Energy management strategy design based on frequency separation, fuzzy logic and Lyapunov control for multi-sources electric vehicles

Bakou Traoré, Moustapha Doumiati, Cristina Morel, Ousmane Soumaoro,
Jean-Christophe Olivier

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Bakou Traoré
ESEO School of Engineering
10 Bd Jean Jeanneteau, Angers, France
bakou.traore@etu-univ-nantes.fr

Moustapha Doumiati
ESEO School of Engineering
IREENA Lab EA 4642
10 Bd Jean Jeanneteau, Angers, France
moustapha.doumiati@eseo.fr

Cristina Morel
ESEO School of Engineering
10 Bd Jean Jeanneteau, Angers, France
cristina.morel@eseo.fr

Jean-Christophe Olivier
Université de Nantes, IREENA Lab EA 4642
37 Bd de l'Universit, Saint Nazaire, France
jean-christophe.olivier@univ-nantes.fr

Ousmane Soumaoro
National School of Engineering (ENI-ABT)
410, Av. Vollenhoven, Bamako, Mali
samou_ soumaoro@yahoo.com

Abstract—**This paper presents a new Energy Management Strategy (EMS) based on frequency separation and fuzzy logic control for a multi-sources system. The studied system is an electric vehicle with hybrid sources including a fuel cell (FC), a battery and an ultracapacitor. Each source is controlled using a DC/DC converter connected to the DC-bus. To maintain a constant DC-bus voltage, a Lyapunov based controller is developed. The overall energy flow of the system is managed using a filtering-based EMS which allows a flexible use of energy sources by self-adapting to the system state evolution. The proposed approach protects the fuel cell and the battery from strong power dynamics, and coordinates the distribution of the energy demand between the battery and the ultracapacitor according to their state of charge. Simulations on MATLAB/SIMULINK, using a real current profile in an urban driving situation, validate the performances of the proposed method.**

Index Terms—**Electric vehicle, Energy management strategy, Multi-sources system, Lyapunov control.**

I. INTRODUCTION

A. Motivation

Electric and hybrid vehicles are becoming serious alternatives to meet the enormous challenge facing the world. Indeed, reducing the fossil fuel consumption and fighting against the climate change, as recommended in the international agreements, necessarily requires to design and use green technologies on a large scale.

In that sense, the transport sector, which is an important part of the world oil consumption, is witnessing the gradual integration of electric vehicles in recent years. Electric vehicles have the advantage of emitting few or no atmospheric pollutants, but are however disadvantaged on the autonomy side, because of the batteries limitations [1]. To improve the autonomy of the vehicle and protect the battery, other sources such as the hydrogen fuel cell (FC) and/or the ultracapacitor (also called supercapacitor) could be added, thus constituting hybrid sources. In operation, the hydrogen fuel cell provides water and heat, in addition to electricity. It does not release

any pollutant into the atmosphere. In addition to this ecological interest, the fuel cell has a much higher specific energy than the battery, according to the Ragone diagram [2]. Therefore, the fuel cell could be associated with other sources like batteries and/or ultracapacitors in a multi-sources architecture. In the case of electric vehicles, the hybridization of the energy source allows to minimize the vehicles weight and to increase their driving ranges [3]. However, because of the degrees of freedom offered by a multi-sources system, it can only be effective if it is controlled by an intelligent energy management strategy (EMS) that coordinates the power distribution between sources taking into account their electrical characteristics.

B. Contributions

This paper presents a new energy management strategy for three sources (a fuel cell, a battery, and an ultracapacitor) mainly based on frequency separation and fuzzy logic control. Besides, Lyapunov controllers are designed to regulate the DC-bus voltage and the currents of sources. This strategy could be implemented in real-time because it requires neither a prior knowledge of the entire mission profile nor intensive computation.

