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# Energy Management and Control Strategy of Hybrid Energy Storage System for Fuel Cell Power Sources

T. Azib<sup>1</sup>, K.E. Hemsas<sup>2</sup>, C. Larouci<sup>1</sup>

**Abstract** – This paper deals with the design of energy management strategy (EMS) for a fuel cell hybrid vehicle (FCHV) with hybrid energy storage system (HESS) using energetic macroscopic representation (EMR). It discusses the design options including power, energy, and operating strategy as they relate to the energy storage system. The studied HESS is composed of battery/ultracapacitor (BAT/UC) system allowing increasing both the power capability and the energy capacity of FCHV. In order to describe the system and organize his control structure, the EMR concept is used, which is well adapted for multiphysics complex systems. EMS has been designed to control the power flow between sources and traction load, and to ensure local protections. It is based on power splitting technique in the frequency domain allowing a natural dynamics control without slop limitation to provide any load demand and to satisfy the sources inherent characteristics: FC, BAT and UC voltage and current limits are considered, as well as slow FC dynamics and HESS state of charge (SOC). Simulation results are presented to check the theoretical analysis, ensure that the system well operates under difference load conditions and demonstrate the robustness and stability of the control strategy with good tracking response. **Copyright © 200X Praise Worthy Prize S.r.l. - All rights reserved.**

**Keywords:** Hybrid power sources, energy management strategy, fuel cell EV, hybrid energy storage system, energetic macroscopic representation EMR.

## Nomenclature

EMS	Energy management strategy
FCHV	Fuel cell hybrid vehicle
EV, HEV	Electric vehicle, Hybrid electric vehicle
HESS	Hybrid energy storage system
EMR	Energetic macroscopic representation
BAT	Battery
UC	Ultracapacitor
FC	Fuel cell
PEMFC	Proton exchange membrane fuel cell
ECE	European driving cycle
DC	Direct current
MCS	Maximum control structure
PCS	Practical control structure
PWM	Pulse width modulation
PI	Proportional integrator
LF, MF, HF	Low, middle and high frequency
$\eta$ (FC, UC, Bat)	Power converters efficiency
$\Delta E_{UC}$	Ultracapacitor energy
$\Delta V, \varepsilon$	Range and error of ultracapacitor voltage
$\alpha, \beta, \gamma$	Model coefficients
$\tau$ (sec, min hour)	Multiple time-constant
A	Tafel coefficient
$C_{Bat}$	Battery capacity
$C_{UC}$	Ultracapacitor capacity
$C_v, C_i$	Voltage and current controller
$d$ (FC, Bat, UC)	Duty cycles of power converters
$E_{Cell}$	Cell voltage
$f_{FS1}, f_{FS2}$	Filtering frequencies
$i_{Coupl1}$ (ref)	Total current sources, reference

$i_{Coupl2}$ (ref)	Total current storage system, reference
$i_{UCcom}$	Ultracapacitor compensation current
$J_{Stack}, I_{Stack}$	Current density, stack current
$k_{R1}, k_{Rl}$	Strategy parameters
$L$ (FC, Bat, UC)	Inductor of power converters
$m, n$	Mass transfer coefficients
$P$ (Load, FC, UC, Bat)	Power of the load and sources
$P_{Trac}, i_{Trac}$	Traction power and current
R	Membrane specific resistance
$R_{Series}$	Series resistance
SOC, SOC <sub>0, min, max</sub>	State of charge, initial, minimum and maximum value
t	Time
$V, i$ (FC, Bat, UC), ref	Voltage and current of the sources, reference
$\dot{V}, \dot{i}$ (FC, Bat, UC), ref	Voltage and current of the sources on the converters output, reference
$V_{Bus}, i_{Cbus}$	DC bus voltage and current
$V_{ocBAT}$	Voltage open circuit
$V, i$ (FC, Bat, UC) min/max	Minimum and maximum current and voltage sources

## I. Introduction

FCHV technology using proton exchange membrane fuel cell (PEMFC) holds much promise for reducing the demand for petroleum in the transportation sector with low emission characteristics [1], [2]. Its potential impact is highly dependent on the system design and the energy management strategy (EMS), in particular, the energy

storage system (ESS). In fact, FCHV uses energy storage technology to improve vehicle efficiency through FC downsizing (decreasing its size and cost), FC lifetime prolongation (limiting FC dynamics) and by recovering energy normally lost during braking events [3], [4].

Nowadays, these energy storage systems can either be stored as mechanical (as in a flywheel) or as electrical energy (as in a battery or ultracapacitor). Almost all existing hybrid power systems of FCHV mainly used electrical storage devices and composed of fuel cell/battery hybrid (FC/BAT) [3]-[6], or fuel cell/ultracapacitor hybrid (FC/UC) [4]-[6]. But unfortunately none of them satisfies perfectly the requirements of the automotive applications. For that reason, it is necessary to associate more than one storage technology creating a hybrid energy storage system (HESS). Research is starting to look at the use of all of these components in a hybrid vehicle [4], [7], [8]. In this work a HESS based on the association of a BAT, as long-term storage device, and a UC, as a short-term storage device, is investigated. The association BAT/UC permits to take advantage of the characteristics of both devices obtaining a high energy density, high power density, high life-cycle and high efficiency [9].

