Control Strategy with Saturation Management of a Fuel Cell/Ultracapacitors Hybrid Vehicule

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***Abstract*—In this paper, a new control strategy including saturation management of hybrid fuel cell/ultracapacitors power source is described. First, an analysis of hybrid architectures using fuel cells and ultracapacitors for automotive applications is presented. Then, a two-converter parallel configuration is more precisely detailed. The model and the control strategy are described using the Energetic Macroscopic Representation (EMR). So, the main originality of this paper is based on the consideration of the systems limits. This leads to a very complete Energy Management Strategy, which has been evaluated and validated in simulation.**

Keywords- Fuel Cell; Control Strategy; Ultracapacitor; Parallel Hybrib Structure; Static Converter; Automotive Applications.

I. INTRODUCTION

Fuel cell vehicles (FCV) have long-term potential as future main-stream vehicles because of their high efficiency and low emission characteristics. Among the available FC technologies, the proton exchange membrane (PEM-FC) is the most likely candidate for automotive applications, thanks to its several attractive features, such as low operating temperatures, relatively low cost and quick start up, simplicity, viability, and high efficiency [1], [2].

During the daily operation of a vehicle, load transitions occur frequently, due to sudden acceleration on highway ramps as well as topography changes. These load demand variations may lead to FC membrane stress due to pressure oscillations and oxygen starvation. These transient troubles generate reduction of the membranes' lifetime [3]. Besides, a sole FC system employed for vehicle propulsion must be sized to meet the largest load of the vehicular system. This may cause difficulty for FC systems to be competitive with conventional vehicular power sources, as the current cost of FC technology is still high as compared to conventional ICE technology. Moreover, recovery of the braking energy cannot be realized, as currently available FC types are not reversible. Finally, hybridization of fuel cells with other energy storage devices (auxiliary energy storage) may enable the benefits of FC lifetime prolongation and efficiency improvement as well as the total system cost reduction [3]-[5]. This storage device can be either batteries or ultracapacitors and has the advantage of fast transient response, high energy efficiency and low system cost. But thermal constraints in vehicular applications are severe and power demands involve important power exchanges in short time intervals, which make the ultracapacitors the most promising for an energy storage unit candidate [6].Therefore, the FC/UC hybrid structure is a viable solution for vehicular applications. Thus, many research efforts are devoted to the Fuel Cell Hybrid Electric Vehicle (FC-HEV), which includes fuel cell hybrid architectures and energy management strategies (EMS).

An energy management strategy (EMS) is one of the most important issues for the efficiency and performance of a hybrid vehicular system and consists in the determination of power sharing between the multiple energy sources in the system. In such a hybrid FC/UC power source, the fuel cell is controlled to satisfy load average power requirements over a long term period; whereas the transient power requirement are ensured by the UCs.

Some energy management strategies with hybrid energy storage systems (Fuel Cell and Ultracapacitors) are presented in [7]-[11] for electric vehicles. The objective of these strategies is to protect FC from load transients but without taking into account the safety operation of the system. In this context, a control strategy with saturation management and dissipation system is investigated to ensure a safe and efficient functioning of the system.

This paper deals with the study of an energy management strategy for a hybrid FC/UCs power source. The system model and the control structure aredepicted using Energetic Macroscopic Representation (EMR). The control strategy is based on Power Frequency Splitting and its originality is related with a saturation management using dissipation system to guarantee continuity and a safe functioning. Finally, the proposed control strategy is evaluated with detailed simulation results using a MATLAB environment.

II. HYBRID POWER SYSTEM DESCRIPTION

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

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

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

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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 [8]-[10], [14].

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 [15]. Its main advantages are simplicity and the reduction of both losses and costs of the power management interfaces. Finally, with the obtained decoupling dynamics, it is possible to obtain close to 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. However, the main drawback is the fluctuating DC bus voltage, which is often incompatible with the load requirements.

In both cases, the hybridation purpose is again the respect of the low fuel cell dynamics mainly due to the 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. In the next section, a control strategy of such a hybrid architecture is described.

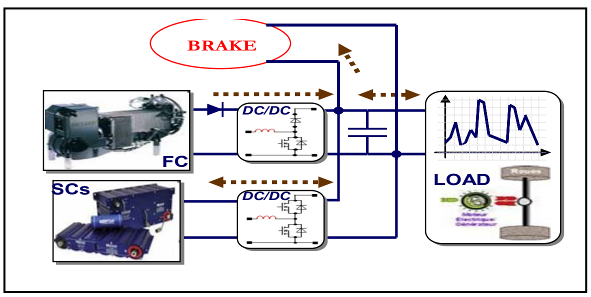


Figure 1. Two converter parallel structure for FC/UCs hybrid power system.

