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Characterisation of a 3 kW PEFC power system coupled with a metal hydride H_2 storage[☆]

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Abstract

Fuel cells and hydrogen storages, eventually integrated in hybrid power systems with hydrogen production from renewables, represent an interesting option for small stationary applications such as power generation in remote sites beyond the grid or back up power for telecom stations.

This paper deals with the CESI RICERCA experiences on a polymer electrolyte fuel cell (PEFC) power system fuelled with the hydrogen supplied by a metal hydride storage. The power system consists of three ReliOn Independence 1000 PEFC units, a battery bank and a 3.3 kWe DC–AC converter (inverter). The hydrogen storage is made of $LaNi_5$ type powders and can supply more than 6 Nm^3 of hydrogen per discharge cycle. The PEFC units, the inverter and the hydrogen storage performances were characterised. These subsystems were integrated into an automated power generation system and connected to a local grid including other power generators, power quality analysers, energy storage systems and electrical loads.

The main features of the integrated system are analysed herein. In particular the overall system stability upon cycling, the heat transfer issues and the possibility of recovering the fuel cell waste heat to extract hydrogen from the metal hydrides are discussed. Finally, during grid-connected operations, the power quality indexes were measured and found in agreement with the EN 50160 standard.

Keywords: PEFC; Metal hydrides; Hydrogen; Distributed power generation

1. Introduction

Hydrogen represents an important option to store energy in a long-term scenario of fluctuating power generation from renewable sources (solar and wind). Independently of the primary energy sources used for hydrogen production (fossil fuel with carbon dioxide sequestration, nuclear, renewable), R&D efforts must be focused henceforward on hydrogen related technologies, such as fuel cells and advanced storage systems.

Fuel cells represent the ideal system to efficiently and cleanly convert the hydrogen chemical energy into electricity. Low temperature polymer electrolyte fuel cell (PEFC) could be an interesting option for small (<10 kW) stationary applications in remote sites, integrated in hybrid systems with photovoltaic (PV) panels and batteries and/or coupled with hydrogen generation from renewables [1–4]. The back up power systems for base transceiver stations of telecom operators [5–7] represent another interesting application for PEFC units. As a matter of fact the costs of traditional lead acid battery back up power plants is rather high, due to periodic battery replacement, maintenance costs and disposal fees and telecom operators are looking for alternative technologies. Some manufacturers are currently developing PEFC units with a few kWe output for this market [8] and small series productions are already available.

Field tests of grid connected and stand alone small stationary PEFC units are in progress. Among them different hybrid systems are under testing that combine fuel cell units with renewable sources (wind or solar) and electric storage systems to power remote site customers [5,6,9]. Modelling activities are focusing the optimisation of the component size and the operating strategies of hybrid systems including fuel cells, batteries, photovoltaic panels, small wind turbines, electrolysers for hydrogen production directly from renewables, etc. [10–13].

Nevertheless several features of these innovative power systems are worth to be systematically investigated. Hydrogen

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storage based on metal hydrides have to face a number of charge and discharge cycles without loosing their storage capability. Waste heat from fuel cells should be used to extract the hydrogen from the metal hydrides and heat transfer is a critical issue in full-scale devices. Performances and reliability of the available PEFC units have to be assessed. Finally the electric power system behaviours in stand alone and grid connected configurations have to be investigated with a view both to the end user and to the electric network. The capability of following typical end user load profiles and of satisfying the power quality standards has to be verified.

This paper deals with the CESI RICERCA experimental activities on a PEFC power system fuelled with hydrogen stored in metal hydrides and connected to a low voltage grid with distributed generators, power quality, energy storage systems and several kinds of electrical loads. Results of the single component characterisations as well as of the integrated system behaviour are reported and discussed.

2. Experimental

The integrated system realised at CESI RICERCA and schematically represented in Fig. 1 is described herein.

The 6.5 Nm^3 capacity hydrogen storage was set up by using commercial intermetallic powders (LabTech Int. Ltd., Sofia, Bulgaria). The intermetallic is of the $LaNi_5$ type, with nickel partially substituted by aluminium ($LaNi_{4.65}Al_{0.35}$).

The PEFC power system consists of three 1 kWe PEFC units, a battery bank and a 3.3 kWe DC–AC converter (inverter). All these items were supplied by SGS future Srl (Cavalese TN, Italy). The PEFC units are ReliOn Independence 1000 with a 48 V DC regulated output. The Independence 1000 units are based on the proprietary "Hot-Swappable Modular Cartridge Technology^{TM}" and include six cartridges of 10 cells each. The battery bank consists of two groups of four 12 V/79 Ah sealed Pb type batteries. The DC–AC converter was realised following CESI RICERCA specifications. It is a 400 V AC, three-phase inverter based on three single-phase Sunny Boy 1100LV units with a maximum rated efficiency of 92%.

The behaviour of each of the three PEFC units connected to the battery bank was investigated both in steady state conditions, with gradually increasing load, and during steep load changes. A water-cooled electronic load (TDI Dynaload, model WCL 488) was used for this tests.

