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Demonstration and development of a polymer electrolyte fuel cell system for residential use

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ABSTRACT

Fuel cell systems, especially those fed with hydrogen, have reached considerable performance targets in laboratory conditions with constant loads and conservative environmental conditions. However, a check of the potential of such systems in real conditions is necessary, particularly in terms of varying electrical and thermal loads and of more severe climatic conditions.

To determine the state of the art of such technology and to develop systems capable of supporting future national energy scenarios within the PNR-FISR project, "Polymeric electrolytes and ceramic fuel cells: demonstration of systems and development of new materials," the development of fuel cell systems ranging from 1 to 5 kW of power and based on either solid polymer (PEMFC) or solid oxide (SOFC) technology are in progress. In this paper, the demonstration of a pre-commercial PEMFC system fed with hydrogen and developed in cooperation with NUVERA is described. The system has been developed in order to determine its limits and capacity in relation to start-up time, response time, consumption, efficiency, reliability, etc. It has currently reached 1000 working hours of continuous performance with variable loads that simulate those of a typical residential dwelling.

1. Introduction

The innovative concept of distributed generation, particularly within a power range of 1–100 kW, is a decisive factor in future energy scenarios and is characterized by power production by end-users capable of providing complex and complete services – including gas supply, electricity, heat and air-conditioning – with considerable advantages in terms of costs to both the suppliers and the end users themselves. Moreover, thanks to the possibility of decreasing transmission loss on the electric grid and drastic reductions in emissions of polluting gases (NO_x, SO, CO_2, etc.), distributed generation presents an interesting alternative to the current centralized system of power production.

Fuel cell systems ensure both high-conversion efficiency and reduced environmental impact. Therefore, they can be used for on-site generation of power to supply, in part, the ever-increasing demand for microgeneration. Fuel cell systems can support such a future scenario either in the short-to-mid term using natural gas or in the long-term by increasing the exploitation of renewable energy sources.

The objectives of this paper are to illustrate the architecture and the operation of a 5-kW PEM fuel cell system, developed by Nuvera FC and CNR-ITAE in the framework of a national project, and to focus on both its performance and the main parameters, evaluated in endurance testing.

The Italian National Project funded by MIUR (Ministry of Instruction, University and Research) and coordinated by CNR-ITAE, consists of innovative PEFC and SOFC systems, energy management, and addressed to the following themes:

- improve of performance and correspondingly, decrease fuel cell costs through the development of innovative materials, components and configurations;
- develop and test fuel cell systems in stationary sectors;
- test demonstration plants, monitor and check the operative behaviour of different fuel cells working with various kinds of fuel;
- improve the hydrogen infrastructure in order to introduce the hydrogen economy, using multi-fuel networks.

The present study aims to increase awareness in terms of the reliability, efficiency, and lifetime of current fuel cell systems. As a matter of fact the 5-kW PEFC system can be considered a plug and play pre-commercial product, the findings in this paper will highlight both its limits and potential in the mid-to-long term for large-scale application of PEM fuel cell systems.

There are two main parameters that characterize the performance of a fuel-cell system. The first and most important is

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efficiency. This parameter is easy to define; furthermore, several guidelines are available for its assessment. The second parameter is the decay in performance of both the stack and the whole system. These two parameters are the main features a customer usually needs to consider in terms of the investment profitability of FC systems compared to other technical solutions available.

In this study, standard methods described in fuel-cell literature are used to identify the two main parameters as well as additional parameters such as response time and self-operating capabilities, the latter meaning the capability of reducing human intervention.

The cost of the systems is not a distinct parameter, as both costs linked to the construction of such systems and costs to end-users are inextricably connected to political and other wide-ranging choices that require more accurate and detailed study.

For all the above mentioned reasons a series of tests have been conducted in order to identify the features and drawbacks of the PEFC system operating under real conditions: extremely variable loads, electric grid integration, indoor and outdoor operations. The goal is to develop a durable and reliable system that can be commercialized in the short-medium term. In the following paragraphs, test results of a 5-kW polymeric electrolyte fuel cell system under real dwelling load conditions are reported. To achieve this, it was necessary to define the main parameters first.

1.1. *Electrical efficiency*

There are numerous definitions of electrical efficiency, from among which the *ASME PTC-50* standard (fuel cell performance test code) was chosen, for it resembles most the approach taken in this study.

$$\eta_{\mathrm{el}} = \frac{E_{\mathrm{n}}}{Q_{\mathrm{total}}} \qquad (1)$$

Eq. (1) is one in which E_{n} is the net electrical energy generated by the system (equivalent to that generated by the fuel cell stack without energy used by the ancillaries) and Q total is the primary energy provided by hydrogen, including:

- chemical energy + pressure level + thermal energy of the fuel;
- thermal energy of any external fluid, including co-generation;
- pressure level and thermal energy contained in the air feed;
- any other form of energy (i.e. mechanical work) from an external source.

