An Intelligent Uninterruptible Power Supply System with Backup Fuel Cell/Battery Hybrid Power Sources

Yuedong Zhan[a,b], Jianguo Zhu[b], Youguang Guo[b,*] and Hua Wang[a]

[a]Department of Automation, Kunming University of Science and Technology

Kunming, 650093, China

[b]Faculty of Engineering, University of Technology, Sydney

PO Box 123 Broadway, NSW 2007, Australia

Emails: yuedong@eng.uts.edu.au, joe@eng.uts.edu.au, youguang@eng.uts.edu.au

*Corresponding author: Tel.: +61 2 95141268; fax: +61 2 95142435, email address:

youguang@eng.uts.edu.au (Youguang Guo)

ABSTRACT

This paper presents the development of an intelligent uninterruptible power supply (UPS) system with hybrid power sources of a proton exchange membrane fuel cell (PEMFC) and a battery, focusing on the architecture of UPS hybrid system and the data acquisition and control of PEMFC. The hybrid UPS system consists of a low cost 60-cell 300W 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 the digital signal processor TMS320F240, other integrated circuit chips, and a simple network management protocol adapter. Based on the designed intelligent hybrid UPS system, experimental tests and theoretical studies were conducted. Firstly, the major parameters of the PEMFC were experimentally obtained and evaluated. Then an intelligent control strategy for the PEMFC stack was proposed and implemented. Finally, the performances of the UPS with the fuel cell/battery hybrid power source and intelligent control were measured and analysed.

Key Words: Uninterruptible power supply (UPS) system; Proton exchange membrane fuel cell (PEMFC); Lead-acid battery; Hybrid power sources; Backup and emergency power applications

1. Introduction

Uninterruptible power supply (UPS) systems play a very important role as the backup and emergency power supply for important applications, such as computers, medical/life support systems, communication systems, office equipments, hospital instruments, industrial controls and integrated data centre to supply uninterruptible and reliable constant voltage and constant frequency power in case of power 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 nonlinear loads, fast transient response to sudden changes of the input voltage or load, on-line operation which means zero switching time from normal to backup mode and vice versa, 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, and low cost, weight and size. With the fast development of personal computers, information technology and network communication technology, the UPS products will take an increscent part in the industrial and domestic markets. In contrast to the traditional ones, modern UPS power source technologies are developed towards high switching frequency, miniaturisation, redundancy, digitalisation, intelligence and networking. The key embodiment of the intelligent UPS system is the monitoring functions of abundant hardware and software.

However, a UPS system based on batteries only is hard to provide sufficient backup power to critical loads, especially when relatively long time supply is necessary [3]. Hence, other energy sources and storage technologies, such as the fuel cell (FC), have been investigated to replace the batteries. Since the FCs can provide electrical power with high energy density, high efficiency and no pollution, they are considered as a promising technology for UPS products. In the near future, the proton exchange membrane fuel cell (PEMFC) and liquid-fed direct methanol fuel cell (DMFC) based on hydrogen are the most promising FCs due to their excellent dynamic characteristics. The present lifetime capabilities of PEMFC are suitable for backup UPS applications. Furthermore, the PEMFC technology fully complies with the demand for a fast cold start (a few seconds) [4, 5].

The UPS system with backup PEMFC and battery hybrid power source should ensure that there is enough fuel and battery capacity for providing the power needed by the external load. When the utility grid power source is interrupted, the hydrogen will be supplied to the PEMFC stack. However, during the start-up of PEMFC stack, or a sudden change of external load, the 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, the rechargeable battery or supercapacitor can be employed to respond fast to the external load and protecting the PEMFC from excessive use.

This paper presents an intelligent hybrid UPS system with the PEMFC/battery hybrid power sources developed for backup and emergency power applications. Fig. 1 shows the schematic diagram of the system, including a 300 W PEMFC stack, a 3-cell lead-acid battery, a single phase high frequency UPS, and the intelligent control and communication units. The UPS is composed of an AC/DC rectifier, AC/DC charger, DC/AC inverter and DC/DC converter, and can supply the linear and nonlinear loads with the 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 responding time to sudden change of the load. The intelligent controller controls the automatic operation of the whole system, which includes when there is a power failure, 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 as a longer term power source, and switching the power supply back to the utility grid when the utility power is resumed. Through the RS-232 or USB interface, the simple network management protocol (SNMP) adapter and specially designed software, the UPS hybrid system can realise the functions of telecommunication, control and power management.

[Fig. 1. An intelligent UPS system with backup PEMFC and battery power sources]

2. Design Considerations and Architectures of UPS Hybrid System

2.1 Design considerations

In designing the UPS system with PEMFC/battery hybrid power sources, the following points have been taken into account: (1) Adopting matured technology for the components of the UPS hybrid system; (2) Easiness to develop serial products; (3) Multiple functions of intelligent controls and network communications; (4) Adopting the digital signal processor (DSP) as the intelligent network controller; (5) Double charging of the battery through the AC/DC charger and/or the PEMFC; (6) Convenience to collect the data and setup parameters for PEMFC and UPS; and (7) Properly choosing the power, voltage and size of the PEMFC stack according to the cost of the

PEMFC, the battery voltage, and the design of the DC/DC converter, etc.

2.2 PEMFC generating and testing system

The PEMFC generating and 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 in the system. The data acquisition and control devices and software have been designed and can be used to control the whole process of the PEMFC generating and testing system and to measure the operational parameters, such as the working temperature, voltage and current of the PEMFC, the pressure, input and output mass flows, and humidity of the hydrogen and air/oxygen, the voltage and current of the battery, and so on. In the PEMFC generating and testing system, there are lots of functions that could be selected, such as the humidifying of the hydrogen and air, the use of air rather than oxygen, and water-cooling or air-cooling.

