ELSEVIER

Journal of Power Sources 92 (2001) 131–138

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Development of a 1 kW polymer electrolyte fuel cell power source

T. Susai[a], A. Kawakami[b], A. Hamada[a,*], Y. Miyake[a], Y. Azegami[b]

[a]*Heating, Refrigeration and Energy Development Center, Sanyo Electric Co. Ltd., 1-1-1 Sakata, Oizumi-cho, Oura-gun, Gunma 370-0596, Japan*
[b]*Commercial Equipment Systems, Company Product Development Center, Sanyo Electric Co. Ltd., 1 Otuki-cho, Ashikaga-shi, Tochigi 326-8534, Japan*

Received 18 January 2000; received in revised form 28 April 2000; accepted 24 May 2000

Abstract

This paper reports on the development of key components, specifications, configuration and operating characteristics of a hydrogen-fueled portable power source with polymer electrolyte fuel cell (PEFC). A 1 kW class fuel cell module operating on an exclusive method of internal humidification was developed for the power source. A dc–ac inverter, in which a general-purpose integrated power module (IPM) was used as a switching device for microprocessor-based power conversion control, was developed to save the cost of generating dc power output from the cell module. The power source supplies full power within 2 min from start-up, and is capable of generating rated 1 kW power for about 3 h and even longer if the cylinders are replaced. This power source has been confirmed to offer a high power generation efficiency of 30% or higher in overall output range, yielding good-quality power with little noise. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Polymer electrolyte fuel cell; Hydrogen; Portable power source

1. Introduction

Fuel cells offer a promising solution to the mounting demand for environmentally friendly, high-efficient, and clean sources of energy. Among them, polymer electrolyte fuel cells (PEFCs) are compact and light weight; provide a high output density at room temperature, plus excellent ease of start-up and shut-down in system operation. Intensive development efforts are being directed at expanding their repertoire of applications to include power supplies to power transportation facilities, stationary power supplies for compact cogeneration facilities, portable power sources, emergency and disaster back-up power supplies and so on.

Engine generators have been commonly used for back-up power supplies to date. Their sphere of use, however, has been limited to outdoors because of their noise and emission problems. With the recent availability of sophisticated computers and communications equipment, demand for portable power supplies soars, or those that can be installed adjacent to indoor equipment to generate power.

The authors have embarked on a program to develop portable fuel cells ahead of other manufacturers. In 1988–1993, the authors have developed methanol-fueled 5 and 10 kW phosphoric acid fuel cells (PAFCs), which were subjected to verification testing under a series of critical conditions to verify their practical usefulness for the Defense Agency [1]. This verification testing hinted the practical usefulness of our fuel cells for use in portable power supplies in technical terms.

Encouraged by this experience, full-scale development was commenced, leading to the commercialization of pure hydrogen-fueled 200, and 250 W, and 1 kW portable PAFCs in 1990 [2–4]. In addition to being free from emissions, such as NO_x and CO_2, these three types of fuel cells had a noise level of 40 dB, less than half that of engine generators with 60–100 dB, with 35–40% power generation efficiency more than two times higher than engine generators. After test marketing of several dozens of units to exploit applications and market places, the fuel cells were verified to be serviceable for extended periods of time with superior calmness, promising a potential market as clean emission power generators.

Attention subsequently shifted from PAFCs to PEFCs to pursue further increase in efficiency and drastic cuts in the start-up and shut-down times and better durability after repeated start-up and shut-down cycles in a downsized cell geometry. To this end, we moved ahead with the development of pure hydrogen-fueled PEFC portable power sources and have finally succeed in the commercialization of the 1 kW PEFC power sources, shipping them on a test basis. This paper reports on the development of the key

---

[*] Corresponding author. Tel.: +81-276-61-8949; fax: +81-276-61-8949.
E-mail address: hama046181@swan.sanyo.co.jp (A. Hamada).

PII: S0378-7753(00)00513-9

components, specifications, and operating characteristics of our pure hydrogen-fueled PEFC portable power sources, and proceeds to discuss the system configuration.

2. Development of components

Requirements for a compact portable power source include the ease with which it can be moved and installed where it is used, and an excellent start-up characteristic. Excellent responses to different kinds of loads (electrical products) that may be connected to the power supply altogether, and a 100 V ac setting to address general purpose electrical products are also prerequisite.

