Analyses of Energy Management Strategies for a PEMFC/UC Electric Vehicle

O. Bethoux[1], G. Remy[1], J. Riera[2], M. Serra[2], T. Azib[3]
[1] Laboratoire de Génie Electrique de Paris, CNRS UMR 8507; SUPELEC; Université Paris 6; Université Paris-Sud;
[2] Institut de Robòtica i Informàtica Industrial (CSIC-UPC), C. Llorens i Artigas 4, Barcelona, Spain
[3] Laboratoire Commande et Systèmes, ESTACA, 34 Rue Victor Hugo, 92532 LEVALLOIS-PERRET
email: olivier.bethoux@lgep.supelec.fr

***Abstract-* In this paper, two energy management strategies considering the hydrogen consumption of hybrid power sources using a PEM Fuel Cell (FC) and Ultracapacitors (UC) are described and compared. First, the Hybrid Electric Vehicle (HEV) architecture and the associated models with their control strategies are described. The two energy management strategies are evaluated based on the Energetic Macroscopic Representation (EMR). The comparison focuses on the global efficiency of the power sources energy management. In particular, a proposed strategy is to manage the UC State-Of-Charge while stabilizing the FC around its maximal efficiency point. Finally, some simulations on a Fuel Cell / Ultracapacitors HEV show the differences between the compared control strategies.**

***Index Terms*- Fuel Cell, Ultracapacitor, Parallel Hybrid Structure, Energetic Macroscopic Representation, Control Strategy, 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 [1], thanks to its several attractive features, such as low operating temperatures, relatively low cost and quick start up, simplicity, viability, and high efficiency [2], [3]. Nevertheless, due to the reaction time of the air compressor, the FC system time response is quite slow compared to vehicle traction power dynamics. Moreover, regenerative braking ability is another key characteristic for energy efficiency improvement in a HEV. For both these reasons, the hybridization of fuel cells with an energy storage unit (ultracapacitor or battery) yields the benefits of FC lifetime prolongation [4] and efficiency improvement [5].

To guarantee the efficiency and performance of a hybrid vehicular system, a relevant energy management strategy (EMS) is one of the most important issues. An EMS consists in the determination of power sharing between the energy source and the storage device in the system. Energetic Macroscopic Representation (EMR) has already proved a powerful tool to analyze this problem and to suggest an efficient control architecture. In [6], the authors consider the system limits and its stability. They suggest a very complete EMS, which has been evaluated and validated via experimental results with small-scale devices. However, the selected strategy is quite conservative since it tends to maintain the state of charge (SOC) of the ultracapacitor storage unit constant. Instead of keeping the SOC reference constant, the EMS can consider this variable as an additional degree of freedom. The EMS can regulate it with the aim of optimizing the hydrogen consumption.

This paper deals with the evaluation of two energy management strategies for a hybrid FC/UCs power source of a HEV. The system model and the control structure are depicted using the Energetic Macroscopic Representation (EMR). The control strategy is based on the charge floating mode of the UC and its originality is related to the rule-based strategy of the UC/FC management. Indeed, the power demand is split between FC and UC sources to manage the SOC of the UC, while the Fuel Cell stays mostly at its maximal efficiency point. The comparison focuses on the global efficiency of the power source energy management. Finally, some simulations on a Fuel Cell / Ultracapacitors HEV show the differences between the compared control strategies using a Matlab/Simulink environment.

II. DESCRIPTION OF THE SYSTEM

Regarding an ECE15 urban cycle, power demands involve important power exchanges in short time intervals [7], [8], which makes the ultracapacitors the most promising candidate for an energy storage unit [9], [10]. Among the major topologies of parallel structures for a FC/UCs hybrid power system, the two-converter parallel structure is widely used [11], [12], as shown in Figure 1.