In the literature, frequency separation and fuzzy logic-based EMS have been used in many works. Authors in [2], [4] and [5] present strategies using simple filtering, adaptive filtering and robust $\mathcal{H}_\infty$ control, respectively. These strategies do not incorporate criteria to increase the system flexibility in case of a source unavailability. Strategies using fuzzy logic are also proposed, especially in [6], [7]. These last do not necessarily take into account the specifications of each energy source in terms of dynamics behavior, which can alter their lifetimes. The strategy proposed in this paper coordinates the distribution of power between the different sources according to their availabilities and physical characteristics. To achieve this, a repartition criterion is introduced to control the current to be supplied by the fuel cell; the value of this criterion is

determined by a fuzzy controller, taking into account battery and ultracapacitor states of charge. This method allows a flexible use of the power sources.

II. Modeling

As shown in Fig. 1, the studied system has three sources: a battery pack, an ultracapacitor pack (UC) and a proton exchange membrane fuel cell (FC). The battery is considered as the main source, the FC, as the autonomy extender and the UC as the dynamic power provider. Each source is connected to the DC-bus via a controlled DC-DC converter. All converters are reversible except that of the fuel cell.
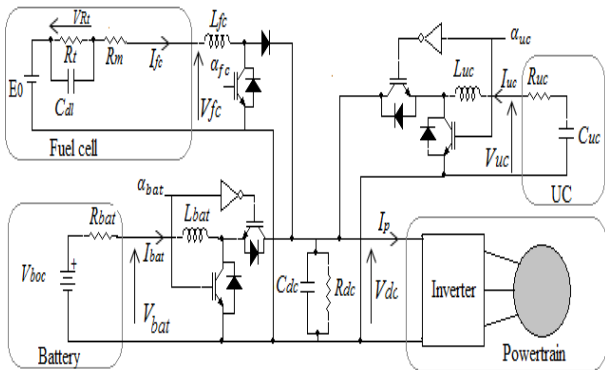

Fig. 1. System architecture.

A. The powertrain

The powertrain is the assembly of the wheels, speed reducer, electric motor, and its power converter. It must develop the traction power necessary to follow the speed profile imposed by the driver. The power demanded by this set constitutes the reference power. This group is powered via the DC-bus by different energy sources. The bus voltage should be kept at $150\ V$ as proposed in some existing works [2], [5]. Considering a constant bus voltage, the powertrain can be modeled as a current source I_P, which is the image of the speed profile. The IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Amnagement et des Réseaux) current profile shown in Fig. 2 is used for simulations. This real load profile current collected using an electric vehicle, is rich in frequency contents and corresponds to an urban driving cycle [5].

B. The fuel cell

The equivalent electrical model of the FC shown in Fig. 1 is considered. In this model, E_0 is the open circuit voltage, R_m is the FC membrane resistance, R_t the transfer resistance, C_{dl} is the double layer capacitance [5]. Its mathematical model is given by (1):

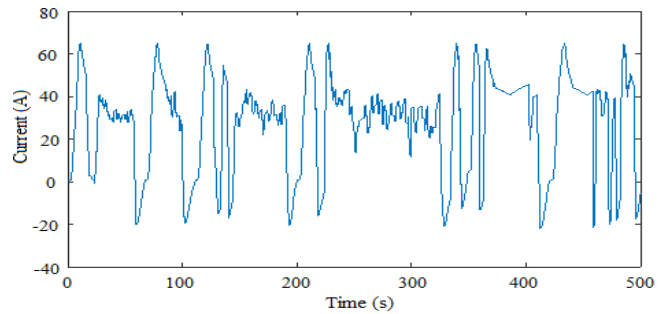$$\begin{cases} V_{fc} = E_0 - V_{Rt} - R_m I_{fc} \\ I_{fc} = C_{dl}\dot{V}_{Rt} + V_{Rt}/R_t \end{cases} \quad (1)$$

Fig. 2. IFSTTAR load current I_p.