The hydrogen flow rate into each PEFC unit was measured by means of a 20 Nl min^{-1} full-scale mass flow meter (MKS Instruments GmbH). The meter was previously calibrated by means of a MKS Califlow type A200, Serial Number 95081001N (reference conditions $T = 0\,°C$ and $p = 760$ mmHg). The uncertainty was certified to be below the 0.7% of the full scale in the whole operating range between 2 and 20 Nl min^{-1}. The flow data were measured every 2 s, corrected by means of the flow meter calibration curve and averaged over a period of at least half an hour. A drum was inserted in the hydrogen line between the PEFC unit and the flow meter in order to mitigate the disturbances due to the periodic purges of the dead end anodic compartment of the PEFC.

The hydrogen flow during the metal hydride storage charging was measured and regulated by means of two 200 Nl min^{-1} full-scale mass flow controllers (MKS Instruments GmbH). A maximum flow rate was fixed that limits the first minutes of charging phase, whereas most of the charge occurs at lower flow rates up to a complete saturation.

In all the experiments described in this paper 99.999% pure hydrogen from pressurised cylinder packs was used. The carbon

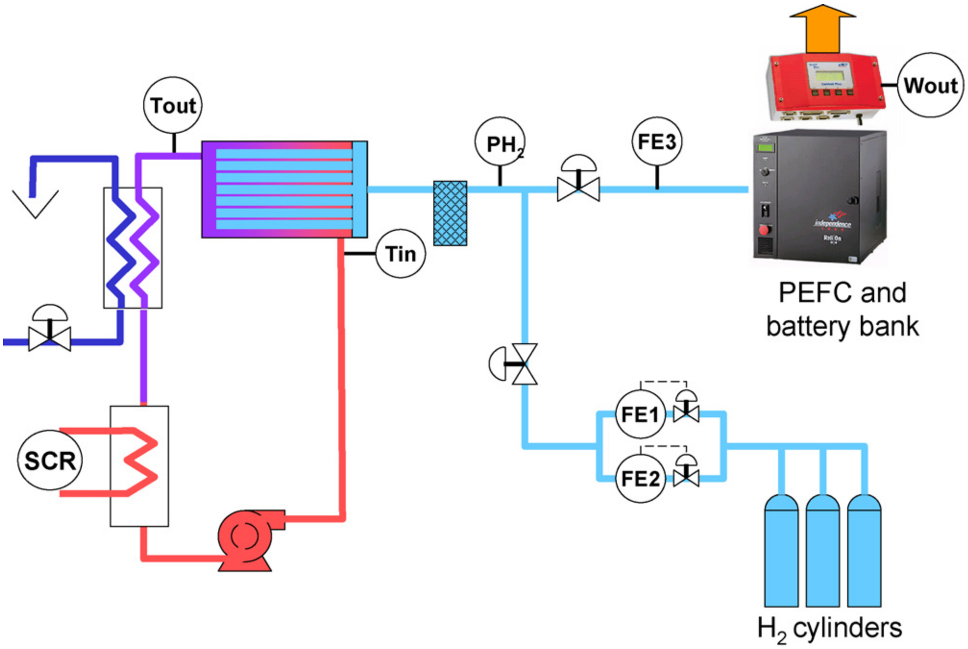

Fig. 1. Scheme of the integrated systems (FE1, 2—hydrogen mass flow controller; FE3—hydrogen flow meter; PH_2—pressure gauge; Tin, out—PT100 temperature gauges; SCR—thyristor unit; Wout—electric power output meter).

monoxide content was analysed on a few hydrogen cylinder batches and was always found lower than 0.15 ppm.

The PEFC power system and the hydrogen storage were coupled and automated. A control system was set up in a LabVIEW^{TM} environment to manage the automatic hydrogen storage charge and discharge cycles.

Finally the integrated system was connected to a local low voltage grid through the DC–AC converter, together with a 23 kWe photovoltaic panel field and a 42 kWe Redox battery (84 kWh capacity). The PV field and the Redox are two of several generating and storage systems that constitute the distributed generation test facility realised at CESI RICERCA within the UE FP5 DISPOWER project. A programmable load was used to simulate end user load profiles and Wally Teamware grid analysers, in power quality configuration, were used to measure power quality indexes with reference to the EN 50160 standard “Voltage characteristics of electricity supplied by public distribution systems”.

3. Results and discussion

Experimental results on single subsystems and on the complete integrated system are presented and discussed hereinafter. At first the hydrogen storage, the three PEFC units and the inverter were separately tested and characterised.

3.1. Metal hydride hydrogen storage scale up

A nickel based, AB_5 type, intermetallic was chosen as storage medium as it offers the possibility of storing large amount of hydrogen in a safe and compact way (see for example [14] and references therein). For small stationary application, the low gravimetric hydrogen density of this hydride is not a critical issue.