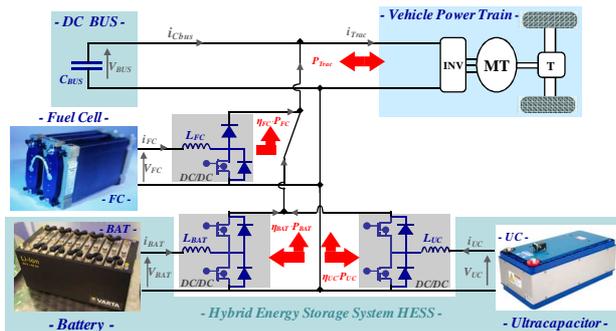


Fig. 1. Structure of Hybrid FC/BAT/UC power source

In order to describe such a complex system as FC/BAT/UC and organize their control architecture, a system model and control tools/methodologies for generating the control structure can be very effective. In this context, energetic macroscopic representation (EMR), an energy based graphical modeling tool, has been introduced to obtain a complete understanding of complex systems providing complete information regarding to the system as its functional perspectives [10]. It allows an accurate graphical description of the multi-physics coupling and allows an easy design of the control scheme. EMR organizes a complex system in interconnected subsystems and implies to take into account the physical causality principles. Indeed, a causal modeling of the different parts of the system simplifies the design of local control scheme. All elements are connected according to the action and reaction principle. The product of the action variable and the reaction variable is equal to the instantaneous power exchanged

between two subsystems. An EMR model allows a simple and systematic deduction of the control structure by using inversion rules. For instance, this representation is successfully achieved to model different light hybrid vehicles [10], their control [11], high redundant military vehicles [12], different electric vehicles [13], [14] and PEMFC system [15]. For these reasons, in our study, the system modeling and its control architecture are depicted using EMR approach. Indeed, in our application, this technique allows highlighting degrees of freedom (control parameters) of the control system and clearly shows how to define a relevant Energy Management Strategy (EMS), which would be a new step toward automatization of the EMS choice and design. The designed EMS uses a splitting frequency approach allowing a natural frequency decomposition of the power demands. Some simulation results, obtained by Matlab Simulink™ software are showed, discussed and compared. It confirms the effectiveness of the system behavior and verifies the control method performances. The proposed hybrid power system and its associated EMS has the following several advantages: 1) It optimize power management and improve system efficiency; 2) during transient power demands, as the FC cannot respond quickly, the HESS will provide or absorb the unbalanced energy, so the dynamic characteristics of the whole system is improved; and 3) the HESS provide peak power, so the power rating of the FC can be decreased (reduce the power stress), reducing the total cost.

The remaining of this article is organized as follows. Section 2 presents the global system modeling (system and control) using EMR. The proposed EMS approach is then discussed in section 3 and validated through extensive simulation under the European driving cycle (ECE), in section 4. Finally, section 5 provides our conclusion and suggestions for future work.

## II. Global system modeling

### II.1. System structure

In this paper, a parallel structure is considered that presents the most advantageous architectures [16], [17]: less component constraints, easy energy management and good reliability. It includes three power sources: a FC, a battery, and an ultracapacitor (Fig. 1). These sources are connected to the same DC bus through appropriate static converters. This hybrid source meets different load power demands, so the whole system features high peak-power capacity and good dynamic characteristics. The power balance in the DC bus must be fulfilled at every time:

$$P_{Load}(t) = \eta_{FC} \cdot P_{FC}(t) + \eta_{BAT} \cdot P_{BAT}(t) + \eta_{UC} \cdot P_{UC}(t) \quad \forall t \quad (1)$$

Where  $\eta_{FC}$ ,  $\eta_{BAT}$  and  $\eta_{UC}$  are the efficiency of the power converters connecting to the different sources. We

assume that the converters efficiencies are known and fixed in our case 90%.

## II.2. Energy Macroscopic Representation

This section presents the model which will be used to design the control part of the system. EMR has been introduced to describe such complex FC/BAT/UC system. This approach has two main advantages: first, it is an energy based graphical representation which respects strictly physical laws. Second, using inversion rules [18-19], control architectures are systematically deduced from their EMRs.

The global system modeling is depicted in upper part of Fig. 5. EMR is based on the action-reaction principle to organize the interconnections of sub-systems according to physical causality (i. e. integral causality). This description highlights energetic properties of the system and also uses normalized shapes and colors to represent different constituents (see Appendix. A): energy accumulators (orange crossed rectangles), energy source (green ovals), electrical conversion (orange squares) and distribution of energy (double squares). All elements are connected according to the interaction principle. The product of the action and reaction always leads to the power exchanged by connected elements (example  $p = v \cdot i$ ) [14]-[19].

The following part shows the sources models to simulate the studied system. The complexity of the dynamic models has been chosen according with the investigated phenomena and were previously validated by experiment and adapted to power levels cases [20], [21]. The equations in the EMR sub-systems blocks modeling the FC/BAT/UC power sources are detailed in Table. 1.

### --- Fuel cell (FC) modeling

FCHV produce his primary electricity using a fuel cell. The fuel cell is powered by filling the fuel tank with hydrogen. Indeed, FC system is a complex multi-physics device with many auxiliary components which can be described at different scales and can be established for different purposes. Our interest in this study is to assess the performances of the whole hybrid system. More precisely, in low dynamic conditions, the fuel cell characteristics can be considered as a voltage source with ohmic, kinetic and mass transfer resistances. The relationship between the FC voltage  $v_{FC}$  and the output current  $i_{FC}$  is given by the following equations:

$$v_{FC} = N \left( \begin{array}{l} E_{Cell} - R \cdot j_{Stack} \\ - A \cdot \ln(j_{Stack} + j_1) - m \exp(n j_{Stack}) \end{array} \right) \quad (2)$$

$$\begin{cases} j_{Stack} = \frac{I_{Stack}}{A_{Cell}} \\ I_{Stack} = \alpha + (1 + \beta) i_{FC} + \gamma (i_{FC}) \end{cases} \quad (3)$$

Where  $A_{Cell}$  is the area of each cell,  $N$  is the stack cell number,  $E_{Cell}$  is the reversible cell voltage,  $j_{Stack}$  is the FC current density,  $R$  is the membrane area specific resistance;  $A$  is the Tafel coefficient;  $I_{Stack}$  stack current,  $m$  and  $n$  are the two coefficients of the mass transfer equation, and  $\alpha$ ,  $\beta$  and  $\gamma$  are coefficients of 2nd order model approximating  $I_{Stack}$  as function of the output current  $i_{FC}$  [21], [22].

