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The Modeling of a PEM Fuel Cell – Supercapacitor – Battery System in Dynamic Conditions

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Abstract-**Today the application of PEM (Polymer Electrolyte Membrane) fuel cell stack in the automotive field is a topic on central interest. Unfortunately, a PEM fuel cell stacks cannot directly supply variable speed drives because of their non-linear behaviour in dynamic conditions. This paper is mostly concerned with the performance evaluation of the PEM fuel cell – supercapacitor system during repetitions of current step variations; in those cases, the supercapacitors cannot be completely recharged before supplying the load in the next dynamic, and the fuel cell stack can be overloaded. We propose the introduction of lithium battery packs and of a DC/DC converter. The obtained results shows that with the proposed configuration, the size of supercapacitors can be significantly reduced, reducing the stress on the battery pack without losses of performance. That will be useful in the design of the control strategy of variable speed drives supplied by the proposed system.**

Index Terms - **Fuel cells, supercacapitors, batteries, current and voltage measurement, testing, transient response.**

I. INTRODUCTION

THE fuel cell (FC) is an electrochemical device that converts chemical energy directly into electrical energy.

With respect to internal combustion engines, fuel cell has higher energy storage capability thus enhancing the range of operation for automobile and is a cleaner source of energy. Fuel cell also has the further advantage of using hydrogen as fuel that could reduce world's dependence on nonrenewable hydrocarbon sources.

The PEM (Polymer Electrolyte Membrane) fuel cell basically requires hydrogen and oxygen as reactants, though the oxidant may also be ambient air, and these gasses must be humidified to prevent membrane dehydration [1, 2, 3]. Each single cell produces about 0.6 V and can be combined in a fuel cell stack to obtain the required electrical voltage and power.

The operating temperature is in the range of 70-100 °C. One of the main weak points of the fuel cell is its slow dynamics. In fact, the dynamics of fuel cell is limited by different phenomena, as the resistance variation of the membrane, due to the temperature, or the hydrogen delivery system itself, which can introduce delays due to the pumps, the valves, and in some cases to the reforming process. Many dynamic FC models are present in literature; they describe FC function, flow gasses, reforming, etc. These models need chemical-physic-electrical parameters that are not usually provided by factories in order to preserve design patent.

In previous research activities [4, 5, 6], we investigated the performance of a fuel cell system in both static and dynamic conditions, especially for the automotive applications, which involve step variations of electric load.

Besides, current step variations abruptly change the fuel cell voltage causing a non-linear behavior (under-voltages). In this case, a parallel supercapacitor becomes an important element to provide energy during transients.

In this paper, our research activity is mostly concerned with the performance evaluation of the PEM fuel cell – supercapacitor system during repetitions of current step variations; in those conditions, the supercapacitors cannot be completely recharged before supplying the load in the next transitory. The obtained results will be useful in the estimation of the system performance and in the design of the control strategy.

II. THE DEVELOPED MODELS

So, the reliability of FCs dynamic simulations depends not only on the model accuracy but also on FC parameters finding. In this case, we adopted a new approach to define the dynamic FC model using measurements obtained by our FC measurement system shown in [4].

Its main features are: 10 cells stack , electrode area of 64 cm^2, nominal power of 150 W, nominal voltage of 6 V, nominal current of 25 A, reactants H_2/air, reformate/air, H_2/O_2; max operating temperature of 70 °C; operating air pressure of 0-34.4 kPa; operating H_2 pressure of 0-34.4 kPa; self-humidified stack.

The electric load at the fuel cell output was implemented using the Agilent N3301A mainframe, with two N3302A electronic load modules. Each module has a current range of 0-30 A, a voltage range of 0-60 V and a maximum power of 150 W.

This system allows constant current, constant voltage, constant resistance and transient modes to be implemented. The electronic load allows both current and voltage to be measured by the PC during the tests, by means of the IEEE 488 interface.

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The experimental current and voltage waveforms have been acquired and used to perform a system identification using MATLAB toolbox [5, 6]; the PEM fuel cell model is in Fig.1. It has been validated with a comparison between the acquired and the simulated voltage and current waveforms (Fig. 2).

