On the use of supercapacitors within stand-alone energy systems

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Abstract

Hydrogen is a valuable alternative for long-term energy storage, particularly for renewable energy based stand-alone systems. The described stand-alone system has been developed and installed at the INETI facilities. The exceeding renewable energy (provided by sun and wind) is used to generate hydrogen, which accumulated as an energy buffer, while the fuel cell uses this stored hydrogen to produce electrical energy when there is insufficient solar/wind energy. To provide the stand-alone system with a reliable energy storage it was designed a system for storing hydrogen based on metal hydrides. In order to supply sudden power demands two options were considered: a standard DC battery bank and a supercapacitor bank. Experimental and simulation results are presented in order to show the installation obtained performance.

Keywords: *renewable energies, stand-alone systems, fuel-cells, batteries, supercapacitors*

1 Introduction

This paper is based on a Stand-Alone Energy System Supported by Totally Renewable Hydrogen Production [1]. The system was conceived for off-grid operation and is composed by solar panels, a wind turbine, a fuel-cell, an electrolyzer, hydrogen tanks and power electronics converters. The basic control strategy for the overall system considers the pressurized hydrogen gas storage as the energy buffer.

The basic logic is that the exceeding renewable energy (solar and wind) is used to accumulate hydrogen, while the fuel cell uses this hydrogen to produce electrical energy within insufficient solar/wind energy. When using the stored hydrogen energy buffer the available power generated from the fuel cell may not be sufficient to meet certain load demands, especially during peak demand or transient events. Thus a DC bank is mandatory, in order to keep the system running.

A standard DC battery bank is usually considered; however supercapacitors have recently been introduced [2,3]. Even if supercapacitor banks cannot store a significant amount of energy they can supply a large burst of power. On the other hand the aging suffered by the battery bank, due to rapid cycles of loading / unloading, can be avoided by replacing them by a bank of supercapacitors.

2 System Description

The stand-alone system is composed by a power supply system, an energy storage system, a load bank, a DC bank and the overall control system.

The power supply system is composed by two independent units of decentralized production, concerning two sources of renewable energies (photovoltaic and wind). The photovoltaic solar unity is composed of ten 53 Wp modules of monocrystalline silicon. They are connected so that the panel nominal voltage is 24 V. The wind generator is composed by a 750 W wind turbine with 3 blades (2,4 m diameter) and a permanent magnets synchronous generator.

The energy storage unit is based on the hydrogen technology. There has been a significant investment increase, both international and national, within the hydrogen technology as the future energy vector. Its use as energy storage potencies the role of renewable energies within the energetic sector. Hydrogen provides an effective way of energy storage solving the renewable energy fluctuation problem, which is a problem within autonomous systems. The energy storage unit comprises an electrolyzer (producing hydrogen from exceeding renewable electrical power), hydrogen containers and a 100 W fuel-cell (producing electrical power from stored hydrogen). The electrolyzer is a 500 W low pressure unit from Alabgas, capable of operating up to 4 bar, with a maximum hydrogen production of 1000 $cm^3 min^{-1}$. The hydrogen storage choice is metallic hydrides (M-H) since volume reductions with considerably less energy input are achieved when compared to other available options. Even though metallic hydrides are very heavy and availability in the market is not fully accomplished yet, hydrogen content in these materials is about 4 times more volume efficient than compressed gas or liquid hydrogen storage, making it suitable for hydrogen storage in the present stationary application.

The load bank is a set of typical loads controlled by a SIEMENS PLC. In this way we can established any load diagram required.

The DC busbar establishes the electrical interface between the production and the load. The DC bank is either a battery bank or a supercapacitor bank.

All sub-systems are equipped with proper power electronic converters. The DC busbar voltage operates around 24 Vdc and the AC load is supplied at 230 Vrms, so it is necessary to consider a power electronics converter that inverts the power and also amplifies its voltage. The control of the overall system is a fully automated process that, regarding the sensor array information, establishes a set of controls that will run all of the system's components.