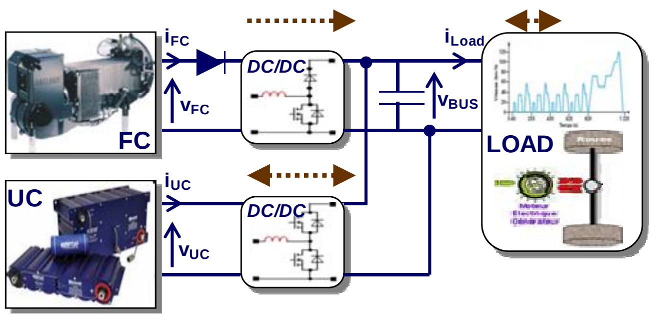

Fig. 1. Two-converter parallel structure for a FC/SCs hybrid power system.

A. Model of the Hybrid Power System

As ultracapacitors are used to supply the fast transient power demands, the Fuel Cell has been modeled using a classical static model [13], as shown in Figure 2. Indeed, the control strategy of the FC/UC should lead to a smooth change of the polarization point of the FC, equivalent to a low dynamic use, which is an important factor for a long Fuel Cell life time [14]. The stack current i_{St} (FC gross current) is directly linked to the hydrogen molar flow rate and hence to the chemical power p_{H2} provided by the hydrogen tank [15]:

$$p_{H2} = \left(\frac{n_{FC} i_{St}}{2F} \right) HHV \quad (1)$$

Where n_{FC} is the number of cells (in the Nexa Ballard system, we consider 46 cells), F the Faraday constant (96 487 C), HHV the enthalpy of hydrogen combustion reaction, also called higher heating value of hydrogen (286 kJ.mol^{-1}).

Consequently, the stack efficiency $\eta_{St} = p_{St}/p_{H2}$ has the same shape as the stack voltage. Figure 3 demonstrates that the stack generates roughly the same amount of DC electricity and waste heat. This feature makes this primary converter the key element in minimizing the FCV hydrogen consumption.

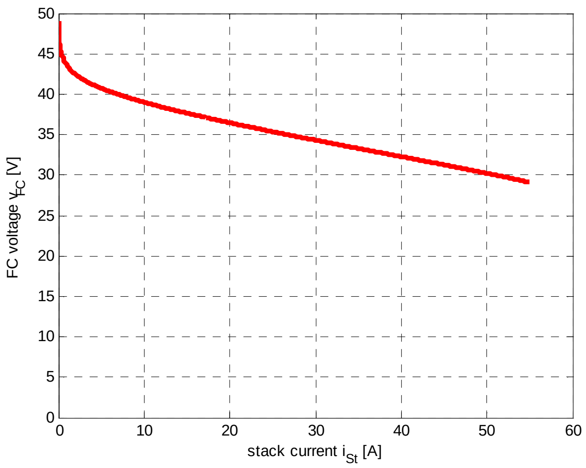

Fig. 2. V-I characteristics of a 1.2kW Nexa Ballard FC stack

Moreover, a fuel cell stack needs a supporting system to supply reactants (air and H_2), remove waste (heat and water) and monitor the whole system. All the necessary components are supplied with an auxiliary electric power derived from the stack. That is the reason why a FC system consumes hydrogen even though it delivers no power to the load ($p_{FC} = 0$) In the same way, the auxiliary power increases when the net electric power rises, since the air compressor is the most significant parasitic load. Figure 3 shows the net efficiency power curve of the Nexa Ballard FC system. At a very low-power level, the power efficiency is close to zero. It first increases sharply with FC net power and then decreases gently slightly below the stack efficiency curve.

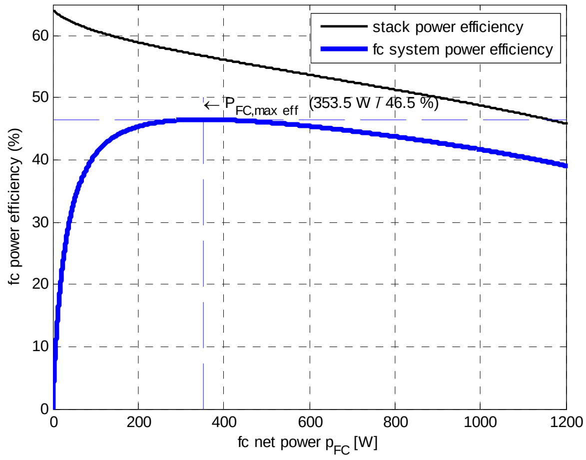

Fig. 3. FC power efficiency as a function of net power (Nexa Ballard)

The Ultracapacitor has been modeled using a capacitor only [15]. Indeed, UC losses can be neglected as they are low compared to the power transmitted and because the UC current control uses an integral correction which acts as a natural compensator.

