INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 37 (2012) 14959–14965

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# Analysis and simulation of a hydrogen based electric system to improve power quality in distributed grids

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ARTICLE INFO

*Article history:*
Received 12 September 2011
Received in revised form
28 December 2011
Accepted 31 January 2012
Available online 25 February 2012

*Keywords:*
Hydrogen
Renewable energy
Distributed generation
Multilevel current source inverter
Power quality

ABSTRACT

Recent advances in hydrogen technologies allow the conversion between electric energy and hydrogen, increasing efficiency and reducing costs. Electric systems based on Hydrogen technology can be used to replace large battery banks in distribution systems, especially in green applications or where there is a big concern for environmental safety. A hydrogen based energy system with storage at high pressure allows smoothing the power variations which appear in electrical systems with a considerable proportion of wind and/or solar generation. A bidirectional Multilevel Current Source Inverter is used to interconnect an electrolyzer and a fuel cell within a low voltage distribution system with high efficiency and reliability. The proposed structure is simulated thoroughly with Matlab/Simulink, showing a proper behavior for the applications of interest.


## 1. Introduction

The search for new methods of energy generation and storage is attracting a significant amount of resources worldwide. Renewable energy sources are today one of the focal points of research in distributed power generation. Energy storage in the form of hydrogen and its transformation to and from electrical energy is an excellent choice, specially in environmentally friendly or green applications [1]. This is due to its relative high efficiency, reliability, low maintenance and almost no pollution generation [2–5] since the only by-product is clean water [6].

Electrolyzers use electrical power and water to generate hydrogen and oxygen. A high pressure electrolyzer generates hydrogen at elevated pressure with high efficiency due to the absence of compressing stages [7]. In turn, the hydrogen can be used in a fuel cell to generate electric power. There are several types of fuel cells, e.g.: alkaline (AFC), solid oxide (SOFC) and proton exchange membrane (PEMFC). A wide variety of mathematical models can be found in the literature that allow to simulate their behavior [2–5,8–11].

In electrical systems where a considerable proportion of the power is generated by wind and/or solar sources the power presents continuous disturbances like peaks and hollows that are of big concern. Depending on the expected frequency and duration of the disturbances, different smoothing methods can be applied to absorb power during the peaks and to release it back to the grid when needed.

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0360-3199/$ – see front matter 
doi:10.1016/j.ijhydene.2012.01.163

Those storage systems can be implemented with a variety of technologies like batteries, capacitors and Superconducting Magnetic Energy Storage (SMES) among others.

In applications where environmental safety is a major concern, energy storage based on hydrogen is an excellent choice. The electrolyzer, the fuel cell and the proposed Multilevel Current Source Inverter (MCSI) are environmentally safe.

To achieve the highest possible efficiency and to control both generation and consumption of hydrogen, it is mandatory to use electronic inverters with bidirectional power exchange capabilities. The inverter allows to take active power from the grid when it is generated in excess, supplying an electrolyzer with a DC current to generate hydrogen. The hydrogen is stored until needed without environmental risks. When the wind or solar generation is not enough to supply the load requirements, the hydrogen can be used in a fuel cell to produce electric energy. The inverter will convert the DC current generated by the fuel cell delivering the required power to the load. This configuration can be used to provide uninterruptible power to a load in weak systems or when the availability of power is not continuous.

In this article a system consisting of a high pressure electrolyzer, a PEMFC fuel cell and a Multilevel Current Source Inverter (MCSI) is proposed. A system overview is presented in Section 2, the electrolyzer, the fuel cell and the MCSI are detailed depicted in Sections 2.1–2.3. The proposal is evaluated with digital simulations whose simulation results are presented in Section 3. Finally some conclusions are drawn in Section 4.