For the experimental setup, a 300 W PEMFC stack has been employed [9]. It is a self-humidified, air-breathing and 60-cell stack with an overall size 10.5 x 7.0 x 22.0 cm^3. Three fans are used to supply the air and cool the stack, which has a maximum operating temperature of 65℃ and an operating pressure of 4.55-5.5 psi for hydrogen. Fig. 3 is a photo of the PEMFC stack.

[Fig. 2. Schematic diagram of the PEMFC generating and testing system]

[Fig. 3. Photo of the PEMFC stack]

2.3 Energy storage components

As mentioned above, the energy storage unit such as battery and supercapacitor is one of the key elements in the UPS hybrid system. The PEMFC plays the role of main power supply under normal conditions, and the battery or supercapacitor provides the rest of the power when the load varies suddenly or when the PEMFC starts up. In this UPS hybrid system, the PANASONIC LC-R127R2CH, 12V/7.2Ah/20HR battery is used. On the other hand, one may use 15 series-connected supercapacitors with the main specifications as 1000 F (±20%), control voltage of 2.5 V, and maximum current of 150 A.

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 an active research area [11]. Digital controllers are immune to drifts, insensitive to component tolerances, ease to implement, and flexible with the control rules by software updating. Compared with the analogue control, the digital control UPS is easier to realise the advanced operations.

In the UPS hybrid system, a DC/AC inverter controlled by the TMS320F240 DSP was 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 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 DC/AC inverter cause little damping. The damping effect can be considered by using a small resistor connected in series with the filter inductor [8]. By the sinusoidal pulse width modulation (SPWM) control principle, the DC/AC inverter can convert the ±380 VDC into a 220 VAC pure sine wave.

[Fig. 4. Circuit schematic model of DC/AC inverter]

2.4.2 AC/DC rectifier

A boost active power factor corrector (PFC) with 160-275 VAC input voltage and fixed output voltage (±BUS=±380V 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.

[Fig. 5. Single-phase active PFC AC/DC rectifier]

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 kinds of low-voltage and high-current power sources, so their output voltage (36 VDC) should be boosted up to about ±380 VDC 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 the schematic diagram of the converter. The operating frequency of power switches Q_1 and Q_2 is 20 kHz.

[Fig. 6. Schematic diagram of DC/DC converter]

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. 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 connecting 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 battery voltage is less than the rated value.

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

3. Intelligent Network and Control

3.1 Concepts of intelligent network UPS

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

(1) Monitoring the voltage and current of the PEMFC stack, and deciding if the UPS is supplied by the PEMFC;

(2) Monitoring the voltage and current of the battery, and deciding if the UPS is supplied by the battery, and if the battery is recharged by the AC/DC charger or the PEMFC;

(3) Monitoring 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, and so on;

(4) Displaying 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 the start-up and shut down of the PEMFC and UPS, and realising automatic operations;

(6) Through the RS-232 or USB interface, exchanging information with the computers, workstations and servers;

(7) Through the SNMP adapter, interconnecting with the LAN and realising 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 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 happen, such as overheated components, overload and over-voltage of 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 works if the battery voltage is lower than the rated value. If the utility grid power source is interrupted, the controller makes the PEMFC to charge the battery when necessary.

3.2 Network communications

The operational status and activity of the traditional UPS system can be transmitted to remote monitoring stations and critical load equipments. Volt-free contacts are usually used for providing simple status information, while an RS-232 serial or USB connection for more detailed information. With the help of an SNMP adaptor, the detailed information can be sent directly to a computer network, enabling 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:

(1) Stage 1: The software tells the workstations on the Internet for sending the data from their RAM memories to the server, and storing all the programs that have not been saved in the WINDOWS;

(2) Stage 2: The software runs together with the other communication devices to store all the data and then shut down the devices in turn;

(3) 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 Setup and Results

4.1 Experimental setup

The experimental setup consists of a UPS hybrid system and its intelligent controller, lead-acid battery, PEMFC generating system and the data-acquisition devices including multifunction I/O unit NI6036E, analogue voltage output unit NI6713, parallel digital I/O interface PCI-6503 and analogue multiplexer with temperature sensor AMUX-64T (National Instruments). The UPS hybrid system with backup PEMFC and battery provides the AC power source and controls the linear loads (e.g. lamp box) and nonlinear 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 the pressure transmitter (type: AUS EX 1354X, Burkert) between the inlets of cathode and anode. The output of the UPS is connected to a lamp load that is used in a constant voltage mode. All physical parameters such as currents and voltages 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 the data-acquisition devices. Fig. 9 shows a photo of the experimental setup.

[Fig. 9. Photo of the experimental setup]

4.2 Experimental results

The experimental test and analysis have been carried out on the PEMFC generating system and intelligent network UPS hybrid system. There are three stages of experimental tests and analyses in the UPS hybrid system. At the first stage, the voltage-current and power-current performances of the FEMFC are 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 performances of the UPS hybrid system are measured with the load of a lamp box and a DELL type of PC computer. The UPS system is connected to the network by RS-232 interface or USB connection as shown in the screen interface in Fig. 10.

[Fig. 10. Network UPS hybrid system interface]

4.2.1 PEMFC stack tests

Based on the developed PEMFC generating and testing system, the performances of the PEMFC stack are tested, including voltage-current, power-current, temperature-current, voltage-cell, and etc. Fig. 11 shows the measured voltage-current and power-current curves.