Similarly, both power converters in fig. 1 are supposed to be perfect DC-DC transformers; the PWM switch duty cycles act as the controlled transformer ratio.

In order to facilitate system analysis and more precisely the energy exchange between FC, UC and the load, the system depicted in Figure 1 can be modeled using the Energetic Macroscopic Representation (EMR), as shown in Figure 4.

B. The Energetic Macroscopic Representation (EMR)

The Energetic Macroscopic Representation (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 appendix presents the main graphical subsystems. The main advantage of the EMR is that the design control structure can be deduced directly from a graphical symmetry of the EMR model. For complex systems such as the FC/UC hybrid system, it is a very convenient tool because it is a systematic inversion approach. For instance, this EMR methodology has been successfully used to model different light hybrid vehicles [18], their control [19], high redundant military vehicles [20], different electric vehicles [21], [22] (EVs, HEVs and FCVs) and PEM FC system [18].

III. CONTROL STRUCTURE

The EMR representation of the hybrid power system allows us to define a relevant Energy Management Strategy (EMS) in nominal control mode. However, the model presented doesn't take into account the source constraints, and specifically, no saturation has been considered so far. The aim of this section is first to insert local limits, so that each component's integrity is ensured. In a second step, the consequence of using local limits is analyzed in order to suggest a suitable EMS in the saturated control mode.

The inversion-based control relies on a step by step inversion [23]. Figure 4 depicts the FC current and the UC current closed-loop controls. We can also see the strategy block referenced "Strategy1" for the repartition of the FC/UC reference currents, and "Strategy2" for the activation of the ohmic dissipation element in case of UC energy overcharge and the load disconnection in case of an overload.

The control design of the two-source subsystems leads to two similar inner control loops, with the voltages V_{FC} and V_{UC} acting as disturbance variables. This part of the model also uses a coupling element in an EMR representation. The inversion of this coupling block leads to a decoupling control block in the inversion-based control (two blue inserted rectangles in Figure 4). This block allows us to compute the two set-points i'_{FCref} and i'_{UCref} out of one single input i_{Coupl}. This calculation is performed using an arbitrary part of the incoming variable i_{Coupl} for one output and the complementary part for the other output. The distribution element reveals a weighting coefficient k_{R1} that can be exploited by a strategy block:

$$\begin{cases} i'_{FC\_ref} = k_{R1} i_{Coupl} \\ i'_{UC\_ref} = (1-k_{R1}) i_{Coupl} \end{cases} \quad (2)$$

Then, different strategies can be applied to define the k_{R1} coefficient, like the power frequency splitting of the power demand [24], Fuzzy-logic control [25], [26], *etc.*

IV. Analysis Of The Energy Management Control Strategies

A. *Charge sustaining*

The first approach is based on charge sustaining. The weighting coefficient k_{R1} is tuned so that the UC State Of Charge (SOC) constantly and slowly tends toward its constant reference set at medium value [6]. Hence, this regulation ensures a good energy potential to assist the FC during a load power transient due to a sudden load increment or an energy surge caused by regenerative braking.

With this mentioned EMS, the EMR control structure works effectively on a European urban cycle (ECE 15) for managing smooth transience to fuel cell current. It ensures UC and DC buses voltage constraints, which prevents each component from collapsing. Finally, the EMS obviously allows to supply the load. In particular, local protections do not disturb the global function. Besides, the EMS remains simple and the algorithm commutates safely between the nominal and saturated modes.