III. CONTROL STRUCTURE OF THE HYBRID POWER SYSTEM

To control such a complex system as FC/UCs hybrid vehicle, a system model and some control tools/methodologies for generating the control structure can be very effective. The next section presents a system model and a control structure.

A. *Model of the Hybrid Power System*

This system model is depicted using EMR (Energetic Macroscopic Representation) (upper part of Figure 2). EMR is a graphical description which organizes the system into interconnected basic subsystems: accumulators of energy (orange crossed rectangles), sources of energy (green ovals), electrical conversion (orange squares) and distribution of energy (double squares). The product of the action and the reaction always leads to the power exchanged by connected elements (example $p = v*i$) [16].

A depicted in Figure 2, three energy accumulators are used to facilitate the energy regulation: a DC Bus capacitor is used to maintain the DC Bus Voltage. Two inductors are connected on FC and UCs respectively and are used to limit the current dynamic regarding the chopper control connected to each source.

B. *Control Strategy of the Hybrid Power System*

An inversion based control can be deduced from the EMR of the system model [17]. This control scheme clearly shows how to impose different strategies (lower part of Figure 2)[9]:

By acting on the control strategy, the energy management can reduce some constraints on the hybrid power system. 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 has been designed and implemented 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 ultracapacitor modules are able to deliver a large power during a short time, voltage perturbations are taken into account by the UCs current (voltage loop). So the outer loop associated to the UCs management has to monitor the DC bus voltage and to insure a constant value of the DC bus voltage reference V_{BUSref}: 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 (UCs). 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 UCs 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 DC Bus voltage and FC/UCs current sensors in order to monitor each power source, as shown in the block diagram of the control strategy in Figure 2.

In the case of the ultracapacitors, their voltage measurement is directly correlated to their state of charge. Hence, the last feedback relies on this measurement. The two converter structure generates inevitable losses associated with every static converter. In particular, the power delivered by the permanent source (FC) is continuously reduced by its converter losses. Nevertheless, such converter and its control are necessary to maintain the DC bus constant.

The energy management strategy is performed using the strategy blocks, as shown in Figure 2. It includes the energy repartition between FC/UCs sources and the system protection strategies. Because strategy is to focus on currents connected at the DC Bus, the current references are not directly related to the FC and UC currents. So, a control block is needed to invert the current modulation due to the chopper. That explains why the current controls are decomposed into two levels in Figure 2. The energy management strategy is described in the next section.