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

4.2.2 Intelligent control strategy tests

The proposed intelligent control strategy has been implemented in the PEMFC test system. When the utility grid power is interrupted, the intelligent controller makes the battery supply the UPS hybrid system and starts up the PEMFC stack, as illustrates 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.

[Fig. 12. Start-up performance of PEMFC]

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

4.2.3 UPS hybrid system tests

The performances of the proposed UPS hybrid system are tested by building an experimental setup with the following specifications: the input voltage of the utility grid = 160-275 VAC, output voltage frequency = 50±5% Hz, PEMFC/battery rated voltage = 36 VDC, input power of the 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 illustrate the input voltage and output voltage of the UPS when the utility grid input AC voltage fails and recovers. Both figures reveal that the uninterrupted output voltage has no overshoots or undershoots, indicating that a high quality output voltage is obtained by the developed UPS system with the PEMFC/battery hybrid power source. It can be seen that very fast dynamic response has been achieved thanks to the absence of overshoot voltages. The performances of the UPS hybrid system are verified as follows: output voltage of the UPS = 220±3% VAC, output voltage frequency = 50±0.5% Hz, input power factor > 0.92, output power factor = 0.7, and the transfer time of zero interruption.

[Fig. 14. Transitional waveform when the utility grid power is interrupted]

[Fig. 15. Transitional waveform when the utility grid power recovers]

Fig. 16 shows the measured efficiency of UPS hybrid system at different loads. It can be found that the UPS output power is preferred to be in the range from 100 to 350 W, and the maximum efficiency of 35% occurs at about 280 W.

[Fig. 16. System efficiency of UPS hybrid system]

5. Conclusion

The design considerations and architecture for an intelligent network UPS system with backup PEMFC and battery power source are presented in this paper. A UPS hybrid system architecture was developed, including a PEMFC generating system and its data acquisition devices, an AC/DC rectifier, AC/DC charger, DC/AC inverter, DC/DC converter and their intelligent network controllers. To realise the intelligent network control of the UPS hybrid system, the 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. Firstly, the PEMFC parameters are obtained experimentally. Then the proposed intelligent control strategy of the PEMFC stack is implemented and examined. Finally, the performances of the UPS hybrid system are tested. The theoretical analyses and experimental results indicate that the developed intelligent UPS with back fuel cell/battery power source are suitable for portable, backup and emergency applications.

References

[1] S.B. Bekiarov, A. Emadi, Uninterruptible power supplies: classification, operation, dynamics and control, in: Proc. IEEE Applied Power Electronics Conference and Exposition, Dallas, Texas, USA, 2002, pp. 597-604.

[2] J. Gonzales, G. Tamizhmani, High efficiency fuel cell based uninterruptible power supply for digital equipment, Journal of Power Sources, 153(2006), pp. 151-156.

[3] Y.R. de Novaes, R.R. Zapelini, I. Barbi, Design considerations of a long-term single-phase uninterruptible power supply based on fuel cells, in: Proc. IEEE 36th Power Electronics Specialists Conference, 2005, pp. 1628-634.

[4] K. Tüber, M. Zobel, H. Schmidt, C. Hebling, A polymer electrolyte membrane fuel cell system for powering portable computers, Journal of Power Sources, 122(2003), pp. 1-8.

[5] E. Varkaraki, N. Lymberopoulos, E. Zoulias, D. Guichardot, G. Poli , Hydrogen-based uninterruptible power supply, Int. J. of Hydrogen Energy, 32(2007), pp. 1589-1596.

[6] B.J. Holland, J.G. Zhu, Design of a 500W PEM fuel cell test system, in: Proc. Australasian Universities Power Engineering Conf., Melbourne, Australia, 2002.

[7] Y.D. Zhan, J.G. Zhu, Y.G. Guo, A. Rodriguez, An intelligent controller for PEM fuel cell power system based on double closed-loop control, in: Proc. Australasian Universities Power Engineering Conf., Hobart, Australia, 2005, pp. 174-179.

[8] Y.D. Zhan, J.G. Zhu, Y.G. Guo, Development of advanced hardware and software of proton exchange membrane fuel cell test systems, Australian Journal of Electrical & Electronic Engineering, 3(2007), pp. 201-210.

[9] Horizon Technology, 300W fuel cell stack operating instruments, available at www.horizonfuelcell.com

[10] W. Choi, et al., Fuel-cell powered uninterruptible power supply systems: design considerations, Journal of Power Sources, 157(2006), pp. 311-317.

[11] Z. He, M. Li, Y. Xing, Core techniques of digital control for UPS, in: Proc. IEEE Int. Conf. on Industrial Technology, 2005, pp. 546-551.

[12] L. Gao, Z.H. Jiang, R.A. Dougal, An actively controlled fuel cell/battery hybrid to meet pulsed power demands, Journal of Power Sources, 130(2004), pp. 202-207.

[13] B.D. Lee, D.H. Jung, Y.H. Ko, Analysis of DMFC/battery hybrid power system for backup applications, Journal of Power Sources, 131(2004), pp. 207-212.

[14] S. Skok, M. Skok, N. Vrkic, Electrical performance test procedure for uninterruptible power supplies, in: IEEE Int. Conf. on Industrial Technology, 2004, pp. 667-671.