The PEM fuel cell system EMR pictogram is a voltage source, represented by a green oval block (Fig. 5). The output is the voltage computed by the fuel cell equations.

### --- Battery (BAT) modeling

As a key component of HESS, batteries are devices that transform chemical energy into electrical one and conversely. For the battery model, an electrical equivalent circuit [22] is selected reproducing lithium-ion I-V characteristics (Fig. 2). The battery EMR pictogram is also a green oval element, with voltage as output and current as input, as depicted in Fig. 2.

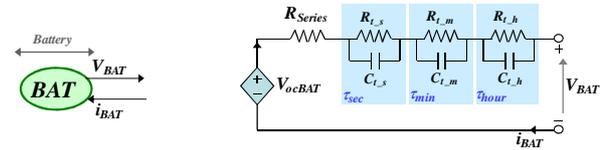


Fig. 2. Structure of Hybrid FC/BAT/UC power source

Where  $V_{ocBAT}$  : voltage open circuit,  $R_{Series}$  : series resistance.  $V_{BAT}$  : the BAT output voltage. The R-C circuits represent multiple time-constant ( $\tau_{sec}$ ,  $\tau_{min}$  and  $\tau_{hour}$ ) to model the BAT transient behavior. These parameters are functions of the SOC [22].

The battery SOC is calculated by the following equation.

$$SOC = SOC_0 + \frac{\eta_{BAT}}{(3600 \cdot C_{BAT})} \int i_{BAT} dt \quad (4)$$

Where  $SOC_0$ ,  $C_{BAT}$  and  $i_{BAT}$  are respectively the initial value of battery SOC, the BAT capacity and the BAT current.

### ---- Ultracapacitor (UC) modeling

Classically, for hybrid systems a UC theoretical model uses a transmission line where the voltage ( $V_{UC}$ ) depends on distributed capacitance [24]. However, to take into account the UC behavior during charge and discharge and to preserve a sufficient accuracy, a RC model is used to describe the nonlinear electrode behavior. As an energy storage unit of HEVs, the UC system is necessarily composed of cells in series to attain the required system voltage and np parallel cells to achieve required current  $i_{UC}$  and total capacity. The Ultracapacitor has been modeled using a capacitor only (Fig. 3). Indeed, UC losses can be neglected as there are low regarding the power transmitted and because the UC

current control use an integral correction which acts as a natural compensator in this EMR representation.



Fig. 3. Ultracapacitor model : EMR (right) and equivalent circuit (left)

--- Power train system modeling

This system is represented by a current source (a green oval block). The current generator imposes the needed current  $i_{Trac}$  at the electrical coupling which returns the voltage  $V_{BUS}$ . The output current  $i_{Trac}$  is the picture of power required by a vehicle realizing a driving cycle. This current is obtained from the traction power  $P_{Trac}$  and the DC bus voltage  $V_{BUS}$  (Fig. 4). The equations of the traction system are detailed in [20] using ECE European driving cycle.

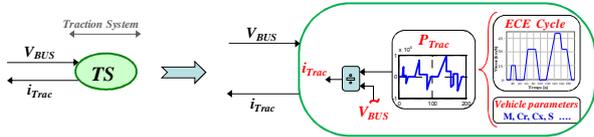


Fig. 4. Traction system model

TABLE I  
DETAILS OF THE EMR AND THE INVERSION-BASED CONTROL

EMR	DC Bus	Inversion-based control
	$C_{BUS} \frac{dV_{BUS}}{dt} = i_{Cbus}$	$i_{Cbus} = C_v (V_{BUSref} - V_{BUS})$ with $C_v$ : voltage controller
<b>Parallel couplings</b>		
	$i_{Cbus} = i_{Comp1} + i_{Trac}$	$i_{Cbusref} = i_{Tracref}$
	$i'_{FCref} = k_{R1} \cdot i_{Comp1ref}$	$i_{Comp1ref}$
	$i'_{BATref} = k_{R2} \cdot i_{Comp1ref}$	$i_{Comp1ref}$
	$i'_{UCref} = (1 - k_{R2}) \cdot i_{Comp1ref}$	$i_{Comp1ref}$
<b>Choppers (Converters)</b>		
	$V'_n = d_n \cdot V_{BUS}$ $i'_n = d_n \cdot i_n$ with $0 < d_n < 1, n = \{FC, BAT, UC\}$	$V_{BUSref}$
<b>Inductors</b>		
	$L_n \frac{di_n}{dt} = V_n - V'_n$ $i_nref = \frac{V'_nref}{d_n}$ (inversion) $V'_nref = C_i (i_nref - i_n)$ with $0 < d_n < 1, n = \{FC, BAT, UC\}$ $C_i$ : current controller	$i_nref$

The analysis of energy paths (highlighted in green on Fig. 5 (upper part)) which is simplified by the EMR, shows that the system has three explicit control variables introduced by the three converters: duty cycles ( $d_{FC}$ ,  $d_{UC}$  and  $d_{BAT}$ ) which allows to control the power flow between the two electrical sources and to control the DC bus voltage. The analysis of the different links shows that:

- $d_{FC}$  acts on  $V'_{FC}$  voltage which is then filtered by  $L_{FC}$ .
- $d_{BAT}$  acts on  $V'_{BAT}$  voltage which is then filtered by  $L_{BAT}$ .