1.2. *Lifetime*

Nowadays, one of the main targets in the performance of fuel cell systems is considerable lifetime, both for stationary and automotive applications.

According to its use, a system's lifetime may vary. For stationary applications, the target is 40,000 working hours with an acceptable decline in performance. Currently, such performance levels are rarely guaranteed by operating systems in real (not in laboratory) applications and have been declared, to date, almost exclusively by Plug Power [1]. Nevertheless, producers and research centres claiming such working hours are assured are increasing for stacks operating under conditions as close to optimal as possible (in a laboratory setting) [2]. Obviously, the lifetime of a fuel cell stack is strictly linked to how it is worked. Although in literature it is possible to find lifetimes between 4000 and 13,000 h with a decay rate ranging from 0.5 to 6 μV h^{-1} [3,4] in steady-state conditions, when more severe working conditions are applied (with extremely stressful load profiles), the rates drop drastically, as low as 600 working hours with a decay-rate of 120 μV h^{-1} [5]. Nuvera claims a decay in performance of 2.6 μV h^{-1} cell^{-1} in steady-state conditions and of 51–52 μV h^{-1} cell^{-1} under particularly stressful conditions (accelerating tests) of 30 cycles h^{-1} [6]. Nevertheless, in the literature there is no common parameter to define lifetime. Usually, the parameters used do not specify the type of application or the loads the systems tested were submitted to; therefore, necessary information is lacking. This said, there are no standards to identify the decay in performance of other competitive technologies as well, such as gas turbines and internal combustion engines.

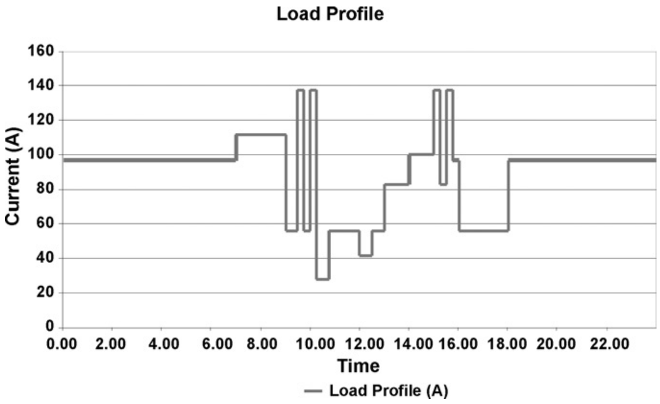

Fig. 1. Variable load profile applied to the FC system in test simulating a dwelling's electric load.

In this study, both the voltage decay of each single cell under constant load conditions and variations in the polarization curve of the stack over time were parameters set for comparison to current findings. That a decline in performance can be both reversible and irreversible will also be discussed. In the former case, the condition is transitory and starting-level performance is regained as soon as optimal working conditions are restored; in the latter, the decay is permanent.

1.3. *Load profiles*

Varying electrical loads means stress, regardless of what kind of generator is used, i.e. internal combustion engine, microturbine, or fuel cell systems. Variations in the speed of mechanical components in terms of the rate at which heat is generated in a kinetic reaction of reagents implies that mechanical stress on materials results in reduced efficiency over time. In order to be competitive in their own markets, new generation devices, among these fuel cell systems and microturbines, must demonstrate a durability comparable to that found in consolidated technologies like ICE.

To assess the current state of art, the system developed in earlier stages of design was submitted to extreme variations in load profiles, ones very close to a residential application's (Fig. 1) with 24-h cycles. The only down-times were those necessary for ordinary or out-of-the-ordinary maintenance procedures.

Moreover, all power generators, including fuel cell systems, demonstrate efficiency as a function of load; this varies, accordingly, to profiles typical of specific technologies. Fuel cells, nevertheless, are generally thought of as functioning at a constant level of efficiency even as loads vary. This is true but only under certain conditions, that is, if the efficiency of the stack alone (without its ancillaries) is taken into account working, specifically, in a range of between 30% and 70% of its optimal load. Efficiency, therefore, is also inextricably connected to the type of application to which an energy device is dedicated.

In this study, load variations are included in the whole working range of the system, with instant variations of up to 100% of optimal power.