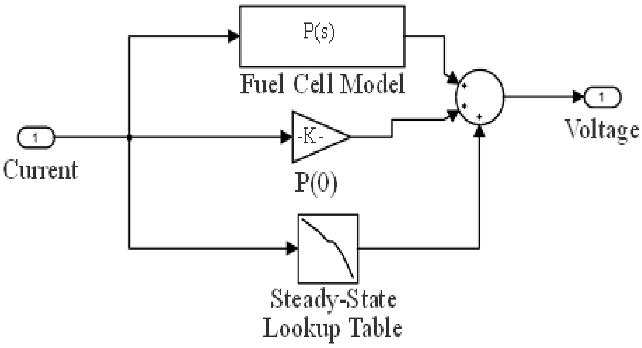

Fig. 1 PEM fuel cell model

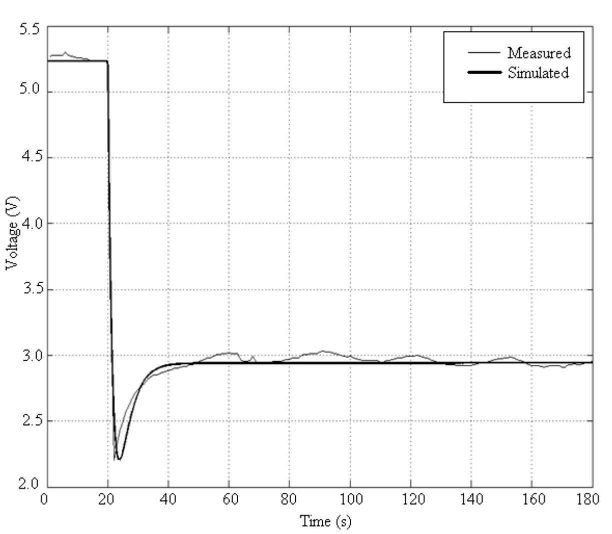

Fig. 2 Simulated and measured voltage response for 10-20 A current step variation

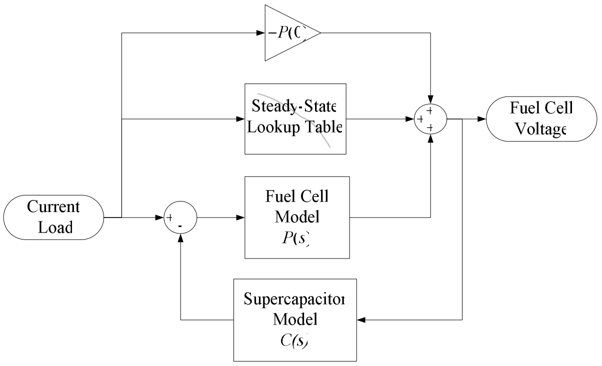

Fig.3 Whole fuel cell model

The FC model has been utilized to evaluate the dynamic behaviour of the whole system when a supercapacitor is parallel connected, by means on the model in Fig. 3.

As an example of the dynamic response of the system, we provide a simulation in which the capacitance value is undersized ($C = 5$ F) for the considered current step variation ($\Delta I = 10$ A), form an initial value of 10 A, causing a transient under voltage for the fuel cell (Fig. 4) and a consequent negative transient current of the supercapacitor with a peak value ΔI (Fig. 5).

These figures show the effect of an undersized capacitance value: for a current step variation, the electric charge required by the load is too high for the supercapacitor that can not provide the total energy.

In that case the supercapacitor can only slightly reduce the transient under voltage ΔV (Fig. 4). This behavior can be critical when dynamic conditions occur as a repetition in few seconds, as in heavy automotive applications in urban transportation.