A small unit, named hydrogen storage (HS) 140 (Table 1), was realised to optimise the metal hydride powder composition and to check the storage cyclability. Nickel was substituted by different percents of aluminium, starting from the $LaNi_5$ reference composition, in order to maximise the amount of hydrogen that is deliverable at a useful pressure to feed a PEFC operating near ambient pressure. Finally the $LaNi_{4.65}Al_{0.35}$ composition was chosen for the storage scale up.

Table 1
Main characteristics of the hydrogen storage prototypes of increasing capacity developed and tested at CESI RICERCA

Parameter	HS140	HS3000	HS6500
Length (mm)	460	1100	470[a]
Diameter (mm)	48	135	30[a]
Number of internal tubes	Single tube	Single tube	37
Powder weight (kg)	1.4	30	50
H_2 storage capacity (Nl)	194	3500	6840
Pressure at room temperature (bar)	2	4	30[b]
Output pressure (bar a)	>1.5	>1.5	>1.7
H_2 volume exchanged (Nl)	≈140	≈2800	≈6000
H_2 volume exchanged with respect to the first charge (%)	72	80	88

[a] Single tube length and diameter.
[b] Maximum allowable pressure.

The second prototype storage, named HS3000 and having an internal fin tube heat exchanger (Table 1), was used for preliminary tests coupled with a PEFC. The HS6500 storage is the last one of the prototypes realised and tested at CESI RICERCA (Table 1). It contains about 50 kg of $LaNi_{4.65}Al_{0.35}$ powders distributed into 37 dead end tubes welded onto a flange. The tube bundle is fully immersed into a vessel that is circulated by the cooling/heating media, usually water and/or glycol. A stainless steel structure was realised that is able to safely operate up to an internal pressure of 30 bar.

It should be pointed out that this storage was designed and set up only for testing purposes and the total weight was not optimised.

3.2. ReliOn Independence 1000 PEFC unit testing

The ReliOn units are PEFC power systems specifically designed for back up and premium power purposes and are currently under testing, among others, in several telecom base transceiver stations. The cartridge structure assures modularity and reliability to the whole system. The fuel cell unit is permanently connected to a battery bank and operates as a battery charger. The batteries supply the energy required for the start up from the “cold state” (defined as “condition of a fuel cell power system at ambient temperature with no power input or output” [15]). The units are air-cooled and can be fed with industrial grade (99.95% pure) hydrogen.

The three ReliOn PEFC units were independently characterised at the CESI RICERCA fuel cell testing facilities. An electronic load was used in the constant current mode to set the desired load values. Data from each unit were acquired by using a proprietary software supplied by ReliOn.

Start-up and shut down both in manual and remote modes were investigated. The data reported in Fig. 2 were recorded during a remotely controlled start-up. No external load was applied during this test. In a short time the power system is ready to supply power. After a short transient the fuel cell output becomes stable around 150 W. This is the power consumed by few ancillary components, like the air blower and the unit control system,

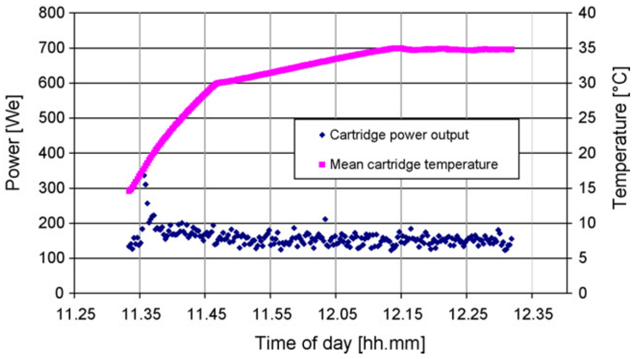

Fig. 2. Start up (remote mode test) on a ReliOn Independence 1000 power system. Behaviour of the mean cartridge temperature and of the cartridge power output during the first hour of functioning without external electrical load.

and that is required to maintain the unit in the "stand-by state" [15] (DC power output null, but unit ready to supply power).

The complete thermal stabilisation required more time. Starting from a laboratory temperature of 15 °C, about 15 min were needed to reach 30 °C, whereas a steady "stand-by state" was obtained after 40 min (Fig. 2).

Different load tests were carried out. The load was increased step by step from the "stand-by state" up to the full load state, thus allowing the cell and cartridge voltage current characteristics to be recorded. The rated power was reached and maintained in thermal equilibrium conditions by all the three units. A homogeneous behaviour of the cell and cartridge voltages was noticed under load conditions in all the units.

The response of each power system connected to the battery bank as a function of steep load rising of increasing amplitude was investigated too. Typical results obtained onto one of the three ReliOn units are reported in Fig. 3.

The unit was maintained in the stand-by state for about 30 min to allow a complete thermal and electric stabilisation. A steep load rise was set by means of the electronic load operating in the constant current mode. The load was maintained for 1 h allowing a complete stabilisation to be achieved and steady state data to be recorded. The external load was then shut off and again the module was kept for half an hour in the stand-by state. This cycle was repeated five times with current steps of 10, 12, 14, 16 and 15 A (Fig. 3) set by the electronic load.