•  $d_{UC}$  acts on  $V'_{UC}$  voltage which is then filtered by  $L_{UC}$ .

•  $d_{FC}$ ,  $d_{BAT}$  and  $d_{UC}$  act symmetrically on the DC bus voltage  $V_{BUS}$  by using the currents  $i'_{FC}$ ,  $i'_{BAT}$  and  $i'_{UC}$ . Hence, they can respond with the same potential dynamics to the traction current  $i_{Trac}$  variations.

As explained in [18-19], an inversion-based control can be deduced from the EMR of the system model directly. The next section is devoted to establishing a control-based model of the structure and an energy management strategy associated to the studied system.

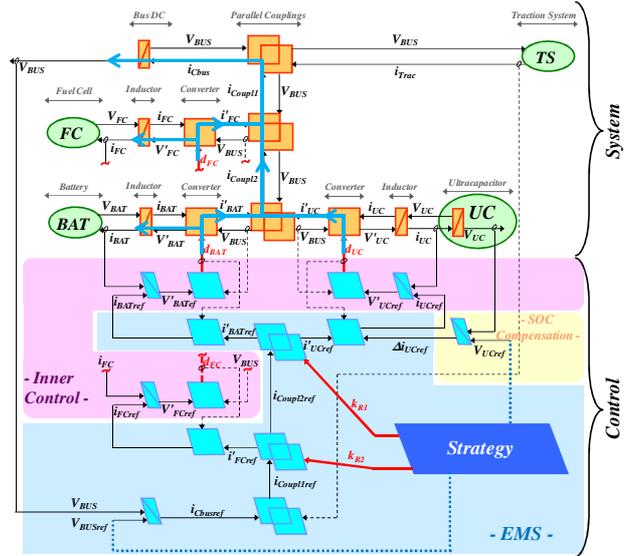


Fig. 5. Traction system model

### II.3. Inversion based control

The inversion-based control relies on a step by step inversion using specific inversion rules and according to the analysis of energy paths which make clear the objectives and constraints of system. For complex systems such as FC/BAT/UC hybrid system, it is a very convenient tool based on a systematic inversion approach. Generally, it leads to a cascaded close loop scheme with P or PI controllers [18], which is certainly the most widely known control structure in industrial applications.

All control blocks are depicted by parallelograms as they handle only information. Since accumulation elements (rectangle with an oblique bar) represent a time-dependence relationship, they cannot be inverted physically, therefore a controller is required. However, conversion elements (triangle) can be directly inverted. Coupling elements (overlapped pictogram) may require supplementary inputs for inversion. In this way, a maximum control operations and measurements can be obtained under the assumption that all variables are measurable. From this Maximum Control Structure (MCS), non measurable signals are neglected if their

effect on the response can be compensated by the controller, otherwise they are estimated to obtain a finally Practical Control Structure (PCS). The entire control scheme (blue elements) is presented in lower part of Fig. 5. Note that, equations in the control sub-systems blocks of the hybrid system are detailed under Table. 1.

The control design of the three sources part leads to three similar inner control loops introduced by the three converters, with the voltages  $V_{FC}$ ,  $V_{BUS}$  and  $V_{UC}$  acting as disturbance variables. The idea is to drive the current of each source controlling each PWM's converter. For this purpose, a classical PI controller has been designed and implemented with an anti-windup compensator so as to take into account the duty cycle range ( $0 < d < 1$ ). The supervisor unit has to evaluate each converter current set-point. However, this model also reveals coupling elements in an EMR representation (electric coupling). The inversion of such coupling constituents leads to distribution elements in the inversion-based control (two inserted blue rectangles in Fig. 2). This block allows to compute the two set-points  $i'_{FCref}$  and  $i'_{Coupl2ref}$  from  $i_{Coupl1ref}$ . In the same way, the two set-points  $i'_{BATref}$  and  $i'_{UCref}$  are calculated from  $i_{Coupl2ref}$ . This second set-points is introduced for managing the HESS. This calculation is realized using a decomposition of the incoming variable  $i_{Coupl1ref}$  for the different output affected to sources. The distribution element reveals weighting coefficients  $k_{R1}$  and  $k_{R2}$  that can be exploited by a strategy block to manage the whole system according to the control objectives (5).

$$\begin{cases} i_{FCref} = k_{R1} \cdot i_{Coupl1ref} \\ i_{Coupl1ref} = (1 - k_{R1}) i_{Coupl1ref} \\ i_{BATref} = k_{R2} \cdot i_{Coupl2ref} \\ i_{UCref} = (1 - k_{R2}) i_{Coupl2ref} \end{cases} \quad (5)$$

These implicit degrees of freedom ( $k_{R1}$ ,  $k_{R2}$ ) are fixed with the intention to define a relevant EMS. So, the control scheme deals with the local energy management (sources limits) as well as simultaneously taking into account the global energy management of the system. In this global level, the EMS is performed using the strategy blocks in order to manage the whole system. In the following, two methods for setting out the power sharing between sources are designed according to the state of charge (SOC) of BAT: charge-depleting mode and charge-sustaining mode.

### III. Energy management strategy of the hybrid power system

An energy management strategy (EMS) is one of the most important issues for the efficiency and performance

of a hybrid vehicular system. It consists in the determination of power sharing between the multiple energy sources in the system while respecting each source characteristics according to some control objectives. In our hybrid system, the objectives of EMS are:

- fulfill the driver's demand for the traction power (load requirements) even during transients fluctuations (improve dynamic characteristics),
- respect the slow dynamic of FC mainly due to compressor response time (increasing it operating life),
- monitor the SOC of BAT in both functioning modes: charge-depleting mode and charge-sustaining mode,
- maintain the SOC of UC to its optimal range,
- manage correctly the system operation and guarantee continuity and safe functioning.