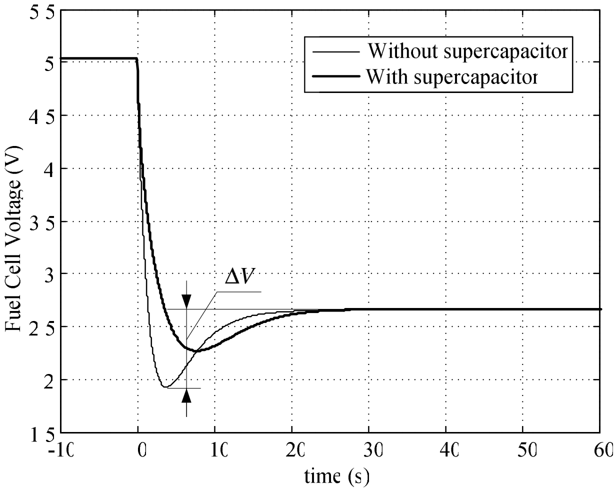

Fig.4 Fuel Cell voltage for a current step variation with an 5 F capacitance value

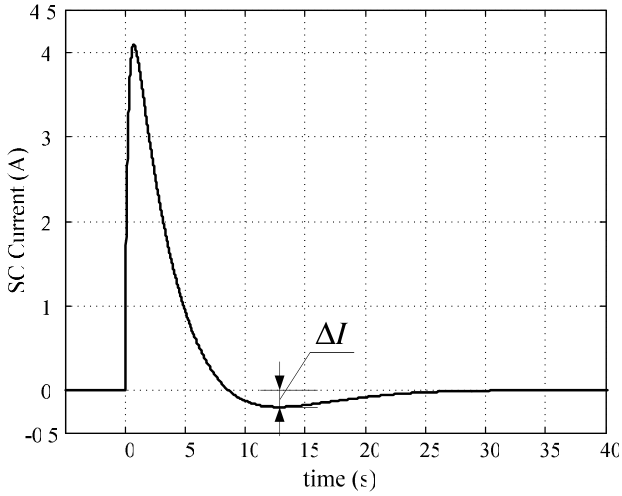

Fig.5 Supercapacitor current for a current step variation with 5 F capacitance value

III. THE OPTIMIZATION OF A PEM FUEL CELL – SUPERCAPACITOR- BATTERY SYSTEM IN LONG-TIME DYNAMIC CONDITIONS

As previously discussed, the fuel cells have a slow dynamic and the initial under voltage, with respect to the steady state value, is recovered only in few tens of seconds (Fig.2). So a supercapacitor is needed to partially or totally avoid the voltage drop when the load requires current step variations.

The FC model has been successfully adopted to study the dynamic behaviour of the system when a supercapacitor is parallel connected, in order to evaluate the minimum supercapacitor value to cut off the current overshoot [6].

The problems are shown in Fig. 6: i) in our tested system, the presence of a parallel-connected supercapacitor of 10 F, for example, is not sufficient to supply energy for a load step current variation, so it is necessary to increase the supercapacitor value to cut off the overshoot; ii) in the other hand, during a repetition of current step variation, the recovery time is not enough to damp the transient.

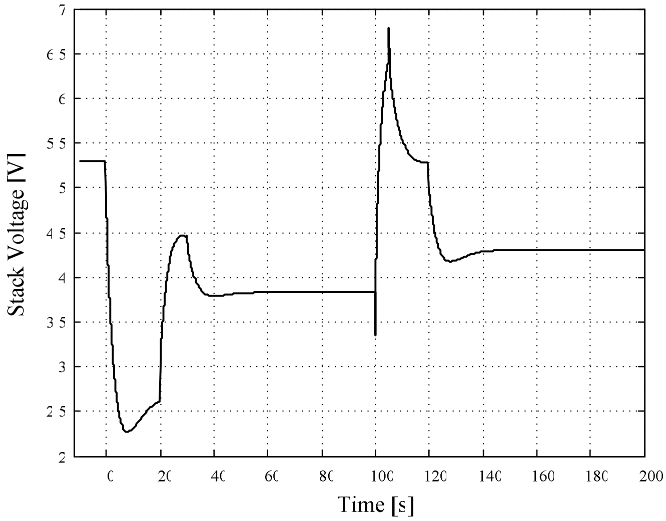

Fig. 6 : Stack voltage response during repetition of current step variation with a supercapacitor of 10F parallel connected

In the present paper, we focused our activity on the study of the behaviour of the fuel cell stack during long-time transitories, with the main aim of reducing the hydrogen consumptions.

