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Application of a polymer exchange membrane fuel cell stack as the primary energy source in a commercial uninterruptible power supply unit

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Abstract

This paper presents construction details of a commercially available uninterruptible power supply system (UPS) in which a PEM fuel cell stack was used as the primary energy source. Results of component testing as steady state fuel cell stack performance are presented and analyzed in the context of project assumptions. Finally, the results of field tests of the complete UPS unit are presented and analyzed. The designed and constructed uninterruptible power supply with fuel cell module can power any electrical device up to 300 W for 80 minutes with 33 grams of hydrogen stored at 124 bar.

Keywords: Proton exchange membrane fuel cell, Stationary application, Hydrogen, Uninterruptible power supply

1. Introduction

Fuel cells supplied with hydrogen have been recognized by world-wide energy policy makers as future electrical energy production technology and hydrogen as an energy storage solution and energy carrier. Thanks to increased financial support and scientists' efforts in the last few years, enormous progress was achieved in fuel cell technology through increased stack power density and extended life time and reduced cost of manufacturing [1–8]. Polymer electrolyte membrane fuel cell (PEMFC) technology development reached a stage and a price level allowing fuel cell to be used as an unconventional energy source in a wide range of commercial applications. Due to technological development, fuel cell stack manufacturers are able to produce units with life times and performances meeting established requirements for stationary and automotive applications. 20 000 and more hours operation time of a fuel cell stack in stationary application was reported [9].

Although governments are convinced of the need to develop alternatives for fossil fuels in energy production processes and find fuel cells useful, the lack of public acceptance for innovative hydrogen technology is still apparent and has to be overcome before "environmentally friendly" technology can be launched on the commercial market.

Among known fuel cell types, PEMFCs have the potential capacity to complement or even substitute the conventional technologies used for uninterrupt-

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ible power supply that are based on combustion engine generators and lead-acid batteries. The new and emerging technology of PEMFC enables the main drawbacks of currently used technologies to be overcome. For example, the problems related to excessive maintenance, high pollution and noise levels that combustion engine generators have are absent from PEMFC based systems. Compared to battery-based UPS, the PEMFC system delivers longer continuous runtime and better durability under hard environmental conditions. The advantages of PEMFC are connected with their low operating temperature (up to 100°C), high electrical efficiency (up to 60%) and flexibility in the generated power range (from W up to MW). Moreover, they are compact, lightweight, non-polluting, low mass and volume power generators which can be used as an energy source in stationary systems as well as in portable applications [10–13]. PEMFC based systems have high specific energy and reliability, and they do not require much maintenance because they have few moving parts. There are many publications that address preparation and investigation of complicated hi-tech systems in which a PEM fuel cell stack was used as energy source [14–16].

The present paper contains a description of design and construction details of a commercially available uninterruptible power supply (UPS) in which a PEM fuel cell stack was applied as a primary energy source by easy substitution of lead-acid batteries. Exchange of energy source was preceded by carefully performed investigations of stack steady state performance in order to verify the feasibility of its use in this application. Results of preliminary tests of modified UPS as well as its operation characteristics are presented and discussed.

2. Design consideration

Preparation and design of the uninterruptible power supply based on commercially available components aimed to prove that there are real possibilities to use fuel cells in modern electrotechnology and innovative solutions.

A fuel cell aided UPS system is an alternative to typical units equipped with lead-acid batteries. Elaboration of equipment based on innovative solutions is essential and can have a positive influence on their dissemination and future commercialization.

The assumption made in the project preparation phase was that all components should be easily available on the market and the final unit (UPS-PEMFC) should have the following specifications:

- rated power 300 W (capacity to generate higher power at short time intervals),
- output voltage 220–230 V AC,
- frequency of output voltage 50 Hz,
- operation time approx. 60 minutes of continuous supply at rated power,
- zero pollution emission, quiet operation—environmentally friendly.

