A new design for an Auxiliary Power Unit (APU) by associating Supercapacitors and a Proton Exchange Membrane Fuel Cell

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Keywords

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Abstract

This paper describes the design and control requirements of an auxiliary power unit (APU) for transportation applications. The design of the APU is based on an association of supercapacitors and fuel cell. Supercapacitors are incorporated to satisfy peak power demands in order to optimize performance of the APU and to reduce its size and therefore also the cost of the fuel cell. After the system description, simulations are performed to optimize the DC/DC converter between the APU components and the DC bus of the vehicle.

1 Introduction

Global air pollution level becomes each year higher, and transportation contributes greatly to it. For instance, in the United States, transportation is responsible for about one-third of the nation's emissions of carbon dioxide [1]. In order to decrease carbon dioxide and other gas emissions, many car manufacturers have already proposed different kind of vehicle configurations (pure electrical vehicles, hybrid vehicles, fuel cell vehicles ...) where the aim is to replace the internal combustion (IC) engine. Beside these solutions, another solution consists in providing only the electrical power needed aboard by a no-emission source.

Indeed, electrical power needed on board of conventional vehicles has greatly increased as equipment is more and more important: air conditioning, power steering, anti lock brake system, multimedia… In 30 years, alternator power has been multiplied 6 times and battery capacities 3 times. Moreover, electrical power should double in the next few years as hydraulic auxiliaries like pumps for instance will be electrified to increase efficiency and reliability. To face this evolution, the association of the alternator rotated by the IC engine and the battery could be replaced by a fuel cell as an auxiliary power unit (APU). The American car supplier Delphi is associated with the car manufacturers BMW and Renault to develop this option [2]. At the present time, only pure fuel cells solutions (based on Solid Oxide Fuel Cells) have been demonstrated. APU are promising for two reasons. The first one is the reduction of gasoline consumption (50% during a city cycle) as the efficiency of the fuel cell system is greater than the one of the association IC engine and alternator. Secondly, auxiliaries can be powered even if the IC engine is shut down.

In this study, we propose an association between a Proton Exchange Membrane Fuel Cell (PEMFC) and supercapacitors to achieve this aim. The power exchange between the fuel cell and the supercapacitors is characterized and the energy flows between DC bus, supercapacitors and the fuel cell are controlled. The main advantages of such a hybridized APU solution are the size reduction (and cost…) of the needed fuel cell and in a better behaviour of the whole APU system in transients.

In a first part of this paper, the chosen supercapacitors and fuel cell are described. Then, the desired specifications for the APU are presented. Finally, the chosen APU structure is presented and the control strategy is provided. As this APU is currently under realization, only simulation results are presented in this paper.

2 Fuel cell and supercapacitors

2.1 Fuel cell description

Among the five types of fuel cells that are available on the market, only two seems to be very interesting for automotive applications: the Proton Exchange Membrane Fuel Cells (PEMFC) and the Solid Oxide Fuel Cells (SOFC). These two kinds are using a solid electrolyte, excluding all risk of leakage of this electrolyte [3]. The main difference between these two technologies resides in their respective operating temperatures: around 80°C for the PEMFC and about 800°C for the SOFC. This implies a longer starting time in the SOFC case but also a simplification of the hydrogen fuelling (in case of an aboard production). Indeed, a better agreement exists between the operating temperatures of the fuel cell and the gasoline reformer.

In this study, we are supposing that hydrogen is directly stored on board, therefore a 500We PEM Fuel Cell has been considered. This fuel cell can only provide a peak current of about 40A (under 12V), which is far to low for the starting of the internal combustion engine. Therefore, it can only be used to ensure the permanent power requirements of the vehicle. The considered fuel cell system is constituted by a PEMFC that can be operated with pure or reformed hydrogen on the anode side and with air or oxygen on the cathode side. The stack is made up of 20 cells (area 100cm^2). The range of the operating temperatures begins at 15°C to go as far as 70°C. Additional to the anode and cathode gas circuits, a coolant deionized water circuit is used to extract the calories from the stack. Fig. 1 presents a view of this stack.