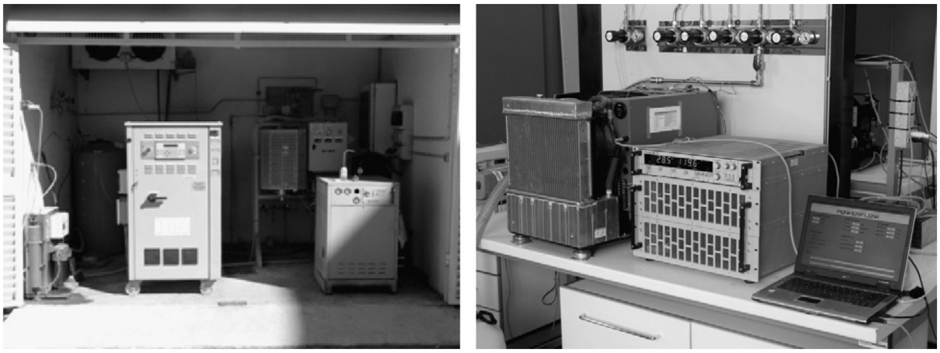

Fig. 2. Test bench for endurance tests is composed of: (a) Electrolyser and purification stage for continuous hydrogen production. (b) The laboratory test bench with the electronic load and the computer for data acquisition.

2. Test station and tests performed

2.1. The test station

Due to the amount of hydrogen necessary for endurance tests, the testbench is comprised of a hydrogen-production system in addition to equipment for testing data acquisition.

The system in Fig. 2(a) is an alkaline electrolyzer, useful for continuously feed the system being tested with pure hydrogen (i.e. simulating the hydrogen supply from a public grid). The system in Fig. 2(b) manages data acquisition, simulation of electrical loads, and safety features (sensors for hydrogen, temperature, etc.), all of which can be controlled and monitored remotely through ADSL.

The management software, developed in a LABVIEW environment, allows the management and recording of data characteristic of the device being tested, from among which the following are most important:

- stack and single cell voltage;
- current generated;
- input and output gases and deionized water temperatures;
- a count of working hours;
- energy produced;
- hydrogen actually consumed.

The two last parameters are absolutely necessary in determining the efficiency of the system studied.

2.2. The system tested

The device being tested (Fig. 3) is a polymeric electrolyte fuel cell system able to supply power within a range of 0–5 kW and to start up and shut down automatically (*plug-in*). Because fuel cells are electrochemical generators that turn chemical energy contained in feeding fluids (hydrogen, methanol, natural gas, etc.) into electricity in a direct current, they are similar to electrochemical accumulators (i.e. lead acid batteries). Unlike previous FC systems to which fuel was fed from an external source, which meant autonomy was dependent on size, in this case autonomy does not depend on the size of the device. The generation of electric power occurs, therefore, without the movement of mechanical components. This leads to a high level of electrical efficiency. Nevertheless, the fuel cell stack must be provided with a far more complex system in order to work. The whole system can be described as follows:

The stack (XDS-900) component of the system is comprised of:

- 40 in-series cells with bipolar steel plates;
- an active area of 500 cm^2;
- MEA (Membrane Electrode Assembly) built on commercial products and in-house formulations of the anodic and cathodic electrocatalysts;
- platinum cathodic loading between 0.4 and 0.6 $\mathrm{mg\,cm}^{-2}$;
- variable working temperatures (between 65 and 80 °C);
- maximum current of 400 $\mathrm{mA\,cm}^{-2}$;
- λ_a (stoichiometric anodic gas coefficient) of 1.05;
- λ_c (stoichiometric cathodic gas coefficient) in the range of 2.2–3.

A control and diagnosis board, thanks to numerous sensors that constantly provide a reading of all operational parameters necessary for management and safety, manages the functions of ancillaries (Balance of Plant).

The stack works in dead-end mode, the anode compartment is closed by a timed-valve that purges it to eliminate water produced by oxygen crossover (from the cathode to the anode) and migrated (due to a concentration gradient). An in-house system

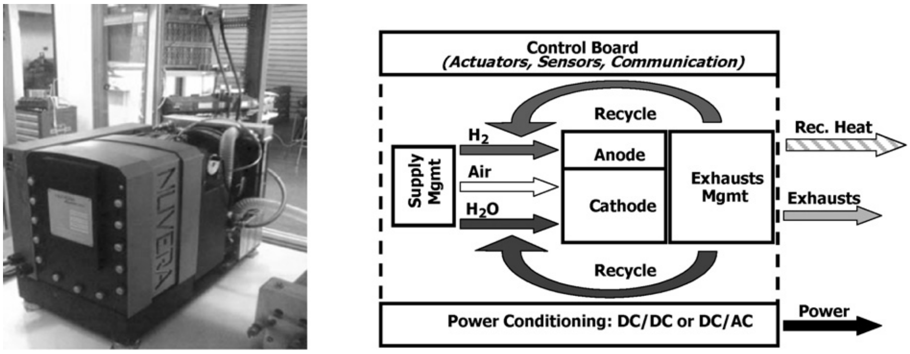

Fig. 3. The fuel cell system developed and under test, and the scheme of the Balance of Plant.

ensures the recirculation of purged hydrogen increasing the fuel utilization factor considerably.

