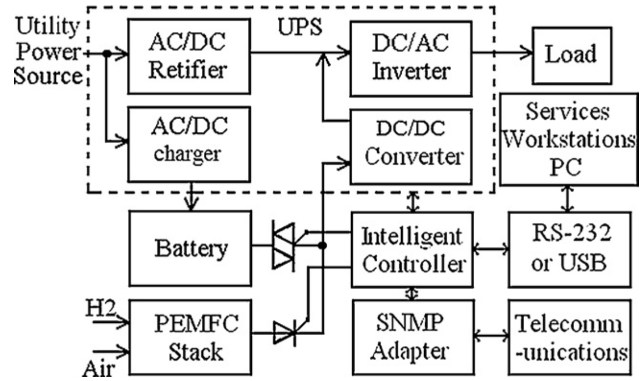

Fig. 1. Intelligent UPS system with a PEMFC and battery power source.

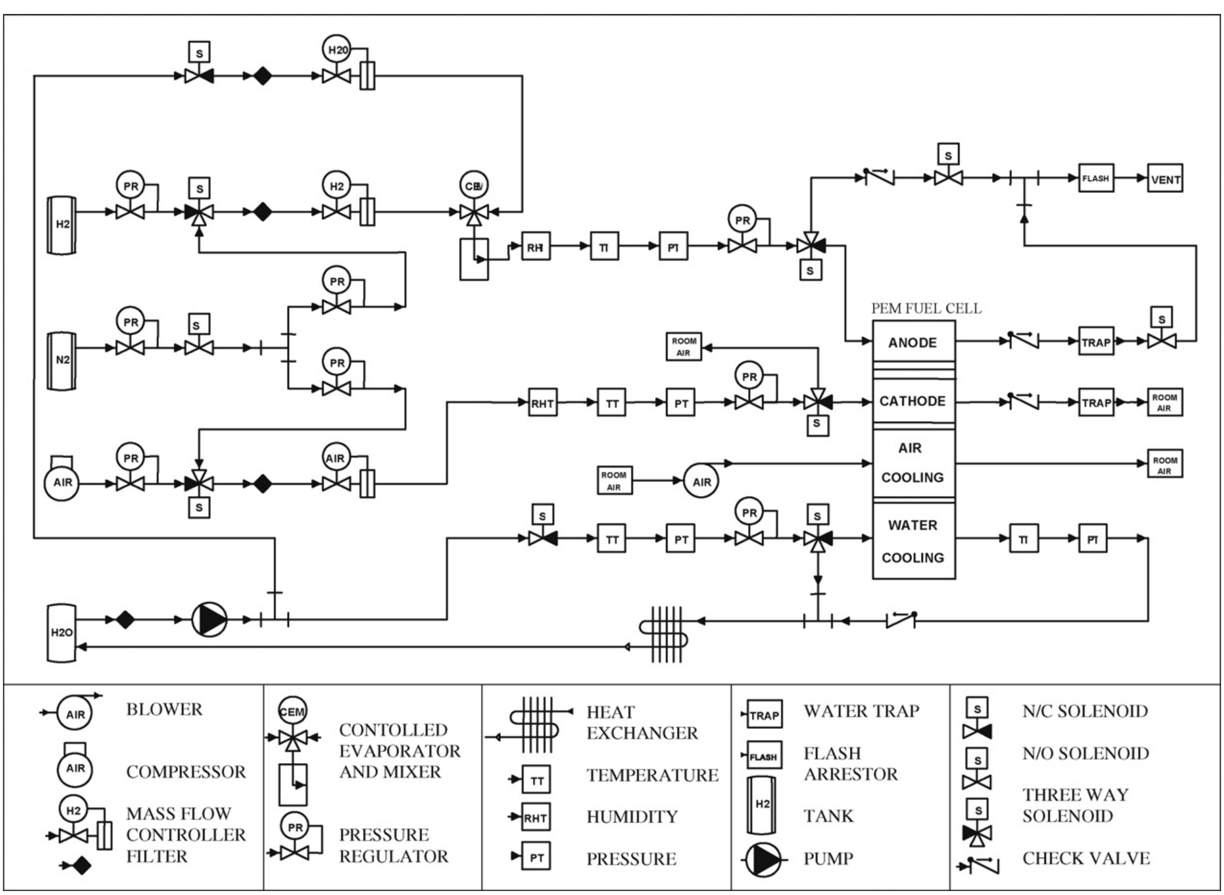

Fig. 2. Schematic diagram of PEMFC testing system.