## 2. System description

The electric system shown in Fig. 1 is composed by a 3 × 380 V – 50 Hz, distribution line supplying a small village or industry, estimated in 50 kW. The electric grid has a significant amount of power from renewable energy sources, from both wind generators and solar panels. The MCSI is connected in parallel with the line, coupled by a small parallel capacitor bank to avoid commutation over-voltages. A high efficiency electronic switch connects the DC side of the MCSI either to the electrolyzer or the fuel cell, depending on the desired power flow direction. As shown in Fig. 2, the control block consists on two proportional-integral (PI) controllers, one of which is activated depending on the device that is connected to the inverter. This configuration allows to adapt the response of the MCSI to the different characteristics of the electrolyzer and the fuel cell. The PI controls the active power exchanged by the inverter with the system, modifying the DC current stored in the main inductors of the inverter. The inverter is synchronized with the electric system by a three-phase Phase Lock Loop (PLL).

When there is enough energy provided by the electric system or when there is an excess of power generated by the renewable sources, the electrolyzer is connected to the DC side of the MCSI. Power flows from the electric grid through the inverter and the electronic switch to the electrolyzer thus generating hydrogen to be stored. In this case, the load is supplied by the power grid (Fig. 3a). When the electric system cannot supply all the power required by the load or the amount of energy from the renewable sources has transitory drop, the electrolyzer is disconnected and the fuel cell is connected to the DC side of the MCSI through the electronic switch. The cell converts hydrogen in electric power, supplying the load through the MCSI (Fig. 3b). The proposed configuration allows to continuously supply a load in a bad quality energy system.

### 2.1. Electrolyzer

A high pressure electrolyzer is a device that uses electrical energy and water to generate hydrogen and oxygen, the hydrogen is stored directly at high pressure without compression stages, outstandingly increasing the overall efficiency of the system.