The schematic of the developed stand-alone system is presented in Fig. 1.

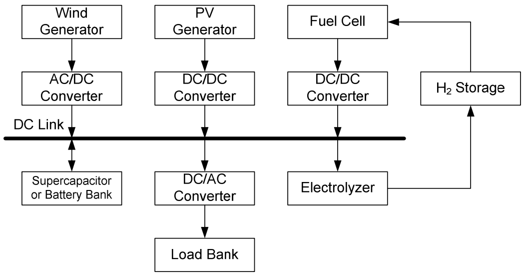


Fig. 1. General scheme of the overall stand-alone system.

3 Hydrogen Storage

The compounds of the type AB_5 appear as strong candidates for stand-alone applications, with maximum capacity for the absorption of hydrogen for 1.90 wt%. Although their reversible capacity is within the range 0.7 - 1.28 wt%, are usually easy to activate at a hydrogen partial pressure of 20 atm, displaying, after activation, a fast absorption and desorption kinetics and a small slope in the pressure-composition isotherms (PC). They suffer slow decomposition with successive absorption – desorption cycles which reduce their storage capacity. The plateau pressure is observed to loose linearity, with a consequent increase in the equilibrium pressure. The partial substitution of element B in type-AB_5 compounds was studied, having chosen $LaNi_5$ with substitutions by Al, to provide a longer service life in the successive cycles of absorption – desorption, improving resistance to decay and thus achieving an alloy with practical interest.

Fig. 2 presents the experimental scheme to associate the fuel cell to the metal hydride hydrogen storage device and provide effective heat transfer.

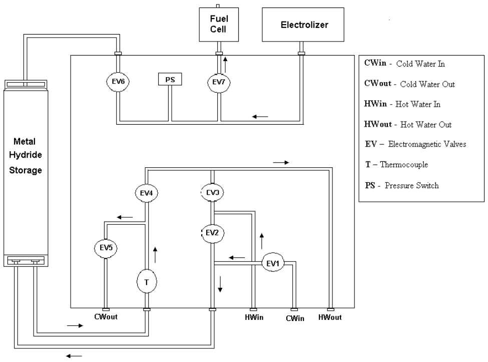


Fig. 2. Experimental scheme to associate the fuel cell to the metal hydride hydrogen storage device

This equipment consists of two units, one for hydrogen's flow control, and another to control the movement of hot or cold water within the reactor storage. The water control unit is based on a reservoir of hot water, a reservoir of cold water and a circuit of tubes with a series of electrically operated valves. The movement of water is supplied by a pump from Watson-Marlow. This device allows hydrogen storage (charge and discharge) based on metal hydrides, as well as supplying a fuel cell, in a secure, fast and simple way. In the charging mode, the hydrogen source is supplied from the metal hydride reactor, where a process of absorption is the storage of hydrogen in the metal. In this process there is liberation of heat, so it is necessary to have the movement of water within the reactor provided by the water control circuit. When discharging the hydrogen releases itself from the metal structure and can be used to power the fuel cell. The de-absorption of the hydrogen from the metal hydride is a process that requires energy and thus causes the cooling of the reactor. To avoid a loss of efficiency in the release of hydrogen, it is necessary to supply energy to the system. Thus, water from the reservoir of hot water is programmed to circulate within the reactor. Using a pressure controller, inserted in the circuit of hydrogen, the power supply to the reactor is only activated when the pressure of hydrogen in the circuit is less than 2 Bar.

Fig. 3 presents the hydrogen absorption rate, during the charging process, considering $LaNi_{4.7}Al_{0.3}$ as the chemical composition for the metal hydride. This alloy shows a high absorption kinetics, achieving total loading of the reactor storage in about 40 min, with a cooling water temperature of 22 º C.