It can be obtained if the fuel cell stack works at the highest efficiency point in steady state conditions.

Starting from previous measurements [4], we adopted the diagram in Fig. 7 for the identification of the working point of the fuel cell stack.

During our measurement activity, we pointed out the difficulty of supply the required current in long-time transitories by adopting only supercapacitors as auxiliary power devices; in the present paper we introduce a lithium battery pack in order to supply the current when the supercapacitor contribution is extinguished. The battery pack can also supply power if hydrogen flux is closed for a small time.

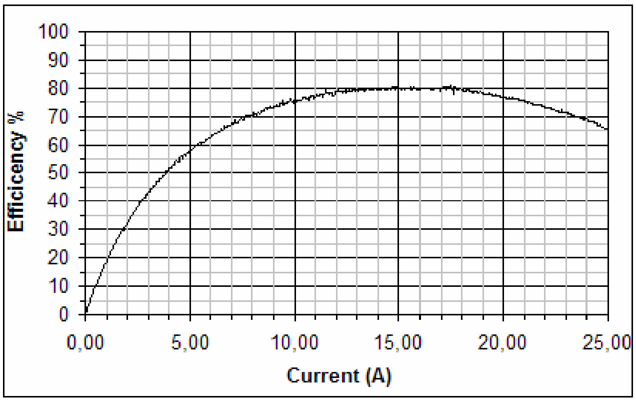

Fig. 7 : Experimental efficiency diagram of the fuel cell stack.

The increased complexity of the overall system can be correctly managed by introducing a DC/DC converter, working on the voltage level as depicted in the block diagram of Fig. 8.

At the current stage of our research activity, we considered ideal behaviour for the battery pack (V* in Fig. 8) and for the DC/DC converter; that hypothesis can be justified by considering the low voltage of the fuel cell stack.

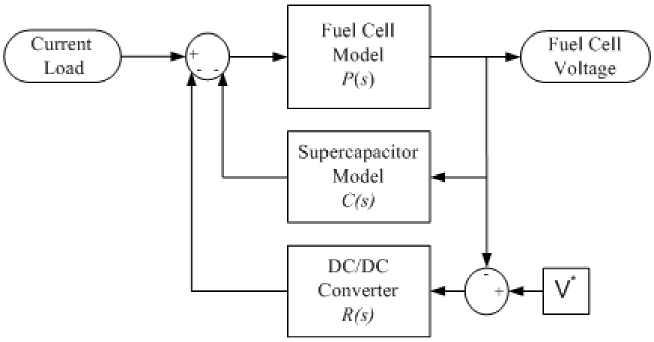

Fig. 8 : Block diagram of the complete system.

The optimization procedures have been focused on the battery size, with the aim of: i) keeping the fuel cell stack in the maximum efficiency conditions, ii) avoiding the output current peaks in the battery pack; iii) evaluate the optimal supercapacitors size.

Starting from Fig. 7, we chose for the fuel cells 16 A, 4.2 V working point. 20, 50 and 80 F supercapacitors have been adopted in our simulations.A complete set of current pattern has been adopted in our simulations, reproducing the load profiles of real variable speed drives in dynamic conditions; one of them is shown in Fig. 9. The sequence of steps up and down has been chosen to increase the stress of the components in our system, with the aim of developing a simulation technique suitable for the application in realistic load diagrams. The effect of the supercapacitors can be observed in Fig. 10; in previous works, in which the battery packs have not been introduced [6], we found that, for our system, 50 F supercapacitor can be the best choice. In this work we propose the adoption of a battery pack and a DC/DC converter, whose effect is the reduction of capacitance needs of the system. In fact, it is possible to reduce the supercapacitor size down to 20 F without a significant effect on the current shape in Fig.11. On the contrary, the increasing of the supercapacitor size must be avoided, because of its effect on the current of the supercapacitor itself, as shown in Fig 12, and on the battery pack current in Fig.10. The battery pack voltage is reported in Fig. 13. The effect of a further reduction of the supercapacitor size has been simulated; with 2F capacitance value the fuel cell stack suffers the effects of load transients, as shown by the voltage diagram in Fig. 14.