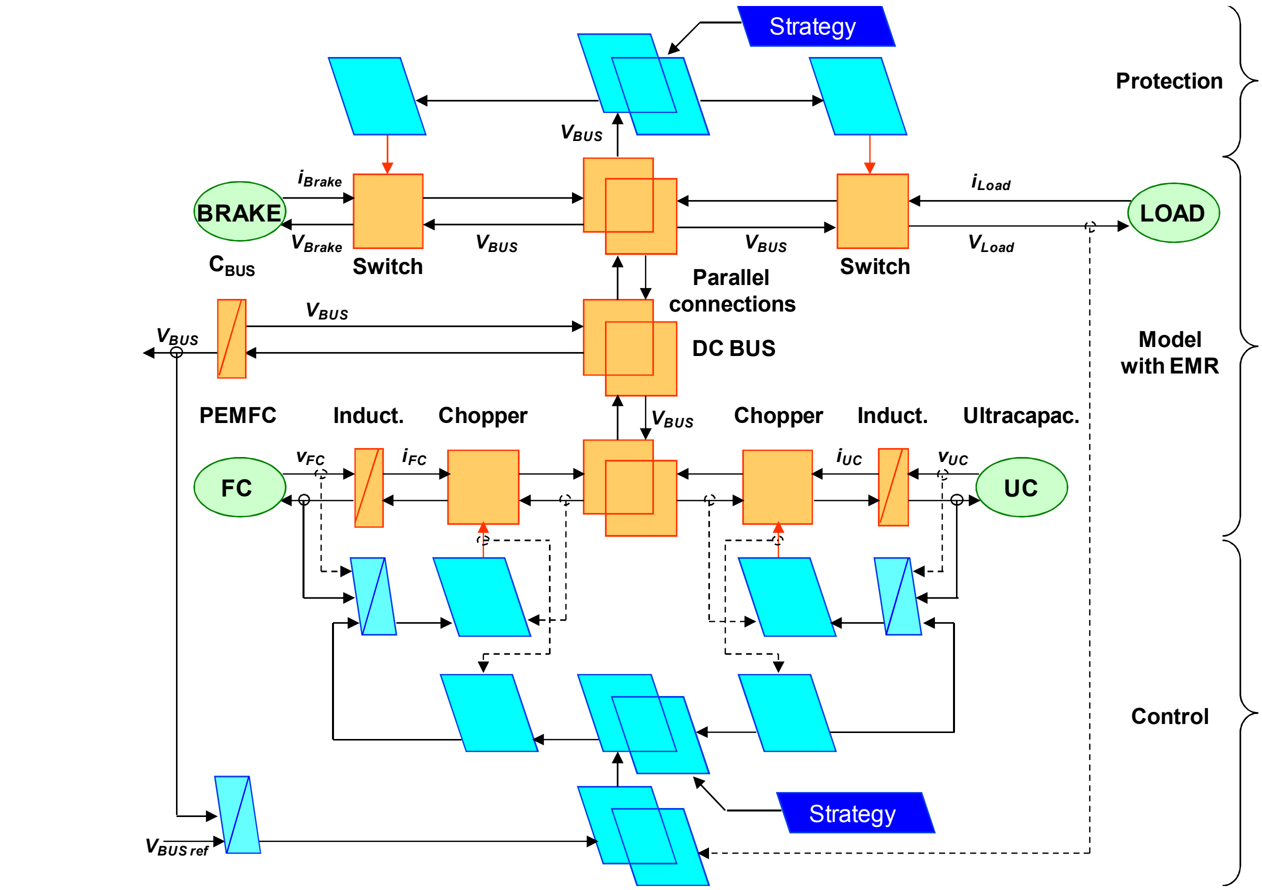
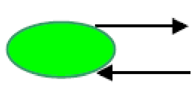
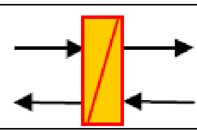
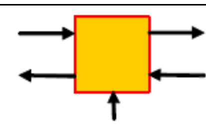
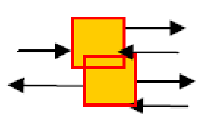
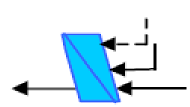
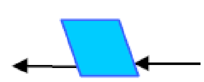


Figure 2. EMR Model of the Hybrid Power System

APPENDIX: SYNOPTIC OF ENERGETIC MACROSCOPIC REPRESENTATION (EMR)

	Source of energy		Element with energy accumulation		Electrical converter (without energy accumulation)
	Electrical coupling device (energy distribution)		Control block With controller		Control block without controller

IV. Energy Repartition Strategy of the Hybrid Power System

The energy repartition strategy called "energy management strategy" (EMS) is one of the most important issues for the efficiency and performance of a hybrid vehicular system. It consists in computing the power sharing between the multiple energy sources in the system while respecting each source characteristics. Indeed, in our hybrid FC/UC power source, the objectives of the EMS are:

- To ensure the load requirements even during fluctuations.
- To respect the slow dynamics of the fuel cell (hence increasing its operating life).
- To maintain the UCs state of charge (SOC) to its optimal range.
- To correctly manage the system saturations and guarantee a continuity of operation and a safe functioning

There are different possibilities for setting out the power sharing between both sources. Two methods are proposed in the following sections.

A. FC/UC Dynamic response decomposition

The dynamic response decomposition principle consists in using each source within the limits of its functioning characteristic. In particular, the main source (FC) is controlled to satisfy load average power requirements over a long term period, whereas the transient power requirement, involving an important amount of power during short time intervals, is ensured by the UCs.

Based on this idea, the first method uses a cascaded closed loop control. The inner loop acts as fast as possible (considering the power converter dynamics) and controls the UCs current in order to regulate the DC bus: as a matter of fact the DC bus voltage is directly affected by the load power changes. The outer loop is tuned to fulfil a low bandwidth response and aims to regulate the UCs voltage. It uses the FC current as control variable. Hence this scheme allows achieving a natural (implicit) frequency power decoupling compatible with each source. Furthermore, the imbricate structure permits a sequential tuning of each closed loop, which makes the parameters adjustment simple. This first strategy has been successfully evaluated in [15]. The main advantages of this method are its easy implementation, its good performance and its robustness towards load variations.