The first step roughly corresponds to the half load power system net output. An average power output at the DC–DC converter terminals of 488 We was actually measured. The difference between the average net unit power output and the average PEFC output, due to the internal power consumption of the unit ancillary equipment, was of about 180 We, a few tenths We more than the power consumed by the unit in the stand-by state (≈150 We).

The fuel cell unit connected to the battery bank quickly satisfied the steep electronic load demand from 10 A up to 15 A (Fig. 3), corresponding to a net module power output around 770 We (3/4 of the rated power). The fuel cell power system electric parameters (cartridge voltage and current, DC–DC converter output) reached the new corresponding steady state in few tenths of seconds. Only very few transient points were recorded during the load rising step (data storage time interval of 15 s).

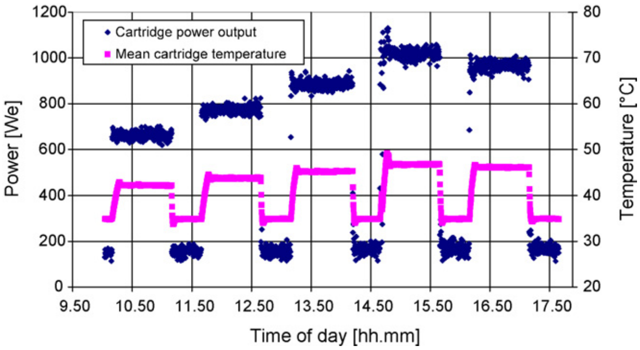

Fig. 3. Cycles of steep load demands and stand-by states carried out on one of the three ReliOn power systems connected to the battery bank. The load steps were set by the electronic load operating at the following constant currents (10, 12, 14, 16 and 15 A). The cartridge power output and the mean cartridge temperature are shown during the cycles.

On the contrary, the response to the 16 A step rise (Fig. 3), corresponding to a stabilised average net unit output of 829 We, was more difficult. The unit power output initially decreases, leaving the battery bank to satisfy the load demand. The fuel cell unit slowly recovered, and for a certain time exceeded the expected power output. During this time the fuel cell unit generated both the energy to recharge the battery bank and that required by the electronic load. Only after about 10 min a steady power output (1014 We average at the cartridge bus and 829 We average at the DC–DC converter terminals) was achieved.

This behaviour essentially depends on the battery bank capacity. This parameter has therefore to be carefully set on the basis of the desired dynamic response of the integrated system.

It should be pointed out, however, that during the 16 A load step transient the ReliOn unit was always in operation and the conditions for the automatic shut down were never reached.

The cell, cartridge and unit parameters were recorded in different, fully stabilised, load conditions together with the flow rate of the supplied hydrogen. These data were averaged and used to calculate the electrical efficiencies of cells, cartridges and power systems with respect to the hydrogen lower (33.33 kWh kg^{-1}) and higher (39.41 kWh kg^{-1}) heating values.

In Fig. 4a and b, the LHV and HHV electrical efficiencies of one of the three units are shown as a function of the net DC power output. This unit was operated at an average laboratory temperature of 18.5 ± 1.3 °C during the test, while the cartridge temperature, that is automatically set by the unit control system,

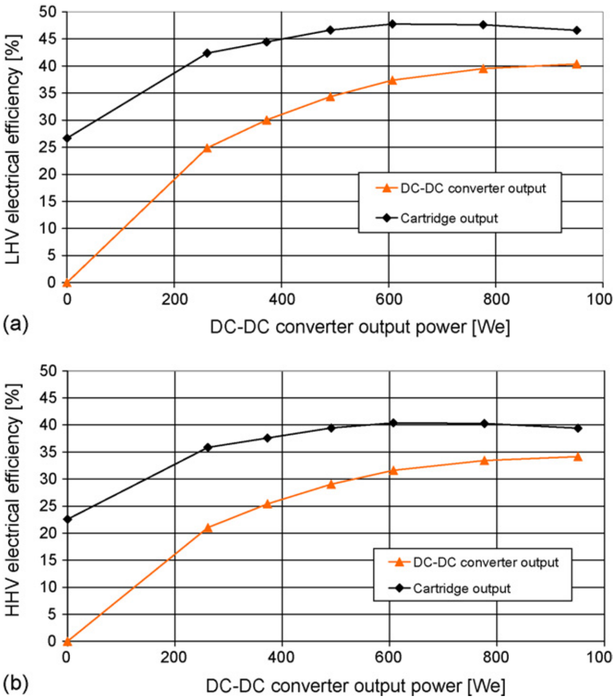

Fig. 4. LHV (a) and HHV (b) electrical efficiencies measured on one of the three ReliOn power systems as a function of the net DC power system output. Both the electrical efficiencies of the cell cartridge assembly and the net efficiencies of the whole power system (DC–DC converter output) are reported.