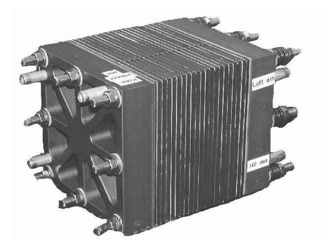

Fig. 1: PEM fuel cell stack.

As it is well-known, many different kinds of physical phenomena (electrochemical, thermodynamical, thermal, etc.) are involved in the evolution of the fuel cell stack. Furthermore, the electrical response of the fuel cell depends not only on the stack itself but also on the response of the auxiliaries that are located around the stack: air compressor, hydrogen expander, electrical converter, etc. Therefore, high dynamical characteristics can only be obtained by hybridizing the fuel cell with another electrical storage element (supercapacitors in our case). Moreover, this hybridization implies also a size reduction of the fuel cell system, leading in a cost reduction of the whole APU system.

Considering the dynamical simulation of the fuel cell stack, a simple model has here been used. This simple model is based on the association of resistances, representing the activation overvoltage and the ohmic losses, a capacitor representing the charge double-layer at the surface of the fuel cell electrode, and a voltage source [3]. This model provides a simple and effective way to analyze the performances of the fuel cell stack. All the parameters of this model have been estimated considering experimental tests done on our 500W PEMFC stack.

2.2 Supercapacitors

Supercapacitors represent one of the most interesting new developments in the field of energy storage. Potential applications concern short time uninterrupted power supplies and peak load [4, 5, 6]. The power density of these supercapacitors is considerably higher than that of batteries, and the energy density is higher than that of electrolytic capacitors for power applications. Because supercapacitors move electrical charges between conducting materials, rather than perform any chemistry, they maintain cycle ability far longer than batteries.

Supercapacitors consist in two activated carbon electrodes and a separator that prevents physical contact of the electrodes but allows ion transfer between them. A carbon-blinder mixture is deposited on aluminium foil to form the electrodes. Supercapacitors are based on the double-layer capacitance at the solid/electrolyte interface of high surface area material. Similar to a traditional electrolytic capacitor, the electrical energy storage is based on the separation of charged spaces in an electrolytic double-layer across the interface of electrode/electrolyte. When a DC voltage is applied as shown in fig. 2, the electric double-layer is formed to store electric energy. The double layer capacitance is proportional to the electrode surface area and inversely proportional to the thickness of the double layer (a few angstroms).

Supercapacitor is a device that consists of a pair of ideally polarizable electrodes Only devices that do not exhibit Faradic reaction over the potential range of operation are considered as electrical double-layer capacitors, and all the charges accumulated are used to build-up a double layer between the conductor and the electrolyte. Charge and discharge of supercapacitor is, in fact, charge and discharge of the double-layer, because no electrochemical reaction is involved.

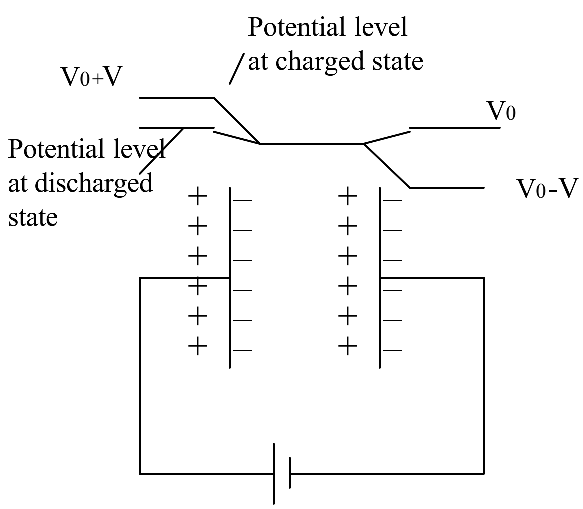

Fig. 2: Principle of a single cell supercapacitor operation

The ions are transferred between the electrodes by diffusion through the electrolyte. The quantity of energy and charge stored in supercapacitors are a function of the supercapacitor capacitance and its serial resistance. Moreover, to maximize the capacitance in order to store the maximum of energy, the activated carbon surface area must be maximized and the double layer thickness minimized.