B. Power Frequency Splitting

The previous method allows controlling the FC dynamic implicitly. Another strategy to share power between sources is to exploit the load power decomposition directly in the frequency domain. It consists in the frequency decomposition of the power load so as to allocate the appropriate frequency components to each source as depicted in Fig. 3. Its main principle is based on the UC use (the fastest energy source) for supplying the high band of the load power frequency spectrum (HF). Conversely, low frequencies (LF) are provided by the fuel cell, which contributes to long-term autonomy.

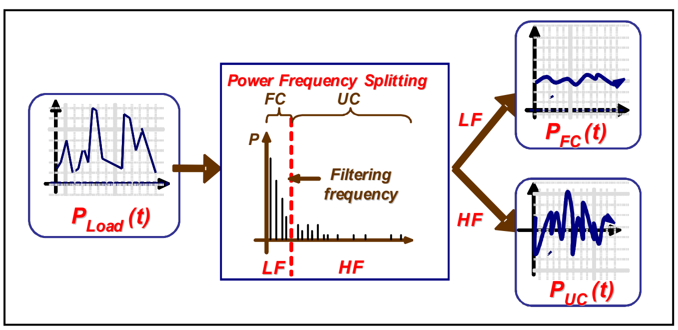


Figure 3. Power Frequency Splitting Principle.

To implement this strategy, a frequency filtering of the load requirement is used. The tuning parameter is the filtering frequency, which is evaluated according to the FC requirements. In this case it is set to 50 mHz and the filter is implemented in a 2^{nd}order low bandwidth filter delivering the FC reference current while the difference gives the UC reference current. Obviously, this strategy does not consider losses, which never can be perfectly evaluated. Consequently, the UCs state of charge will gradually drift. As the FC is the unique primary source, a corrective term Δi_{FC} is added through a corrector which monitors the UCs voltage. Obviously, this corrector is tuned to ensure a very low dynamic compared to the filter response.

With this method, the technical specifications of the FC are held explicitly and hence make this method very attractive. Moreover, the EMS adjustment is also extremely simple.

C. Comparison of the Block Strategy techniques

Table I present a qualitative comparison between the FC/UC Dynamic response decomposition technique and the Power Frequency Splitting technique:

TABLE I
COMPARISON OF BLOCK STRATEGY TECHNIQUES

Name	FC/UC Dynamic Response Decomposition	Power Frequency Splitting
Advantages	Easy to implement, Good performance, Robust to load variations	Easy to tune, Good performance,
Drawbacks	Loop frequency decoupling	Drift of the UCs Voltage
Tuning parameter	1 s	50 mHz

D. Saturation management strategy

The system parameters (N_{cell}, S_{cell}, C_{UC}, V_{UCnom}, *etc.*) have to be suitably computed so as to fulfill the load requirements. Nonetheless, the real use may be different from the forecast use leading the system to reach its own limits. In this case, the global structure has to remain sturdy. In particular, both hardware and the control scheme must take this possibility (risk / prospect) into account. The objective of this section is to properly manage the system saturations and guarantee a continuity of operation and a safe functioning.

In case of a huge and unforeseen power increase, the UCs' energy may become insufficient. In this occurrence, the load power has to be limited, which is the aim of the load power modulator. In a case of a great or a long time reverse load power, the UCs may not be able to store all this energy. In these circumstances, a dissipative device has to be turned on.

The best way to supervise the system's limitations is to monitor the DC voltage. At present, any important decrease of V_{BUS} indicates that the balance between load and sources is permanently lost, which is symptomatic of the first case. Conversely, any important V_{BUS} increase is a symptom of the second case. Consequently, the EMS ensures the system security if the DC voltage goes out of its rated range ($V_{BUSnom}-\Delta V < V_{BUS} < V_{BUSnom}+\Delta V$).

Table II present the different saturation cases that can occurred and the adapted response of the EMS:

TABLE II
DIFFERENT CASES OF EMS RESPONSES

Saturation case	EMS Response
100% UCs Voltage VBUS +ΔV	Brake module on
50% UCs Voltage VBUS -ΔV	Load saturate

V. SIMULATIONRESULTS

As shown in Fig. 4, the hybrid FC / UCs power source and its dedicated control scheme deduced from the EMR analysis have been tested in simulation using Matlab/Simulink software tools. The FC is modeled using the average static I-V curve of the Nexa fuel cell designed by Ballard, while the ultracapacitor and the DC-DC converter losses are neglected. As far as energy management is concerned, these simulation assumptions have already been validated on our own test bench [15]. However, these working assumptions are not sufficient to analyze efficiency issues [4] or stack small time-scale behaviors.