2. Design and architecture of UPS hybrid system

2.1. Design considerations

In designing a UPS system with a PEMFC/battery hybrid power source, the following criteria have to be addressed: (i) adopting matured technology for the components; (ii) easiness to develop modular products; (iii) multiple functions of intelligent controls and network communications; (iv) employing a digital signal processor (DSP) as the intelligent network controller; (v) dual charging of the battery through the ac–dc charger and/or the PEMFC; (vi) convenience to collect the data and set-up parameters for the PEMFC and the UPS; (vii) correctly choosing the power, voltage and size of the PEMFC stack with respect to cost, the battery voltage, and the design of the dc–dc converter.

2.2. PEMFC testing system

The PEMFC testing system, as shown in Fig. 2 [6–8], consists of a PEMFC stack, water-cooling components, air-cooling, H_2 humidifying and filtering, and temperature and pressure monitoring. Three types of gases: hydrogen, nitrogen and air/oxygen, are used. The data-acquisition and control devices and software have been designed and can control the whole system with measurement of operational parameters, such as: the working temperature; voltage and current of the PEMFC; the pressure, input/output mass flows and humidity of the hydrogen and air/oxygen; the voltage and current of the battery. Many functions can be selected, e.g., humidification of the hydrogen and air, use of air rather than oxygen, and water-cooling or air-cooling.

For the experimental set-up, a 300 W PEMFC stack is employed [9]. It is a self-humidified, air-breathing, 60-cell stack with an overall size 10.5 cm × 7.0 cm × 22.0 cm. Three fans are used to supply the air and cool the stack, which has a maximum operating temperature of 65 °C and an operating pressure of 4.55–5.5 psi for hydrogen. A photograph of the PEMFC stack is given in Fig. 3.

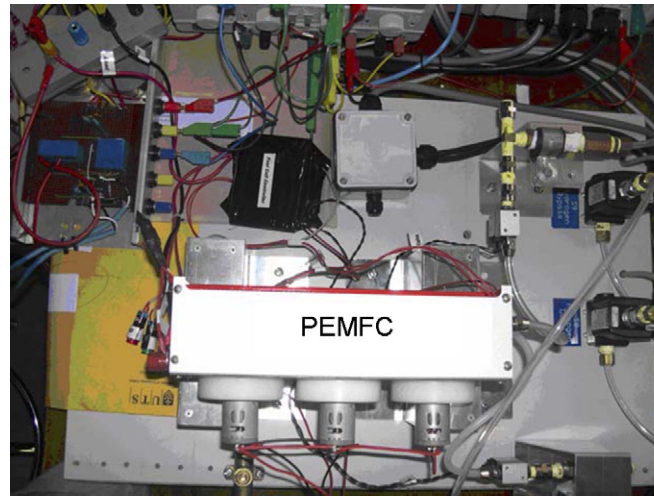

Fig. 3. Photograph of PEMFC stack.

2.3. Energy-storage component

As mentioned above, an energy-storage unit, such as battery or a supercapacitor, is a key component of the UPS hybrid system. The PEMFC plays the role of main power supply under normal conditions, whereas the battery or supercapacitor provides the (extra) power required when the load varies suddenly and the power when the PEMFC starts up. In this UPS hybrid system, the PANASONIC LC-R127R2CH, 12V/7.2Ah/20HR battery is used. Alternatively, 15 series-connected supercapacitors can be used with the main specifications of 1000 F (±20%), control voltage of 2.5 V, and maximum current of 150 A [10].

2.4. Hardware designs of UPS system

2.4.1. dc–ac inverter

With the rapid development of modern power electronics technology, the digital control of power converters using advanced DSP has become a subject of research area [11]. Digital controllers are immune to drifts, insensitive to component tolerances, easy to implement, and flexible with control rules