ranged between 35 °C in the stand-by state and 48 °C at the maximum rated power output. As expected, the efficiency measured at the cartridge bus bar (unregulated DC voltage) was almost completely independent of the net DC power output in a wide range from partial load (0.5 kWe) to full load (1.0 kWe). In this range the cell efficiency is between 47% and 48% (LHV). The voltage of a fuel cell decreases as the current density increases, thereby decreasing the fuel cell efficiency. In real devices this effect is combined with different losses due to ancillary components, thus resulting in a more complex behaviour of the electric efficiency versus power output. The higher cell efficiency at partial load can be appreciated only on the cartridge efficiency, which is almost independent of the power output in a wide range, and slightly decreases at the maximum rated power. The behaviour of the electrical efficiency of the complete unit, calculated by using the regulated net DC power output, is more affected by the energy consumption of the unit ancillary components, typically between 150 and 180 We, that weights more at the lower power outputs.

The maximum net DC efficiency was reached in the three units at the rated power of about 1 kWe. At this operating condition all the three units exhibited peak net DC efficiencies around 40% (LHV) and 34% (HHV) or slightly better and exceeding in any case the rated performances indicated by the manufacturer.

3.3. Electrical characterisation of the PEFC power system, battery bank and DC/AC converter system

The efficiency of the electrical board, composed of three single phase DC–AC inverters, control system, measurement and protection devices, to interface the AC grid was calculated starting from the results of the hydrogen consumption and the electric output measurements. The efficiency of this subsystem is around 89% in a wide power range and slightly decreases to 88% at full power output of the PEFC power system (3.0 kW). The efficiency curve is shown in Fig. 5.

The net AC efficiency of the PEFC power system at the rated power of 3 kWe is therefore 35% (LHV) and 30% (HHV). A peak net AC efficiency of 36% (LHV) was calculated between 2.0 and 2.5 kWe.

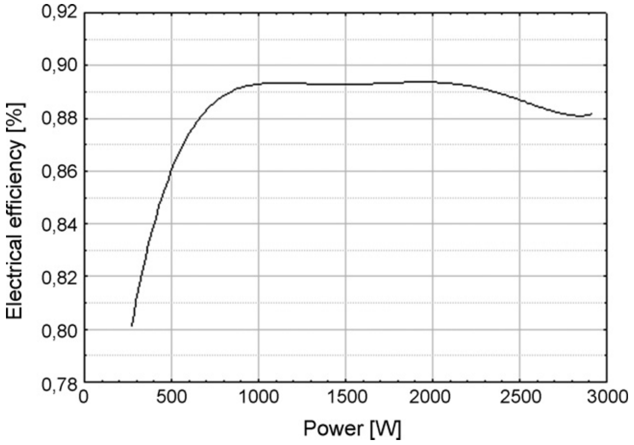

Fig. 5. DC–AC converter (inverter) efficiency as a function of the net AC electric power output.

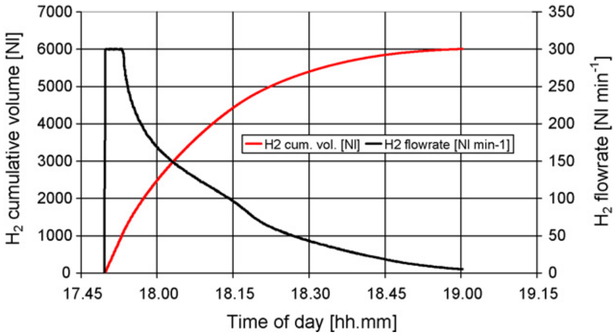

Fig. 6. Metal hydride storage charging phase at constant 5.7 bar g pressure, end of charge when the gas flow rate decreases below 5 Nl min^{-1}.

3.4. PEFC and metal hydride hydrogen storage coupling

The HS6500 hydrogen storage was coupled with the PEFC power system into an automated integrated system.

At first a few tests were performed to verify the proper functioning behaviours of each component of the experimental circuit. In particular the PEFC units were conditioned following the constructor specifications and the HS6500 storage was charged for the first time. A total amount of 6840 Nl of hydrogen were stored in about 90 min with a maximum flow rate fixed at 150 Nl min^{-1} by means of a mass flow controller. The charging phase was interrupted when the flow rate decreased below 2 Nl min^{-1}. Previous tests carried out on the same storage, however, indicated that the same amount of hydrogen could be stored also in shorter times (about 7 Nm^3 in 14 min).

Then the influence of the different parameters was investigated in order to define, among others, a standard charge/discharge cycle to be repeated automatically for a statistically meaningful number of times. In particular the effects of the gas pressure and the water temperature during the hydrogen charge/discharge, as well as the effects of the external electric load demand were studied.

At the end the following operating conditions (Figs. 6 and 7) were defined for the automatic cycling.