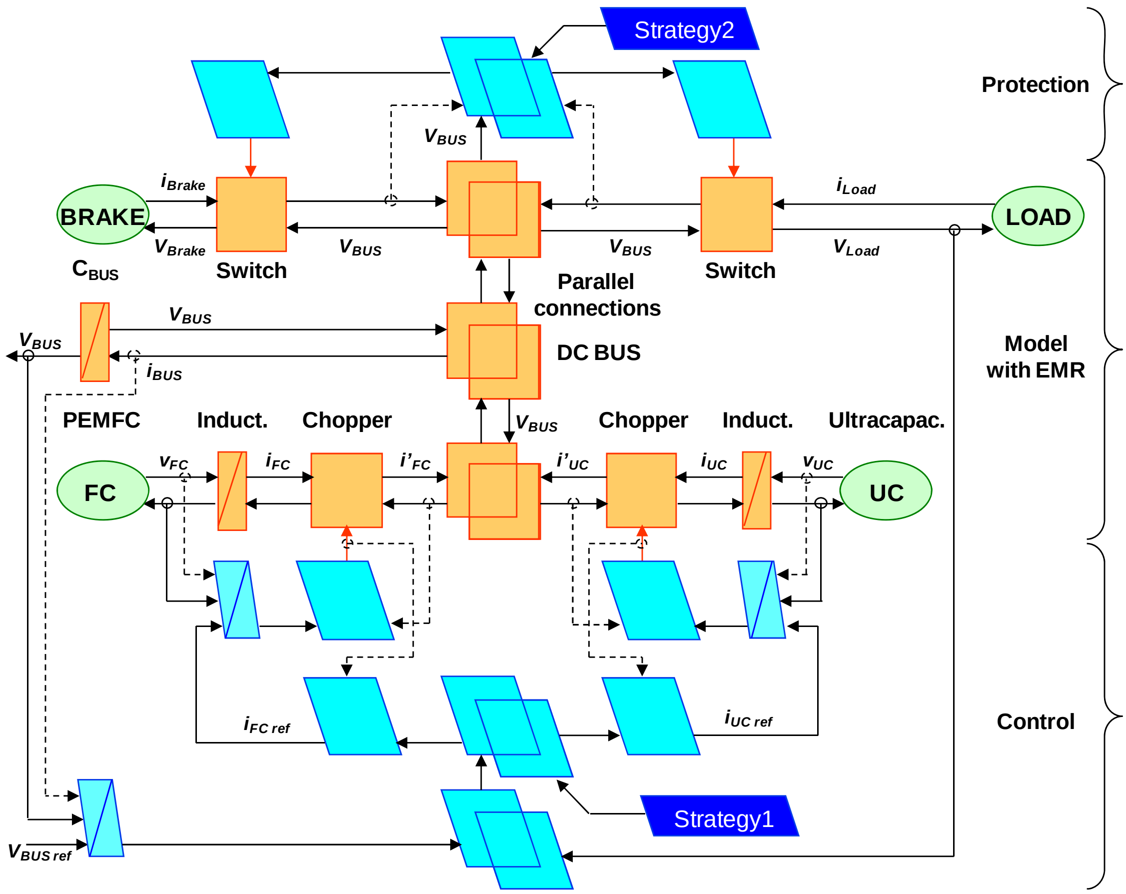

Fig. 4. EMR Model and control structure of the Hybrid Power System

Nevertheless, the previous strategy arbitrarily sets one crucial EMS degree of freedom. Indeed, the EMS forces the FC to smoothly adjust its power as soon as the UC SOC is unbalanced and regardless of the current FC efficiency. As UC bank is designed for significant kinetic energy recovery, it has a large capacity and it is interesting to experiment whether allowing substantial UC SOC fluctuations reduces cumulative hydrogen consumption [27]. The main idea is to delay UC rebalancing so as to favour periods of time when the FC operates close to its maximum efficiency point.

For this purpose, the following subsection analyses the FC as a energy converter and deduces some key rules for any EMS.