C. The battery

In this work, a simple model consisting of the association of a voltage source V_{bat} and resistance R_{bat} is used (see Fig. 1). Its state of charge SOC_{bat} is estimated by charge counting (integration of the battery's current):

$$\begin{cases} V_{bat} = V_{boc} - R_{bat}I_{bat} \\ SOC_{bat} = \frac{1}{Q_n}(Q_o - \eta \int_0^t I_{bat}(\tau)d\tau) \end{cases} \quad (2)$$

where V_{boc} and I_{bat} are respectively the battery open circuit voltage and the battery current. Q_o is the battery initial capacity, Q_n represents the nominal capacity, and η is the faradic efficiency.

D. The ultracapacitor

Several models of UC are described in the literature. Among these models, there are in particular the distributed constant model, the localized constant model and the behavioral model with two branches [8], [9]. The model used in this work consists of the association of a capacitance C_{uc} and a series resistance R_{uc} (Fig. 1). The relation between the voltage V_{uc} and current I_{uc} is given by (3) :

$$\begin{cases} V_{uc} = V_{uc0} - R_{uc}I_{uc} \\ I_{uc} = C_{uc}\dot{V}_{uc0} \end{cases} \quad (3)$$

Noting by V_{ucmax} the maximum value of its open circuit voltage V_{uc0}, and its state of charge SOC_{uc} is estimated using (4):

$$SOC_{uc} = 100\frac{V_{uc0}^2}{V_{ucmax}^2} \quad (4)$$

E. Converters

The power sources are controlled through three power converters: a boost converter for the FC and two buck-boost converters for respectively the battery and the UC. For control purposes, each converter is represented by its average model :

$$\begin{cases} L_{fc}\frac{dI_{fc}}{dt} = V_{fc} - V_{dc}(1 - \alpha_{fc}) \\ L_{uc}\frac{dI_{uc}}{dt} = V_{uc} - V_{dc}\alpha_{uc} \\ L_{bat}\frac{dI_{bat}}{dt} = V_{bat} - V_{dc}\alpha_{bat} \end{cases} \quad (5)$$

where V_{fc}, V_{bat} and V_{uc} are the FC, the battery and the UC voltages, respectively; I_{fc}, I_{bat}, I_{uc} are their respective currents. α_{bat}, α_{fc} and α_{uc} are the respective converter duty ratios. L_{bat}, L_{fc} and L_{uc} are the converters inductance. V_{dc},

R_{dc} and C_{dc} are the voltage, resistor and capacitor of the DC-bus, respectively.

F. The DC-bus

Applying Kirchhoff law to the DC-bus node (see Fig.1), the V_{dc} average electrical behavior could be given by:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}[\frac{-1}{R_{dc}}V_{dc} - I_P + I_1 + I_2 + I_3] \qquad (6)$$

where $I_1 = I_{fc}(1 - \alpha_{fc})$, $I_2 = I_{bat}\alpha_{bat}$ and $I_3 = I_{uc}\alpha_{uc}$ are the converters output currents.

III. ENERGY MANAGEMENT SYSTEM

As shown in Fig. 3, the proposed energy management circuit is mainly composed of a DC-bus voltage regulator, a fuzzy controller and two passive filters. The management approach is based on an online distribution of the power demand between the three sources using frequency separation and fuzzy-decisions. Fuzzy rules determine the distribution of the power taking into account the state of charge of the storage systems (battery and ultracapacitor) and the value of the power demand. Then, filters are added to provide a spectral distribution such that the fuel cell and the battery are not subject to high power dynamics to preserve their lifetime [10].

The voltage regulator must keep the bus voltage as constant as possible at $150\ V(\pm 10\ V)$. To achieve this, a Lyapunov controller is built. The current I_L determined by this controller represents the current needed to maintain constant DC-bus voltage despite of the powertrain load current I_P. According to its spectral composition, its magnitude and the state of charge of the battery, the current I_L is distributed between the fuel cell, the battery and the ultracapacitor.