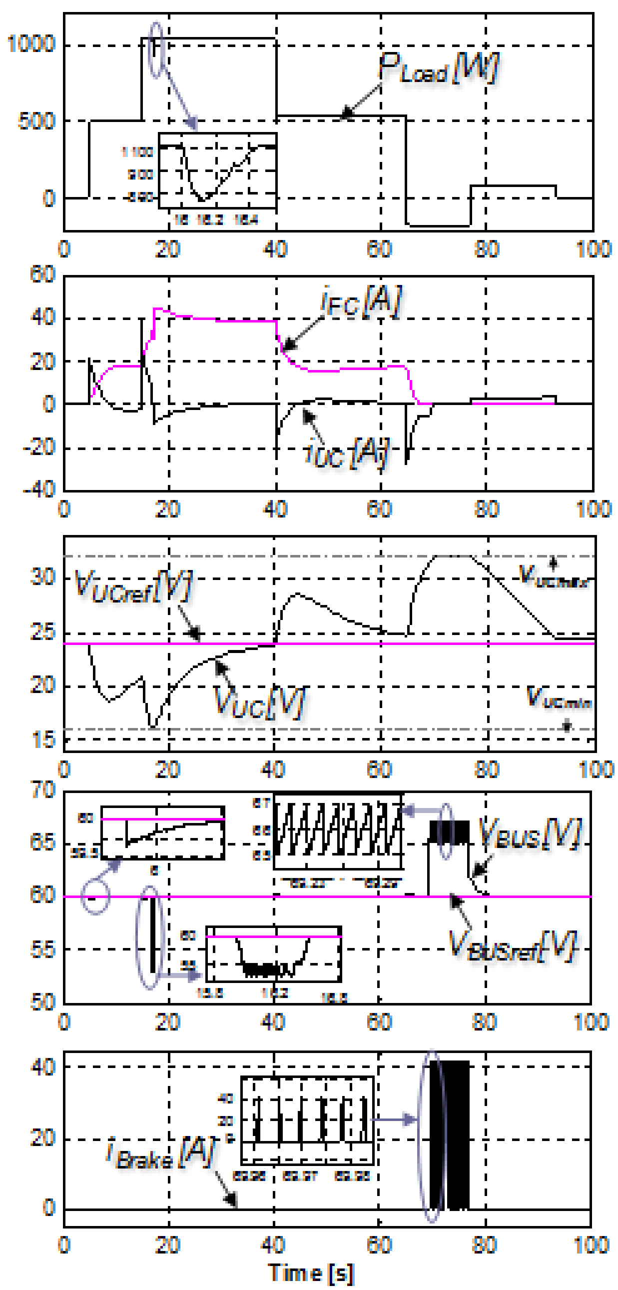


Figure 4. Simulation Results.

A. Simulation parameters

Many load profiles have been performed on the simulation scheme in order to test the global system, either in linear mode or in saturation mode. The load cycle shown in fig 4.a consists in many rising and falling edges. This severe profile is typical of a vehicle power demand in urban requirement [15].

Table 3 shows the electric characteristics of both sources:

TABLE III
ELECTRIC CHARACTERISTICS OF HYBRID SYSTEM

Fuel Cell: Parameter Name	Value
Open circuit voltage	45 V
Rated voltage	26 V
Rated current	46 A
Ultracapacitors: Parameter Name	**Value**
Capacitance	6 F
Rated Voltage	32 V
Rated Current	50 A
Optimal Voltage (V_{UCref})	24 V
Inductors & Capacities : Parameter Name	**Value**
Inductor L_1	200 µH
Inductor L_2	100 µH
Rated Current L_1	50 A
Rated Current L_2	50 A
Capacities C_{BUS}	14 mF
Optimal DCBusVolatge (V_{BUSref})	60 V

VI. CONCLUSION

In this paper, the structure of a parallel hybrid FC/UC power source has been analyzed with the Energetic Macroscopic Representation. This tool is well adapted to this problem, since it deals with energy exchanges in a complex multi-source structure. Moreover, it allows the designer to directly deduce a very relevant control scheme.

The originality of this paper lies in the consideration of the systems limits. This leads to a very complete Energy Management Strategy, which has been evaluated and validated in simulation.

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