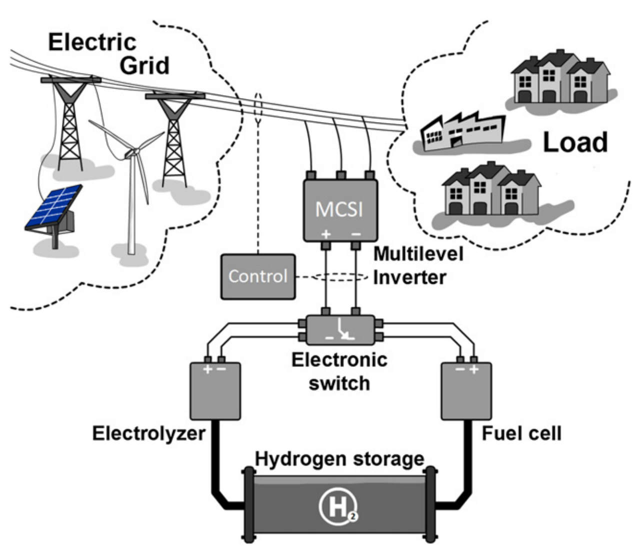


**Fig. 1 – Electric grid with renewable sources and the hydrogen system.**

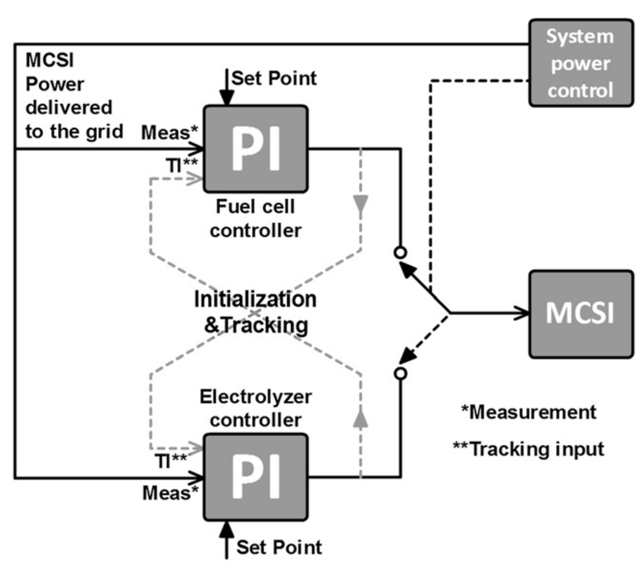


**Fig. 2 – Control block.**

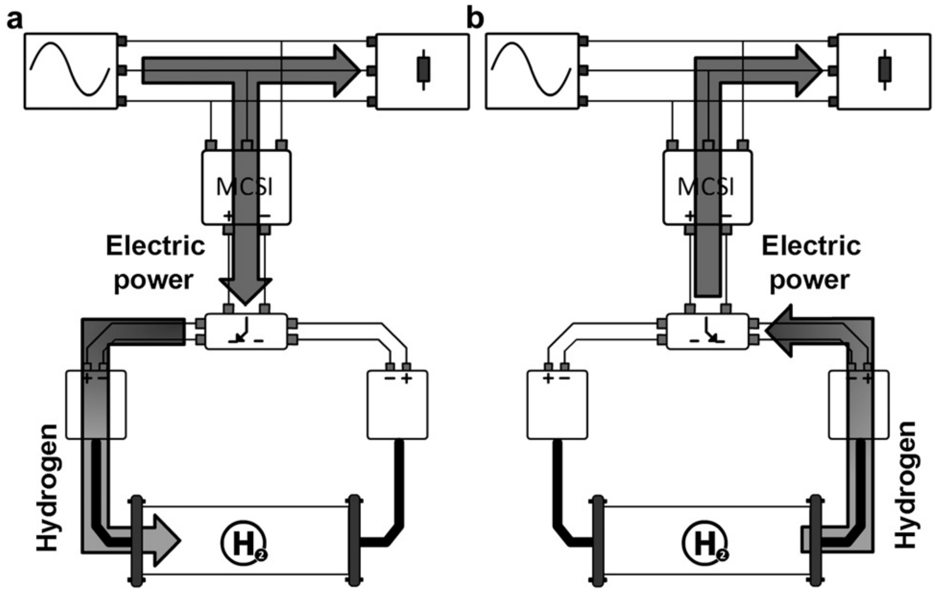


**Fig. 3 – Schematic diagram of the bidirectional power flow of the proposed system, a) producing hydrogen, b) generating electrical energy.**

The mathematical model of the high pressure electrolyzed used has been obtained from [9] and it has been verified with experimental results [7]. Assuming that the operating point is in the high current region, the parasitic elements of the current can be neglected. Thus, the input current and voltage of the electrolyzer can be modeled as $V = i\rho nl\{(l/\sigma) + [A/(\rho l)]\} + nB$, where $\rho$, $\sigma$, $l$ and $n$ are physical parameters [9]. $A$ and $B$ are constants obtained via experimental results in a prototype. In this case $A = 0.0061$ y $B = 1.8311$ thus the linearized model results, $V = 0.4439i + 54.93$.

### 2.2. *Fuel cell*

A fuel cell is an electrochemical device that converts chemical energy into electrical energy, by means of a chemical reaction in an electrolyte, generating water [7] and heat as waste [10]. There are many types of fuel cells, differentiated mainly by the electrolyte used. A schematic diagram of a generic fuel cell is shown in Fig. 4. In the proposed system, a PEMFC in the Ohmic Polarization Region [12] is used because they show adequate operation characteristics for the voltage, current and power levels under consideration. A detailed mathematical model can be found in [2,3,8,10,11]. PEMFC is emerging as one of the most promising technologies when dealing with the replacement of fossil fuels for electric power generation.

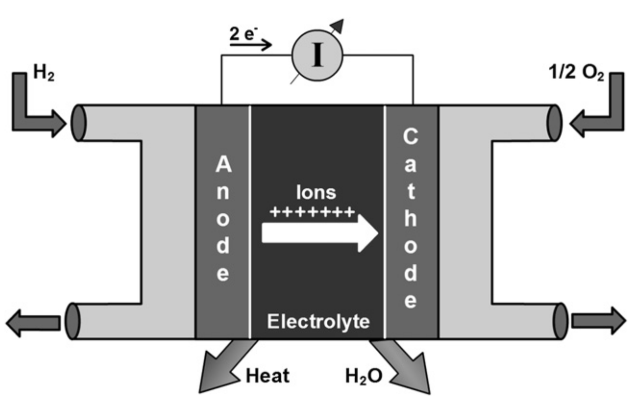


**Fig. 4 – Schematic diagram of a fuel cell.**

The fuel cell consists on the stack of 900 elements with a nominal power of 50 kW at a nominal voltage of 625 V with a maximum efficiency of 55%. The mathematical model is developed in the toolbox "SimPowerSystems" of Matlab/Simulink [4]. The PEMFC is preferred operated in the Ohmic region because of the better efficiency [8].