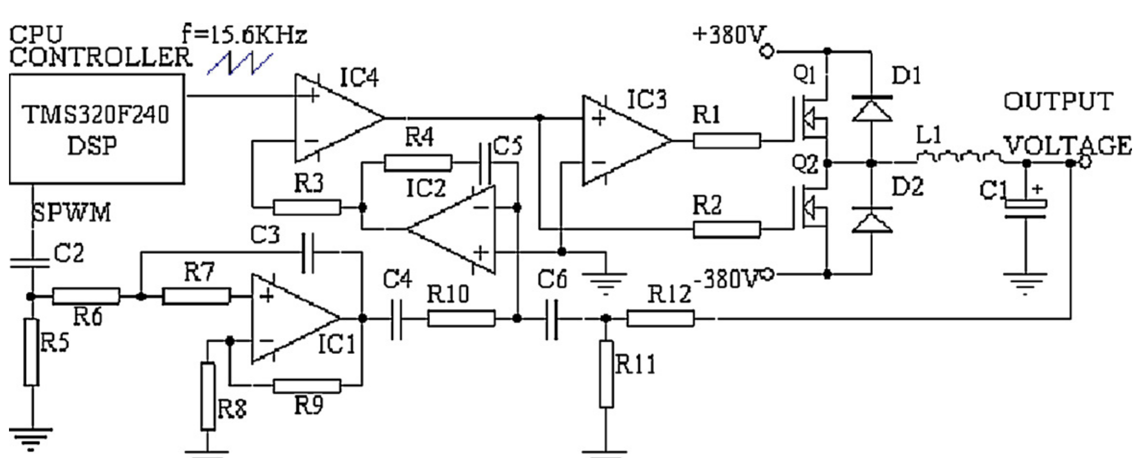

Fig. 4. Circuit schematic model of dc–ac inverter.

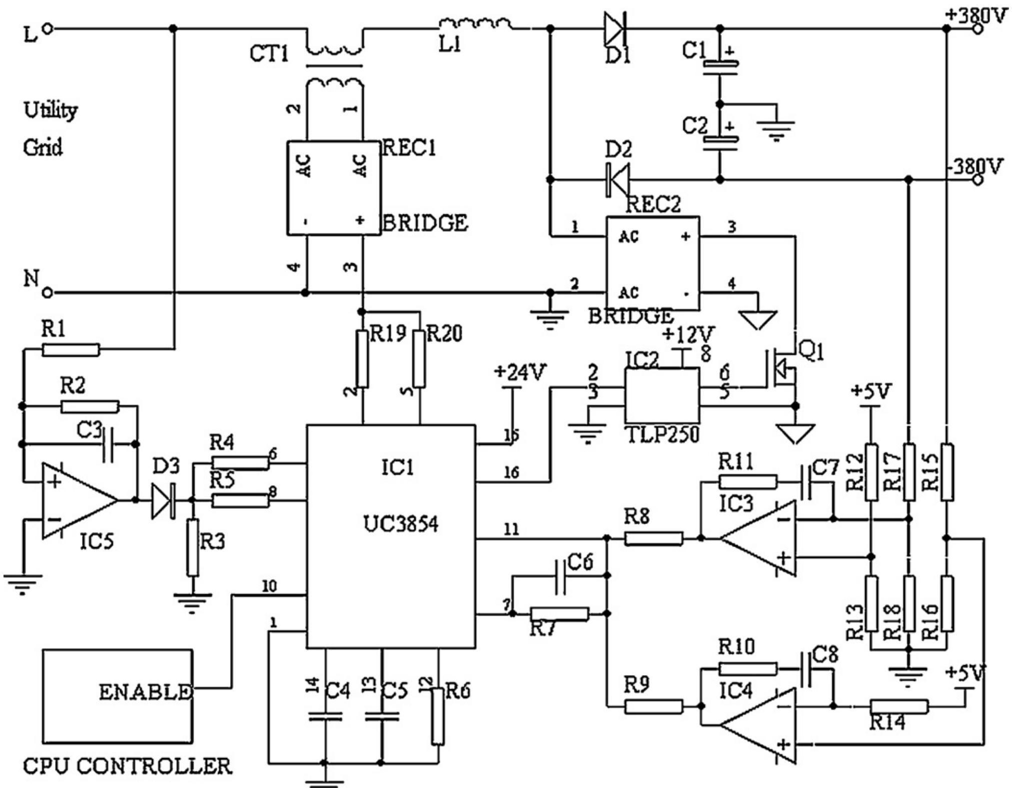

Fig. 5. Single-phase active PFC ac–dc rectifier.

by software updating. Compared with the analogue control, the digital control UPS is easier to realize for advanced operations.

In the UPS hybrid system, a dc–ac inverter controlled by the TMS320F240 DSP is designed to supply the load with a pure sine wave, as shown in Fig. 4, where the half-bridge inverter, LC filter and load are considered as the plant to be controlled. Since the switching frequency (the designed operating frequency = 20 kHz) is much higher than the natural frequency and the modulation frequency, the dynamics of the dc–ac inverter are mainly determined by its LC filter. The dead-time effect and inevitable loss in every part of the inverter cause little damping. The damping effect can be considered by using a small resistor connected in series with the filter inductor [8]. Using the sinusoidal pulse-width modulation (SPWM) control principle, the inverter can convert the ±380 V dc into a 220 V ac pure sine wave.