Although the rated power of the fuel cell stack planned for installation is 500 W, the nominal power of the UPS is reduced and predicted to be approximately 300 W. The reason for this is the power consumption of the balance of plant components installed in the whole system such as: air compressor, solenoid valves, electromagnetic relays, etc., as well as the efficiency of the DC/AC inverter. Nevertheless, the estimated power is still sufficient to support the operation of a few electrical devices in the case of a voltage drop or net power supply failures. Rated output voltage and its frequency meet the requirements of presently produced electrical devices and have values of 220–230 V and 50 Hz, respectively. The predicted continuous operation time at the rated power of the fuel cell power supply is expected to be 60 minutes, which is sufficient to safely finish work with electrical devices (i.e. data saving and system shutdown during PC operation).

3. Results and discussion

The experimental part of the described work is divided into two stages. In the first stage suitable elements meeting the requirements of the project are selected and their performance and operating parameters, such as fuel cell stack steady characteristics, are measured. In the second stage the selected elements are integrated into the system according to

Figure 1: UPS with fuel cell module, 1—fuel cell stack, 2—hydrogen container and gas pressure reducer, 3—power controller with DC/AC converter, 4—batteries, 5—air compressor

Table 1: Technical specification of installed PEMFC stack

Electrical Parameters
Rated power 500 W Rated current 50 A Rated voltage 10 V DC Rated current density 500 mA/cm^2 at 0.7 V (measured for single cell) Stack efficiency >40% at 500 W Number of cells 16, effective working electrode area 100 cm^2
Hydrogen requirements
Purity H_2 CO<1 ppm Flow rate 7.5 SLPM Humidity 70–95% RH
Air requirements
Flow rate 35 LPM Usage efficiency 500 W Humidity 70–90% RH
Operation conditions
Temperature 70–80°C Pressure range of reactant gases 1.0–2.5 bar

the design, and the operation characteristics of the complete UPS-PEMFC system are measured and analyzed.

3.1. UPS construction

A commercially available 800 VA (480 W) Powercom unit, BNT 800AP model, was selected for DC voltage conversion to the useful alternate current. In parallel to the originally installed battery (12 V, 10 Ah), a 500 W stack was connected to significantly extend the operation time of the unit. Application of PEMFC stack requires a supply of hydrogen and air or pure oxygen, so the construction was equipped with a hydrogen tank and an air compressor. Operation of the power supply with fuel cell module was controlled by an electronic system. All construction components were installed in a Tango 22U cabinet, as presented in Fig. 1.

The reason for selecting an oversized enclosure was the need to easily disseminate the new and emerging fuel cell technology and present its application. The components of the system are clearly visible and principle of fuel cell based UPS operation can be explained and demonstrated. The other reason was easy access to the system components during the experimental work. After all testing is completed and the system operates correctly the system can be housed in a more compact way.

The specifications of the fuel cell stack selected for installation are presented in Table 1. The producer-guaranteed rated power of the stack is 500 W, which fully meets the project's assumptions. It is possible to generate peak power, up to 1 kW, but at short time intervals. In such cases it is essential to control stack temperature to avoid overheating.

Due to its low working temperature PEMFC requires a supply of pure hydrogen. Stack operating temperature of below 100°C is too low for reforming processes to proceed and therefore it is not possible to supply the stack with hydrogen-rich gases (i.e. C_nH_{2n}). Moreover, a contaminated fuel has a negative impact on the properties of the platinum catalyst and causes degradation. For the installed fuel cell stack class 5.0 purity hydrogen must be delivered, meaning 99.999% hydrogen content. Of the many available hydrogen storage methods in the proposed study, fuel storage in a pressurized container was chosen.