In Fig. 6, a typical charging curve of the HS6500 is reported. The hydrogen is stored into the metal hydride storage at the

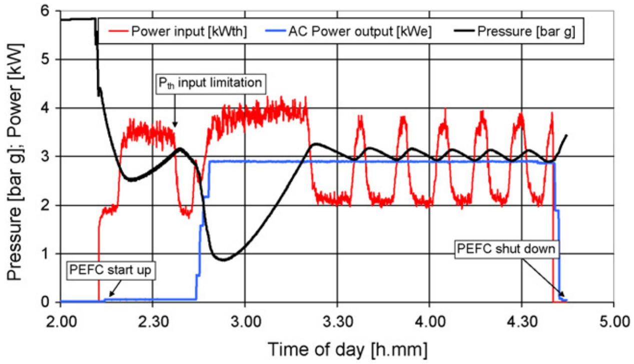

Fig. 7. Metal hydride storage discharging phase at 3.0 bar g regulated pressure.

pressure of 5.7 bar g and at the maximum allowed flow rate of 300 Nl min^{-1}. The charge is stopped when the pressure in the storage reaches 5.7 bar g with the hydrogen flow rate that is typically below 5 Nl min^{-1}. In this conditions, the charging phase lasts about 70 min.

A typical HS6500 discharge phase to feed the PEFC power system is shown in Fig. 7. The hydrogen discharge to feed the PEFC power system is started when the HS6500 temperature reached 43 °C. This can be defined as the storage "hot stand-by state". In fact, at this temperature, the storage can promptly satisfy any kind of hydrogen demand from the PEFC power system maintaining the gas pressure above the 0.7 bar g limit at which PEFC units automatically shut down. The HS6500 temperature is then regulated in order to keep the hydrogen delivered to the three PEFC unit inlets at 3 bar g. A limitation is also fixed on the maximum thermal power that can be supplied to the hydrogen storage (Fig. 7). This thermal power should never exceed the maximum amount of usable heat that is produced by the fuel cell. This limit is set to assess the possibility of recovering the heat produced by the fuel cell to extract the hydrogen from the storage. The PEFC power system AC output is increased step by step to the rated power in 4 min as follows: 0.6 kWe at $t = 0$ min, 1.5 kWe at $t = 1$ min, 2.1 kWe at $t = 2$ min and 2.95 kWe at $t = 4$ min. The flow rate of the hydrogen supplied to the PEFC power system increases with the electric power output.

To reach the stand-by state the HS6500 has to be heated independently of the fuel cell operation. The amount of thermal energy required depends on several parameters, including the ambient temperature and, during continuous automatic cycling, on the water temperature at the end of the hydrogen charging phase. In any case an average 1.4 kWth is estimated to be needed to reach the stand-by state of the HS6500 storage. A suitable optimisation of the water circuit, however, is expected to significantly lower this amount of energy.

During 3 bar g regulated discharging phases, such as the one reported in Fig. 7, an average 2.58 kWth is supplied to the HS6500 storage to maintain the full PEFC AC power output of 2.95 kWe. This power is roughly twice that expected on the basis of literature data on the energy required to extract hydrogen from $LaNi_5$ intermetallics. Once again there is a wide margin for the optimisation of the heat transfer between the metal hydride powders and the cooling/heating medium with respect to the HS6500 design. But in any case the thermal energy is far below the amount of heat produced by a fuel cell power system operating at a steady 3 kWe output.

The PEFC units used in the present experiments are air-cooled and operate at rather low temperatures, but water cooled PEFCs functioning between 60 and 70 °C are available. The direct thermal coupling of a $LaNi_5$ based hydrogen storage and a PEFC is feasible and is needed to keep an overall acceptable efficiency of the integrated system.

A statistically meaningful number of complete cycles were carried out on the integrated system in the above-mentioned operating conditions. In Fig. 8, the total amount of hydrogen exchanged in more than 50 complete cycles is reported. The storage performances were stable over all this cycling period. Up to now, after about 100 cycles, no appreciable decay of the HS6500 storage prototype performances was noticed.

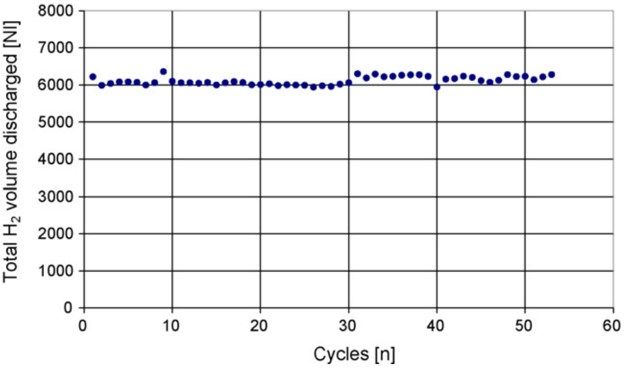

Fig. 8. Results of an automated cycling test on the PEFC–hydrogen storage integrated system. Total amount of hydrogen discharged during each cycle as a function of the number of cycles.

3.5. Behaviour of the integrated system in a local grid including PV panels, a Redox battery and a programmable load simulating an end user demand

Finally the integrated system described in this paper was connected to the Distributed Generation test facility settled at CESI RICERCA for power quality tests. This facility was supported by the European Community within the DISPOWER project of the 5th Framework Programme and by the National Research Project named GENDIS 21.