Therefore, proper EMS is important to affect these objectives. There have been many papers on control strategies of hybrid system energy management. The most widely acknowledged real-time control strategies are based on Rule-based strategy using the evolution of the state of the system [25], [27]. In this case, separate control algorithms are proposed to control the system when the operating mode changes due to load power variation. Despite this methodology is able to manage power flow allocation, its implementation is hampered by the need to switch from one control algorithm to another one. This can result in demanding a high instantaneous current of the FC "chattering phenomenon", risking to damage the system. Thus, to overcome these obstacles, a EMS based on DC link controller using a frequency decomposition of the power demand (power frequency splitting) or frequency decoupling technique (cascaded loop) are well adapted to this supervision strategy specifications. Indeed, the first control strategy is based on a parallel voltage-current loop (cascade) [7], [29]. The main drawback of this approach is the fact that EMS employs slope limitation to control every source dynamic, which can lead to undesirable interaction between the loops and losing the whole system stability. To attenuate this issue, EMS based on power frequency technique is suggested and investigated. It is well adapted to this supervision strategy with the advantages of high efficiency, high power quality (in terms of voltage and current, fluctuations, sags and swells), simple and intuitive, and presents a good performances in terms of energy management (optimal power sharing) without slope limitation (natural dynamic decoupling).

From the inversion-based control of EMR that leads naturally to cascaded control loops, a strategy block (blue) is added in order to introduce the EMS (optimal power sharing). Assuming that each load power variation modifies the DC bus voltage, it is essential to use a

controller to monitor the DC link (DC bus voltage  $V_{BUS}$ ) and allows to generate the load perturbation. This controller can also be built as a Proportional Integrator (PI) with a time response ten times higher than the current loops to respect dynamics decoupling.

The proposed control strategy is based on power splitting technique in order to impose an appropriate operating point for each component of the hybrid system. It uses the distribution coefficients  $k_{R1}$  and  $k_{R2}$  to allocate the appropriate power frequency components to each source thought the converter currents as depicted in Fig. 6. Its main principle is to exploit the load power decomposition directly in the frequency domain, the UC used (the fastest energy source) for supplying/absorbing the high band of the load power frequency spectrum (HF) and the middle frequency (MF) part is absorbed/supplied by BAT. Conversely, low frequencies (LF) are provided by FC, which contributes to long-term autonomy.

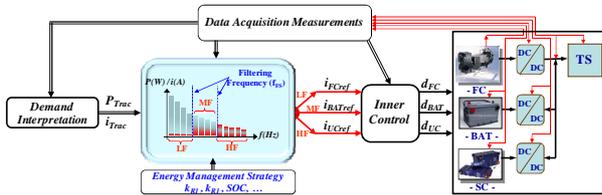


Fig. 6. Traction system model

To implement this strategy, two splitting frequencies of the load power requirement are considered. It only uses the current-time information to compute the output power reference, as depicted in Fig. 7. The tuning parameters are the filtering frequencies ( $f_{FS1}$  and  $f_{FS2}$ ) associated to two second order low pass filters, which are evaluated according to the FC and BAT requirements. They guarantee the general current balance equations (5).

The first filtering frequency ( $f_{FS1}$ ) is adjusted to respect the low dynamics of the fuel cell. Previous work [20] has shown that even FC functioning at a low frequency (0.01 Hz), an important parasitic hysteresis V-I curve occurs and has an effect on the electric output of the stack (hysteresis losses) due to reactant diffusion phenomena (oxygen starvation). The hysteresis width increases with frequency until some limit, where it becomes impossible for the FC system to follow the load demand. This experiment demonstrates that the FC response at 0.05 Hz allows to retrieve a compromise between losses and dynamic performances. Consequently, the first filtering frequency ( $f_{FS1}$ ) is taken at 0.05 Hz. This choice leads to enhance both FC generator efficiency and stack lifetime.

The second filtering frequency ( $f_{FS2}$ ) is introduced to determine the power split ratio of the dual BAT/UC sources. It allows HESS to respond to transient power requests, to compensate the intrinsic limitations of the main source (FC) and to recover kinetic energy when

braking. The idea is to make use of the benefit of both devices – the high energy content of the battery and the high power of the UC using each source -, thanks to their suitable characteristics as a storage device. So, this parameter is properly calculated from the desired operation mode in relation to battery state-of-charge: charge depleting and charge sustaining modes.

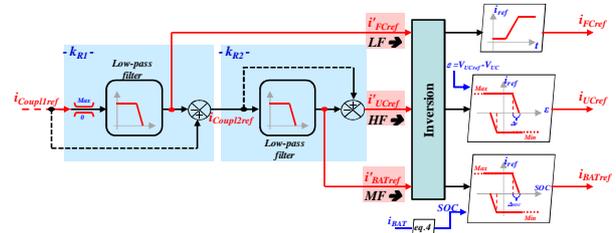


Fig. 7. Power Splitting Strategy

In the first case, the FCHV operates in "charge depleting" mode, in which it freely draws down the onboard battery to meet vehicle power demands. Once it reaches its minimum SOC threshold (30%), it must be recharged from electric recharging station (electrical grid). In this mode, we assumed that BAT helps fuel cell (up to 20%) to meet their power needs ( $P_{FC}$ ) and that strategy tends to deplete the BAT in order to minimize fuel consumption.