In order to ensure sufficient fuel for fuel cell stack operation, a 3.5 liter container with 124 bar pressure was selected. In view of these parameters it is possible to store approximately 33 g of pure hydrogen, which at 1 bar (stack inlet pressure) would be 434 liters. The nominal fuel flow rate for the installed stack is 7.5 SLPM and for 1 hour operation time it needs 450 liters of hydrogen. This quantity of hydrogen stored in a pressurized container is sufficient for 1 hour of system operation when the gas flows through stack and gas outlet are opened. In the dead-end configuration, when the fuel outlet is closed, excluding purging, almost 100% of the hydrogen is used in the stack; this way the operation time is extended significantly and the efficiency of the system is improved considerably. Measurements were also performed with containers of smaller capacity.

The correctness of the choice of hydrogen storage container is proved by theoretical calculations. Taking into account the power density for hydrogen (3.20 kWh/m^3 at normal conditions) and quantity of the stored gas, it is possible to generate 1.4 kW of continuous power in the time period of 1 hour. This calculation does not take into consideration the efficiency of the energy conversion which takes place in the stack. The stack efficiency presented in Table 1 is 40% at 500 W. Considering stack efficiency, the calculation of total power generated from the fuel stored in the container yielded a value of 650 W in 1 hour when the voltage of 0.7 V at single cell is assumed.

The oxygen needed for fuel cell operation is supplied together with air and delivered to the stack with the aid of an air compressor. Gast model 22D1180DC with 90 W and 12 V DC was installed in the system and is capable of supplying 30 SLPM of gas at 0.5 barg. The air flow rate is consistent with fuel cell stack supplier recommendations concerning air delivery, with a flow rate of 35 SLPM, which was presented in Table 1.

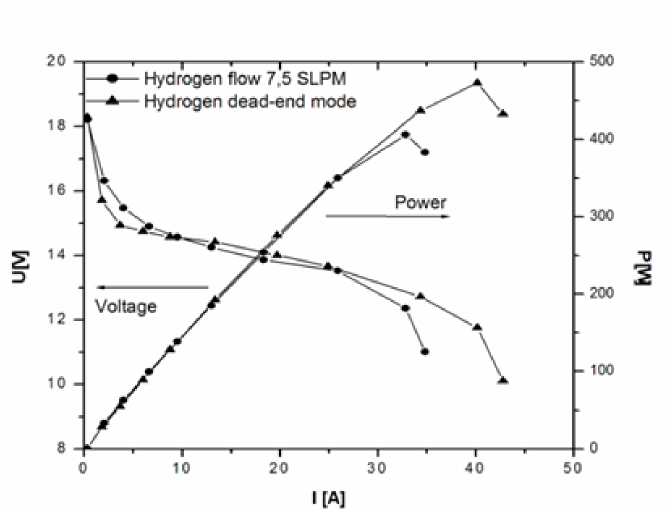

Figure 2: Comparison of characteristics of installed stack measured at various hydrogen flow options, temperature 25°C, pressure of gases 0.3 bar

3.2. Steady state PEMFC stack performance

Current-voltage characteristics were measured in galvanostatic mode at "dead-end" (closed) and opened hydrogen output by use of a testing stand described elsewhere [17]. A comparison of obtained results is presented in Fig. 2.

As can be seen, there is a power gain of more than 10% in favor of the characteristic measured at the dead-end mode over the one measured at opened hydrogen outlet. The higher power value obtained for the dead-end mode is probably caused by better gas pressure distribution along the stack, which can improve the homogeneity of fuel concentration on the electrodes. This way, the concentration losses observed are reduced for the high current characteristic region. The effect of reduction of concentration losses is easily seen in Fig. 2 for the high current region and current values greater than 30 A. With continuous hydrogen flow, maximum power of 400 W was measured at 0.32 A/cm^2 current density and 0.66 V average single cell voltage. In dead-end stack operation mode, the current density measured for the same average cell voltage increased to 0.41 A/cm^2 resulting in power increase to 490 W.