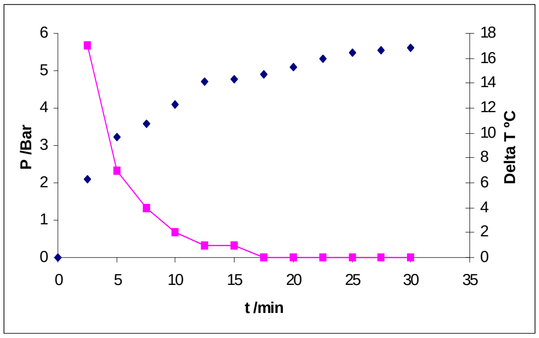


Fig. 3. Pressure of the reactor, after stabilization for 2.5 minutes, obtained in the process of loading the reactor containing alloy $LaNi_{4.7}Al_{0.3}$, the cooling water temperature was 22º C.

Fig. 4 presents the pressure of the reactor containing metal hydrides during discharge for different hydrogen flow-out.

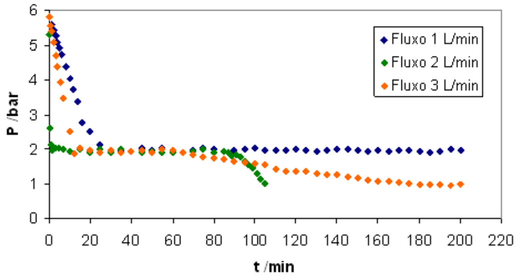


Fig. 4. Discharge curve obtained for the reactor containing the alloy $LaNi_{4.7}Al_{0.3}$ for flow velocities between 1 and 3 $Lmin^{-1}$. Water temperature ~70ºC and delivery pressure programmed for 2 bar.

It was possible to observe a rapid decrease in pressure in the initial download time, reaching a level close to 2 bar. This rapid decrease in pressure is explained by the fact that, until the pressure of the programmed controller is reached (2 bar), there is no water flow within the reactor. This leads to a decrease in temperature of the reactor and the consequent decrease of the hydrogen desorbed.

4 System Control

The basic control idea within energy storage is that the electrolyzer generates hydrogen whenever there is an excess of solar or/and wind energy. This means that if the solar and wind energy are more than enough to meet the load requirements the energy excess will be used to produce hydrogen. Whenever the wind and solar energy are insufficient to face the load demand the fuel cell uses the stored hydrogen to produce the required lack of energy.

Several interlocks are considered to protect the system. A typical example is the one that does not allow the electrolyzer and fuel cell to work at the same time, thus the electrolyzer should only work when in presence of excess power.

5 DC Link

The DC link serves as interface between the production sub-system and the electrical load. In the production sub-system one can consider the Photovoltaic Modules, the Wind Generator and the Fuel Cell. Whenever there are no renewable resources available the control system relies on the fuel cell in order to provide the power demanded by the load. However the fuel cell may not be sufficient to satisfy rapidly load changing demands. In this way a DC buffer is mandatory. One can establish a set of batteries or supercapacitors to meet sudden load changes.

Supercapacitors are devices that provide higher power densities than conventional batteries. Their charge/discharge times can be extremely fast, their are reliable, maintenance-free and present long lifespan.

Fig. 5 presents the considered load demand for a typical summer day.

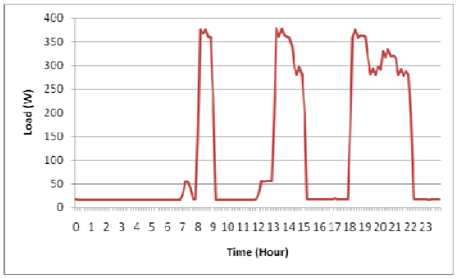
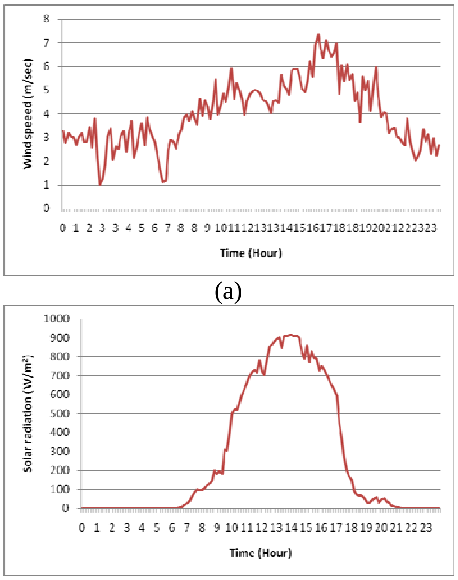


Fig. 5. Stand-Alone system load demand for a typical summer day.