As known, proton conduction (H^+) within membranes is ensured by the presence of a precise amount of water. In the evaluated stack, this conduction was ensured by the water produced and the liquid water injected into the cathode from an external loop by a pump. The injected water also cools the cells that the stack is composed thanks to the latent heat absorbed during the water evaporation. In this way, two goals were achieved: (1) water still present in the anode decreased and (2) as a result, the necessity of anodic purges was reduced, thereby ensuring a more homogeneous humidification of the stack. Among active cells, in fact, some were dedicated to an air-feed humidification of the stack and, as they were homogenously distributed throughout the stack, a constant amount of water was assured.

The Balance of Plant, that assures stack operations, is composed of:

- an air blower;
- a pump for water circulation;
- a fan to chill and condense re-circulated water coming out the stack's cathode;
- a loop for off-anode hydrogen recirculation.

The blower feeds filtered air to the cathodic inlet, while hydrogen is fed at a pressure of 1.7 bar abs into the anodic inlet. The water used for humidifying and cooling, together with water produced by the electrochemical reaction on the cathode side, comes out condensed through a heat exchanger (air-water) using an appropriate fan to chill it. The water in liquid state is stored in a tank under the heat exchanger (storage tank). After a deionizing stage that ensures a water conductivity of less than 5 $\mu S\,cm^{-1}$, a pump picks up the water from the storage tank and puts it in the cathode side to humidify the membranes and chill the cells of which the stack is composed.

All the ancillaries are powered by the FC stack except during the start-up and shut-down phases; in these cases an external power source provides the necessary supply. All functions are automated and managed by an electronic control board in accordance with optimal algorithms that take into account the main functional and safety parameters (temperature, pressure, cell and stack voltage, power and current produced).

Another peculiar feature is the management of ancillaries. Unlike what is reported in literature, during ordinary operations, the air blower, the water recirculation pump, and the fan work at only two pre-determined operational power levels. This means the water and air necessary for to the stack operations are not proportional to the current generated (variable stoichiometry), and in every case is more than what would be considered optimal. This implies inefficient consumption by ancillaries and affects overall efficiency, which should be better. However, this implies further that the ancillaries do not affect response time even at high-load variations [4] because there is no variation in the power supplied to the ancillaries.

Lastly, for a grid connection or the use of electricity generated in residential units, a modification of the system's characteristic parameters through a power-conditioning device (inverter) is necessary. In fact, the fuel cell system produces electricity at a direct current within a voltage range of 40–26 v. A downstream inverter has to generate a voltage of 230 Vac—50 Hz (European grid).

Nevertheless, for tests, a DC/DC converter (step up double half bridge H) was used to regulate and stabilize voltage at 48 Vdc in order to supply direct loads. In the second stage of tests, an inverter was used as well, and the electrical power produced was provided to the grid, thus showing operation under such conditions was possible.

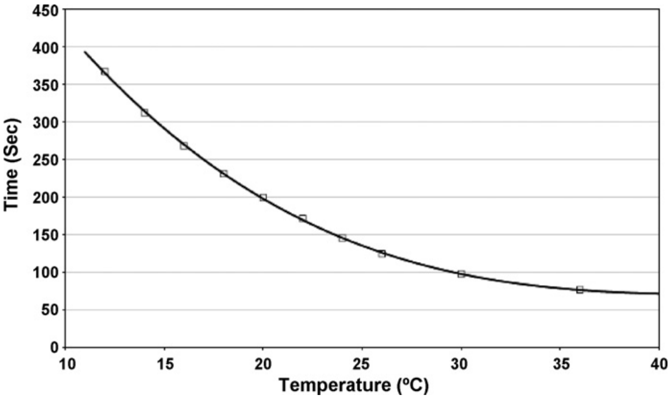

Fig. 4. Warm-up times for the FC system at different room temperatures.

2.3. Tests performed

The tests performed allowed a characterization of the system, its durability both under continuous working conditions and extreme variations of loads. Levels of efficiency, since operating conditions changed as a function of time elapsed, were recorded as well.

Experiments to determine the main features and their performance were carried out according to FCTESTnet protocol [6]:

- start-up;
- stack polarization curves and the system's performance curves;
- load-following and response time;
- life-time.

2.3.1. Start-up

First, the system was submitted to start-up tests according to FCTEST net PEFC SC 5-5 protocol (testing the starting power density as a function of time at low temperatures). Tests were done at different temperatures using a climatic chamber capable of taking systems down to −20 °C. Immediately, results showed the necessity of an external power source to supply both the control board and ancillaries during start-up and shut-down operations. In these stages, the system requires a current of about 13.5 A (P = 648 W) from an external source (as the stack is not yet producing).