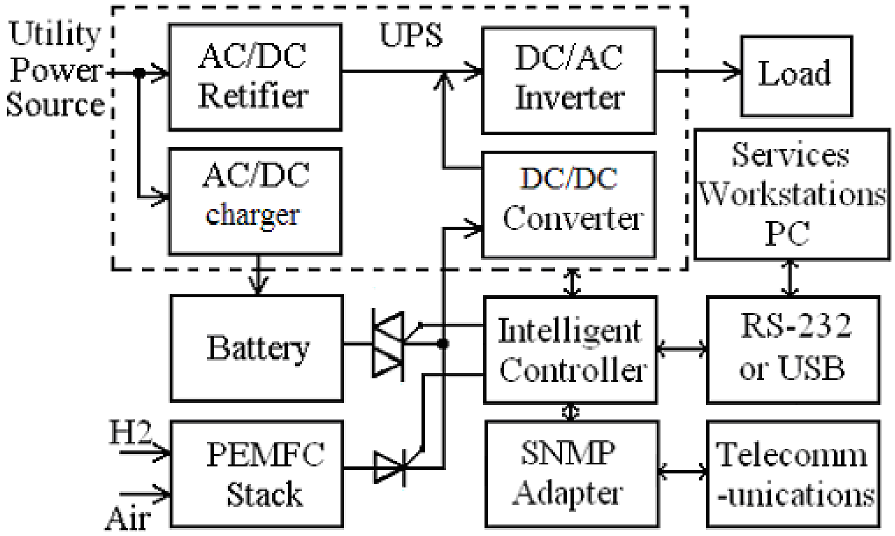

Fig. 1. An intelligent UPS system with backup PEMFC and battery power sources

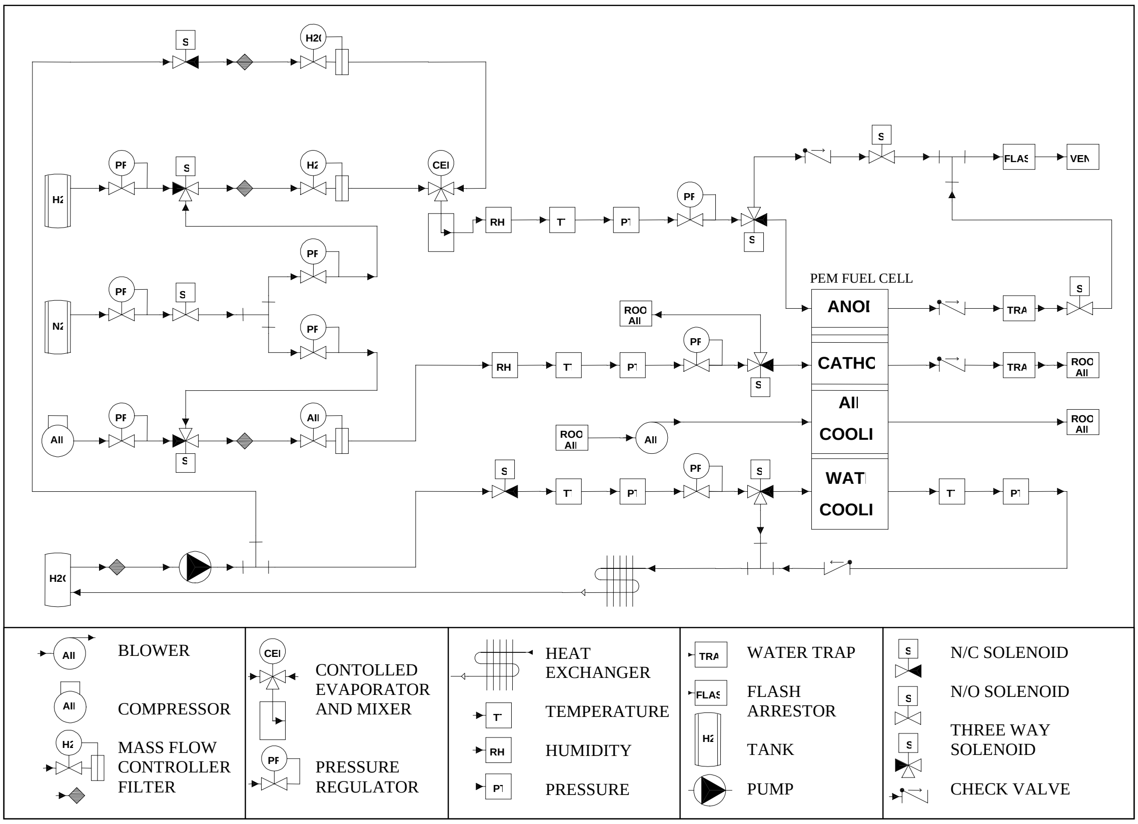

Fig. 2. Schematic diagram of the PEMFC generating and testing system

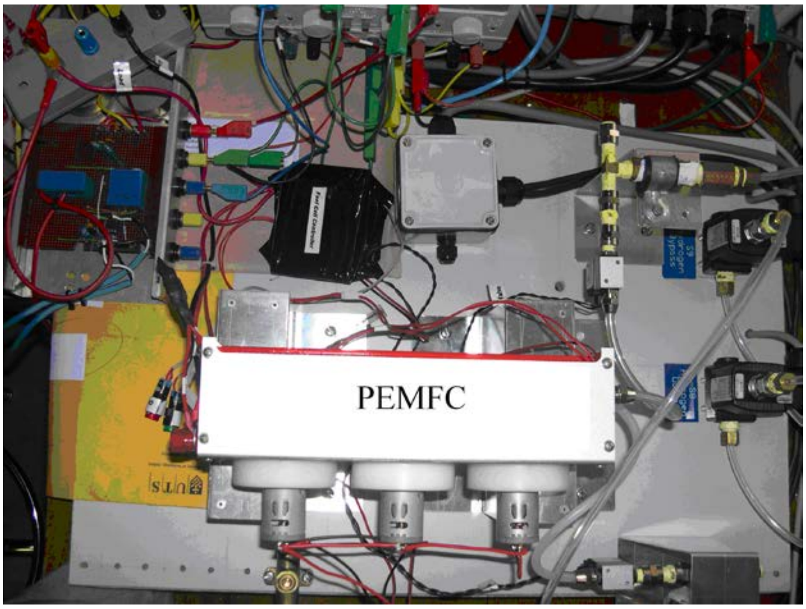

Fig. 3. Photo of the PEMFC stack