To use supercapacitor in transportation applications, it is necessary to study its electrical and thermal behavior in its operational environment. An electric model of supercapacitor for simulation, which takes into account temperature variations, has been achieved in the L2ES laboratory [7].

Conway [8] proposes an equivalent circuit based on transmission-line model, which involves distributed capacitance and resistance like the impedance characteristics of a transmission line. However, in power electronic applications, the supercapacitor electric behavior can be described by an equivalent electric circuit with two RC branches [6, 7] This model is not complex and the simulation time is reduced compared with the model of transmission line with five RC branches for example. In this study, the electrical model of supercapacitor used is the circuit with two RC branches.

3 APU specifications

The considered APU specifications are based on the power consumption of a typical transportation heating element: an electric air heater. This heating element is, in most cases, directly connected on the DC electrical bus of the vehicle. The power consumption of this element can be described as follows (fig. 3): during a short time (in our case 10s), electrical resistive elements are fed and brought to a high temperature level; then, during a much longer time (in our case 60s), fans are only blowing on these resistive elements to provide the heat into the passenger compartment.

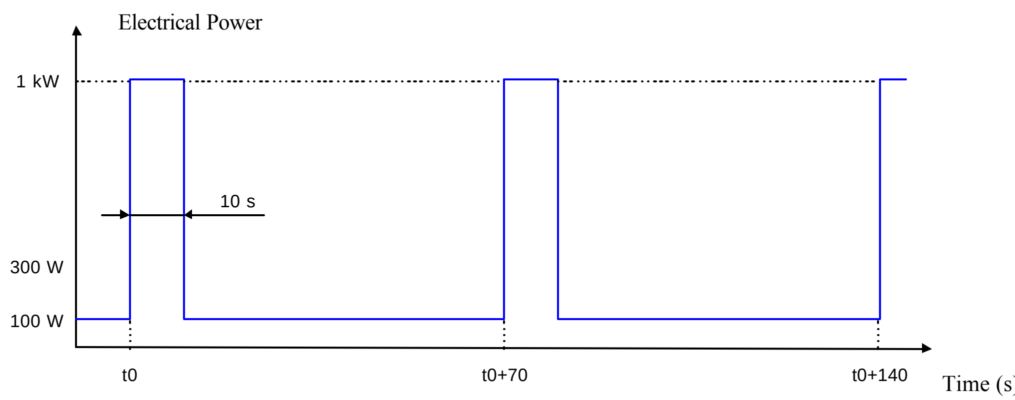

Fig. 3: Power consumption of the electric air heater.

During the heating phase, the power demand is equal to 1kW whereas during the blowing phase, it is only equal to 100W. As it can be seen on Fig. 3, the power demand is a very dynamical one; the fuel cell system alone is not able to respond to this power requirement. This fact underlines the necessity of hybridization.

Despite its nominal power (equal to 500W), the fuel cell stack power supply will be, in this study, limited to 300W. The main reason of this limitation resides in the fact that the ageing effect of the fuel cell stack is voluntary left out of account. Indeed, it is well-known that the electrical performances of a fuel cell stack are decreasing over time.

Thus, supercapacitors will have to ensure the transients whereas the fuel cell stack will be dedicated to recharge the supercapacitors and to provide the power needed by the blowers.