3.3. UPS operation characteristics

To estimate UPS operation time from one full hydrogen container, the series of characteristics were measured and standard software UP-

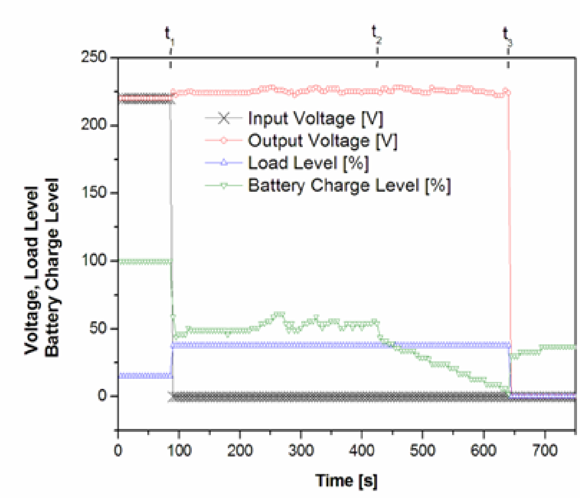

Figure 3: Results of operation time measurement of the UPS supported with fuel cell module supplied with 1.2 g of hydrogen

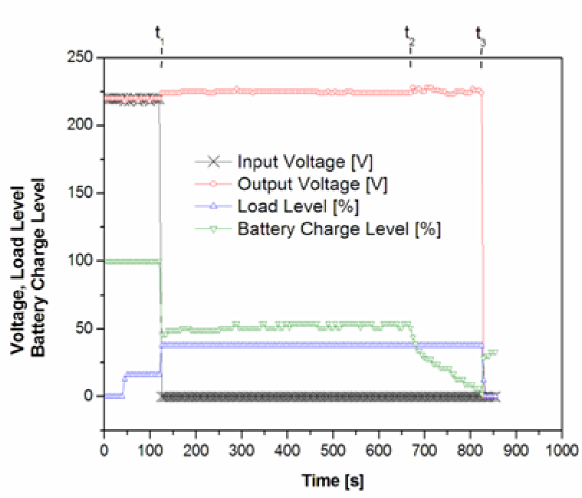

Figure 4: Results of operation time measurement of the UPS supported with fuel cell module supplied with 1.6 g of hydrogen

SMON Plus V2.72 was used. As a first step, the operation time for active UPS mode (without grid power) was measured. Operation without the fuel cell stack, only with an installed battery, gave 420 seconds of operation time for load of 300 W. Time measurement started when grid power disappeared and stopped when the battery was fully depleted.

The next set of measurements was performed with a fuel cell supported UPS unit. The stack supported battery aided production of electrical energy through the use of hydrogen stored in a 150 ml capacity high pressure (124 bar) container. The mass of stored gas was 1.2 g. The measurement results are shown in Fig. 3.

By adding the fuel cell module, UPS operation time was extended to 550 seconds. At time t_1 marked in Fig. 3, the grid power was disconnected and UPS was operated using electrical energy stored in the battery and in the form of hydrogen. As can be seen, the battery charge level does not decrease rapidly but for a short while stays at the level of 50%. This is as a result of fuel cell operation and electrical energy generation. After time t_2 marked in the figure, the stored hydrogen is depleted and the fuel cell is unable to support the battery. As a result, the battery is completely discharged and after time t_3 the UPS turns off. The same experiment, whose results are presented in Fig. 4, was performed with a larger amount of hydrogen. The hydrogen for the stack supply was stored in a 200 ml tank under 124 bar pressure. UPS operation time was extended to 695 seconds.