The power sources may be fueled by natural gas, propane, butane, and other kinds of hydrocarbon fuels, as well as pure hydrogen. From a viewpoint of compactness and load responses, pure hydrogen comes as a most advantageous choice. Hence, the use of pure hydrogen as a fuel was first decided. Further, an output power setting of 1 kW (100 V ac) was established, as it seemed to essentially cover the total power needs for compact electrical equipment. The following development goals were then set for the key components of the portable power sources:

1. development of an easy-to-control fuel cell module;
2. development of a simple yet high reliability hydrogen supply system;
3. development of a high efficiency inverter;
4. development of a compact yet high performance controller.

2.1. Fuel cell module

To run the fuel cell module in a PEFC successfully, it is necessary to keep the wetting of the solid polymer membrane at all times. This is normally done by humidifying reaction gases and feeding them to the cell. Two methods available to achieve this humidifying are external humidification, whereby an external humidifier provides vapor, and internal humidification, whereby a humidifying facility is installed inside the fuel cell module to effect humidification. Of these, internal humidification is more advantageous from a viewpoint of making for a smaller, simpler fuel cell module. The authors have developed a uniquely structured internally humidified fuel cell module. Fig. 1 shows the structure of a single cell featuring this humidification facility. The single cell is composed of a MEA (membrane/electrodes assembly) consisting of a cathode and an anode, and a gas separator having a reaction gas channel on both sides adjoining the cathode and anode. The greatest feature of this humidification method lies in direct supply of water in a liquid state to the hydrogen channel, concurrently with hydrogen as a fuel gas. Hydrogen and water are supplied to the hydrogen channel through fine opening in the headers located at upper side of the gas separator. A constant supply of water to the hydrogen channel allows the hydrogen gas moving over the hydrogen channel and the anode to be wetted directly. As a result, the solid polymer membrane can be kept in a satisfactorily wetted condition at all times, regardless of the operating status.

The cost of the gas separator has a significant bearing on cutting the cost of the cell module. As shown in Fig. 1, one gas separator is arranged for each cell to serve as a path of feeding a reaction gas to and from the cells and also as a current collector. Requirements for the gas separator include satisfactory electrical conductivity, gas shielding, mechanical strength, heat and corrosion resistance. Carbon plates with enhanced gas shielding are mainly used to fill these requirements. The gas separator requires complex contour machining in many of their parts, including the reaction gas supply/exhaust ports, the gas passage, and the gas seal. Forming all these parts by cutting would incur a prohibitively high cost. To cut the gas separator cost, we have

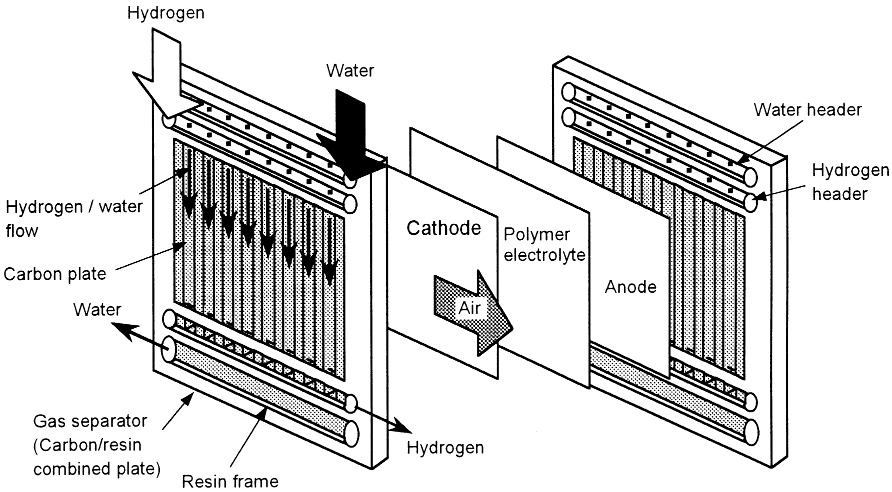

Fig. 1. Concept of the internal humidifying method and carbon/resin combined plate.

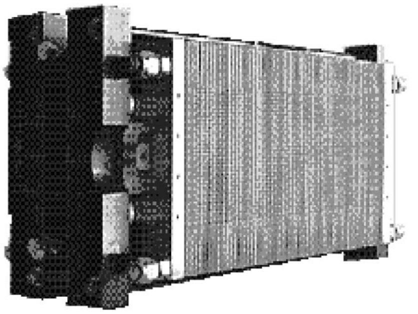

Fig. 2. Exterior view of the 1 kW class module.

developed carbon/resin combined plates having their peripheral areas being composed of a heat resistant resin for ease of forming, with only the gas channel through which current flow being made of a carbon material.