One disadvantage of the fuel cells is that the voltage is not constant but varies with the current taken from the cell. Then, the use of power electronics converters is essential to interface the PEMFC with the electric systems regardless of the cell operating point. The MCSI allows to adjust the current taken from the cell to get as close as possible to the zone of maximum efficiency [4,8,13].

### 2.3. *Multilevel current source inverter*

The standard practice is to use full-wave rectifier circuits to supply the electrolyzer, whether they are controlled rectifiers (Tyristors) or just diodes rectifiers. These circuits introduce harmonics back into the electric grid and they are not suitable to re-inject electric energy to the grid. The use of a MCSI allows an accurate control of the current delivered to the electrolyzer, heading to operate near the maximum efficiency point. It is possible to compensate power factor and/or harmonics with a slightly modification of the control scheme of the inverter to implement an active filter, when this is a requirement of the application [14].

In this article a seven levels MCSI [15,16] is used to connect the fuel cell or the electrolyzer with the electric system. The

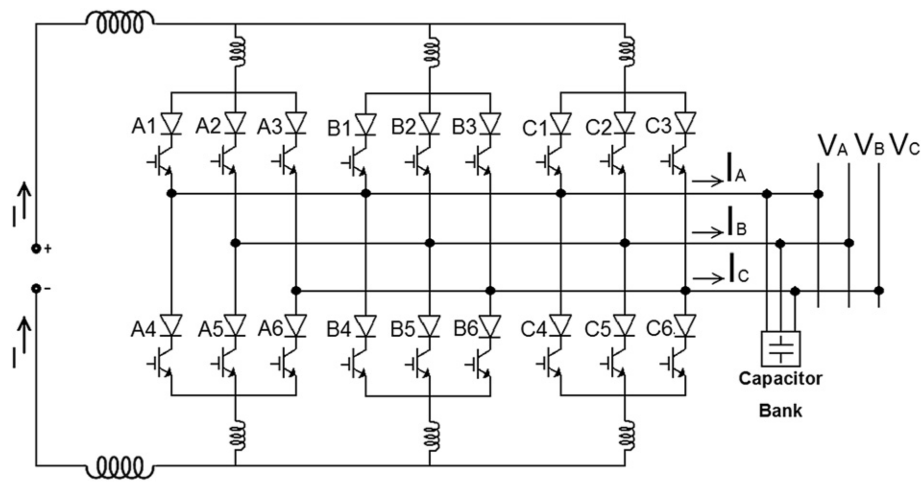


**Fig. 5 – Schematic diagram of the multilevel current source inverter (MCSI).**

schematic diagram of the inverter is shown in Fig. 5. It consists on three identical modules with the capability of producing the seven levels output current shown in Fig. 6. Each module has six switches with bidirectional voltage blocking capabilities and two inductors to balance the current through them. All the balance inductors are identical and conduct the same amount of current, easing the design, construction, operation and maintenance. A small capacitor bank avoids high over-voltages caused by the commutation of the current with inductive loads. The current of each module can be regulated by the use of the well known Phase Shifted Carrier Sinusoidal Pulse Width Modulation (PSC-SPWM) [16–19].

A digital sequential state machine selects the zero state that minimizes the number of switch commutations in a cycle reducing power dissipation and increasing efficiency [16–18]. The modulation strategy, the state machine and the control logic are implemented in a Field Programmable Gate Array (FPGA) [16,19] which is a powerful tool that permits to save costs and development time allowing parallel process of multiple high speed logical tasks.

