Structure and Control Strategy for a Parallel Hybrid Fuel Cell/Supercapacitors Power Source

T. Azib, O. Bethoux, Member IEEE, G. Remy, Member IEEE, and C. Marchand, Member IEEE
Laboratoire de Genie Electrique de Paris (LGEP) / SPEE-Labs, CNRS UMR 8507; SUPELEC; Universite Pierre et Marie Curie P6; Universite Paris-Sud 11; 11 rue Curie, Plateau de Moulon F91192 Gif sur Yvette CEDEX
toufik.azib@lgep.supelec.fr

Abstract—In this paper, two control strategies for two parallel hybrid fuel cell/supercapacitors power source are described. First, different hybrid architectures using fuel cells for automotive applications are analyzed. Two parallel hybrid configurations are more precisely detailed and their control strategies are explained. Then, experimental validations using a Nexa Ballard PEM-FC as main source and BOOSTCAP Maxwell supercapacitors as auxiliary source are presented to illustrate the effectiveness of the proposed control strategies.

Keywords—Fuel Cell; Supercapacitor; Parallel Hybrid Structure; Static Converter; Control Strategy; Automotive Applications.

I. INTRODUCTION

Automotive applications have to face more and more stringent environmental norms, especially since clean air and climate change have become a societal concern [1]. Therefore, hydrogen fuel cells (FC) are becoming a potential propulsion technology for automotive transportation. But, despite the potential of these technologies for the reducing of the environmental impact, many issues that have to be overcome are studied: fuel cell stacks (membrane, catalyst) [2], main subsystems including air compressor [3], hydrogen storage and distributing infrastructure [4] and vehicle integration [5]. Indeed, the FC conditions for use are investigated regarding vehicle requirements, such as FC lifetime and failure recovery [6], low dynamics and decreasing of efficiency at high current density [7].

In this paper, the power electronics architectures for automotive applications are analyzed. Automotive power supplies require both reliable operating modes and load profiles with high ratios of peak power to average power, whereas fuel cells are unfortunately limited by their inherent characteristics [8]. Furthermore, FC systems have erratic behaviors due to changes in the stack state (membrane flooding or drying, channels drowning of the gas supply, reactive concentration drop) which may imply transient power drops, a poor efficiency at high power (linked to electrochemical properties and auxiliary systems) and poor response to instantaneous power demands (limited by the air delivery system).

Consequently, a commercially viable FC car solution cannot rely on this supply power source only.

Thus, FC need to be associated with other sources which provide the short pulse energy and make up for the temporary failure of FC. Nowadays, these auxiliary sources can be either batteries or supercapacitors (SCs) [9] [10]. But thermal constraints in automotive applications are severe and the braking power requested is even greater than the accelerating power. Sometimes batteries are not able to support this high power charge and the discharge conditions, whereas supercapacitors can operate even at low temperatures (e.g. -20°C), and are already industrially manufactured. Therefore, for fast car power demands, supercapacitors are probably the best suited components. At that point, the design challenge is to choose power components, to design an adapted architecture and also to define the appropriate associated control strategy.

In this paper, those two last issues are investigated in order to suggest a hybrid power source structure which takes into account automotive requirements: high efficiency, low volume and low cost [8] [11]. Then, two structures of parallel hybrid power source are compared and analyzed using a fuel cell (FC) as main source and supercapacitors (SCs) as secondary source. For both structures, a control strategy is developed in order to achieve the energy management of these different sources as well as of fulfilling load demands. Experimental results on a test bench composed of PEMFC and supercapacitors are described. The obtained results validate the principle of the proposed one converter parallel hybrid power source structures and the effectiveness of their associated control strategy (structures and supervision).

II. HYBRID POWER SYSTEM DESCRIPTION AND CONTROL STRATEGY

Different hybrid fuel cell system configurations have been suggested and investigated (series, parallel, and cascade) [12] [13]. It has also been proven that the parallel structure is most advantageous [14] [15]: fewer component constraints, easy energy management and good reliability.

Two major topologies of parallel structures for FC/SCs hybrid power system can be distinguished:

- Two converters parallel structure (Figure 1);
- One converter parallel structure (Figure 2).
A. Two converter parallel structure description

The two converter structure consists in associating a static converter and a control loop to each power source, as shown in Figure 1. This control strategy generates a large number of degrees of freedom in the control design. This classical hybrid structure has been validated in various works [18] [19]. Figure 3 shows the control structure for the two converter parallel structure:

The idea is to drive the current of each source by the means of an inner current loop controlling each PWM’s chopper. For this purpose, a classical PI controller have been designed and implemented it with an anti-windup compensator so as to take the duty cycle range into account ($0 < \alpha < 1$). The supervisor unit has to evaluate each converter current set-point. In the case of an unknown load, each load power change modifies the bus voltage; hence its measurement is needed for the supervisor. As the supercapacitor modules are able to deliver a large power for a short time, voltage perturbations are taken into account by the SCs current (voltage loop). So, the outer loop associated to the SCs management has to monitor the DC bus voltage and to insure a constant value of the DC bus voltage reference $V_{BUSref}$ (set at 48V): the faster this voltage tracking, the smaller the $C_{BUS}$ capacitance value. This second controller is also a PI controller with a time response ten times slower than the current loops.