In the second case, "charge-sustaining" mode is functionally equivalent to vehicle operation in a conventional HEV. During this mode of operation, the vehicle maintains the SOC within a limited operating envelope and assures its control toward its reference, using stored battery energy to optimize FC operation, and recharging via either regenerative braking or FC (main source).

In consequence, each source current set-point is restricted using as follows:

$$\begin{cases} i_{FC \min} \leq i_{FC}(t) \leq i_{FC \max} \\ i_{BAT \min} = -i_{BAT \max} \leq i_{FC}(t) \leq i_{BAT \max} \\ i_{UC \min} = -i_{UC \max} \leq i_{UC}(t) \leq i_{UC \max} \end{cases} \quad (6)$$

In addition to these current boundaries, BAT and UC are also limited in SOC since overpassing their rated inducing their fast destruction. Whereas under passing a certain limit (commonly set as half of rated value) leads to poor efficiency due to high current and insignificant power. To ensure the UC voltage range and BAT SOC, the control strategy modifies the UC and BAT current limits gradually, when the UCs voltage value moves toward one of its boundaries (Fig. 8-a and b) :

-  $i_{UCrefmax}$  ( $i_{BATrefmax}$  for BAT) is turned down to zero when  $V_{UC}$  (SOC for BAT) comes up to  $V_{UCmin}$  ( $SOC_{Min}$ ).

-  $i_{UCrefmin}$  ( $i_{BATrefmin}$  for BAT) is turned up to zero when  $V_{UC}$  (SOC for BAT) comes up to  $V_{UCmax}$  ( $SOC_{max}$ ).

Consequently, this security system is based on dynamic current limits and ensures a local protection of both sources.

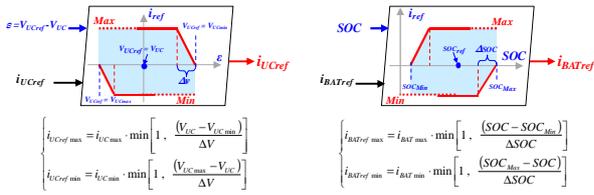


Fig. 8. Power Splitting Strategy

Furthermore, the UC is set as an accumulator block, so a PI controller has to be tuned with a slower corrective action compared to the filter dynamics. The compensation signal  $i_{UCcomp}$  is combined with the UC reference  $i'_{UCref}$  monitors the UC voltage ( $V_{UCmin} = V_{UCmax} / 2 < V_{UCref} < V_{UCmax}$ ). The storage device can then return to its optimal value defined as:  $V_{UCref} = 0.75 * V_{UCmax}$ . The reference  $V_{UCref}$  is constant and determined so as the amount of the UC energy can collect  $+ΔE_{UC}$  is equals to the restore one  $-ΔE_{UC}$ .

The objective of this 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 (inversion) the current modulation due to the converters.

Finally, with this EMS, we pointed out that, the control strategy is designed to achieve the high-efficiency operation region of the individual power source and to regulate current and voltage at peak and average power demand, without compromising the performance and efficiency of the overall system.

#### IV. Simulation results

Simulation results are presented in the following section of the paper for FC powered EV, using HESS battery and ultracapacitor based on the EMR and the inversion-based control. It was carried out on Matlab software, Simulink and SimPowerSystems Toolboxes. The results are taken by considering the urban driving cycle (ECE-15 driving cycle) which leads to a specific traction power/current (Fig. 9) to evaluate the dynamic response of a developed methodology and making suggestions through the development in the overall structure. This specific traction power/current trace (Fig. 9) shows both positive and negative values, highlighting the motoring and regenerative functions. The data used for the simulated system is given in Appendix. B.

Fig. 10, 11 present the simulation results (response of the hybrid system) obtained using respectively the charge depleting and charge sustaining mode. For both simulations, it is assumed that initial BAT SOC is 80%

and initial UC voltage is 75%. Furthermore, the frequencies cut-off of the filters which compute the weighing coefficient  $k_{RI}$  and  $k_{R1}$ . This filters implementation are Butterworth second order low-pass filters with a 50 mHz and 250 mHz cut-off frequency respectively. The following figures show: FC/BAT/UC power response ( $P_{FC}$ ,  $P_{BAT}$ ,  $P_{UC}$  [w]), FC/BAT/UC current response ( $i_{FC}$ ,  $i_{BAT}$ ,  $i_{UC}$  [A]), DC bus voltage response ( $V_{BUS}$ ,  $V_{BUSref}$  [V]), BAT SOC (%) and UC voltage response ( $V_{UC}$ ,  $V_{UCref}$  [V]).

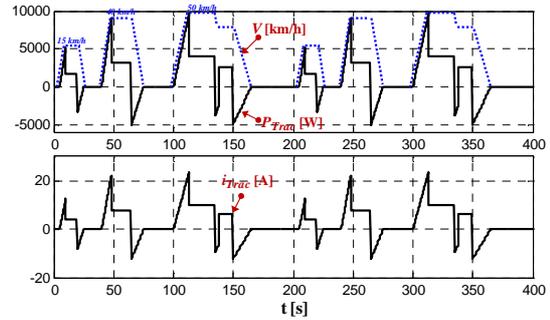


Fig. 9. Traction power/current profile (ECE-15 driving cycle)

- The simulation starts ( $t_0 = 0$  s) with no load power demand, the BAT and the UC are initialized with their reference SOC and the DC bus voltage with its reference value. Then, the load power sharply changes with ramp increases (acceleration from zero speed) and falling edges (deceleration starts and braking); the load power dynamics roughly range from -10 kW to 10 kW.

- In both modes, the UC (power and current) reacts immediately after each load power edge and behave as a high-band pass filter with a time response of few milliseconds (high dynamics). They supply the transient energy demand not ensured by the FC and BAT.