Voltage Source Inverters (VSI) have been used to interface fuel cells and smart grids recently [5] and as active filters to

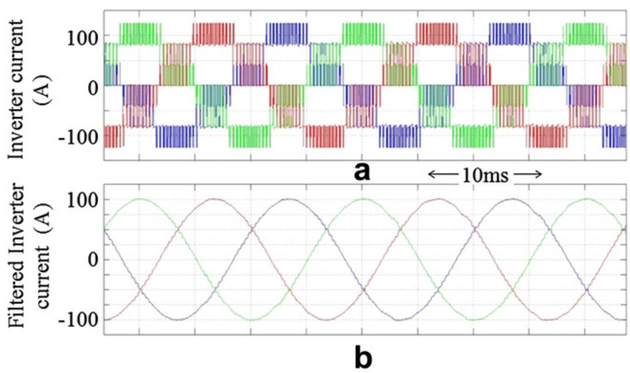


**Fig. 6 – Inverter output current. a) raw, b) filtered by the coupling capacitor bank.**

reduce harmonic content and power factor correction [20]. But the VSI require a boost stage to interface to the cell or the electrolyzer [21]. On the other hand, Current Source Inverters have a large inductor on the DC side, taking an almost constant current from the load. This feature reduces the number of necessary components increasing efficiency and reliability. Moreover they are an excellent option to interface either the electrolyzer or the fuel cell to the power grid without the need of extra electronics.

Although inductors are heavier and bulkier than capacitors, they have a much higher MTBF and the failure method is not pollutant. Inductors can stand high voltage ripple without losing their performance and their characteristics hardly suffer from degradation, with the only condition of providing enough heat sink. This implies safer inverters with longer MTBF, less maintenance requirements and a low danger of pollution. Besides, inductors built with high temperature superconductors will reduce losses, turning MCSI into the most efficient solution for multilevel inverters [22].

Moreover, multilevel topologies present several advantages regarding total harmonic distortion and stress on inductors and power switches [23,24]. So they are preferred against three levels topologies in despite of the increasing complexity of the circuit and control [17].

The MCSI proposed is composed by identical modules allowing the implementation of fault tolerant topologies just adding a fourth module in a hot-spare configuration as shown in [16].

The electronic switch is made with two low-losses-IGBT, with series diodes, to provide bidirectional voltage and current blocking capabilities.

## 3. Simulation results

The system behavior has been simulated with Matlab/Simulink, using mainly the models in the “SimPowerSystems” toolbox. Only 400 ms are shown because the dynamics of the fuel cell and the electrolyzer have been minimized, as in

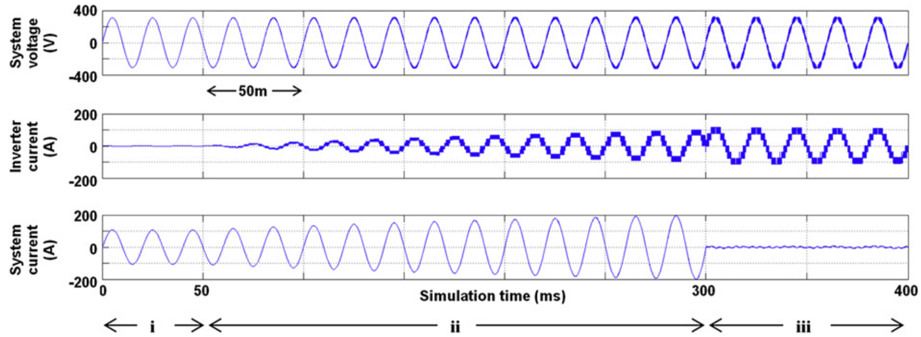


**Fig. 7 – Simulation of the behavior of the system.**

a worst case scenario, to verify how fast the MCSI can adjust the power to and from the electric grid. In a real case, where both the electrolyzer and the fuel cell have their own dynamics, the inverter would perform accordingly well because its dynamic and response time is much faster that the hydrogen based devices. The fast response of the inverter allows to compensate fast voltage sags and swells, from solar and/or wind energy, allowing to store energy temporally in the inductors.