Fig. 2 is an exterior view of a 1 kW class module operating on the exclusive method of internal humidification with carbon/resin combined plates. The fuel cell module is assembled of 52 cells, each having an electrode area of 100 cm^2, stacked on top of one another. Fig. 3 shows the output characteristics of this module and Fig. 4 shows cell voltage distributions in the module for output currents of 40 A. With 40 A current output (about 1.4 kW), an uniform cell voltage was derived under about 20 mV. Consistent performance was observed with a cell stack built of a low platinum loading electrode (about 0.3 mg/cm^2), making a way for successful volume production.

Fig. 5 shows the relationships between the cell voltage and the air utilization in the fuel cell module. Both hydrogen and air that are fed to the cell module are not humidified. Fig. 6 shows the relationships among the reaction air dew point, the cell voltage, and the cell internal resistance on the basis of external humidification. With the previous method of external humidification, an inadequate rate of air humidification would dry the membrane to increase the cell internal resistance or would cause water to reside on the cathode to increase the concentration polarization, resulting in a cell voltage drop. A good cell performance would require controlling the rate of air humidification according to the air utilization. However, as shown in Fig. 5, the fuel

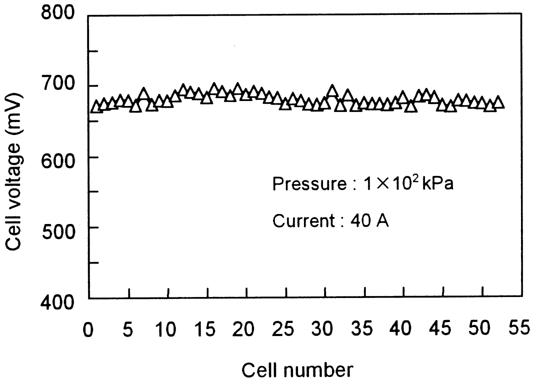

Fig. 4. Cell voltage distribution of the 1 kW class module.

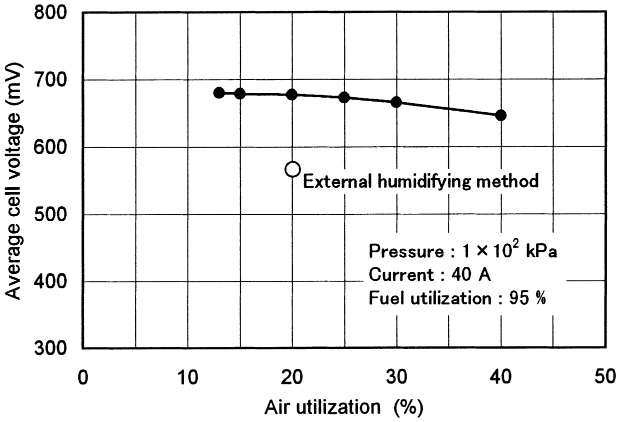

Fig. 5. Relationship between the cell voltage and the air utilization of the 1 kW class module.

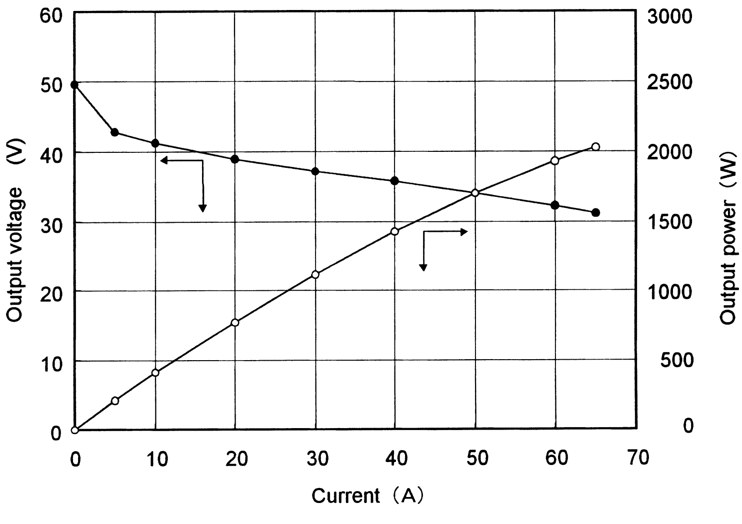

Fig. 3. Output characteristics of the 1 kW class module.