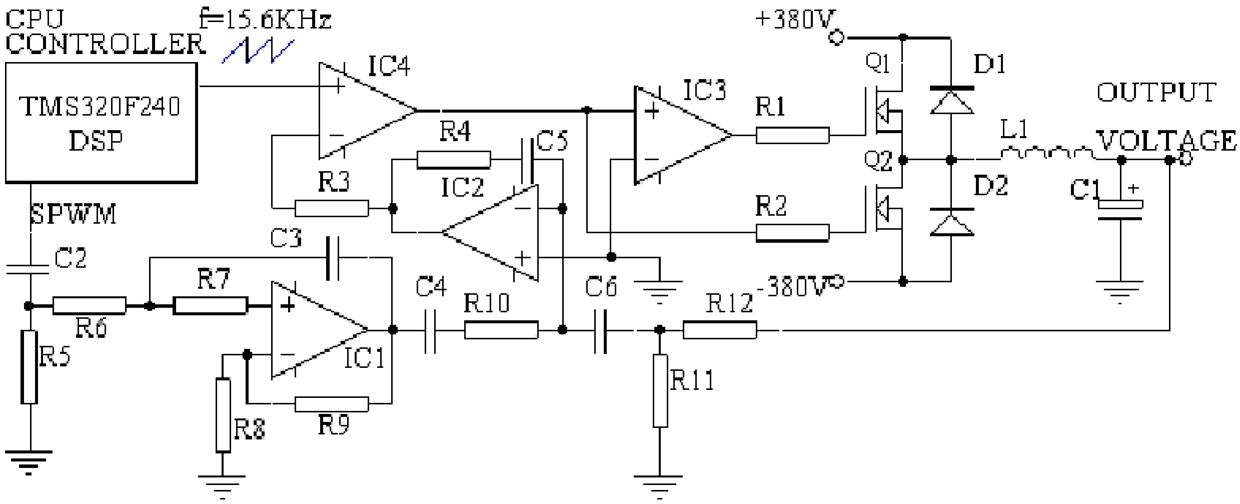

Fig. 4. Circuit schematic model of DC/AC inverter

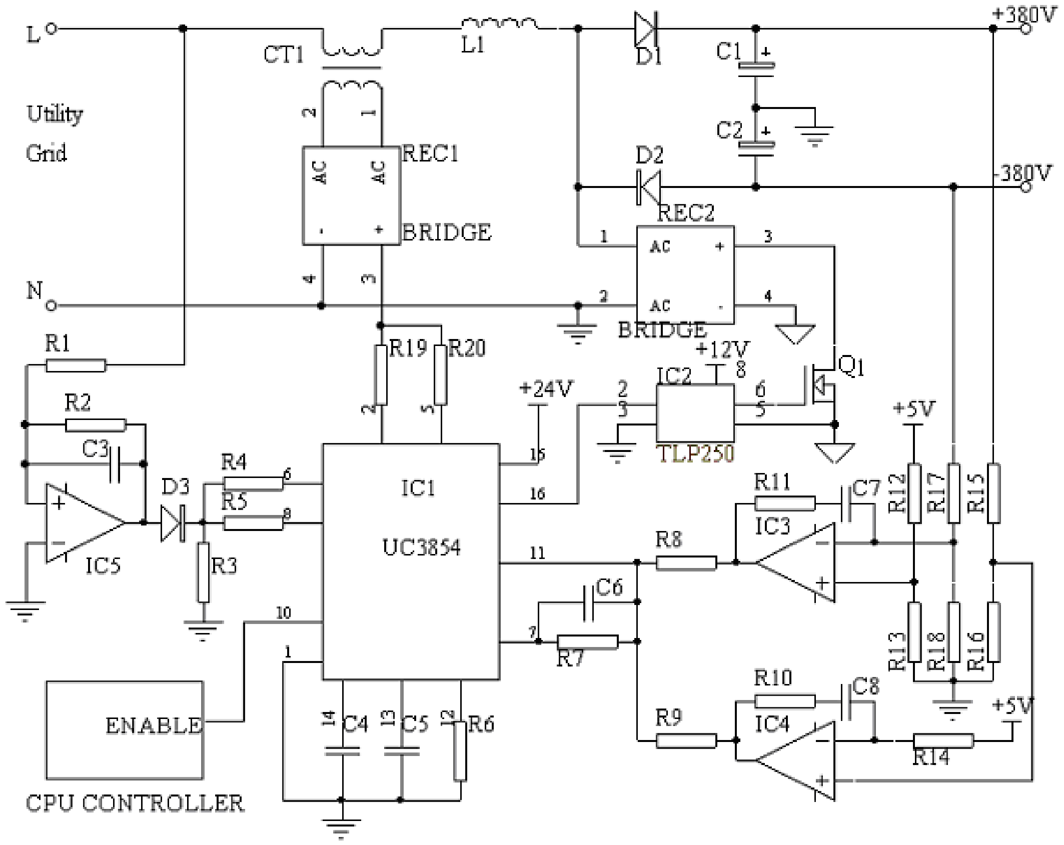

Fig. 5. Single-phase active PFC AC/DC rectifier

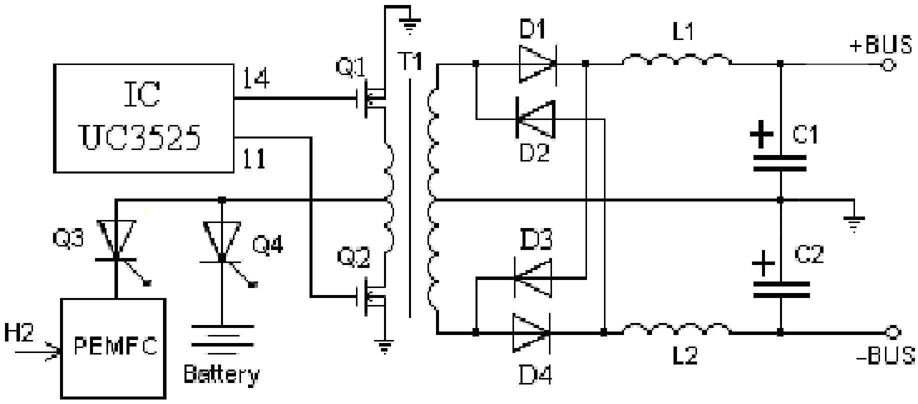

Fig. 6. Schematic diagram of DC/DC converter

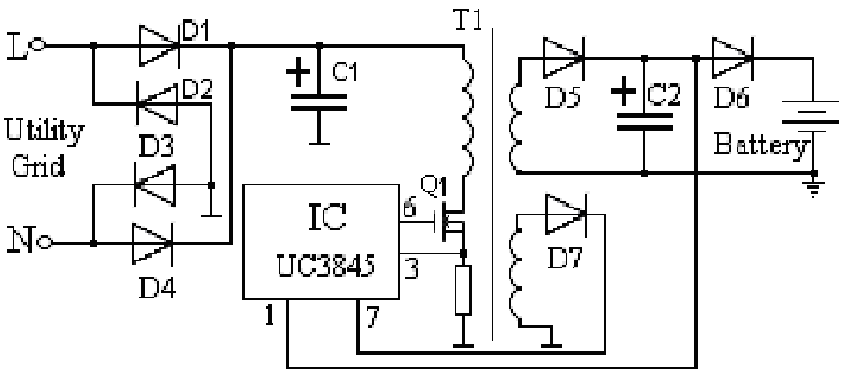