2.4.2. ac–dc rectifier

A boost active power factor corrector (PFC) with a 160–275 V ac input voltage and a fixed output voltage (±BUS = ±380 V dc) was designed based on a high power factor pre-regular UC3854, which can control the input power factor (PF) of the ac–dc boost PWM rectifier to be close to 1, the THD of the input current less than 5%, and the frequency band of its current amplifier to be wide by adopting the average current control and constant frequency control. Fig. 5 shows the single-phase active PFC ac–dc rectifier and its working pattern. The operational frequency of UC3854 is 100 kHz.

2.4.3. dc–dc converter

A general and practical dc–dc converter for the UPS hybrid system was designed based on a regulating pulse-width modulator UC3525. The PEMFC and battery are two types of low-voltage and high-current power source, so their output voltage (36 V dc) should be boosted up to about ±380 V dc before the UPS dc–ac inverter converts them into a 220 V, 50-Hz ac source. This boosting action is performed by the dc–dc converter. Fig. 6 shows a schematic diagram of the converter. The operating frequency of power switches Q_1 and Q_2 is 20 kHz.

2.4.4. ac–dc charger and PEMFC charging

A basic switch power system with universal input voltage and adjustable output voltage is designed as the battery charger based on a high-performance current mode PWM controller UC3845. Fig. 7 shows the schematic circuit model of the ac–dc charger.

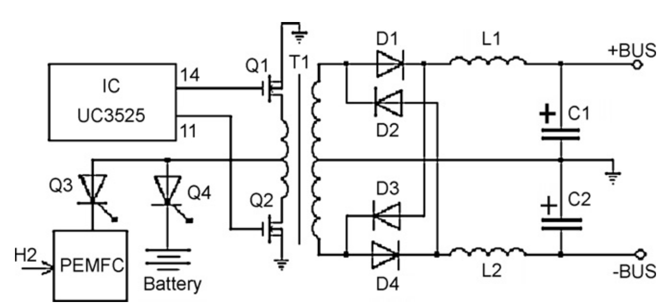

Fig. 6. Schematic diagram of dc–dc converter.

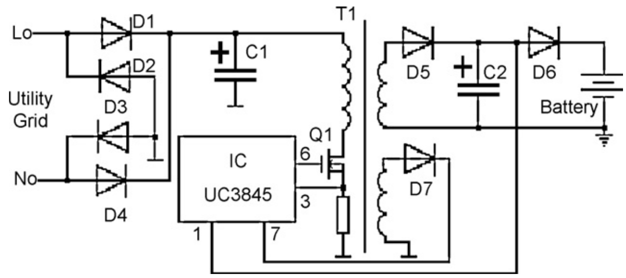

Fig. 7. Schematic diagram of ac–dc charger.

In this UPS hybrid system, for the needs of theoretical analysis, experimental study and practical product development, a passive connection diagram is designed similar to the actual one by implementing a device that connects the PEMFC and battery [12,13], as shown in Fig. 8. When the utility grid power fails and the PEMFC supplies the UPS hybrid system in the normal mode, the PEMFC can also charge the battery if the voltage of the latter is less than the rated value.

3. Intelligent network and control

3.1. Concept of intelligent network UPS

Besides normal functions, the developed intelligent UPS hybrid system has the following capabilities:

(1) Monitoring of the voltage and current of the PEMFC stack, and then deciding whether the UPS is supplied by the PEMFC.
(2) Monitoring of the voltage and current of the battery, and then deciding whether the UPS is supplied by the battery, and whether the battery is recharged by the ac–dc charger or the PEMFC.
(3) Monitoring of the parameters of the UPS, including the voltages and frequencies of the utility grid input and dc–ac inverter output, the positive and negative output voltages of the ac–dc rectifier and dc–dc converter, the UPS temperature, etc.
(4) Display of the parameters, and controlling and recording the failure information when the utility grid power is interrupted or the UPS is improperly working.
(5) Real-time controlling of the start-up and shut down of the PEMFC and UPS, and realizing automatic operations.
(6) Through the RS-232 or USB interface, exchange of information with the computers, workstations and servers.