Following the start-up stage, in producing the power required the system warms up reaching a fixed working level with an output of cathodic gases at a temperature of 38 °C. This stage lasts from a minimum of 80 s (with room temperature (humidification/cooling) at 40 °C) to a maximum of about 370 s, with a corresponding water temperature of about 10 °C (Fig. 4).

2.3.2. Characteristic performance curves

The operational curve characteristic of a stack (polarization curve) illustrates the device's performance unambiguously. The curve of the fuel cell stack in the system tested is shown in Fig. 5. It demonstrates how the stack works down to a minimum voltage (0.65 V $cell^{-1}$). This limit is well-suited for high levels of electrical efficiency and a decrease in stress on the cell's materials, thereby ensuring longer durability.

There is a considerable difference between theoretical efficiency (computed according to the most common equations in literature) and the system's efficiency computed using Eq. (1). This is caused primarily by high levels of consumption as a result of ancillaries and anodic purges that reduce hydrogen utilization. The efficiency curve is shown in Fig. 6. It demonstrates how actual efficiency varies considerably with low loads but remain generally constant at 50% (according to hydrogen LHV) when power levels are between 2.5 and 5.0 kW. The aggregate power consumption for the ancillaries is 350 W and 520 W for the two operating steps.

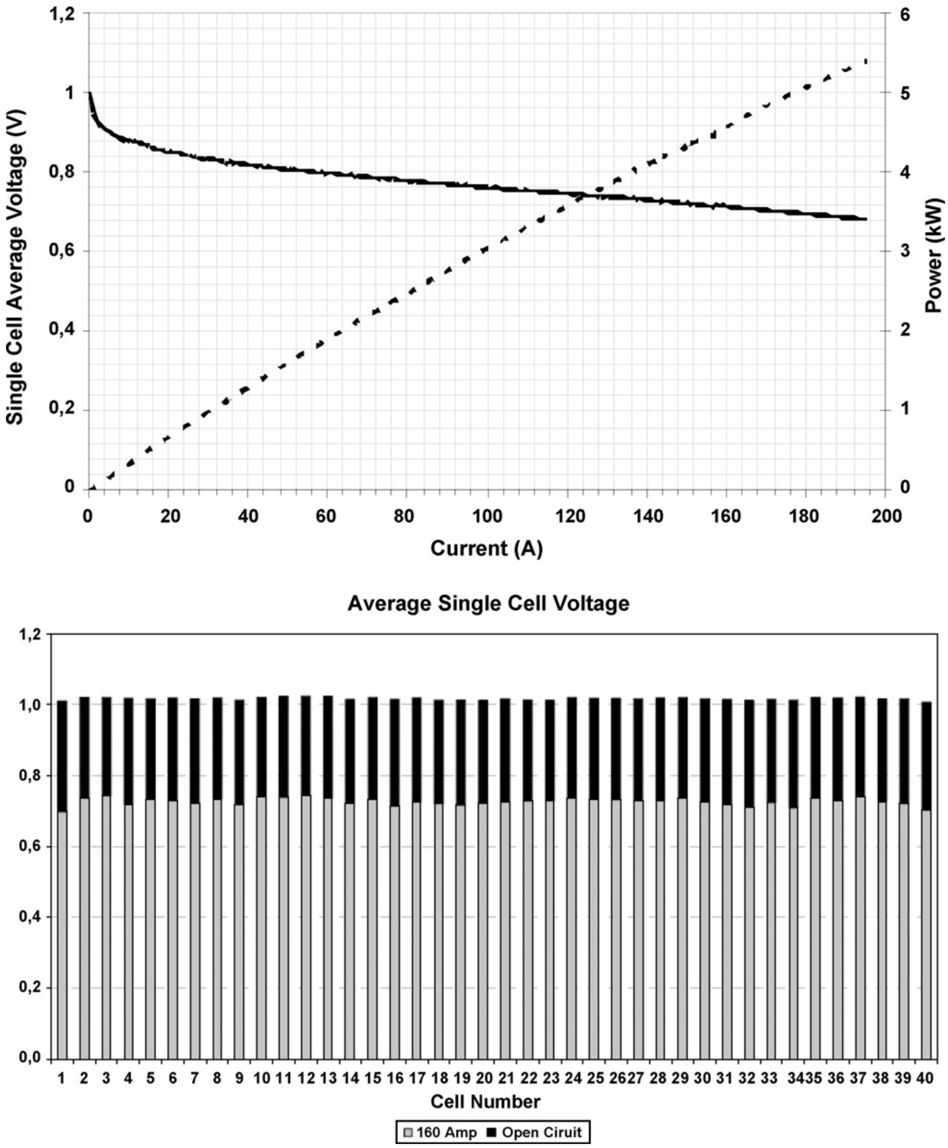

Fig. 5. Polarization curve and voltage distribution for the XDS 900 stack. The voltage distribution was obtained at two different current levels: OCV and 160 Amps.