Fig. 7. Schematic diagram of AC/DC charger

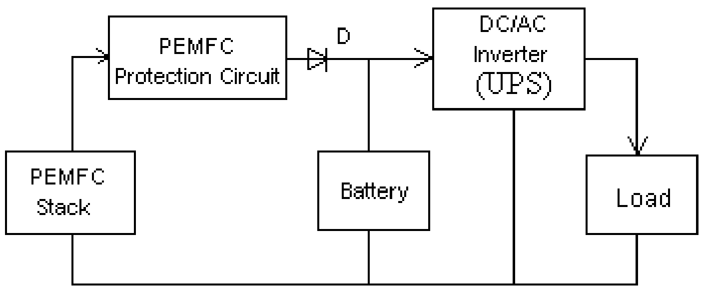

Fig. 8. Schematic diagram of connection between PEMFC and battery

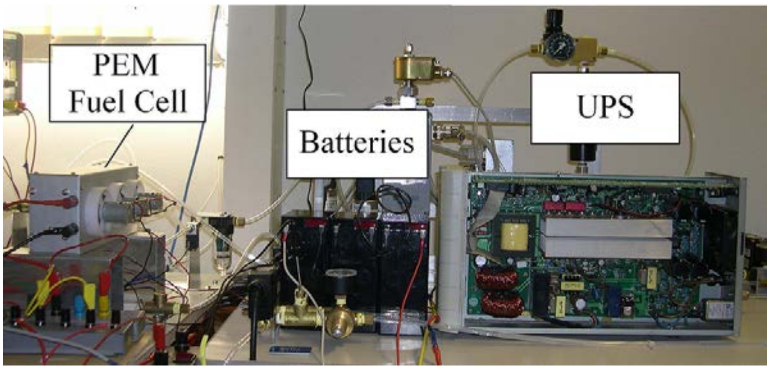

Fig. 9. Photo of the experimental setup

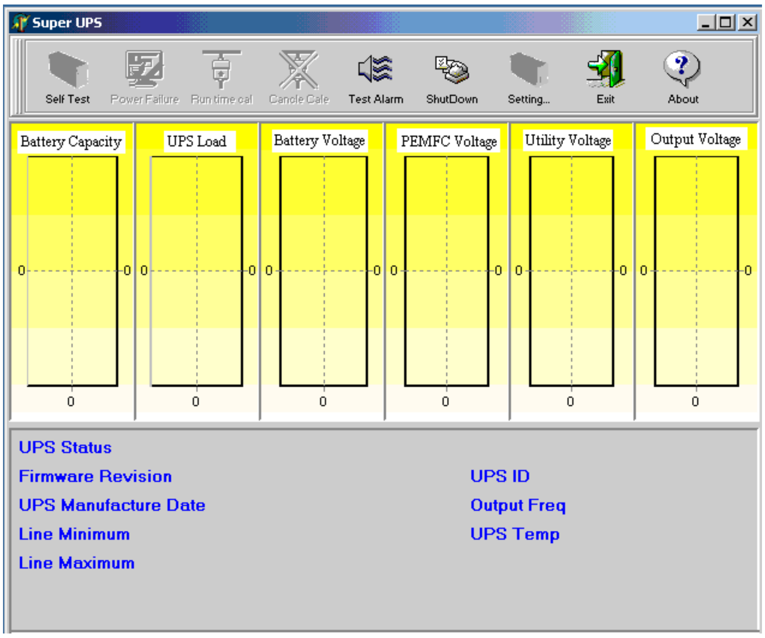

Fig. 10. Network UPS hybrid system interface