4 Supply design

4.1 Structure of the supply

The design of the vehicle DC supply is based on a serial structure. An overview-scheme of this structure is given in Fig. 4. Firstly the main generator is a 500 W PEM fuel cell. Next we have a boost chopper which controls the output current of the fuel cell with a supervision of the supercapacitor tank voltage. The supercapacitor tank supplies (or takes) the power peaking. It's composed of 12 cells 2,5 V / 800F in serial configuration. Supercapacitors voltage varies according to the output power. The voltage range is maintained between 50% and 100% of the nominal tank voltage (in our case 30V). The tank has an automatic cell voltage balancing in order to protect him from locally excess load of one (or more) cell. The last module is a buck chopper. It controls the vehicle DC network voltage at a constant value (around 14V).

Another possible configuration could have been a parallel arrangement (Fig. 5). In this case, the chopper connected to the supercapacitor tank should have been bi-directional versus current while in the serial structure only simple unidirectional converters are used.

Thus, considering the serial structure, two strategies have to be considered: a boost chopper / supercapacitors / buck chopper strategy and a buck chopper / supercapacitors / boost chopper strategy. In the first case, the voltage level on the supercapacitor tank is much higher, leading in a minimization of commutation losses (due to the reduction of current level between the two choppers).

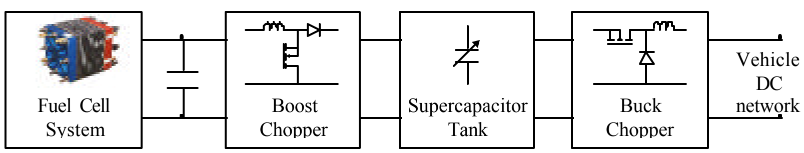

Fig. 4: General scheme of the supply (serial structure).

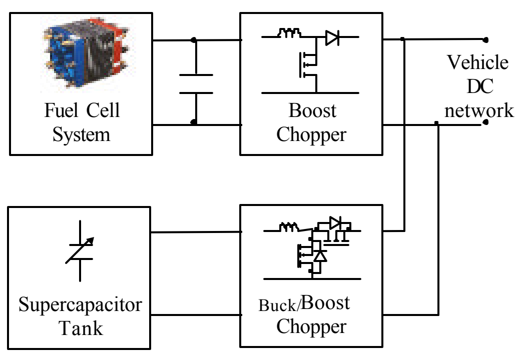

Fig. 5: General scheme of the supply (parallel structure).

4.2 Control system

4.2.1 Principle

The main parameter of this structure is the output current of the APU which is in fact the current required by the DC network load. In one hand, when there is no dynamic current solicitation, supercapacitors supplied nothing and the fuel cell stack provides all the current. On the other hand, if the DC network suddenly requires a power rise, the supercapacitor tank provides the power so that the fuel cell has enough time to react.

To achieve this aim and before applying a power demand on the fuel cell system, it is necessary to furnish to the fuel cell control system an instruction so as to increase the gas flows (oxygen and hydrogen). After the desired set point gas flows are obtained, the fuel cell system is able to provide the required power. This procedure ensures that the fuel cell stack suffers no major damage. When the gas flows are established, the boost chopper control increases gradually the fuel cell current set point until the whole current, including the current for the supercapacitor tank refill, is reached. Fig. 6 represents a theoretical regulation cycle.

During the first four seconds after the current solicitation, supercapacitors are ensuring alone the current demand. Then, after the gas flows are correctly settled, the fuel cell stack is able to provide the whole current, including the supercapacitors recharge current. It can be noted, thanks to Fig. 6, that the supercapacitor tank voltage never goes under 20V (about 66% of its nominal value) during the considered cycle.