A. DC-bus voltage regulation loop

Maintaining the DC bus voltage at $V_{dcref} = 150\ V$ is a key point in the development of the control circuit. A Lyapunov function-based controller is proposed. The stability of the proposed controller can be inherently satisfied which is shown in the controller design process. The idea consists of finding an energy function depending on the regulation error $e_r(t) = V_{dcref} - V_{dc}(t)$ that asymptotically tends to zero. Equation (6) can be written in the form :

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}[\frac{-1}{R_{dc}}V_{dc} - I_P + I_L] \qquad (7)$$

with $I_L = I_1 + I_2 + I_3$, the total output current of the sources converters.

Let consider the following energy function V :

$$V = \frac{1}{2}f^2 > 0. \qquad (8)$$

with $f(t) = k_1 e_r(t) + k_2 \int_0^t (t) e_r dz$, function of the error and its integral.

To ensure that $f(t) \to 0$ as $t \to +\infty$, V must be a Lyapunov function with $\frac{dV}{dt} = \dot{V} < 0, \forall\ f \neq 0$.

The exponential stability with a decay rate k could be verified if:

$$\dot{V} = -kV = -\frac{k}{2}f^2, \forall k > 0. \qquad (9)$$

It can be deduced that:

$$\dot{V} = f\dot{f} = -\frac{k}{2}f^2. \qquad (10)$$

Therefore:

$$\dot{V}_{dc} = \frac{kk_1 + k_2}{2k_1}e_r + \frac{kk_2}{2k_1}\int_0^t e_r dz \qquad (11)$$

To guarantee that $e_r(t) \to 0$ as $f(t) \to 0$, parameters k_1 and k_2 must be positive according to Routh-Hurwitz stability criteria.

Based on the expression (7), the continuous control law is:

$$I_L = C_{dc}\frac{kk_1 + k_2}{2k_1}e_r + C_{dc}\frac{kk_2}{2k_1}\int_0^t e_r dz + \frac{V_{dc}}{R_{dc}} + I_P \quad (12)$$

where k, k_1 and k_2, are the controller parameters to be tuned to ensure fast dynamic response. The total load current I_L is splitted between sources according to its spectral composition. As shown in Fig. 3 the current reference of each source converter is determined by (13) in the frequency domain by:

$$\begin{cases} I_{1ref} = K_d H_1 I_L \\ I_{2ref} = K_{bat} H_2 (I_L - I_{1ref}) \\ I_{3ref} = K_{uc}(I_L - I_{1ref} - I_{2ref}) \end{cases} \qquad (13)$$

Where I_{1ref}, I_{2ref} and I_{3ref} are respectively the reference currents of the FC, the battery and the UC converters. H_1 and H_2 are the transfer functions of the low-pass filters F_{fc} and F_{bat} respectively. The factors K_d, K_{bat} and K_{uc} are determined by a fuzzy controller according to the continuous evolution of the system state.

B. Fuzzy controller

A Mamdani Fuzzy Logic System (MFLS) [11] is used to perform a repartition of the current I_L between the sources by determinating on its outputs the power distribution criteria K_d, K_{bat} and K_{uc}. The last two are used to limit the charge and the discharge of the battery and the UC.

The inputs of the MFLS are the battery state of charge SOC_{bat}, the UC state of charge SOC_{uc} and the current I_L.

The design of the MFLS were done using MATLAB fuzzy logic toolbox in 3 steps: the fuzzification, the rules edition and the defuzzification.

The fuzzification is achieved using trapezoidal membership functions (TMF) in order to reduce the computation complexity and to allow a smooth transition, unlike the sinusoidal and Gaussian type functions [6].

The input I_L has four TMF designated as Negative (N), Low (L), Medium (M) and High (H). The variables SOC_{bat} and SOC_{uc} have three TMF (L, M and H) (Fig. 4). The outputs K_d, K_{bat} and K_{uc} have respectively five (VL, L, H and VH), two (VL and VH) and two (VL, VH) membership functions (Fig. 5). VL and VH stand for Very Low and Very High respectively.