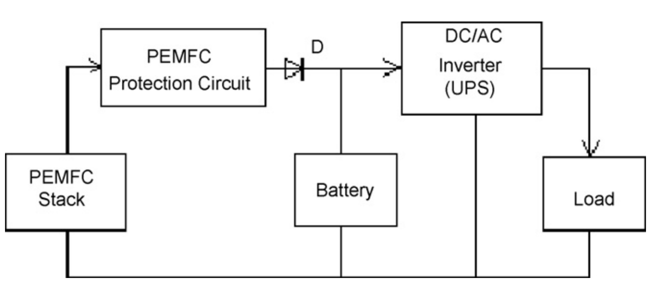

Fig. 8. Schematic diagram of connection between PEMFC and battery.

(7) Through the SNMP adapter, interconnection with the LAN and realizing the network monitoring and management.

3.2. New concepts of intelligent controller

In the developed UPS hybrid system, the intelligent controller is designed based on a TMS320F240 DSP, in which the controlling programs are written into its EPROM. The controller sends signals to the external circuits of the DSP to generate the modulated pulses of the SPWM, as well as to measure and record the status of the UPS hybrid system. When faults occur, such as overheated components, overload and over-voltage of the UPS, under-voltage of PEMFC stack and battery, the intelligent controller outputs a control signal to blockade the dc–ac inverter, and the UPS hybrid system is switched to the state of BYPASS. The intelligent controller also generates an alarm signal. When the above failures disappear, the UPS hybrid system can be automatically switched to the state of INVERTER.

The intelligent controller can determine the charging mode of the battery. When the utility grid power source is in the normal state, the ac–dc charger operates when the battery voltage is lower than the rated value. If the utility grid power source is interrupted, the controller directs the PEMFC to charge the battery when necessary.

3.3. Network communications

The operational status and activity of the traditional UPS system can be transmitted to remote monitoring stations and critical load equipment. Volt-free contacts are usually used for providing simple status information, while an RS-232 serial or USB connection is employed for more detailed information. With the help of an SNMP adaptor, detailed information can be sent directly to a computer network and thus enables information management and shutdown action across the network [14]. The designed software for the intelligent network UPS power management can make the UPS hybrid system become a network peripheral device and automatically shut down in the following three stages:

Stage 1: The software directs the workstations on the Internet to send data from their RAM memories to the server, and stores all the programs that have not been saved in the WINDOWS.
Stage 2: The software runs together with the other communication devices to store all the data and then shut down the devices in turn.
Stage 3: The software can work long enough time for the server to write the data into the hard disc and then shut down the server.

4. Experimental set-up

The experimental set-up consists of the UPS hybrid system and its intelligent controller, lead–acid battery, PEMFC generating system and the data-acquisition devices including a multifunction I/O unit NI6036E, an analogue voltage output

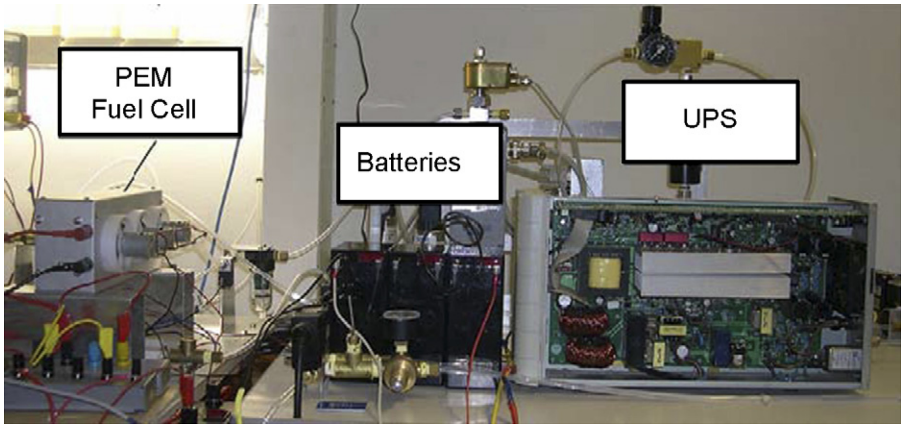

Fig. 9. Photograph of the experimental set-up.