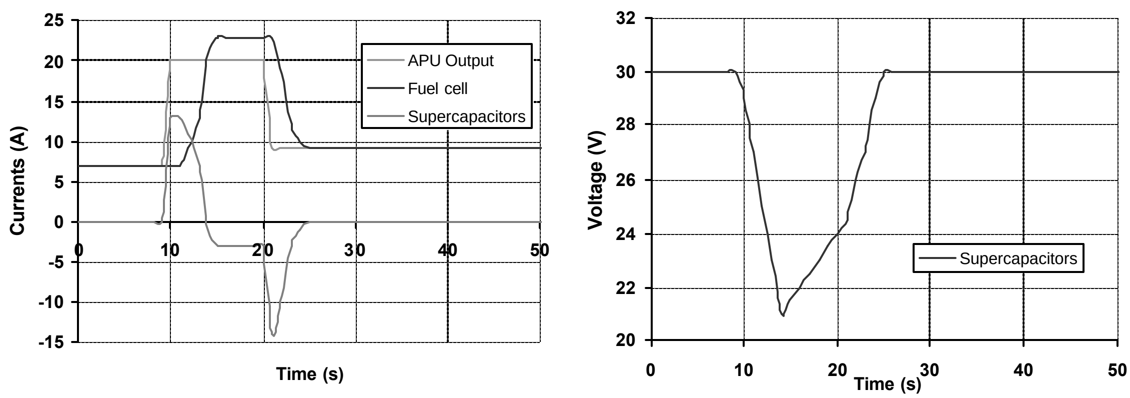

Fig. 6: Theoretical regulation cycle.

4.2.2 Regulation

The boost chopper control system is based on a hysteresis control with constant frequency. The buck chopper is driven by a PWM control with a proportional integral regulator. These regulators are programmed on a microcontroller which supervises the APU system (fig. 7).

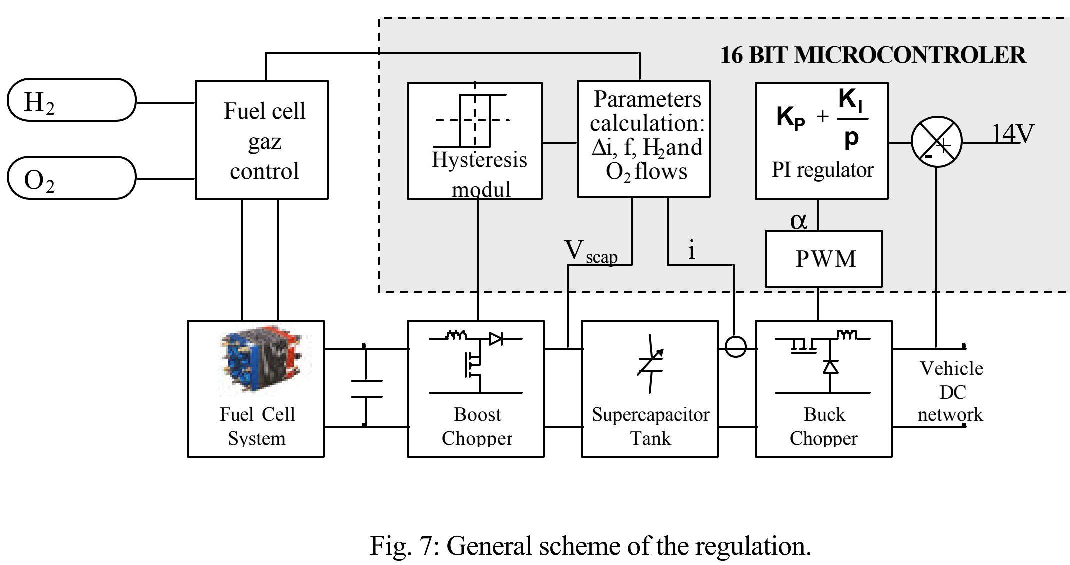

Fig. 7: General scheme of the regulation.

4.2.3 Simulations results

The parameters of the simplified models of the fuel cell and supercapacitors have been determined by experience. All the APU system (fuel cell, supercapacitor and control) has been simulated with the SABER software. For example, we have simulated the following power solicitation: the initial power is about 90W and provided only by the fuel cell. Then the power request rises to 900W during 10 seconds and goes back down. Fig. 8 shows the obtained simulation results.