The rules edition consists of defining a certain number of instructions to make the link between the input and the output variables using operators IF, OR, AND. A set of 36 fuzzy rules is defined in heuristic manner to favor the fuel cell when the
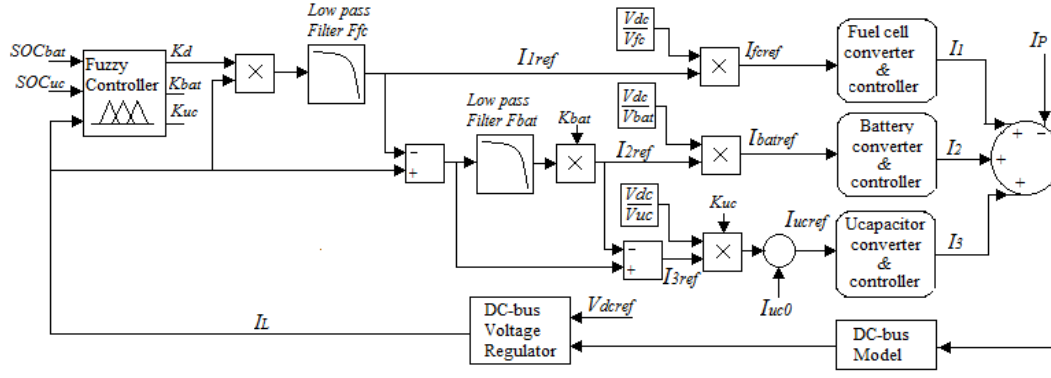
Fig. 3. Control scheme.

current is high and to limit the charge and the discharge of the UC, depending on the state of charge of the battery.

If the battery is charged ($SOC_{bat} = H$) or moderately charged ($SOC_{bat} = M$), Low values (VL, L, or M) are assigned to K_d and high value (VH) to K_{bat} in order to favor the battery according to I_L value (N, L, M, H).

If the battery is discharged ($SOC_{bat} = L$), high values (VH or H) are assigned to K_d and low value (VL) to K_{bat} to favor the FC according to I_L value (N, L, M, H).

The values of K_{uc} (VL or VH) are attributed according to the SOC_{uc} (L, M, H) and to the sign of I_L (N or L, M, H) in order to avoid the over charge and the deep discharge of the UC.

The defuzzification consists in computing the abscissa of each output variable using centroid method on the resulting fuzzy set.

The possible values of a given output, taking into account the defined rules, is its decision area. The decision areas of the designed MFLS are depicted in Fig. 6, 7 and 8.

K_d (between 0 and 1) determines the proportion of the current I_L intended to the fuel cell before filtering. It depends mainly on I_L and SOC_{bat} as shown in Fig. 6.

K_{bat} (between 0 and 1) stops charging or discharging the battery by multiplying its current by 0 or 1, depending on its state of charge SOC_{bat} and of the sign of the current I_L. As shown in Fig. 7, K_{bat} depends mainly on I_L and SOC_{bat}.

K_{uc} (also between 0 and 1) stops or allows the charge or the discharge of the UC, according to its state of charge SOC_{uc} and of the current I_L.

C. Low-pass filters

In order to protect the battery and the FC from strong current dynamics, two first-order low-pass filters F_{fc} and F_{bat} are used (see Fig. 3). Their transfer functions noted respectively H_1 and H_2 are given by (14):

$$H_i(s) = \frac{2\pi f_i}{2\pi f_i + s}, i \in \{1, 2\} \quad (14)$$

where f_1 and f_2 are the filter cut-off frequencies.
The filter F_{fc} is used to filter the fuel cell current and the filter F_{bat} for the battery current. The higher frequencies are directed to the UC. The FC filter has a lower cut-off frequency
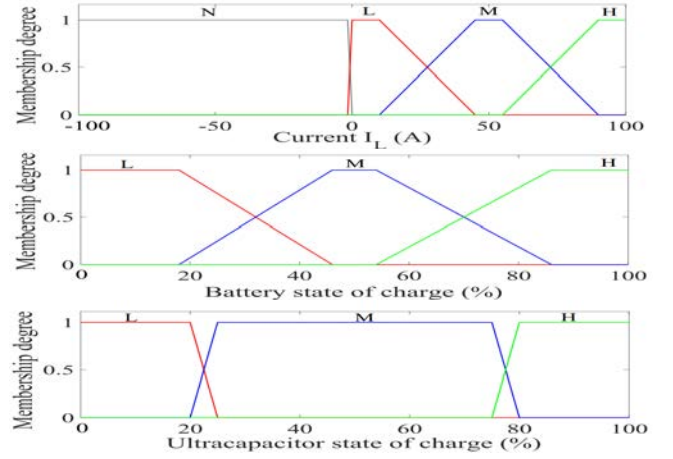