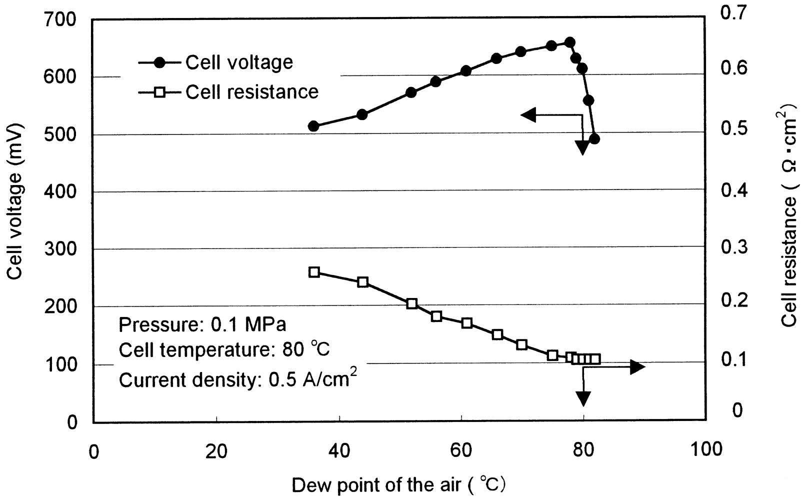

Fig. 6. Relationship among the cell voltage, the cell resistance and the reaction air dew point.

cell module operating on the new method of internal humidification was found to show a satisfactory cell performance across broad range of the air utilization even when dry air was supplied to the module. This was probably because the sufficient amount of water supply to the anode allowed the solid polymer membrane was constantly to be kept in a wetted condition. Fig. 7 shows time related changes in the voltage and temperature that are observed when the fuel cell module was operated under a constant load (40 A) at room temperature. The voltage became slightly lower with time until the temperature exceeded 45°C. Low water vaporizing rate in this temperature range causes increase of liquid product water amount in the cathode. As a result, it was considered that concentration polarization increased with time and the voltage became lower. When the temperature exceeded 45°C, it was considered that the voltage began to rise because water vaporizing rate became higher and the gas diffusion was recovered. After that, the fuel cell module was heated to about 60°C following the connection of loads to it, a stable cell voltage was obtained without needing to control the rate of air supply in the meantime.

These findings verified the stable output characteristics of the uniquely structured internally humidified cell module without needing complex controls of the rate of reaction gas supply to the cell module, the rate of humidification, and the working temperature.

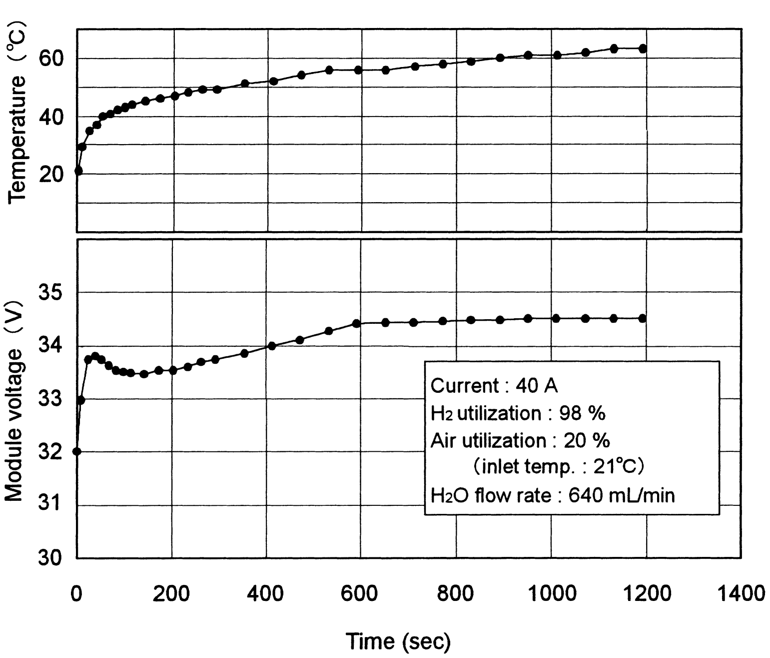

Fig. 7. Time-related changes in the voltage and temperature that are observed when the fuel cell module is run under a constant load at room temperature.