B. FC energetic study

The scenario of a constant load demand is considered. One way is to provide this desired power exclusively with the FC without soliciting (using / utilizing) the energy storage device. The alternative solution is to use the UC so that the FC operating point can switch between the FC optimal point and another point. In this latter situation, the load power point is obviously between the chosen and the optimal points. Moreover, the UC SOC ripple adjusting defines the period of the FC power switching (cycle). Noting α_{opt} the duty cycle of the optimal point, the mean cycle hydrogen power consumption can be computed with the following expression:

$$p_{H2} = \alpha_{opt} \cdot p_{H2}\left(P_{FC,\max\,efft}\right) + \left(1-\alpha_{opt}\right) p_{H2}\left(P_{FC,ch}\right) \qquad (3)$$

Where: $$\alpha_{opt} = \left| \frac{P_{Load} - P_{FC,ch}}{P_{FC,\max\,efft} - P_{FC,ch}} \right|$$

Finally, whatever the chosen point, the resulting fuel consumption is greater than in the first case corresponding to direct FC delivery [28]. Figure 5 illustrates the cycle efficiency while adopting Pch = 0 W if $P_{Load} \le P_{FC,\max\,eff}$ and $P_{ch} = P_{FC,\,rated}$ otherwise.

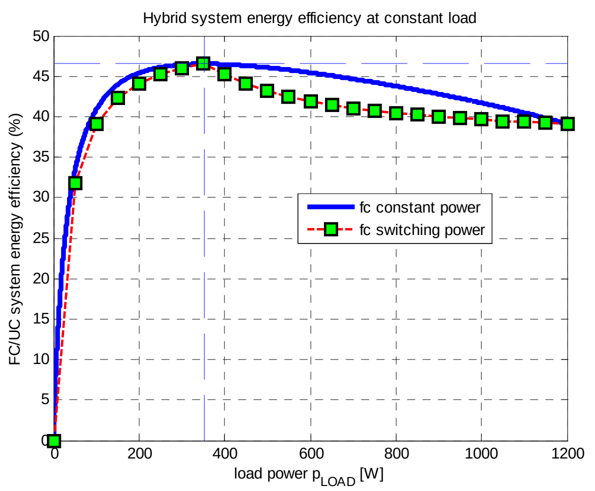

Fig. 5. Power efficiency comparison of direct FC supply and optimal point use in constant load.

In a nutshell, this energetic analysis leads to the following conclusions:

- If a constant load condition occurs, the EMS must be able to enforce load following. In automotive applications, this situation can really happen; for instance a vehicle driving at constant speed on a flat road in a suburban scenario.
- If the whole load profile can be known at the beginning of the trip, the optimized hydrogen consumption is achieved with constant FC power (set at the mean route power) and the UC providing the mismatch between FC vehicle powers.

Following these guidelines allows us to suggest an innovative EMS and also permits to propose an EMS comparative methodology.

C. Proposed innovative EMS

In fact, the real load profile is quite uncertain even if the journey is well-known because of traffic disturbances (traffic lights, traffic density, etc), driver behavior (acceleration/deceleration, driving speed, alternate routes, …) and vehicle state (vehicle mass, tire pressure, etc). As a result and owing to the limited UC energy storage ability, the best option is to give priority to FC load following while preferring operation at the point of maximum efficiency. For this purpose, the proposed strategy takes the UC SOC into account.

- If the load power is below a given threshold ($P_{L,min}$), then FC power is set to FC maximum efficiency power ($P_{FC,max\ eff}$) as long as UC SOC remains below the UC SOC reference (SOCref).
- If the load power is above a given threshold ($P_{L,max}$), then FC power is decreased from a certain amount ($P_{FC,dec}$) on condition that UC SOC stays above the UC SOC reference (SOC_{ref}).

Regenerative braking and fast load power changes (due to considerable acceleration demand) make the UC SOC fluctuate. The EMS tries to restore this temporary energy unbalance at the most appropriate time regarding the FC's specific consumption. In order to reduce the hydrogen consumption, the EMS parameters (namely $P_{L,min}$, $P_{L,max}$, $P_{FC,dec}$, SOCref) are tuned.

D. EMS comparison

Both strategies are tested on the same load profile. It consists in raising and lowering power edges between -500 W and 1000 W. Even though shorter than any driving cycle, this power requirement is representative of a vehicle power demand and enables a first but credible evaluation of the proposed EMS.