Fig. 4. Fuzzy modeling of input linguistic variables SOC_{bat}, SOC_{uc} and Current I_L .The letters H,L and M mean High, Low and Medium values.
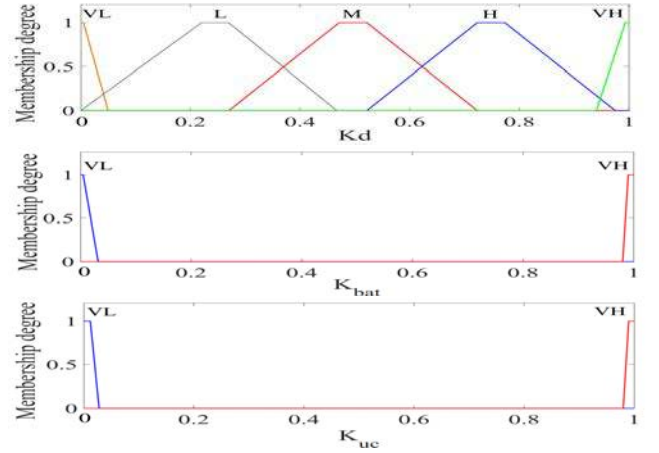

Fig. 5. Fuzzy modeling of output linguistic variables K_d,K_{bat} and K_{bat}. VH and VL mean very high, very low values.

than the battery filter. This means that the frequencies covered by the FC are also covered by the battery but the latter covers wider bandwidth than the FC. This allows some control flexibility in case of unavailability of one of the two sources.
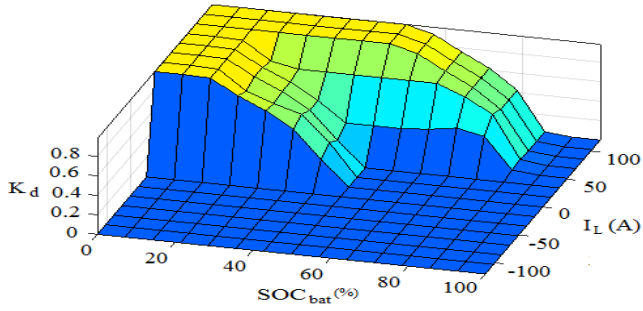
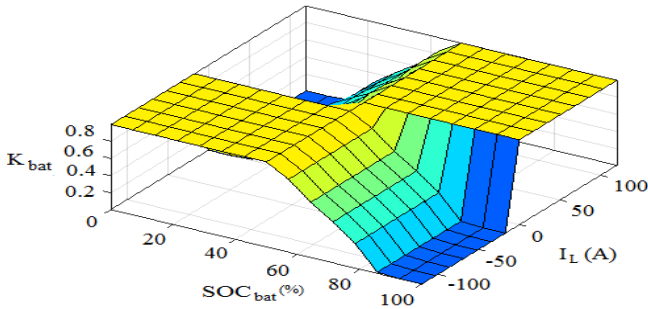Fig. 6. Decision area of the Fuzzy controller ouput K_d.