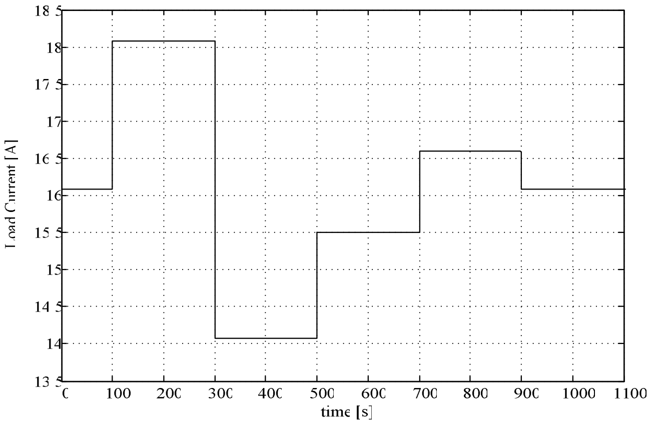

Fig 9. The load current pattern

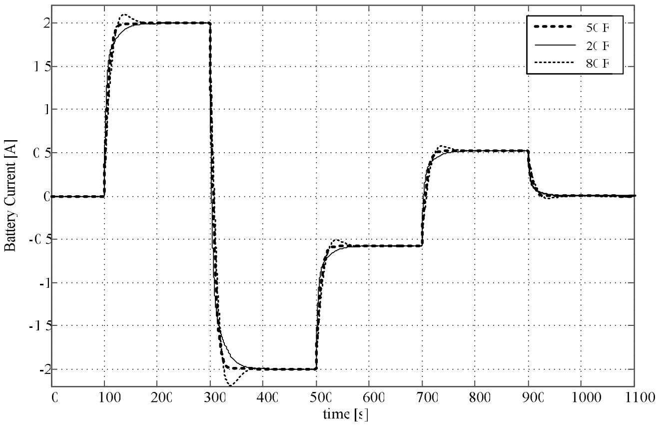

Fig. 10 Battery pack current

IV. CONCLUSIONS

The topic of this paper, is mostly concerned with the performance evaluation of the PEM fuel cell – supercapacitor system during long-time transitories; in those conditions, the supercapacitors cannot be completely recharged before supplying the load in the next transitory; moreover, the increasing of the supercapacitors size can introduce an undesired overload on the fuel cell stack.

Our activity has been focused on the study of the behaviour of the fuel cell stack by applying repetitions of current step variations, with the main aim of keeping the fuel cell stack at the highest efficiency point in steady state conditions. A lithium battery pack and a DC/DC converter have been introduced in the system.

The simulations results presented in the paper suggest the reduction of supercapacitors size, without losses of performance of the system.

The developed model can be successfully adopted for the design of the supply system for variable speed drives in the automotive field, in which the battery packs and DC/DC converter are already used, and the decreasing of the stress on the battery pack is one of the main aim in the automotive design.