For the considered day the renewable resources conditions are presented in Fig. 6.

The modelling of a supercapacitor bank presents some problems. Some authors propose the use of three parallel resistance-capacitor series branches (fast, medium and slow) plus a leakage resistance [4], as presented in Fig. 7.

This model presents resistance-capacitor series branches, which makes simulation in programs such as Matlab/Simulink impossible for long time periods. In this way a different model is usually used [5], considering a series equivalent internal resistance plus a resistance-capacitor parallel branch, as presented in Fig. 8.



(a)

(b)

Fig. 6. Stand-Alone System renewable resources for a typical summer day: (a) wind speed, (b) solar irradiation.

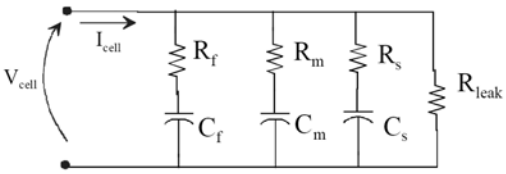


Fig. 7. Supercapacitor short term equivalent circuit.

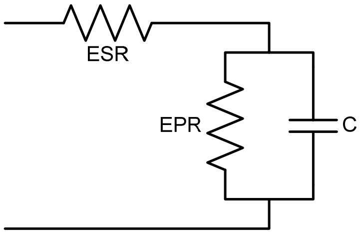


Fig. 8. Supercapacitor short term equivalent circuit.

Considering standard 2600F/2.5V supercapacitors, a series of 11 supercapacitors where considered for each branch in the supercapacitor bank. This allows to keep the DC voltage between 23V and 27V. One must recall that the DC link nominal voltage is 24V. Five parallel branches were considered, as presented in Fig. 9.

In the present stand-alone system the battery or the supercapacitor bank are used as a short time power supply, that meets the load demand while the fuel cell does start. This is particularly important during load peaks.

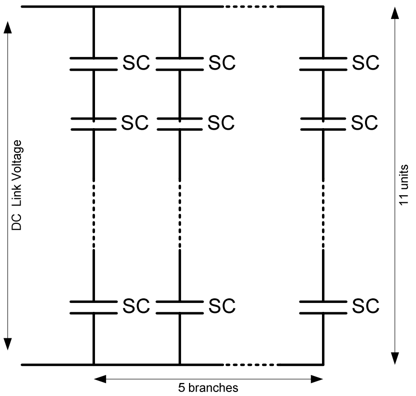


Fig. 9. Supercapacitor bank.

Fig. 10 presents the evolution of the load demand and respective power production for the peak demand at 18:00 hours. This peak load demand is coincident with the decrease of the solar radiation. The continuous line represents the renewable power production (wind and photovoltaic) and the dashed line represents the load demand.