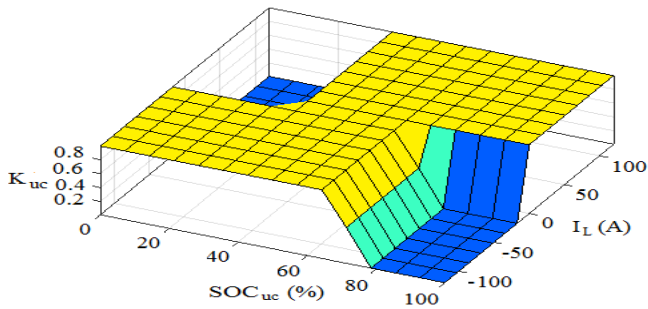Fig. 7. Decision area of the Fuzzy controller ouput K_{bat}.

Fig. 8. Decision area of the Fuzzy controller ouput K_{uc}.

The two frequencies must be chosen according to the dynamic characteristics of the two sources. An objective way to choose these frequencies is to use the notion of source specific frequency as in [12]. This frequency is defined by the equation (15) :

$$f = \frac{p(W/kg)}{e(J/kg)} \qquad (15)$$

$p(W/kg)$ is the source specific power and $e(W/kg)$ its specific energy. So, a source with low specific power and high specific energy like the fuel cell will have low specific frequency and its current dynamic will be strongly attenuated.

D. UC state of charge regulation

For the protection of the UC and the proper functioning of the system, it is necessary to limit its charge so as not to exceed the maximum voltage of the UC and to limit its discharge so that it can be able to supply the system in its frequency zone, especially when the battery is discharged. This protection is done in two steps : in one hand by the fuzzy

controller output K_{uc} which cancel its load current if ever the SOC_{uc} reaches its extreme values, and in other hand by a proportional controller defined by (16) as

$$I_{uc0} = \beta(SOC_{ucref} - SOC_{uc}), \qquad (16)$$

where I_{uc0} is the regulation current, SOC_{ucref} is the reference SOC of the UC, and β is the controller gain tuned to have a sufficiently slow dynamics allowing the UC to assist the FC and the battery.

E. Current control loops

To track the reference currents I_{fcref}, I_{batref} and I_{ucref} determined after filtering, Lyapunov controllers are developed. These controllers are designed as presented in Section III.A, and are tuned to ensure that the time response of each current control loop is negligible compared to that of the DC-voltage regulation loop.

IV. SIMULATIONS RESULTS

To validate the performance of the proposed strategy, numerical simulations have been performed with MAT-LAB/SIMULINK software. The IFSTTAR load profile [2] shown in Fig. 2 is used to validate the proposed energy management strategy. This load profile shows different driving conditions including acceleration, deceleration and braking phases.

The initial state of charge of the UC is fixed at 50 %. The simulations were carried out with different state of charge of the battery to evaluate the performance of the fuzzy controller.

When the battery is fully or moderately charged, it becomes the main source of energy of the system; however, for strong current demands, it is assisted by the FC. As we can see in Fig. 9, the highly variable currents are directed towards the UC. Fig. 13 shows the spectral repartition of Load current between power sources. The FC and the battery share the low frequencies, depending on the state of charge of the battery, while the UC supplies the high frequency currents.

When the battery is discharged, it no longer contributes: the FC becomes the main power source and provides energy to the vehicle in its frequency range. As discussed before the highly variable currents are always directed to the UC, as shown in Fig. 10.

Whether the battery is charged or not, the DC-bus is well maintained at $150\ V$. As shown in Fig. 11, over the entire
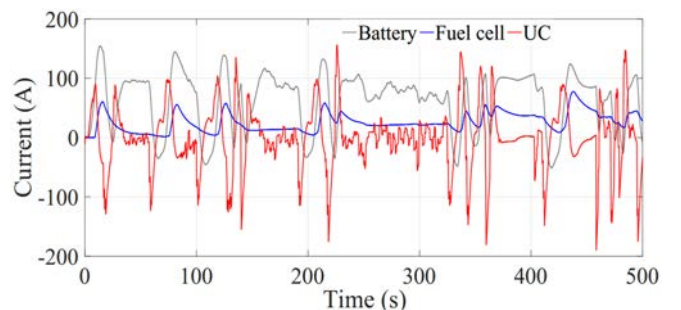