The test facility consists of renewable generators, co-generation plants, energy storage systems and controllable loads that can be connected to different points of an automated low voltage grid working in radial, ring and meshed configurations.

For our testing purposes the PEFC power system was connected to the test facility grid in radial configuration together with several photovoltaic modules for a total nominal power of 24 kWe, a 42 kWe/2 h Vanadium Redox Battery, a programmable and remotely controllable resistive–inductive three-phase load of 100 kWe plus 70 kVAR. The overall scheme of the test is shown in Fig. 9. A Wally Teamware grid analyser in Power Quality configuration was used to measure Power Quality indexes and was placed on the secondary side of the MV/LV transformer. Two Wally grid analysers were placed onto the Redox and PV lines, respectively, for transient analysis.

Different parameters including voltage, current, frequency, active and reactive power, power factor were sampled every 2 s by SIEMENS SIMEAS T meters connected to the feeders as indicated in Fig. 9.

A typical day of testing consisted of a 5 kWe step increase of the programmable load from 0 to 15 kWe and a 3 kWe step increase from 15 to 24 kWe followed by a 8 kWe step decrease to 0 kWe. During this period the PEFC power systems contributed with a maximum output of 2.65 kWe, the maximum power from Redox battery and PV modules was of 25 and 10 kWe, respectively.

The PEFC power system integrated in the grid with Redox battery and PV system did not have any adverse effect on Power

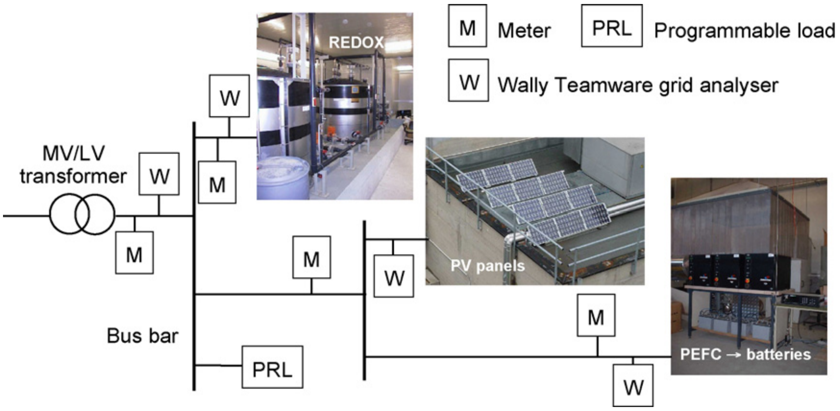

Fig. 9. Schematic representation of the local grid used for the PEFC power system test in grid connected mode (M: power, current and voltage meter; W: Wally Teamware grid analyser in power quality configuration; PRL: programmable electric load).

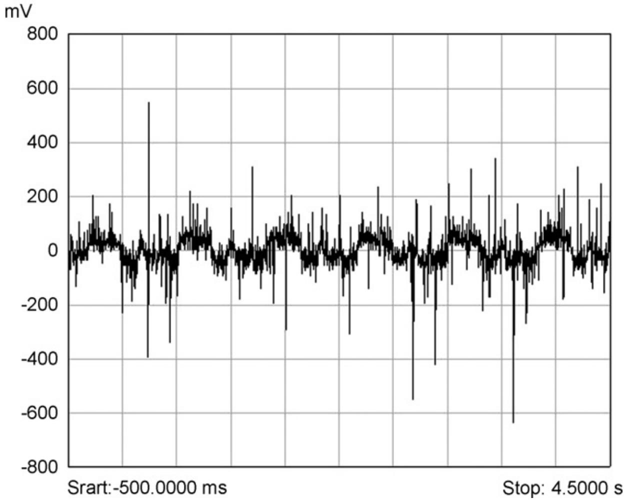

Fig. 10. Noise on DC bus during PEFC power production of 2.65 kW (500 ms/div, 200 mV/div).

Quality indicators (harmonic distortion, frequency variation, flicker, etc.).

The variations of the PQ indicators resulted always small and remained within the values indicated in IEC standards EN 50160 "Voltage characteristics of electricity supplied by public distribution systems" during all the operating conditions.

In particular on the AC side the PEFC inverters provide an almost sinusoidal current curve and the content of classical harmonics up to 2.5 kHz (EN50160) is unimportant. Actually, the modest perturbation caused by each IGBT (Insulated Gate Bipolar Transistor) switching at the 16 kHz frequency could give some problems only in case of using the power cable for communication (power line communication). This perturbation is present also on DC bus so that the PEFC is subjected to spikes (up to 600 mV) and ripples when works in grid connected mode as shown in Fig. 10.

4. Conclusions

A metal hydride storage system was successfully scaled up starting from commercial $LaNi_{4.65}Al_{0.35}$ powders. A prototype named HS6500, with a tubular structure filled with 50 kg of metal hydride powders and a useful capacity of 6 Nm^3 of hydrogen, was set up.