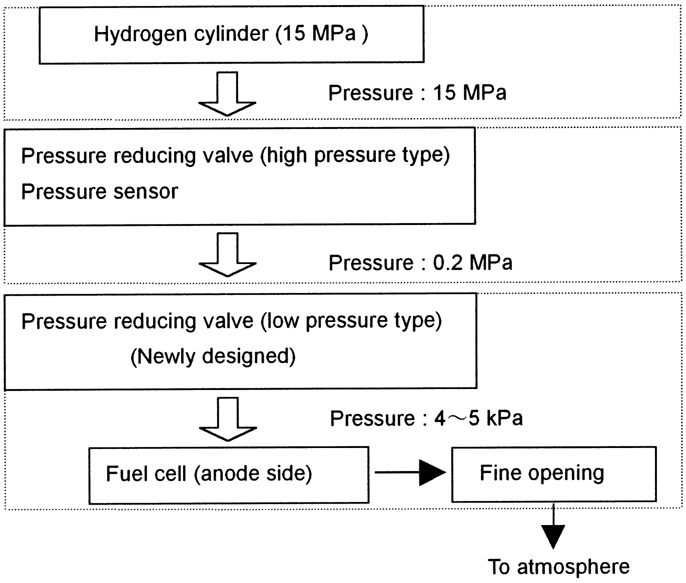

Fig. 8. Schematic diagram of the hydrogen supply system.

2.2. Hydrogen supply system

The hydrogen supply system may be fueled from a high pressure hydrogen cylinder, a hydrogen storage alloy tank or the like. A hydrogen storage alloy tank is capable of storing a large volume of hydrogen in a compact vessel under low pressure. It was used with the 250 W portable PAFCs developed earlier [2]. One problem about using a hydrogen storage alloy tank was that users had to purchase a dedicated hydrogen storage device to charge the tank with hydrogen. A decision was made therefore to use a relatively readily available high pressure hydrogen cylinder as a fuel source.

Fig. 8 schematically shows the hydrogen supply system. A stable supply of hydrogen gas from the hydrogen cylinder to the fuel cells is needed to retrieve stable power from the fuel cells. This system has been developed with a primary view to achieving a high degree of flow rate controllability in a simple structure. The hydrogen supply system consists of a pressure sensing mechanism, two steps of pressure reducing valves placed in series, and a hermetically sealed piping containing a piping with a fine opening in the downstream section. The high pressure hydrogen gas (up to 15 MPa) that is fed from the hydrogen cylinder passes through the high pressure piping and is reduced to 0.2 MPa through a preliminary pressure reducing valve with a built-in pressure sensor. Then, the hydrogen gas is further reduced to a low pressure of 4 kPa or through a newly developed secondary pressure reducing valve before it is fed to the sealed piping that contains the fuel cell module. In this set-up, as hydrogen gas is consumed through a generating reaction of the cell module, the secondary pressure reducing valve keeps the secondary pressure constant, providing a new supply of hydrogen to make up for its consumption. Hence, load specific flow rate control takes place automatically. Only a small volume of hydrogen is discharged through the fine opening in the downstream piping of the cell module, thereby preventing traces of impurities contained in the hydrogen cylinder to be accumulated in the cell module.

2.3. Power inverter

The power supply system is set for an output of 100 V ac single phase to support general purpose electrical equipment. A dc–ac inverter was developed to save the cost of generating dc power output from the fuel cell module. From a cost performance viewpoint, a general purpose integrated power module (IPM) is used as a switching device for microprocessor-based power conversion control. Fig. 9 shows the dc–ac inverter circuit. The IPM simplified the step-up chopper and the inverter circuitry, cutting component requirements. The microprocessor control has made it possible to implement complex power controls and to change control parameters with ease by way of software and also cut the operation tuning time required drastically.

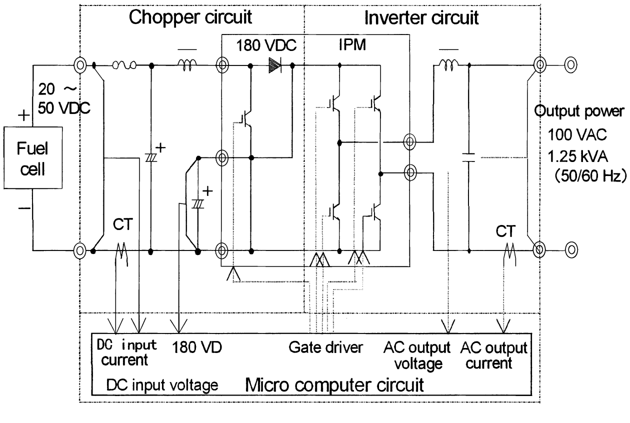

Fig. 9. Circuit diagram of the dc–ac inverter.

Table 1
Specifications and characteristics of a dc–ac inverter

Output voltage	100 V ac (50/60 Hz)
Switching device	IPM
Power conversion control	Microprocessor-controlled
Primary circuit power conversion efficiency	85–90%
Relative harmonic content	5% or less

The fuel cell module used in the power supply system has its output varied between 20 and 50 V dc under the influences of the output current and time related changes. A dc input voltage of 141 V (peak value of the ac waveform) at least is required to derive 100 V ac with the inverter. The power inverter developed this time features a step-up chopper circuit as the primary dc–ac inverter circuit to boost the input voltage up to 180 V dc and a four switching device full bridge power inverter circuit as the secondary inverter circuit.