unit NI6713, a parallel digital I/O interface PCI-6503 and an analogue multiplexer with a temperature sensor AMUX-64T (National Instruments). The UPS hybrid system with back-up PEMFC and battery provides the ac power source and controls the linear loads (e.g., lamp box) and non-linear loads (i.e., PC), while the data-acquisition system measures and records the required information. In the PEMFC generating and testing system, both hydrogen and air are regulated by two mass-flow controllers (type: F-201C-GAS-22V and F-112AC-GAS-22V, Bronkhorst). The temperature and humidity of air and hydrogen can be measured at the inlet by the hydrotransmitter (type: HD2008TV1, Delta OHM) as well as by the pressure transmitter (type: AUS EX 1354X, Burkert) between the cathode and anode inlets. The output of the UPS is connected to a lamp load that is used in a constant voltage mode. All physical parameters such as the current and the voltage of the UPS hybrid system, the PEMFC stack and battery, the gas mass flow of the hydrogen, the pressure, relative humidity and temperatures of air and hydrogen are recorded with data-acquisition devices. A photograph of the experimental set-up is given in Fig. 9.

5. Experimental results

There are three stages of experimental tests and analyses of the UPS hybrid system. At the first stage, the voltage–current and power–current performance of the FEMFC is measured by varying slowly the load with a rheostat. At the second stage, the proposed intelligent control strategy of the PEMFC stack is employed when the utility grid power is interrupted. In the final stage, the performance of the UPS hybrid system is measured with the load of a lamp box and a Dell type of PC computer. The UPS system is connected to the network via an RS-232 interface or USB connection, as shown in the screen interface in Fig. 10.

5.1. PEMFC stack tests

Based on the developed PEMFC testing system, the performance of the PEMFC stack is tested, including voltage–current, power–current, and temperature–current. The measured voltage–current and power–current curves are given in Fig. 11.

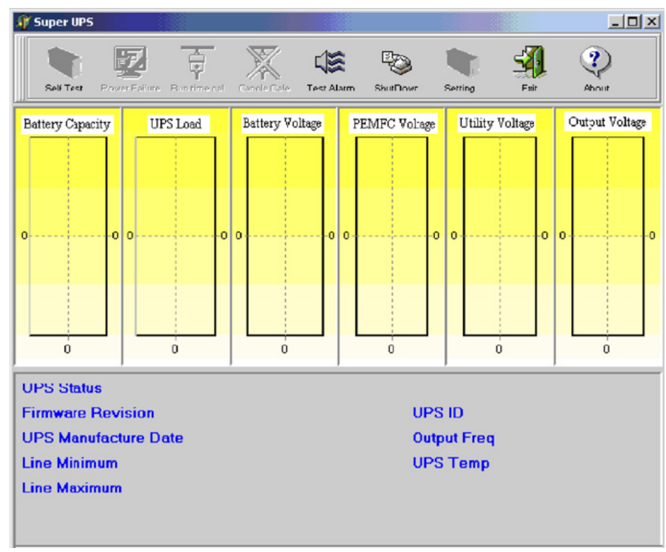

Fig. 10. Network UPS hybrid system interface.

5.2. Intelligent control strategy tests

The proposed intelligent control strategy has been implemented in the PEMFC test system. When the utility grid power

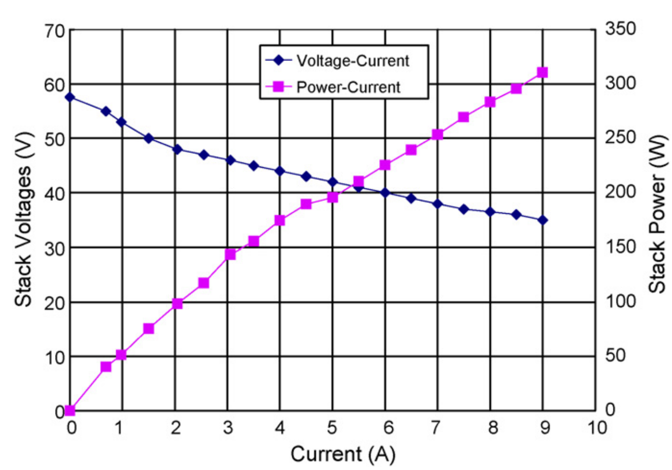

Fig. 11. Voltage–current and power–current characteristics of PEMFC.