- Besides, the FC (power, current and voltage) reacts slowly to the load changes and responds as a low-band pass filter with a time response of few seconds. Thus, frequency splitting control strategy effectively prevents the FC from responding to a large current slope which is very important for FC life time.

- FC, BAT and UC currents responses show that the control strategy impose to each source respecting its own characteristics. As can be seen, the main source current  $i_{FC}$  smoothly increases with a 4 A.s-1 slope. The minimum FC current threshold is fixed at 2 A (2% of FC rated) in order to avoid related corrosion phenomena.

- For convention purposes, it should be noticed that the positive sign of  $i_{BAT}$  and  $i_{UC}$  means BAT and UC recover energy and the negative one means the BAT and UC supply load.

- BAT would have to complement UC to assist the FC in meeting the power demand (middle dynamics), because in the proposed strategy, the BAT operates as a

buffer to make up the power difference between FC / UC and the vehicle required power. This will avoid the fuel starvation phenomenon under high peaks. Moreover, the BAT power, after a sharp increase (discharging), decreases slowly to a constant discharge according to the BAT SOC mode.

- Indeed, it can be seen that the BAT SOC tends to sustain the target value 80% using charge sustaining mode (Fig. 10). Conversely, in charge depleting mode (Fig. 11) where BAT helps FC power needs up to 20 % (FC is less used), which explains a more important BAT power level in steady state than sustaining mode, SOC tends to decrease with increasing distance. So, it must be recharged from the grid after it has reached its minimum SOC level.

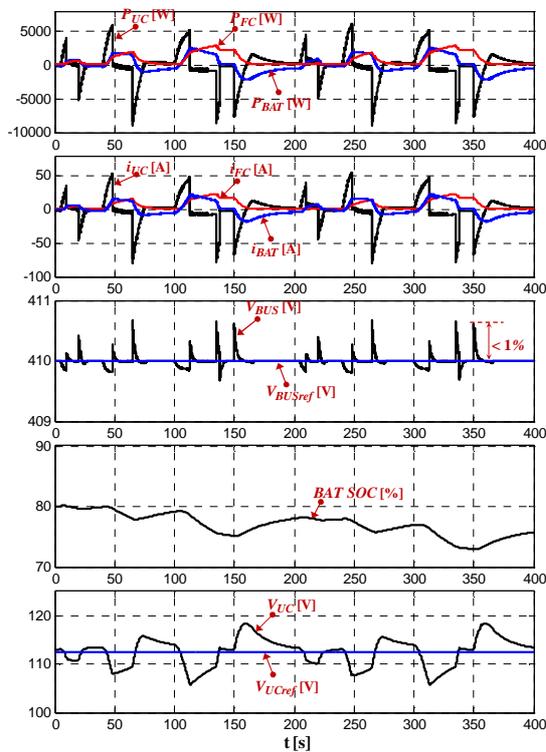


Fig. 10. Simulation results in charge depleting mode

- Furthermore, the UC SOC is well managed since, in steady state, UC voltage tends to its reference value (112.5 V) and no energy is extracted for UC ( $i_{UC}(t)=0$ ).

- In the meantime, the slow FC reaction ensures a good regulation of the UC voltage which explains the small overshoot of FC power during the transient UC voltage compensation where it provides more power to propel the vehicle and charge UC.

- The DC link voltage  $V_{BUS}$  is slightly affected by the power load variations. A very low overshoot (less than 1%) and no steady state error are observed (the reference  $V_{BUS}=410$  V is followed perfectly). These results prove the effectiveness of the regulation voltage loop and the

proposed EMS.

- Note that for deceleration and braking mode, HESS current sign changes in order to absorb over energy from the DC bus during the recovery mode and as long as the fuel cell produces electrical energy, inducing the increase of the UC and BAT SOC.

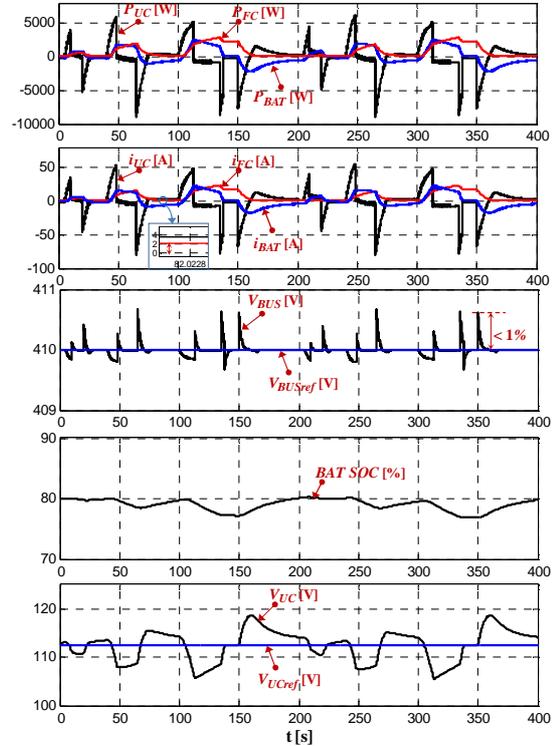


Fig. 11. Simulation results in charge sustaining mode

- In addition, for the currents closed loops, the currents follow well their trajectories references without static error (Fig. 12, 13) for both modes, which makes relevant the inner control. It demonstrates the power enhancement capability of a controlled hybrid system and the complementarity of sources used together to meet the transient and steady-state loads.