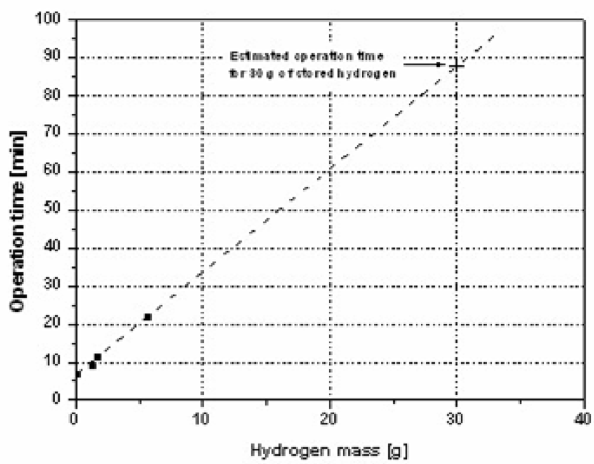

Figure 5: Operation time vs. mass of stored hydrogen

The aim of the measurements was to estimate the operation time of the UPS unit with a fuel cell module which uses fuel stored in a 3.5 liter high pressure tank in which it is possible to store 33 g of hydrogen. Assuming a linear dependence of operation time on hydrogen mass, the characteristic presented in Fig. 5 can be plotted.

Based on this experiment it can simply be estimated that the system will be able to deliver 300 W of electrical power continuously for 80 minutes.

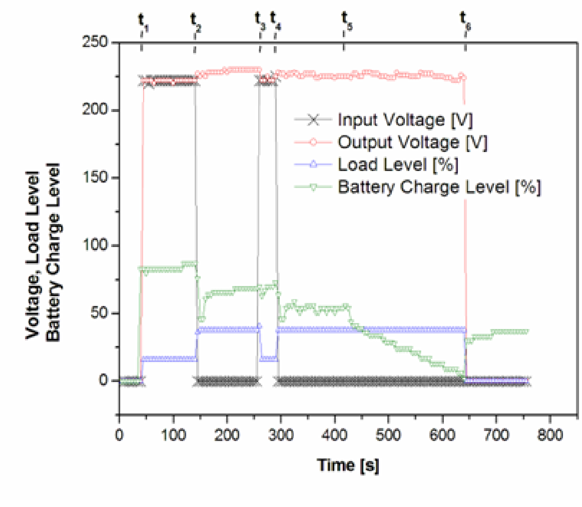

Figure 6: Operation characteristic of the system

Fig. 6 presents the results of measurements of the entire system during operation. There was no special strategy or load profile applied during this test. Random power grid blackouts were simulated and PEMFC-UPS response to those failures is demonstrated. Different values related to unit operation in active and inactive mode are plotted versus time.

At time t_1 the system is switched on. After time t_2 the power grid failure occurs and UPS starts to operate in active state. During the fuel cell start-up the only source of energy is the installed battery pack which discharges quite rapidly. After a few seconds the control system performs the fuel cell start-up procedure according to the fuel cell stack operation manual and the fuel cell stack is connected in parallel with the battery. The battery charge level increases and stabilizes at 60%. After time t_3, the grid power recovers and the fuel cell stack is disconnected. At time t_4 the grid power failure occurs once again. The energy needed for external devices supply is drawn at first from battery and then the fuel cell is connected. Connection of the stack causes an increase in the battery charge level which remains at the stable state level until time t_5. After this time the hydrogen in the tank is depleted, the fuel cell stack stops operation and the battery starts discharging very rapidly. At time t_6 the system switches off due to a lack of energy source.

4. Summary

Application of a polymer exchange membrane fuel cell stack as a primary energy source in an uninterruptible power supply unit is proposed in this paper. The designed and constructed uninterruptible power supply with fuel cell module can continuously power any electrical device up to 300 W for 80 minutes. Operation time is limited only by the capacity of the hydrogen tank. A high pressure container with 3.5 liter capacity was installed in the system and enabled storage of 33 g of hydrogen.

The described UPS-PEMFC construction is complete and ready for operational testing. Preliminary measurements and tests showed possible future ways of system development through use of the following:

- air cooled stack construction with opened cathode side,
- application of supercapacitor instead of battery,
- use of the metal hydride hydrogen storage method,
- designing a DC/AC converter that matches the stack's electrical parameters,
- a low-noise air compressor.

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