The simulation parameters are the followings:

- Fuel cell: 12 V / 500 W
- Supercapacitor tank: 12 cells 2,5 V / 800 F
- Vehicle DC network : 13 V

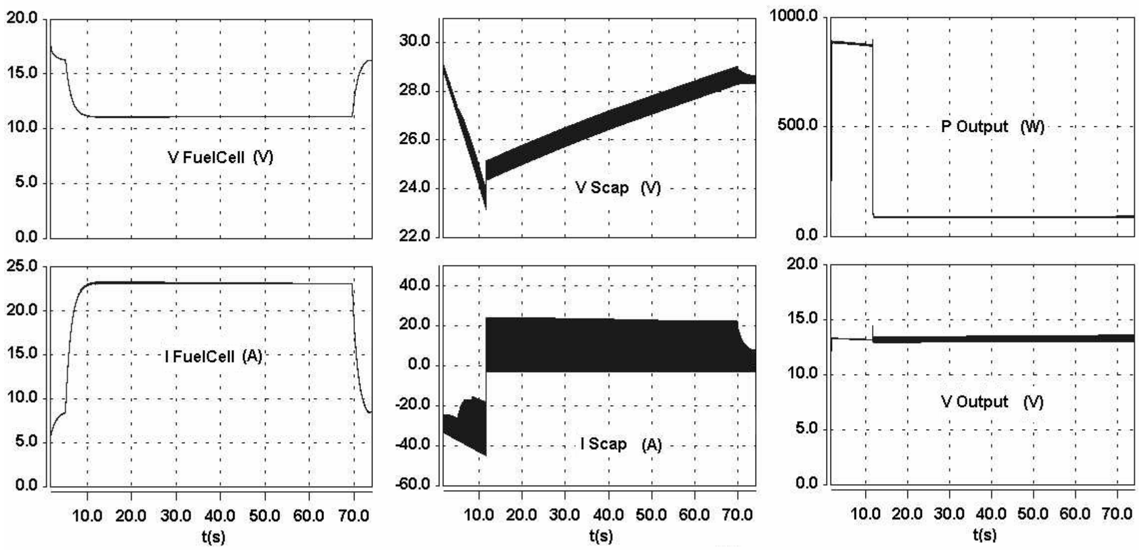

Fig. 8: Simulation results

The supercapacitor tank supplies immediately the current necessary to respond to the power solicitation whereas the fuel cell current is growing slowly. The fuel cell current is here intentionally limited at 23 A. After the initial power rise, the fuel cell recharges the supercapacitor tank at a constant power and supplies the output power (90W). Recharge stops when the supercapacitor voltage reaches its nominal value (30V). Then the fuel cell supplies only the output power. As it can be seen on these results, the behaviour of the APU system fits the desired specifications.

5 Conclusions and perspectives

The application of fuel cell APU for transportation arrives in the context of a significant trend to electrification of vehicle accessories (electric air conditioning, power steering and brakes …). The two main advantages of a fuel cell APU solution lie in a significant reduction of gasoline consumption (about 1l/100km) and in the possibility of providing power during extended internal combustion engine-off periods [9].

A novel scheme of a hybridized APU has been proposed in this paper. It associates a PEM fuel cell, which is widely regarded as the likely fuel cell choice for automotive applications, to a supercapacitors tank.

In a first part of this paper, a full description of the considered PEM fuel cell and supercapacitors is provided. Secondly, the required specifications for the APU are presented. Then, a structure of power supply is proposed, including its control strategy; simulation results are finally proposed, underlining the well-behaviour of the proposed APU. Of course, the next stage is the experimental validation of the proposed APU structure. The experimental APU is currently under realization in the L2ES laboratory.

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