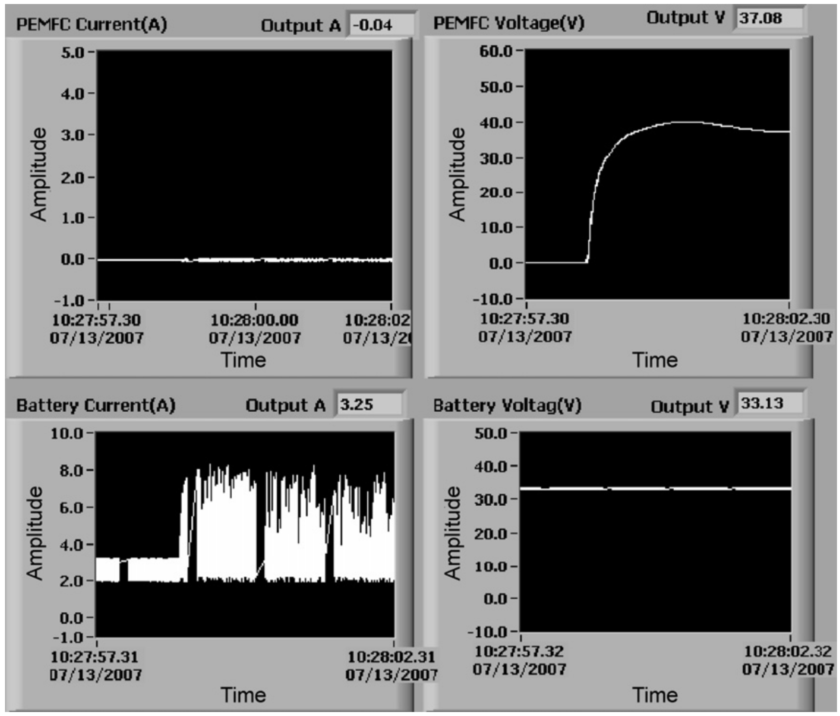

Fig. 12. Start-up performance of PEMFC.

is interrupted, the intelligent controller directs the battery to supply the UPS hybrid system and starts up the PEMFC stack, as illustrated in Fig. 12. After the voltage of the PEMFC stack is stable, the intelligent controller switches the power source from the battery to the PEMFC, as demonstrated in Fig. 13.

5.3. UPS hybrid system tests

The performance of the proposed UPS hybrid system is evaluated by building an experimental set-up with the following specifications: the input voltage of utility grid = 160–275 V ac,

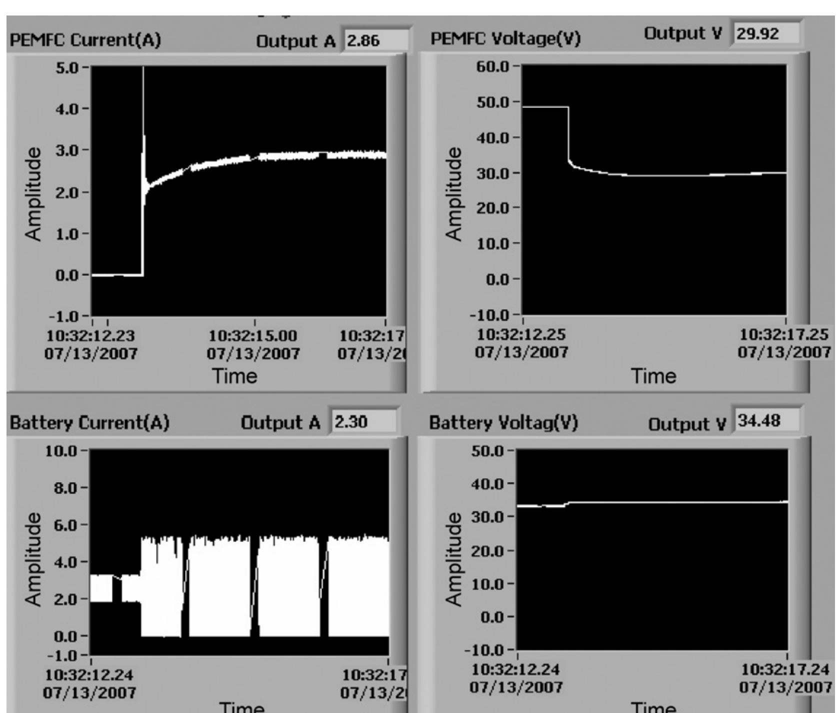

Fig. 13. Switching of UPS power source from battery to PEMFC.