But this power reaction leads to a slow change in the state of charge of this impulse source (SCs). The auxiliary power state of charge is taken into account by the main supply and it must remain suitable ($V_{Nom}/2 \leq V_{SC} \leq V_{Nom}$): by slowly changing the current of the fuel cell (limited by the slope controller), the storage device can then return to its optimal value (compensation loop) defined as: $V_{SCref}=0.75*V_{Nom}$. In the case of a well-known load demand (which is often the case in a driving system), a feedforward action can be added to the SCs current set-point. Although parameters linked to the FC are more uncertain, the selected controller is also a PI controller associated with a voltage adaptable anti-windup compensator.

This architecture requires many voltage and current sensors in order to monitor each power source, as shown in the block diagram of the control strategy in Figure 3.
B. One converter parallel structure description

The one converter structure consists in connecting the fuel cell directly to the load and in using a single buck-boost converter to adjust the power demands, as shown in Figure 2. Its main advantages are simplicity and the reduction of both losses and costs of the power management interfaces.

The hybridation purpose is again the respect of the low fuel cell dynamics mainly due to compressor response time, and to handle the state of charge of the auxiliary storage device. To face this challenge, fuel cell power has to be monitored, as well as the impulse energy source and its state of charge.

Figure 4 shows the control strategy block diagram for the one converter parallel structure. Only one control value is required: the PWM command of the SC chopper. Thus, the first control loop is designed to drive the SCs current loop. Indeed, controlling this current is essential in order to protect the chopper (as well as the super-capacitors) against breaking over-currents.

The supercondensator current reference value is calculated for the minimum values of the passive components in order to lower their price, their weight and their volume. As explained earlier, the inductance $L$ is designed to filter the supercondensators current ripple $i_{SC}(t)$ induced by the switching frequency. Hence, we can design a classical PI controller and implement it with an anti-windup compensator taking the duty cycle range into account ($0 < \alpha < 1$). Furthermore, the capacity $C_{BUS}$ is designed to insure a constant value of the DC Bus $V_{BUS}(t)$ during the inner loop tracking and $C_{SC}$ is a large storage device designed to decouple the fuel cell dynamics from the load dynamics. So the second cascaded closed loop allows us to monitor the DC bus in the voltage loop: the faster this voltage tracking, the smaller the capacity $C_{BUS}$ value. This control is possible because the average current provided by the chopper to the DC bus is linked to the average supercapacitor current $i_{SC}(t)$ and the selected controller is also a PI controller associated with a voltage adaptable anti-windup compensator.

The two cascaded control loops allow for the accurate management of the supercapacitor current as well as the DC bus voltage. This point is very important, as the fuel cell operating point is defined by the control of the fuel cell voltage.

With a relatively fast DC bus loop, the fast perturbations can be rejected as well as smoothly controlling the power delivered by the fuel cell. So with the DC bus voltage monitoring, it is possible to obtain indirect control of the fuel cell dynamics. This slow change allows us to drive the supercapacitor voltage (compensation loop): indeed, it must be neither too low nor too high to have a good response in both discharge mode and recovery mode ($V_{Nom}/2 \leq V_{SC} \leq V_{Nom}$). This compensation loop also uses a PI controller for driving the state of charge of SCs to their reference ($V_{SCref}=0.75*V_{Nom}$).

Finally, with the obtained decoupling dynamics, it is possible to obtain the same functions with a one converter structure as a two converter structure, but without the drawback of a second converter use and its associated losses.

III. EXPERIMENTAL RESULTS

A. Test Bench description

The experimental set-up of the hybrid fuel cell / Supercapacitors power source uses a Nexa BALLARD PEM fuel cell stack as the main source, with a nominal power of 1200W. The auxiliary source is obtained with a Maxwell SC module associating two modules in series: Maxwell BM00250 (each module is achieved with a series connection of six individual “2.7V, 1500F” elements). The power converters DC/DC are realized with standard IGBT modules (SEMITRANS: SKM50GB123D). A real-time dSPACE DS1104 controller board is used for the energy management control strategy designed using Matlab/Simulink. The experimental environment is shown in Figure 5.
B. Test Bench parameters

- The Nexa BALLARD PEM fuel cell stack has a nominal power of 1200W related to a rated current of \( i_{\text{nom}} = 46 \, \text{A} \) and a rated output voltage of \( V_{\text{nom}} = 26 \, \text{V} \).
- Two Maxwell modules in series (BMOD0250) with the following characteristics: \( C=125 \, \text{F}, \, V_{\text{nom}}=32 \, \text{V}, \, i_{\text{nom}}=200 \, \text{A} \) and \( V_{\text{SCref}}=24 \, \text{V} \).
- The SCs and FC associated inductor respectively have a value of 200 \( \mu \text{H} \), 300 \( \mu \text{H} \) with a nominal current of 125 A and 75 A. The bus capacitor has a 44 mF value and ensures quite a smooth voltage ripple of the DC link (\( V_{\text{BUS,ref}} = 48 \, \text{V} \)).
- The switching frequency of the PWM for the IGBT of the chopper is settled at 10kHz.