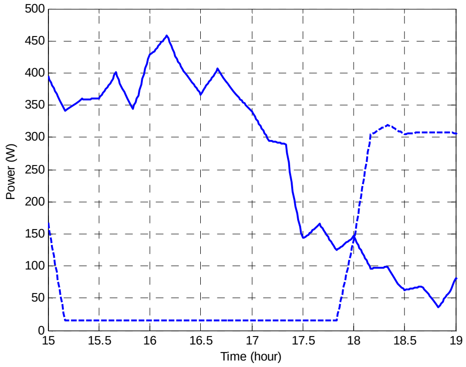
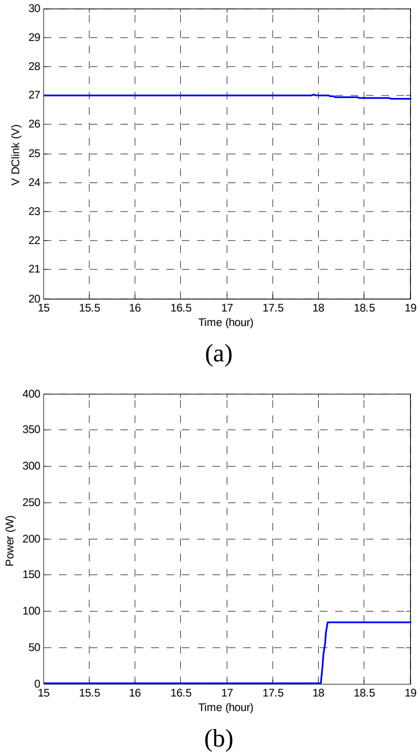


Fig. 10. Load demand and renewable power production for load peak at 18:00 hours.

Fig. 11 presents the results (DC link voltage level and fuel cell power production) considering a battery connected to the DC link. The fuel cell starts its operation in order to meet the increasing load demand, and the DC link voltage drops from 27 to 26.7 Vdc. The needed power to meet the load demand will supplied by the fuel cell and the battery, which acts as an energy storage device.

Fig. 12 presents the same results (DC link voltage level and fuel cell power production) considering a supercapacitor bank connected to the DC link. Again the fuel cell starts its operation in order to meet the increasing load demand, but in this case the DC link voltage drops from 27 to 23.5 Vdc. This drop is in line with projected supercapacitor bank. The needed power to meet the load demand will supplied by the fuel cell and the supercapacitor bank, which is not an energy storage device. This is the reason why the fuel cell needs to supply more power than the previous case. Even the supercapacitor bank it is not an energy storage device it is sufficient to meet sudden load demands, without the need of an extra battery. There is an higher drop in the DC link voltage but the stand-alone system keeps running without any failure.



(a)

(b)

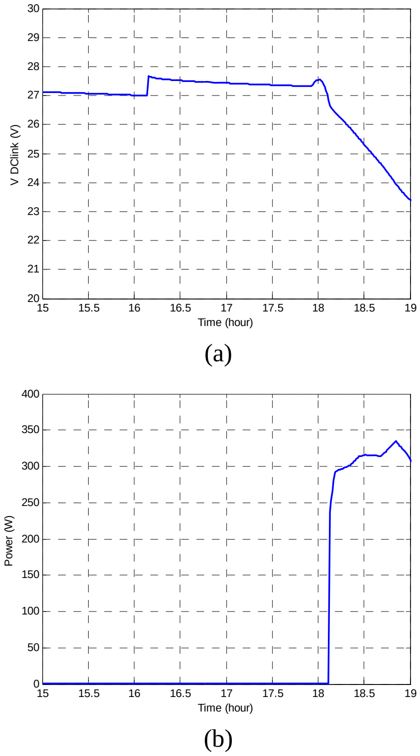
Fig. 11. DC link voltage (a) and Fuel Cell power production (b) considering a battery.

6 Conclusions and remarks

This paper presented the hydrogen storage and the use of a DC link supercapacitor bank in a stand-alone energy system supported by totally renewable hydrogen production.

The developed metal-hydrides based hydrogen energy storage device shows a good performance for the case of stand-alone systems.

Even if the supercapacitor bank cannot store a significant amount of energy it can supply a large burst of power. On the other hand the aging suffered by the battery bank, due to rapid cycles of loading / unloading, can be avoided by replacing them by a bank of supercapacitors. The use of supercapacitors implies greater deviations in the DC link voltage; however its use is sufficient to keep the system running.



(a)

(b)

Fig. 12. DC link voltage (a) and Fuel Cell power production (b) considering a supercapacitor bank.

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