The control microprocessor in the dc–ac inverter converts the input voltage, the input current, the intermediate voltage (dc voltage resulting from boosting), the output voltage, and the output current from ac to dc to direct switching pulse signals to the IPM. The intermediate voltage converted from ac to dc, and the ac output voltage are feedback controlled at 180 V dc and 100 V ac at control frequencies of 7.5 and 15 kHz, the same frequency as switching, respectively. Table 1 summarizes the specifications and characteristics of the dc–ac inverter developed this time. The primary circuit has a power conversion efficiency of 85–90%, with a relative harmonic content of less than 5%. A conversion efficiency as high as 90% was achieved despite the adverse input conditions for an inverter — a low voltage and a high current.

2.4. Controller

The controller starts up and shuts down the power supply system, supervises its operating status, produces self-diagnostic indications in times of faults, carry out communication with remote monitors and so on. It incorporates a 24 V dc output auxiliary equipment power supply circuit that is powered from the fuel cells to power auxiliary equipment, such as solenoid valves and fans. Cell temperature, hydrogen pressure and other sensor settings are fed to the control microprocessor to downsize and economize on the control board. The single chip microprocessor contains an A-D converter, a control switch, signal I/O ports, and a serial communications port for communicating with a remote monitor. Microprocessor based control of the dc–ac inverter has eliminated a power detection circuit by allowing power measurement data input through sessions of communication.

3. Portable 1 kW PEFC power source

Fig. 10 shows the appearance of the portable 1 kW PEFC (FCP-10KHA). Table 2 summarizes its power specifications.

Fig. 10. Appearance of the 1 kW PEFC portable power source.

Fig. 11 shows the system configuration of the power source. It comprises a fuel cell unit, a hydrogen feeder, a power converter, which converts dc power generated from the fuel cells to ac output, and a controller, which provides control over the system as a whole.

Ni–Cd secondary batteries are equipped in this power source. When the power source starts up, these batteries supply electric power for the controller and auxiliary equipment.

The power source has its hydrogen cylinder compartment and the unit assembled into a single cabinet for easy transportation. Two commercially available 10 l hydrogen cylinders (hydrogen volume 1.5 m^3) can be loaded with the unit front panel open. Key components, including the fuel cell module and controller, separated by partitions are placed on the back of the hydrogen cylinder compartment. There is a water supply port on the top panel of the unit and load connection receptacles in the front panel.

Fig. 12 shows the power source start-up sequence flow. All operations are microprocessor-controlled automatically. Pressing the start switch in the control unit starts up the fuel cell power source. The start-up sequence begins with the water circulating pump wetting the fuel cells, the solenoid valve opening to supply fuels (hydrogen), and the blower starting to feed reaction air. Electric power for these parts is supplied from Ni–Cd batteries. After the open circuit voltage of the fuel cells is verified, the power supply to the auxiliary

Table 2
Power source specifications

Type	FCP-10KHA
Rated output	1 kW (1.25 kVA)
Output voltage	100 V ac (50/60 Hz)
Power generation time	About 3 h (1 kW output)
Fuel	Hydrogen (10 l cylinder×2)
Dimensions	550 mm (W)×500 mm (D)×103 mm (H)
Weight	78 kg (excluding cylinders)
Start-up time	2 min or shorter
Noise level	40 dB (a characteristic)
Operating temperature	0–40°C

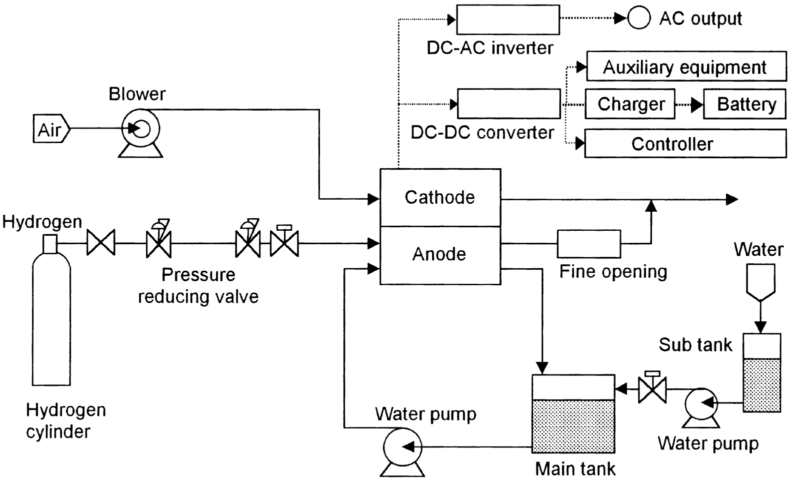

Fig. 11. System configuration of the 1 kW PEFC portable power source.