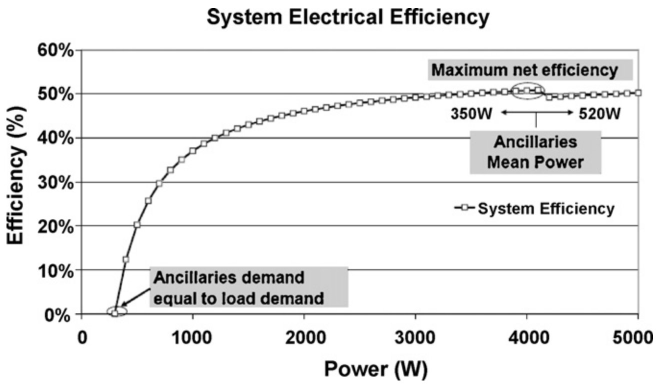

Fig. 6. System efficiency curve for the FC system in test. The ancillaries are supplied with the power generated by the stack.

2.3.3. *Load-following and response time test*

According to FCTESTnet TM PEFC ST 5.5 protocol (Testing the transient response of a PEFC stack), the system was tested to ensure operation in load-following mode. For this, pulse load tests were performed with $0-x\%$ load steps, verifying both the stack and DC/DC behaviour (Fig. 7).

As shown in Fig. 7, there are no relevant variations in regulated voltage (48 Vdc) after the power conditioning device; this ensures the level of efficiency required for response.

This parameter is closely related to the design of the regulator and is usually studied in dedicated projects, the aims of which are both to improve the quality of power (in terms of output power parameters) and to avoid the influence of power conditioning devices on the stack's performance.

In order to evaluate the response times of a fuel cell system without power conditioning devices, the transient generated by power variations was studied using an oscilloscope (Agilent DSO 6032A). To determine the system's response and compare it to that of other devices, such as lead acid batteries, a *fall time* was used. In electronics, this parameter is the time required for the amplitude of a pulse to decrease (fall) from a predetermined level (generally 90%

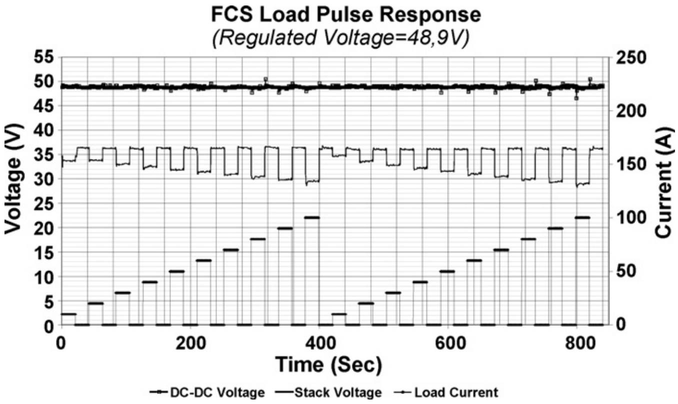

Fig. 7. Pulse Load Test to verify the system's behaviour with high load variations up to a maximum power of 5 kW.

of maximum excursion) to another level (typically 10% of maximum range).

The system had a response time of 320 ms at the highest stress levels (0–5 kW) (Fig. 8).

The fall-time obtained for the system tested is reassuring, especially when compared to other electrical devices already established on the market, i.e. batteries (285 ms), as it shows the ability of FC devices to compete in terms of performance today.

In Fig. 9 is an example of a test performed on a lead acid battery pack.

The substantial difference between the two electrochemical devices, although they are similar, does not permit a fair comparison. In this study, in order to compare the two variable load responses, two kinds of architecture with the same level of voltage at an open circuit (OCV) of 36 V (3 batteries of 12 V each and 200 Ah each connected in series) were chosen.

In conclusion, tests demonstrated that the response of a developed fuel cell system is comparable to that of known devices. Also, its ability to respond to extreme variations in stress shows excellent potential for supplying residential loads.

2.3.4. Endurance test

Although the performance of the fuel cell system studied was wholly satisfactory, one of the main obstacles to commercialization is the actual lifespan of such devices. Therefore, according to FCTESTnet TM PEFC SC 5.7 (*Testing voltage as a function of current density following a dynamic profile versus time*) and ASME PTC 50, endurance tests of the system were conducted, reaching the first target of 1000 h for a total amount of 3500 kWh produced.