The response of the system to different typical situations is shown in Fig. 7:

i) At the beginning of the simulation, the system is providing the power required by the load. The inverter and the associated hydrogen system remain disconnected.

ii) At 50 ms, the MCSI is connected to the system taking power from the grid and supplying the electrolyzer. The inverter takes active power from the grid to charge the inductors. It can be noticed that the current from the grid grows as long as the inverter is absorbing energy.

iii) At 300 ms, the electronic switch disconnects the electrolyzer and the fuel cell is connected to provide energy to the grid. The control block reverses the power flow modifying the phase of the current generated by the inverter. The system current falls almost to zero since the load is supplied by the inverter with the energy taken from the fuel cell, consuming the stored hydrogen.

When the MCSI is connected to the grid, high frequency harmonics are injected into the system voltage. This harmonics does not interfere with the normal behavior of the system, with a THD that is less than 5%, even considering up to the 50th harmonic as requested by IEEE in the Std. 519-1992 [25].

A detailed simulation experiment of the connection of the electrolyzer to the grid is shown in Fig. 8. It can be noticed how

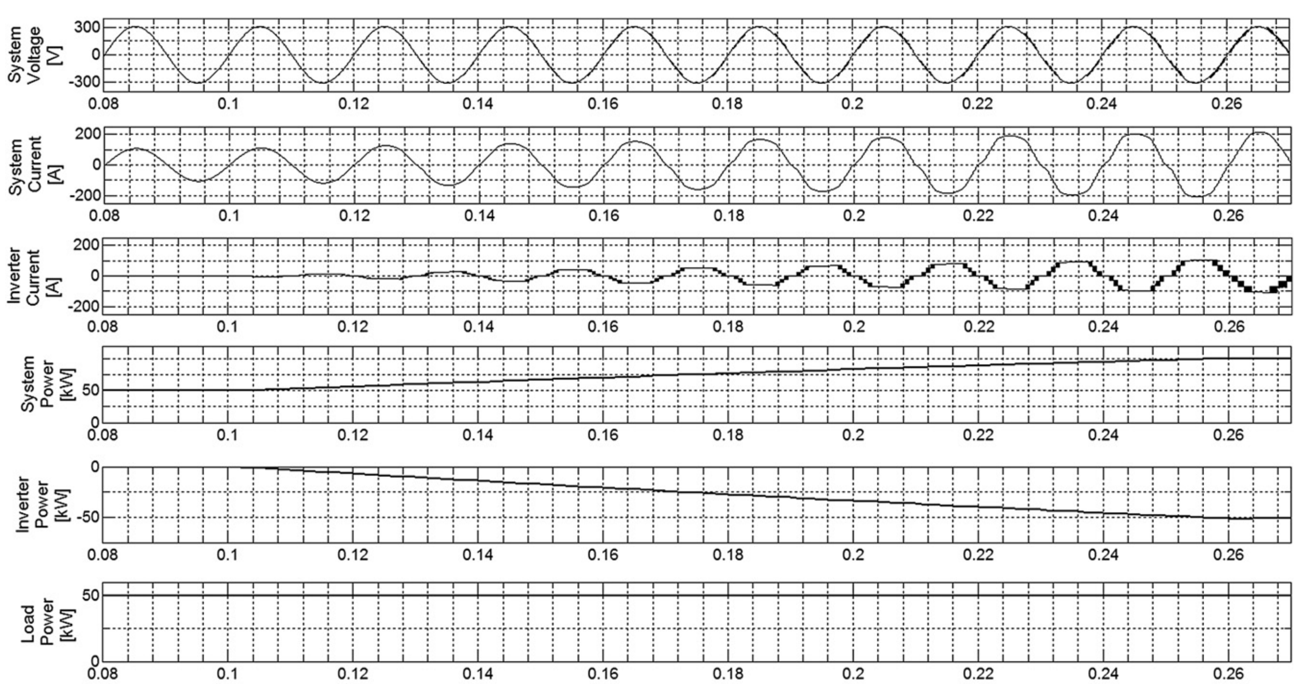


**Fig. 8 – Detailed analysis of the connection of the electrolyzer and the MCSI.**

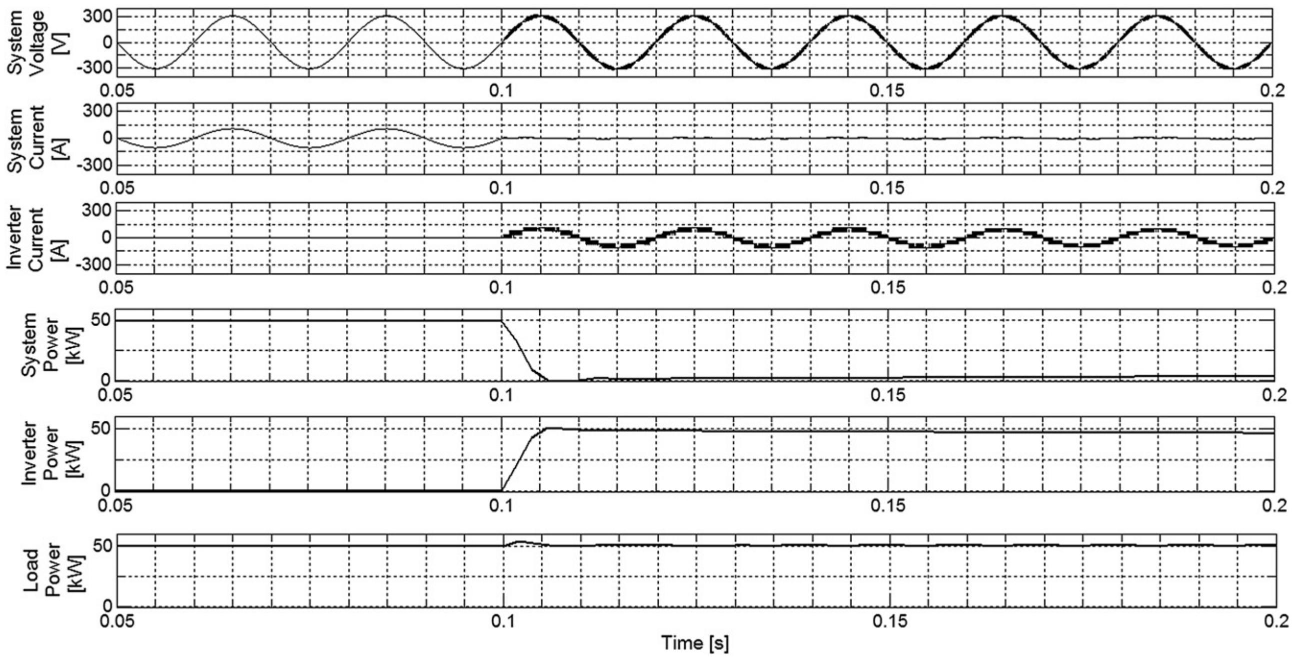


**Fig. 9 – Detailed analysis of the connection of the fuel cell to the system.**

the current provided by the electric grid rises as the inverter increases the energy stored in the inductors. Also the power consumed by the inverter from the grid, that is provided to the electrolyzer, rises with time since it is proportional to the DC current of the inverter.

A detailed simulation experiment of the connection of the fuel cell to the grid is shown in Fig. 9. It can be seen that when the inverter is providing the power required by the load, the system current and power fall to almost zero.

The connection of the inverter and the electrolyzer into a system where the load consumes both active and reactive power is shown in Fig. 10. It can be notice that the system current rises when the inverter takes from the grid the energy that is absorbed by the electrolyzer. For the first 250 ms the control block of the inverter is configured to exchange active power only. At $T = 250$ ms, the inverter is configured to compensate part of the reactive current of the load. It is possible to configure the control strategy of the MCSI to generate reactive power as well as active power [14].