The two sources are the 1200-W, 46-A, and 26-V Nexa Ballard for the FC system and a UC bank of 26 F, 30 V, corresponding to Maxwell Technology modules.

The two on-line EMS are compared to the off-line method consisting in measuring the average mission power. Imposing this value as the permanent FC power setpoint gives the optimal solution as far as no storage limitations are concerned. Clearly on the simulated driving cycle, the final UC SOC is similar to the initial one in this strategy. On the contrary, on-line strategies may encounter discrepancies between initial and final UC SOC. In this case, the FC recharges the UC at the maximal efficiency point until the UC SOC reaches its initial value.

The main variable waveforms of the hybrid system (Load power, FC power, UC power and UC voltage) are depicted in Fig. 6, Fig. 7 and Fig. 8. Each simulation starts with a UC voltage at its reference value, namely 21.0 V. Any strategy respects the same constraints: that is to say $(di_{FC}/dt)_{MAX} = +20$ A/s, $(di_{FC}/dt)_{MIN} = -40$ A/s. Moreover, whatever the strategy, the UC auxiliary source reacts immediately after each load power edge (high-band pass filter) while the FC slowly reacts to the load (low-band pass filter).

More specifically, we can note that the first strategy [6] (based on a slow UC voltage compensation loop) leads to a UC recharging/discharging at inappropriate times. Indeed, at t = 5 s, the FC power is close to the maximum power (and consequently bad power efficiency) whereas the charge sustaining EMS decides a FC overpower so as to reach the UC reference SOC. Besides, during the load power step close to the FC optimal power ($8\ s \le t \le 10\ s$), the first strategy doesn't choose to follow the load and sets the FC power at a low reference which is also improper regarding FC power efficiency. Lastly, as the system used the UC extra energy at the wrong time ($8\ s \le t \le 10\ s$), the strategy requires the FC to follow the load when its power rises sharply ($10\ s \le t \le 12\ s$). Finally, the system consumed 13.0 kJ of chemical energy (H_2), and the UC SOC increased to a final value of 22.73 V.

On the other hand, the innovative strategy doesn't impose any FC overshoot even though the UC SOC is under its reference value ($4\ s \le t \le 6\ s$). Even if the UC has extra energy, the EMS sets the FC power to FC optimal power during the 500 W load stage. Furthermore, during the next step ($8\ s \le t \le 10\ s$). it deeply decreases the FC power compared to the load following option in order to increase FC efficiency; at that moment, electric power can be easily provided by the extra energy of the UC. In conclusion, this strategy consumed 12.5 kJ of chemical energy (H_2), and the UC SOC increased to a similar final value of 22.74 V.

Setting the FC power at a constant value during the complete cycle enables us to compare both previous performances to an optimal value, obviously obtained with an off-line strategy. The present cycle leads to select a 7.15 A FC current; the associated hydrogen energy consumption is 9.6 kJ, whereas the UC final voltage is 21.00 V. To fill the UC auxiliary source to the same value as the two on-line strategies requires to collect 0.983 kJ of electric energy to the FC. With the assumption of an optimal conversion (46.5 % efficiency), it needs 2.1 kJ of extra chemical energy. As a result, the final H_2 optimal consumption is 11.7 kJ.

As a final point, testing this particular load profile, the charge sustaining EMS leads to 11,1 % overconsumption while the innovative strategy induces a smaller 6,8 % rate.