PEFC power systems from ReliOn were carefully characterised and connected to a local distributed generation grid through a DC/AC converter (inverter). The power system behaviours during the start up, the stand by and on load states were analysed. Steady state data were recorded and the electric efficiency was calculated as a function of the power output. The maximum net DC efficiencies of all the fuel cell units were found around 40% (LHV) and 34% (HHV) or slightly better and exceed the manufacturer specifications. The inverter efficiency was found around 89% in a wide operation range.

Then the hydrogen storage and PEFC power system were coupled into an automated and integrated power generation system that was characterised and cycled. Up to now, after about 100 cycles, no appreciable decay of the HS6500 storage prototype performances was noticed.

Heat transfer between the metal hydride powders and the cooling/heating medium is a critical issue. In any case, upon the optimisation of the heat transfer processes in the storage system, the direct thermal coupling with a water-cooled fuel cell operating around 60–70 °C appears feasible. The thermal coupling with the cell is required to maintain an acceptable overall efficiency of the whole power system.

Finally the PEFC power system was successfully operated in grid-connected mode. A peak net AC efficiency of 36% (LHV) was calculated between 2.0 and 2.5 kWe for the power system connected to the grid. All the power quality complied with the EN 50160 standard "Voltage characteristics of electricity supplied by public distribution systems". Only small perturbations caused by each IGBT switching at the 16 kHz frequency were noticed.

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References

[1] J.T. Kuo, T.Y. Wang, Operation evaluation of solar hydrogen fuel cell and battery based power system, in: Proceedings of the 2nd European PEFC Forum, Luzern, Switzerland, 30 June–4 July, 2003, pp. 833–839.

[2] K. Sapru, S. Ramachandran, Z. Tan, An integrated PV–electrolysis metal hydride hydrogen generation and storage system, in: Proceedings of the DoE Hydrogen Program Review, NREL/CP-570-28890, 2000.

[3] S. Busquet, F. Domain, R. Metkemeijer, D. Mayer, Stand alone power system coupling a PV field and a fuel cell. Description of the selected system and advantages, in: Proceedings of the PV in Europe Conference, Rome, Italy, 7–11 October, 2002.

[4] S. Busquet, J. Labbe, P. Leroux, R. Metkemeijer, D. Mayer, Stand alone power system coupling a PV field and a fuel cell: first experimental results, in: Proceedings of the 2nd European PV-Hybrid and Mini Grid Conference, Kassel, Germany, 25–26 September, 2003.

[5] P.A. Lehman, C.E. Chamberlin, G.S. Chapman, N.T. Coleman, R.A. Engel, D.A. McKay, M.W. Marshall, A.M. Reis, J.I. Zoellick, Field testing of a PEM fuel cell in an integrated power system, in: Proceedings of the 2002 Fuel Cell Seminar, Palm Springs, CA, 18–21 November, 2002.

[6] P.A. Lehman, C.E. Chamberlin, J.I. Zoellick, R.A. Engel, D.S. Rommel, Fuel cell/photovoltaic integrated power system for a remote telecommunications repeater, in: Proceedings of the 14th World Hydrogen Energy Conference, Montreal, Canada, June, 2002.

[7] M.P. Argumosa, A.V. Serrano, Integration and evaluation of a power system for remote application based on PV panels and PEM fuel cell, in: Proceedings of the 2002 Fuel Cell Seminar, Palm Springs, CA, 18–21 November, 2002.

[8] K.A. Adamson, Fuel Cell Today market survey: small stationary applications, Fuel Cell Today, December 2005, Fuel Cell Today website: www.fuelcelltoday.com.

[9] A.M. Chaparro, J. Soler, M.J. Escudero, E.M.L. de Ceballos, U. Wittstadt, L. Daza, Data results and operational experience with a solar hydrogen system, J. Power Sources 144 (2005) 165–169.

[10] K. Ro, S. Rahman, Two-loop controller for maximizing performance of a grid-connected photovoltaic-fuel cell hybrid power plant, IEEE Trans. Energy Convers. 13 (3) (1998) 276–281.

[11] S. Kelouwani, K. Agbossou, R. Chabine, Model for energy conversion in renewable energy system with hydrogen storage, J. Power Sources 140 (2005) 392–399.

[12] M.J. Khan, M.T. Iqbal, Dynamic modelling and simulation of a small wind-fuel cell hybrid energy system, Renew. Energy 30 (2005) 421–439.

[13] D.B. Nelson, M.H. Nehrir, C. Wang, Unit sizing and cost analysis of stand alone hybrid wind/PV/fuel cell power generation system, Renew. Energy 31 (2006) 1641–1656.

[14] A. Züttel, Materials for hydrogen storage, Materials Today, September 2003, pp. 24–33.

[15] IEC—International Electrotechnical Commission, Technical Specification TS 62282-1, Fuel cell technologies—Part 1 Terminology, first ed., 2005-03.