First, the profile of the load demand is presented. It represents sudden power demands on a reduced time scale of 200 seconds (\( P_{\text{LOAD}} \) at t = 10s, 45s, and 95s). At once, here, the recovery mode is not yet available, but the decrease of the power load (at t = 65s, 150s and 185s) temporarily creates an identical power flux.

Second, the supercapacitor current \( i_{\text{SC}} \) and fuel cell current \( i_{\text{FC}} \) are shown. The compensation action is very effective according to the dynamic fluctuations of the load. Besides, a supercapacitor energy transfer to the DC link is made in order to compensate the energy deficiency, which is not supplied by the fuel cell. As FC current \( i_{\text{FC}} \) does not support any sudden rise, FC current has a smooth behavior regardless of the load changes. Indeed, the control supervision immediately reacts by modifying the supercapacitor current reference. It confirms the efficiency of the fast internal current loop. It must also be highlighted that the fuel cell recharges the supercapacitors if their current becomes negative (\( i_{\text{sc}} \)). The supercapacitors energy flux is bi-directional, corresponding either to the load power demand or load recovering. As long as the fuel cell produces enough electrical energy, for every declining power load, the state of charge of impulse source (SCs) increases. Then, good performances are achieved for the current and compensation loops. This whole approach is valid for both structures.

Third, the DC link voltage \( V_{\text{BUS}} \) and its reference \( V_{\text{BUS,ref}} \) are presented. For the two converters structure, the \( V_{\text{BUS}} \) voltage is slightly affected by the power load modifications, but it always follows its reference. It proves the effectiveness of the regulation voltage loop. The second structure is characterized by a direct connection of the FC to the DC link. The controlled voltage \( V_{\text{BUS}} \) decreases smoothly, involving a simultaneous increase of fuel cell current (limited by the slope controller). The FC current always follows its reference \( V_{\text{BUS,ref}} \) and proves the effectiveness of the regulation voltage loop.

Fourth, the SCs voltage \( V_{\text{SC}} \) and its reference are shown. The state of charge of the SCs is maintained around the optimal value \( V_{\text{SCref}}=24\,\text{V} \), which proves that the compensation loop is effective and that the fuel cell perfectly drives the SCs voltage to its reference \( V_{\text{SCref}} \). It is valid for both structures and for any load fluctuations.

Finally, the fuel cell Voltage \( V_{\text{FC}} \) is presented. This voltage depends on the fuel cell operating set point. Then, to manage the FC current dynamics, it is necessary to control the FC voltage dynamics. Indeed, for the two converters structure, the FC current has a smooth behavior whatever the load fluctuation. The FC current rises in a few seconds (limited by the slope controller) and leads to the similar behavior of the FC voltage. Similarly, for the one converter structure, the dynamic of the DC link voltage is efficiently controlled. It also ensures a smooth functioning of the fuel cell. Then, for every decrease of the power load, the state of impulse source (SCs) increases as long as the fuel cell produces electrical energy. DC link voltage increases smoothly and induces a simultaneous decrease of fuel cell current (limited by the slope controller). The related energy is recovered by the supercapacitors, regarding the voltage limitation of the DC bus.

![Image of experimental bench](image-url)
The hybrid power source perfectly responds to all changes of the current load:

- The fuel cell only responds to slow current changes;
- Supercapacitors only respond to fast current changes.

The experiment results reveal and confirm the efficiency of the control strategy of both structures.

Thus, the fuel cell slow dynamics are respected using the auxiliary source (SCs), and still assume the load requirements. Finally, the efficiency of the one converter structure is similar to the two converters structure.

Furthermore, in automotive application, weight and cost are major constraints, thus, with comparable performances, it is better to choose the one converter parallel structure.

Figure 6. Experimental results for a complete load cycle.

a. Two converters structure
b. One converter structure
IV. CONCLUSION

In this paper, the structure and the control strategies of two parallel hybrid power sources have been presented. Both structures use a fuel cell for permanent and slow transient energies and supercapacitors modules for impulse energy. Control management strategies have been validated by experimental tests on a PEMFC/SCs system. Results show that even with reduced degrees of freedom, the one converter parallel structure could well manage energy demands of the load. This structure has comparable performances to the classical two converters structures which:

- Respect the slow dynamics of the fuel cell (which increase its operating life) and guarantee the transient load by using the SCs.
- Maintain the state of charge of the SCs to its optimal.
- Assure the load requirements for even fluctuations.

REFERENCES