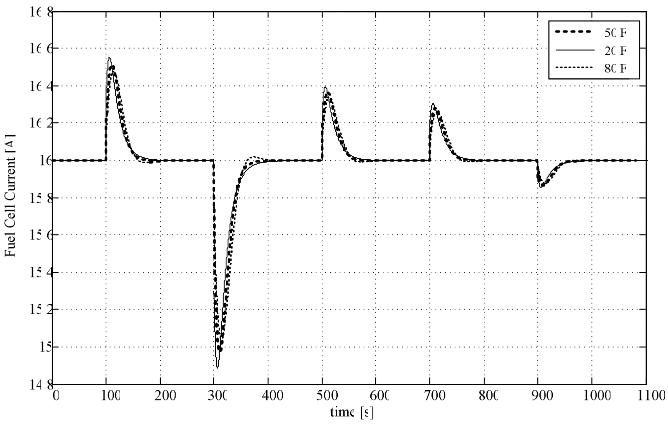

Fig 11. Fuel cell stack current

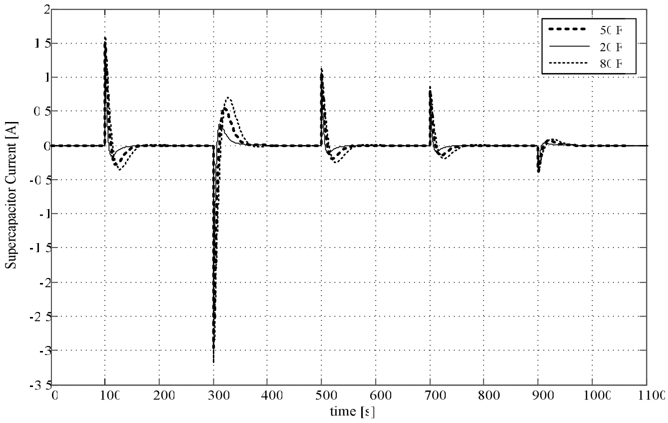

Fig. 12 Supercapacitor current

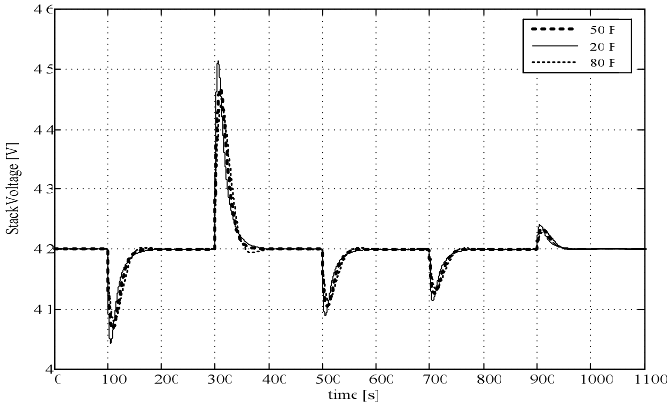

Fig. 13 Battery pack voltage

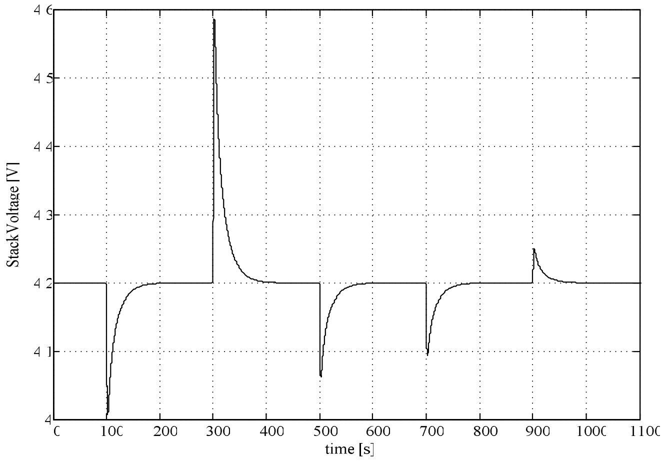

Fig. 14 Fuel cell stack voltage in a system with 2F supercapacitor.

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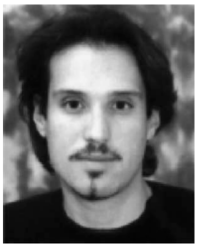
VI. BIOGRAPHIES



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Nicola Rotondale received the degree in electrical engineering from the University of Naples, Naples, Italy, in 1973. In 1978, he was appointed Assistant Professor of Electrical Machines Design at the University of Naples. From 1977 to 1983, he was a Lecturer of Electrical Machines Design at the University of Calabria, Cosenza, Italy. From 1983 to 1989, he was an Associate Professor of Power Electronics at the University of Naples. Since 1990, he has been a Full Professor of Power Electronics at the University of L'Aquila, L'Aquila, Italy. His studies deal with linear induction motors, fault analysis and diagnosis of ac machines, and design and application of power converters.