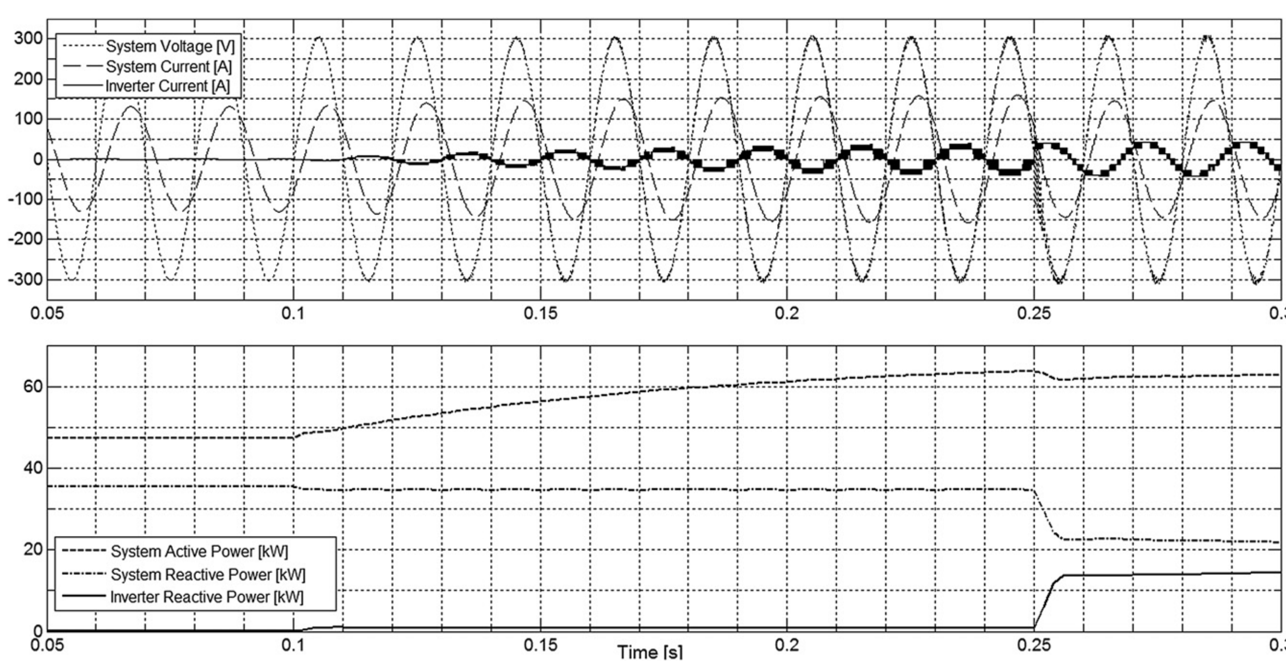


**Fig. 10 – Inverter and electrolyzer connected to a system with active and reactive power.**

## 4. Conclusions

An efficient, ecologic and safe alternative for energy storage in electric systems has been introduced and evaluated through simulations. An environmentally friendly hydrogen generation and consumption arrangement is proposed to improve the power quality in distributed generation systems where a considerable proportion of the power is generated by wind and/or solar sources. As simulations demonstrated, an MCSI is an excellent choice to exchange electric energy with the grid, supplying an electrolyzer to produce hydrogen or being supplied by a fuel cell to generate electric power. The MCSI proposed is the simplest topology to connect both the electrolyzer and the fuel cell to the electric grid, with high efficiency, reliability and fault tolerant capabilities. The presented topology can be used also as active filter and to compensate reactive power in the system.

It can be concluded that the proposed system is a good choice in distributed generation systems, or smart grids, to smooth the peaks and hollows of generation without affecting the load or systems stability.

## Acknowledgment

The authors would like to thank Lic. Ricardo Lauretta for providing the empirical data and his experience with the high-pressure-electrolyzer.

This work was supported by Universidad Nacional de La Plata (UNLP), Instituto Tecnológico Buenos Aires (ITBA), CONICET and ANPCyT.

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