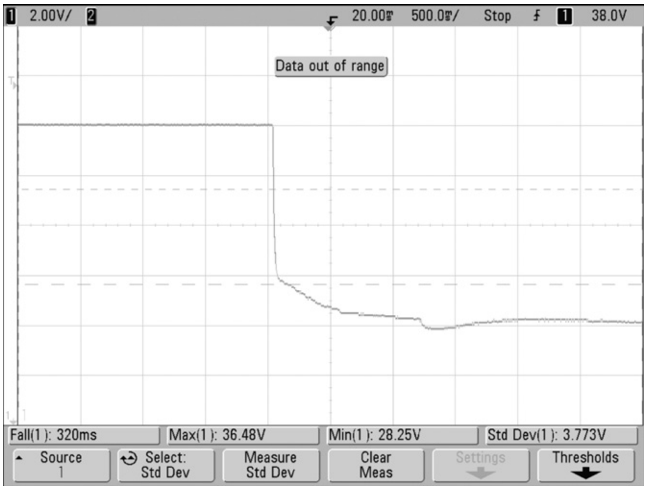

Fig. 8. PEFC system's fall time with power variations of 0–100% (0–5 kW) without the DC/DC in order to verify the stack transient. The figure shows the oscilloscope (Agilent DSO 6032A) screen in which is also reported the value of the Fall Time (320 ms).

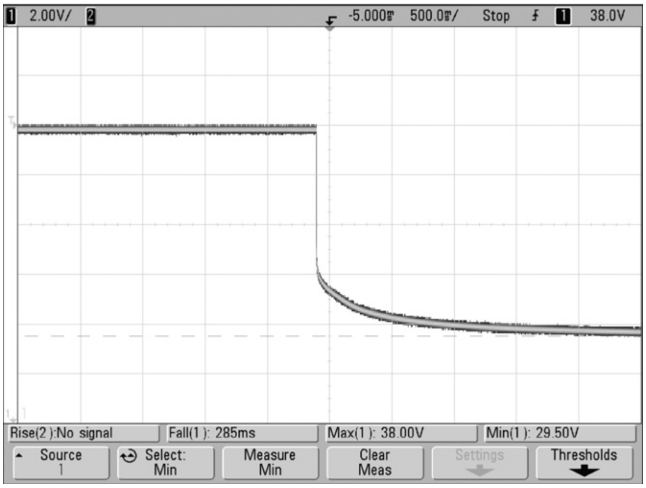

Fig. 9. Response at a load step of a battery pack of 36 V. The figure shows the oscilloscope (Agilent DSO 6032A) screen in which is also reported the value of the Fall Time (285 ms).

The tests were divided into two stages: the first one in which the device was working under the load-following conditions previously described; the second at constant power to verify the *decay-rate* in *steady-state* conditions and compare the results with findings in current literature.

The system generated power with an average efficiency of 55% and a capacity factor of 74%. The capacity factor is the ratio of the average power generated to the peak power of the device; it is useful in determining how the system can be used most effectively.

The tests allowed an outline of the performance of the main parameters, which is shown in Table 1.

Critical parameters found after the first 1000 working hours were linked, primarily, to components of the ancillaries and, to a lesser degree, to a decline in the performance of the stack. 70% of failures were attributed to electronics and 30% to ancillaries (deionization cartridge and air compressor). After the first 150 h of operation, the stack was damaged by deionizing resin released from the broken cartridge, so both the air compressor and stack were repaired. Once restored to correct working order, the system was again submitted to test cycles.

Upon reaching 1000 working hours, no significant decline in the overall performance of the system was observed. This can be seen in Fig. 10, in which OCV levels (Open Circuit Voltage) of the fuel cell stack versus hours in operation are shown. During the first stage (0–150 h), the stack already showed OCV levels that were lower than those recorded after removing the deionizing resin.

During the second stage of the experiment, higher and slightly variable OCV levels were recorded over time, showing that a reduc-

Table 1
The main parameters for the endurance test results.

Total hours	Capacity factor	Power	Average efficiency
Phase 1			
150	74%	0–5 kW	54.8%
Phase 2			
850	74%	0–5 kW	55.5%
Aggregate			
1000	74%	0–5 kW	55.4%

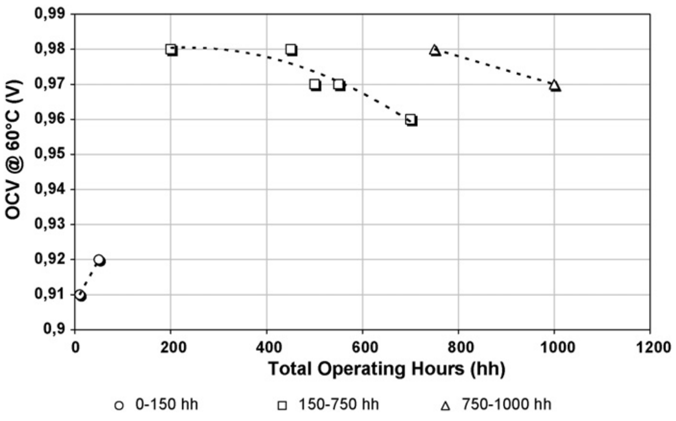

Fig. 10. Open Circuit Voltage of the Fuel Cell stack in tests at different working hours showing the decay rate mainly linked to transitory phenomena.