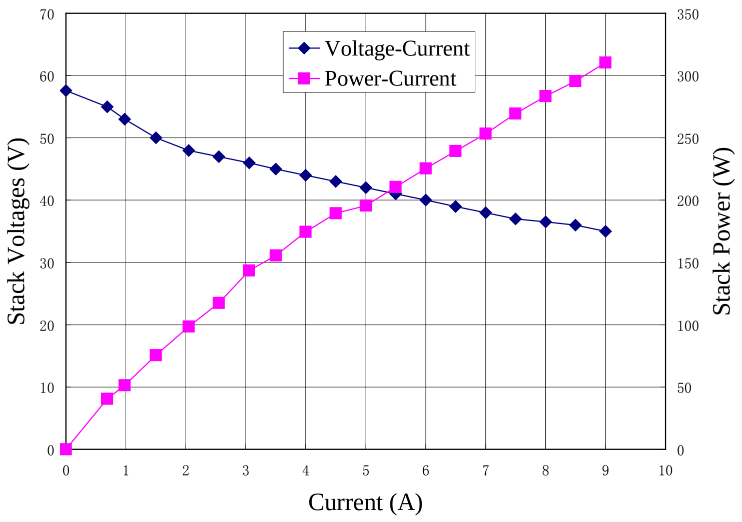

Fig. 11. Voltage-current and power-current characteristics of PEMFC

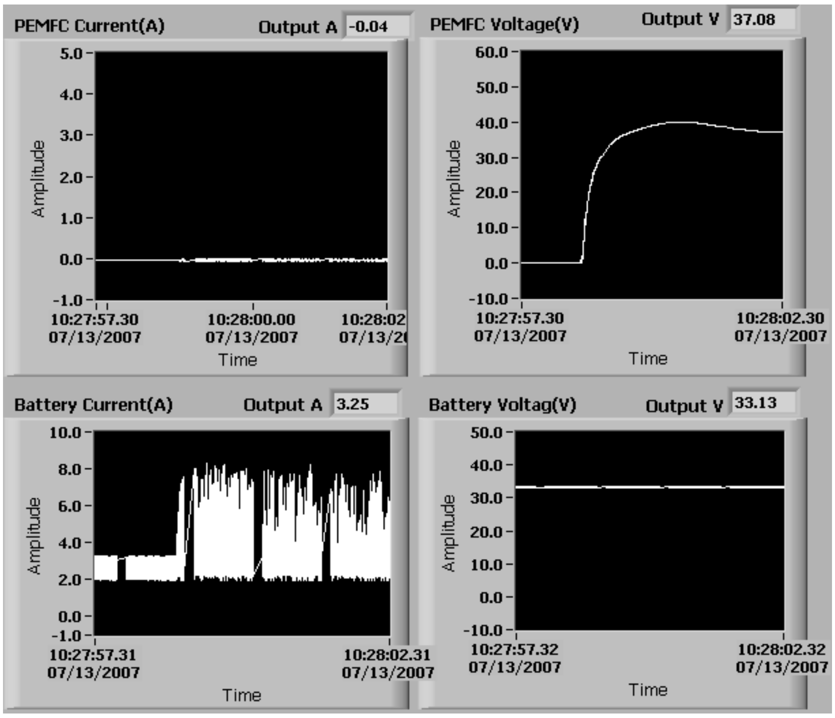

Fig. 12. Start-up performance of PEMFC

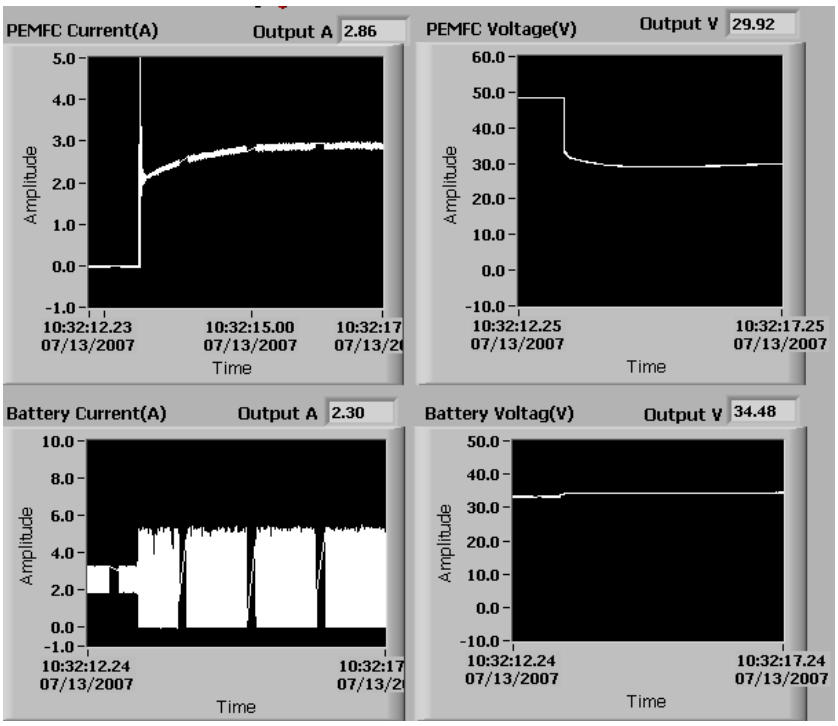

Fig. 13. Switching of the UPS power source from battery to PEMFC