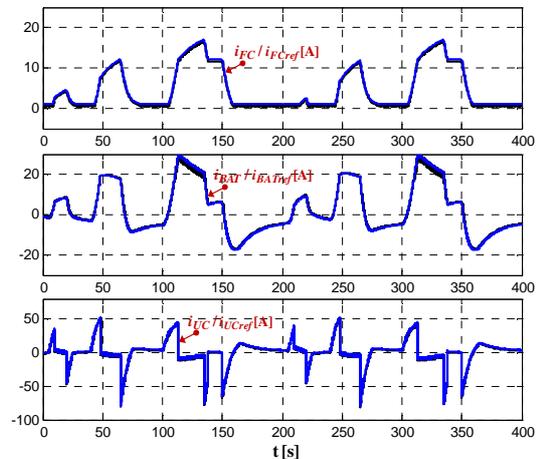


Fig. 12. Currents trajectory (Charge depleting)

According to these simulation results, it should be

mentioned that both modes have similar performances with no chattering phenomenon under the considered load power demands. In addition, the robustness and the stability of the proposed EMS (frequency splitting control) towards load variations without slop limitation are exhibited. Therefore, the preferred mode depends on the application. In automotive domain, a larger BAT SOC would be used, allowing the vehicle to be driven at low power levels for a longer period of time without recharging the battery which makes relevant the combination of both modes.

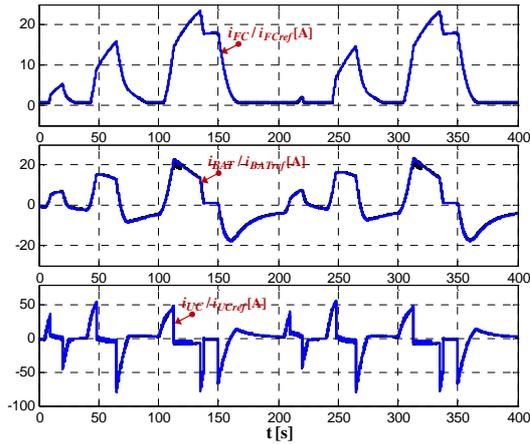


Fig. 13. Currents trajectory (Charge sustaining)

## V. Conclusion

This paper deals with the electrical power hybridization of a PEMFC, which has already been proved to be relevant for FC lifetime enhancement. A HSSE has been proposed to provide or to absorb the dynamic power when the load varies and the fuel cell cannot respond immediately, so the system dynamic characteristics are improved. Indeed, the combining of different power sources allows achieving higher energy density, power density, and fuel efficiency. Therefore, the power rating of the fuel cell can be decreased, which reduces the total system cost. In order to ensure that the system operates with high efficiency, this paper proposes complete EMS scheme, based on power splitting approach to balance the power flow and to control local protections (limits) of every source according to the operation condition of the considered hybrid system (FC/BAT/UC).

In particular, the following keypoints can be observed:

- Transient response is improved using the fastest source UC reducing the FC and BAT stresses which increases its lifetime.
- A simple and effective methodology is used exhibiting the robustness and the stability of system to ensure the load requirements even during fluctuations and

to guarantee a continuity of operation and a safe functioning.

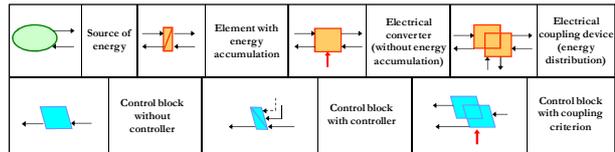
- EMS correctly manages the energy of system by sharing out naturally the power demand of the system into three parts depending on the frequency without slop limitation to satisfy the sources inherent characteristics, FC, BAT and UC voltage and current limits, as well as slow FC dynamics.

- This study proves that EMR is well adapted to this problem, since it deals with energy exchanges in a complex multi-source structure and it allows the designer to directly deduce a very relevant and reconfigurable control architecture.

The studied hybrid system can be easily adapted to different sources requirements and can be scaled to many applications. Furthermore, the study may be extended to achieve in such a way that each source is optimally used using adaptive power splitting technique.

## Appendix

### Appendix. A. Synoptic of Energetic Macroscopic Presentation



### Appendix. B. Electric characteristics of hybrid power system

Fuel Cell: Parameter Name	Value	Inductors & Capacities: Parameter Name	Value
Open circuit voltage	150 V	Inductors $L_{FC}/L_{BAT}/L_{UC}$	450/600/600 $\mu$ H
Rated voltage	80 V	Capacities $C_{BUS}$	1 mF
Rated current	100 A	Optimal DC-Bus Voltage	410 V
Minimum current	2 A	Sampling frequency	20 kHz
Ultracapacitor: Parameter Name		Battery :Parameter Name	
Rated Voltage	150 V	Open circuit voltage	180 V
Rated current	200 A	Rated current	120 A
Capacitance	48 F	Series resistance	2.7 $\Omega$
Optimal Voltage	112.5 V	$SOC_{ref}$	0.8 (80%)
Minimum voltage	75 V	$SOC_{min}$	0.3 (30%)
$\Delta V$	4 V	$\Delta SOC$	0.03 (3%)
Control parameters			
Inner control (current controller PI)		DC bus controller PI / UC SOC controller PI	
Proportional gain (FC)	0.32	Proportional gain (DC bus)	16
Integral gain (FC)	46 $rad.s^{-1}$	Integral gain (DC bus)	30 $10^3 rad.s^{-1}$
Proportional gain (BAT, UC)	0.76	Proportional gain (UC SOC)	0.5
Integral gain (BAT, UC)	109 $rad.s^{-1}$	Integral gain (UC SOC)	10 $rad.s^{-1}$
Frequency splitting parameters			
Filtering frequency ( $f_{SF1}$ )	50 mHz	Filtering frequency ( $f_{SF2}$ )	250 mHz

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