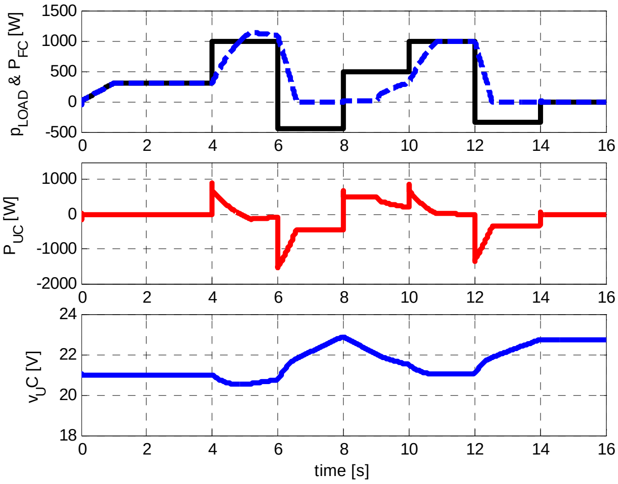

Fig. 6. Hybrid system response on a load cycle using “charge sustaining” EMS

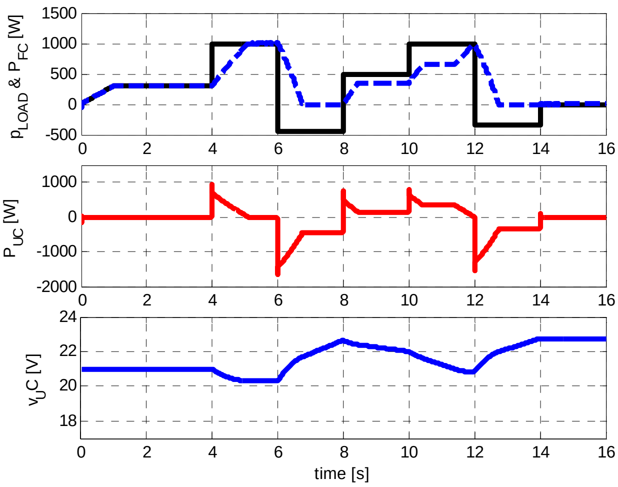

Fig. 7. Hybrid system response on a load cycle using innovative EMS

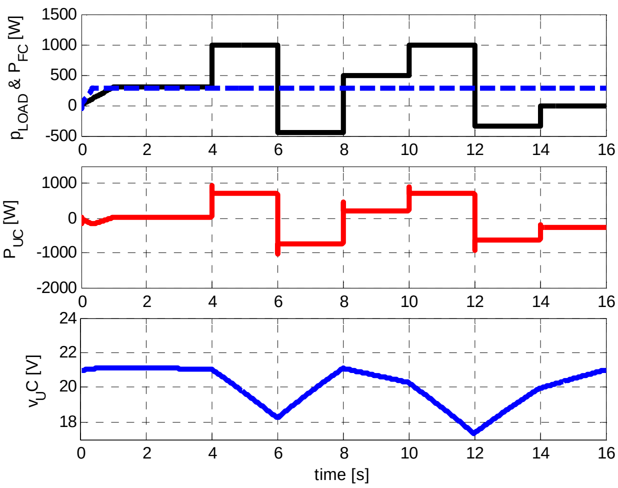

Fig. 8. Hybrid system response on a load cycle using off-line optimal EMS

V. CONCLUSION

In this paper, we are focusing on the reduction of the hydrogen consumption of a FC/UC hybrid VEH. We have thoroughly analyzed the hybrid FC/UC system efficiency, which has allowed us to highlight the key points of such a system. It enables us to exhibit the optimal strategy, which is only feasible if the whole cycle is known (off-line optimization) and serves as a reference. This analysis has also allowed us to suggest an innovative EMS. Afterward, this strategy has proved to be more efficient than the previous one and is attractive thanks to its simple real-time implementation. The on-going work consists in testing the innovative EMS on a complete urban cycle and in determining the optimal setting of the EMS tuning parameters. The second perspective is also to run experiments on our test bench to validate the current assumptions.

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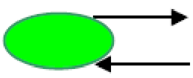
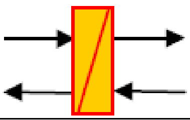
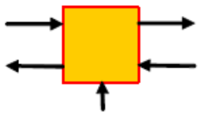
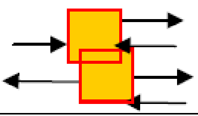
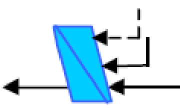
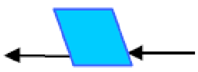
APPENDIX: SYNOPTIC OF ENERGETIC MACROSCOPIC REPRESENTATION (EMR)

	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