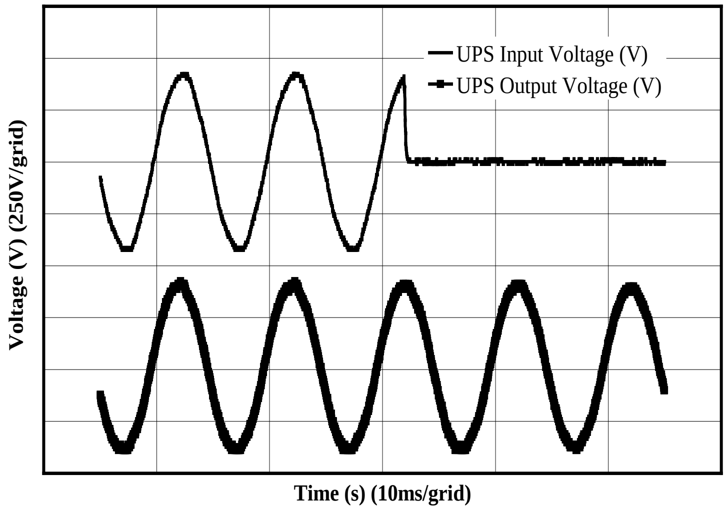

Fig. 14. Transitional waveform when the utility grid power is interrupted

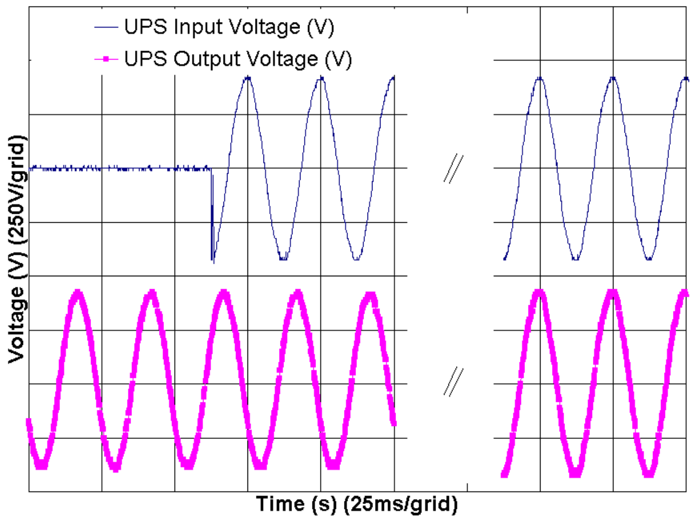

Fig. 15. Transitional waveform when the utility grid power recovers

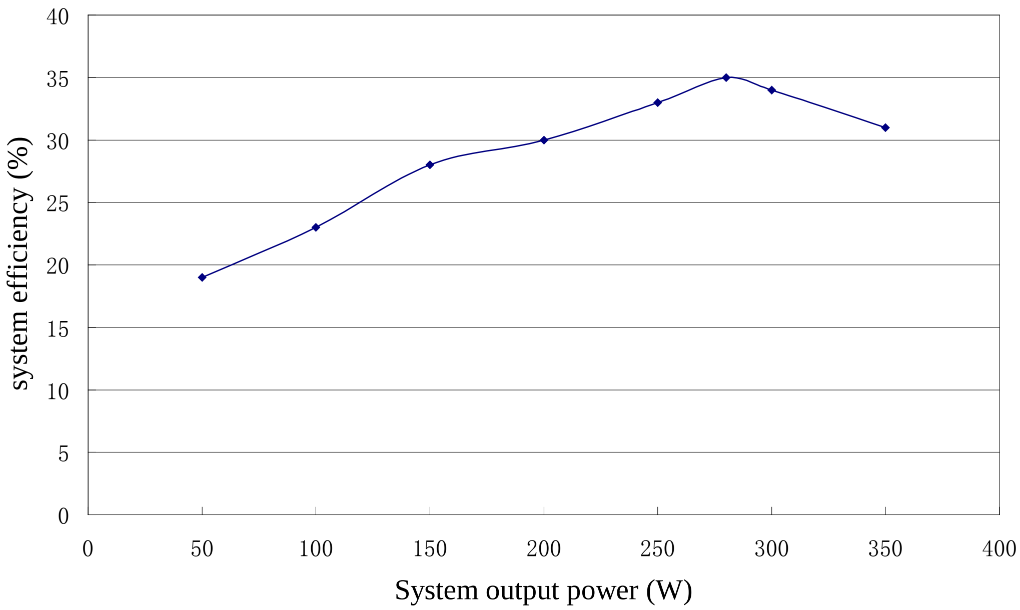

Fig. 16. System efficiency of UPS hybrid system