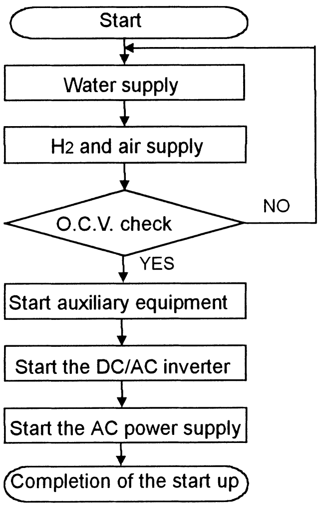

Fig. 12. Start-up sequence flow of the 1 kW portable power source.

equipment is switched from the Ni–Cd batteries to an auxiliary equipment power supply circuit that is powered by the fuel cells. Subsequently, the dc–ac inverter is actuated to continue with gas supply to the fuel cells until the generation stand-by state reaches a state of stability, when power output is commenced. This start-up sequence takes about 2 min to complete. Fig. 13 shows the start-up characteristics. The power supply is capable of generating rated 1 kW power for about 3 h and even longer if the cylinders are replaced. Water consumption of this power source varies with output power. When the output power is 1 kW, the consumption is about 1 l/h. Fig. 14 shows the relationships between the output and the operating time.

Safety features cut off the hydrogen supply automatically in the event of unusual cell temperature rises, hydrogen leaks, or quakes.

Fig. 15 shows the electrical characteristics of the output. The output voltage changes slightly with the output power. Fig. 16 shows the relationships between the power generation efficiency and the output power. While the power generation efficiency varies with output in engine generation, this power supply has been confirmed to offer a high power generation efficiency of 30% or higher in each output range, yielding good quality power with little noise.

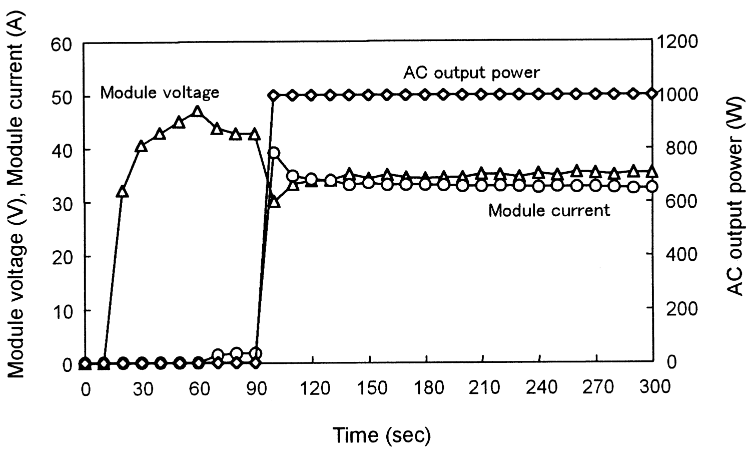

Fig. 13. Start-up characteristics of the 1 kW PEFC portable power source.

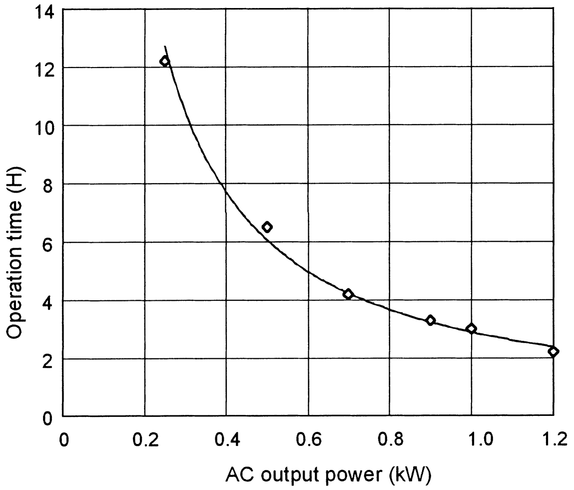

Fig. 14. Relationship between ac output power and operation time of the 1 kW PEFC portable power source.