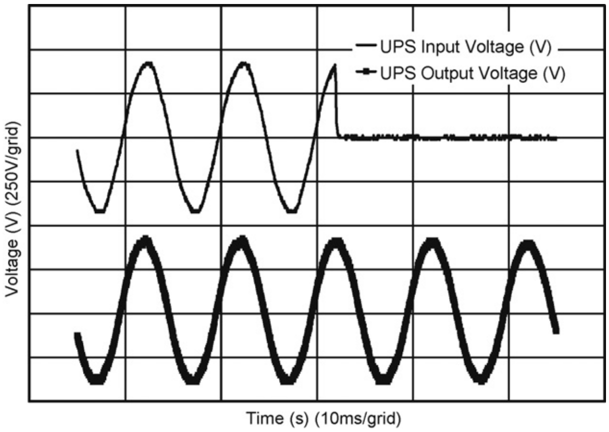

Fig. 14. Transitional waveform when utility grid power is interrupted.

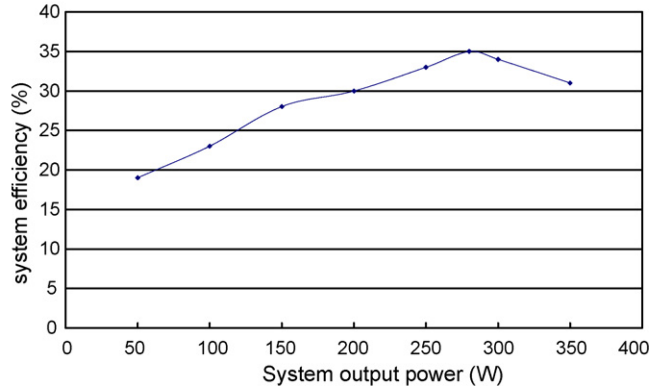

Fig. 16. System efficiency of UPS hybrid system.

output voltage frequency = 50 ± 5% Hz, PEMFC/battery-rated voltage = 36 V dc, input power of load = 286 W. The experimental load is a Dell computer (HP-U2106F3, 213 W) and a monitor (E772p, 73 W). Moreover, a lamp box is used as the supplementary load.

Figs. 14 and 15 show the input voltage and output voltage of the UPS when the utility grid input ac voltage fails and then recovers. Both figures reveal that the uninterrupted output voltage has no overshoots or undershoots, which indicates that a high-quality output voltage is obtained by the UPS hybrid system. It can be seen that a very fast dynamic response has been achieved thanks to the absence of overshoot voltages. The performance of the UPS hybrid system is verified as follows: output voltage = 220 ± 3% V ac, output voltage frequency = 50 ± 0.5% Hz, input power factor >0.92, output power factor = 0.7, and a transfer time with zero interruption.

The measured efficiency of the UPS hybrid system at different loads is presented in Fig. 16. It is seen that the UPS output power prefers to be in the range of 100–350 W, and the maximum efficiency of 35% occurs at about 280 W.

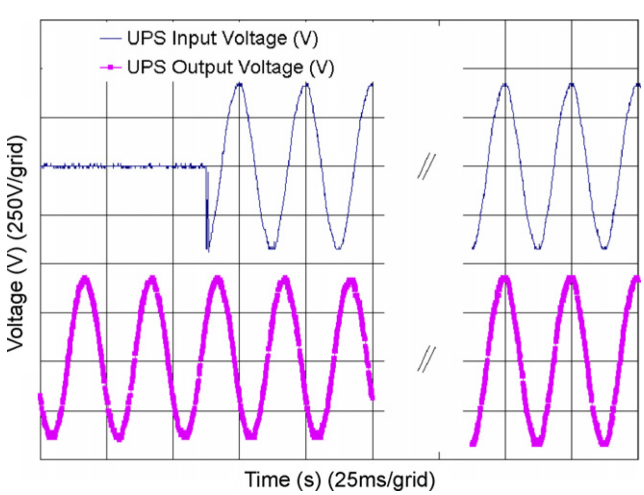

Fig. 15. Transitional waveform when utility grid power recovers.

6. Conclusions

The design considerations and architecture for an intelligent network UPS system with back-up PEMFC and battery power source have been presented. A UPS hybrid system architecture is developed and includes a PEMFC generating system and its data-acquisition devices, an ac–dc rectifier, ac–dc charger, dc–ac inverter, dc–dc converter and associated intelligent network controllers. To achieve intelligent network control of the UPS hybrid system, a TMS320F240 DSP chip and SNMP technology are employed and implemented. Based on the designed UPS hybrid system, three stages of experimental test and analysis are conducted. First, the PEMFC parameters are obtained experimentally. Next, the proposed intelligent control strategy of the PEMFC stack is implemented and examined. Finally, the performance of the UPS hybrid system is evaluated. The theoretical analyses and experimental results indicate that the developed intelligent UPS with a fuel cell/battery power source is suitable for portable, back-up and emergency applications.

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