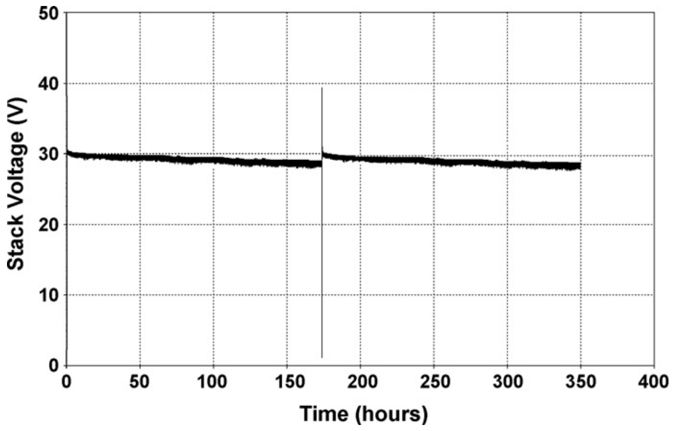

Fig. 11. Stack voltage profile during Time Test performed at constant current (two cycles of 175 h each) showing the decay rate mainly linked to transitory phenomena.

tion in the system's level of performance is reversible and most likely linked to the flooding and swelling of membranes. A sufficiently long pause always ensures restoration to original levels of performance. In the Fig. 10, OCV decreases in tests that are conducted continuously between 150 and 750 h, that is, without start-stop cycles; however, restoration to original OCV levels is recorded after a period of stopping for about 50 h between the two tests.

This trend was noticed even during start-stop cycles in rapid sequence. In Fig. 11, a test performed at the constant power of 3.7 kW with 175-h cycles is shown.

It is evident that at a constant load, the voltage decay of the fuel cell stack disappears as soon as the system is turned off and on again. This transient phenomenon can be linked to the presence of excessive water in both the cathode and anode (*flooding*). Such flooding is, in fact, eliminated during the start-up stage through extended purges, suggesting an improvement to the water management system currently under development for an advanced version of this device.

The decay rate is quantified in 40 μV h^{-1} $Cell^{-1}$, similar to data published by other authors taking into account that tests on the FC system were conducted both with pulsed and steady loads [3–6].

3. Conclusions

A series of tests was carried out in order to evaluate the performance over time of a PEFC system developed within the FISR project "Polymeric and Ceramic Electrolyte Fuel Cells: A Demonstration of Systems and the Development of New Materials." The tests aimed at identifying parameters on which development should be focused and developing a prototype that would meet the requirements of commercialization in the short-to-mid term.

In conclusion, tests demonstrated the following about FC system developed:

- it is capable of supplying power within a range of 0–5 kW and starting up and shutting down automatically (*plug-in*);
- efficiency varies considerably with low loads but remains generally constant at 50% (according to hydrogen LHV) when power levels are between 2.5 and 5.0 kW;
- its response to variable loads is comparable to that of known devices (i.e. batteries), and its ability to respond to extreme variations in stress shows excellent potential for supplying residential loads;
- upon reaching 1000 working hours, no significant decline in the overall performance of the system was observed, 40 μV h^{-1} $Cell^{-1}$.

Even so, significant improvements must be made:

- increase the reliability of electronic components and the Balance of Plant: components like the control board or deionizer cartridge seriously affected the FC system operations by causing unexpected stops and compromising the overall reliability. For the next generation FC system new dedicated components will be designed or chosen.
- improve water management in the stack and in the whole system: it is clear that the water content in the stack affects its performance, i.e. reducing voltage during time-test at constant current due to the effects of flooding and swelling on MEAs. A great amount of water is sent to the cathode side as liquid phase for humidification and cooling purposes, but because the control strategy for the pump is not optimized yet, as discussed previously, the amount of water fed to the stack in most of its operative range is not suitable. A different algorithm optimizing the amount of water injected into the stack has to be developed. The FC system is already undergoing tests to reach a significant targeted number of working hours and the new generation is still in a work-progress.

Nevertheless, the tests performed have shown that PEFC systems fed with hydrogen can meet the requirements of commercialization in the short term, in stationary applications, for instance, in which hydrogen is produced by renewable energy sources thanks to electrolysis, or for telecom sites.

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