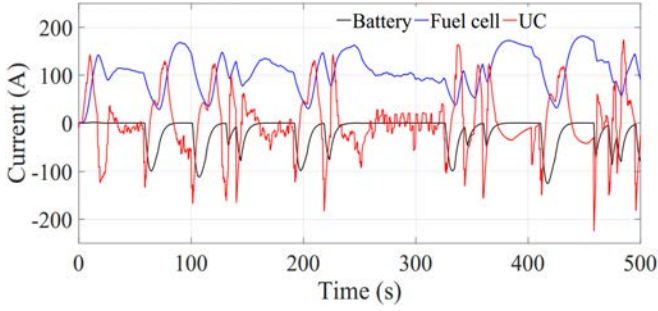Fig. 9. Sources currents with IFSTTAR Load profile.

Fig. 10. Sources currents with IFSTARR Load profile when the Battery is discharged.

driving cycle its maximum value is $150.5\ V$ and its minimum value $149.6\ V$. This confirms the pertinence and rapidity of the developed controllers.

The UC state of charge, initially fixed to 50%, never reaches its maximum and minimum value as shown in Fig. 12, so it is well protected from the overcharge.
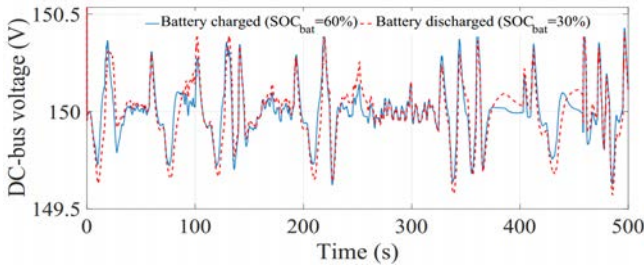

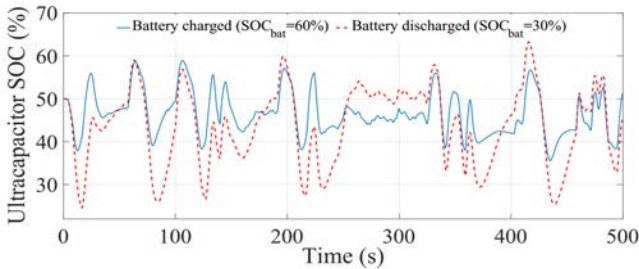Fig. 11. DC-bus voltage when the battery is charged and discharged

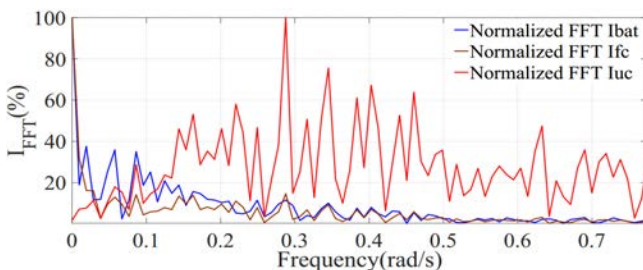Fig. 12. UC state of charge when the battery is charged and discharged

Fig. 13. Normalized Fast Fourier Transform (FFT) of sources currents.

V. Conclusion

In this paper, a new energy management strategy using fuzzy logic and filtering is presented. This strategy uses a battery and a fuel cell depending on their availabilities. It offers a certain freedom of use of the sources compared to the usual energy management methods based on frequency separation. The battery, considered as the main source, contributes according to its state of charge, while highly variable currents are supplied by the UC. The flexibility of the developed EMS allows the FC, used as autonomy extender, to progressively assist, in its frequency range, the battery for important power demands, and to be the main power provider according to its maximum power when the battery is discharged. Thus, each source is used on its frequency range to be protected against harmful power dynamics.

The designed Lyapunov controllers ensure good tracking of the DC-bus voltage and the currents of the different power sources to theirs reference values.

The improvement of the proposed approach considering the FC hydrogen consumption as an additional criterion for sources selection is the subject of our current works.

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