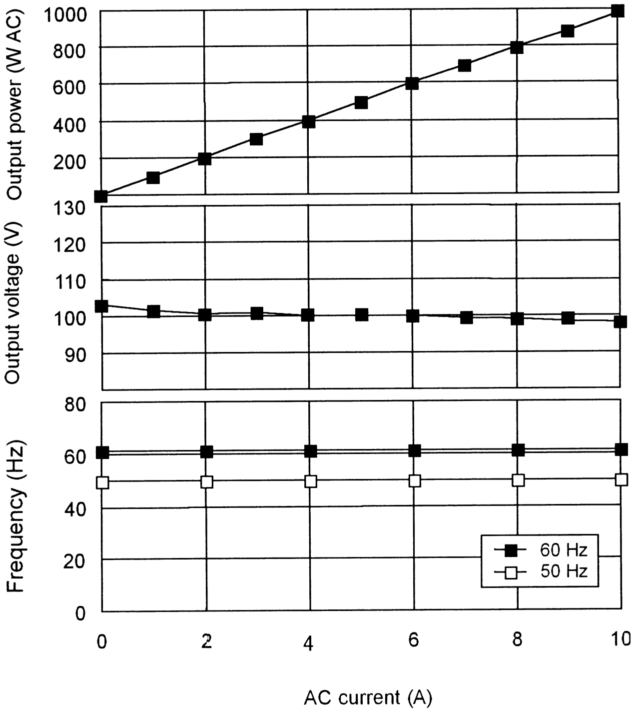

Fig. 15. Electrical characteristics of the 1 kW PEFC portable power source.

4. Conclusions

A 1 kW-class portable power source which uses pure hydrogen as a fuel was developed. A PEFC module employs an internal humidification arrangement, where hydrogen and water flow concurrently through the fuel gas passage in the fuel cell module. By employing this arrangement, solid polymer membrane is automatically controlled to maintain its appropriate wetting condition, and stable power output can be ensured without setting up a humidifier. In order to control the amount of fuel supply automatically, a simple system with a combination of double series pressure reducing valves was employed. Furthermore, we have newly developed an inverter that employs a general purpose intelligent power module as a switching device and a microprocessor to control electric power conversion, which has enabled to achieve a high electric power conversion efficiency of approximately 90%.

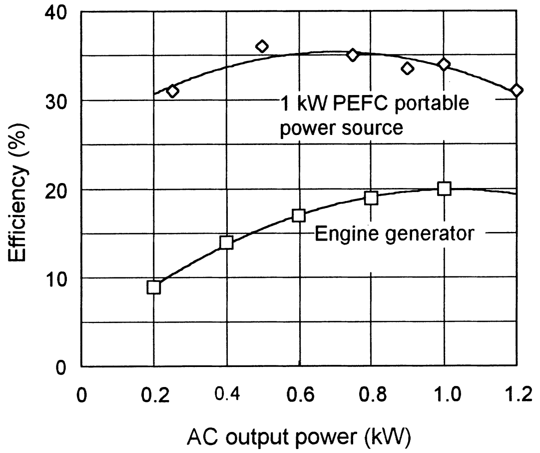

Fig. 16. Relationship between ac output power and efficiency of the 1 kW PEFC portable power source.

The portable power source boasts the following operation characteristics:

1. start-up time at room temperature: within 2 min;
2. operation time at 1 kW output with two 10 l hydrogen cylinders: approx. 3 h;
3. generation efficiency in fully-loaded area: more than 30%.

As anticipated during the design stage, the power source has proven to be superior in performance compared to conventional generators.

Amid concern over the increase in environmental problems, a PEFC power source with quiet and clean operation is expected to be applied to a wide variety of applications, ranging from backup power sources to home power generation systems. Although, we have used hydrogen as a fuel for the power source discussed here, we are also developing power source systems which are able to utilize various types of fuels, such as natural gas, LPG and liquid alcohol such as methanol. To obtain wide acceptance for these power sources, we will commit ourselves to perfecting technology, raising reliability and reducing costs.

References

[1] K. Soukura, S. Yonemochi, H. Kato, M. Kumeta, in: Proceedings of the Eighth International Symposium on Alcohol Fuels, Tokyo, 1988, 935 pp.
[2] A. Hamada, O. Tajima, N. Nishizawa, in: Proceedings of the Conference on International Fuel Cell, Chiba 1992, 71 pp.
[3] A. Watanabe, H. Mukai, N. Nishizawa, T. Ito, Y. Nomura, Sanyo Technical Rev. 26 (1) (1994) 18.
[4] K. Shindo, A. Fuju, S. Yamamoto, T. Nakaoka, T. Yasuo, Sanyo Technical Rev. 29 (2) (1997) 17.