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Energy management and control of a fuel cell/supercapacitor multi-source system for electric vehicles

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Abstract—This article presents a control strategy of a multi-source system dedicated to automotive applications, aiming to maximize the global system efficiency. A parallel-architecture of the multi-source system is considered, composed of a fuel cell as a primary power source, a supercapacitor as a secondary storage element, which provides peak power in fast transients, and power converters for the power sources interconnection to the DC bus. The power management is realized as a two-level control structure. The first level contains inner control loops for fuel cell/supercapacitor currents and a DC bus voltage control loop, designed using PI controllers. The higher level consists of an energy management supervision system based on the equivalent consumption minimization strategy. The fuel cell power demand is computed by minimizing the hydrogen mass consumption with respect to system physical constraints. The performances of the proposed control structure are evaluated in simulation, in terms of fuel economy, using an urban driving cycle.

Index terms— energy management, supervision system, ECMS, real-time multi-level control strategy, multi-source system, fuel cell, supercapacitor, automotive applications.

I. INTRODUCTION

According to the latest studies, the carbon dioxide (CO_2) emissions have a major contribution to the greenhouse effect due to fossil energies combustion, mostly in the transport field, where an important quantity of greenhouse gas emissions is produced [1]. For environment preservation, it is necessary to explore ecological means to produce energy such as renewable or electric energy sources. Therefore, in the automotive field, multi-source systems have been considered for electric vehicles powertrains.

The use of a fuel cell (FC) as main power source provides an interesting solution, although its slow dynamics demands to be assisted by a secondary supply/storage element, such as a supercapacitor (SC) or a battery, which is able to produce peak power demand during fast transients and to recover energy during the braking phase. Generally, several architectures have been investigated as it concerns multiple sources interconnection to the DC bus: series, cascade or parallel architecture [2]. In this article, the control strategy is elaborated for a parallel FC/SC multi-source system with both sources connected to the DC bus through DC/DC power converters. The proposed control approach has the following objectives: to stabilize the multi-source power supply system, to regulate the DC bus voltage in order to guarantee a stable supply voltage for an

electric motor and to maximize the global system efficiency by minimizing the hydrogen mass consumption.

In the literature, different control strategies have been considered for power supply systems of electric/hybrid vehicles powertrains. Passivity-based control has been employed to regulate the DC bus and the secondary storage element voltages of different multi-source systems (FC/SC [3], [4] or FC/battery [5] configurations). Lyapunov-based control [6] and sliding mode control [7] have also been applied to power supply systems for electric vehicles, using one or two additional storage elements (FC/SC, FC/SC/battery). In addition to this, cascade control using PI-controllers has been considered, with inner loops for current regulation of power electronic devices and outer loops for voltage regulation of the secondary source (SC or battery) [8] and of the DC bus. Also, decentralized model predictive control [9], [10], and singular perturbation control approach [11] have been used for a FC/SC supply system of an electric vehicle.

The purpose of the supervision level is to manage the power split between the FC and the additional storage/supply elements while reducing the fuel consumption and maximizing the system efficiency. Different energy management strategies (ruled-based [12] or optimization-based [13]) have been applied and validated using a static model of the fuel cell. For optimization-based strategies, the solution is obtained by minimizing an objective function subject to system physical limits, integrated as constraints. Thus, the supervision level of an electric vehicle multi-source power system has to compute the fuel cell power which minimizes the hydrogen mass consumption and satisfies the physical constraints: positive FC power, limited variation of the FC power, maximum capacity of the secondary storage element.

The optimization problem can be solved on-line or off-line based on the knowledge of the driving cycle. Off-line optimization methods (dynamic programming [14]-[15], Pontryagin's minimum principle [16]) use the assumption of full knowledge of the driving cycle. However, the solution optimality depends on the employed method and its complexity can be an issue for real-time implementation as it requires a high-capacity storage. The advantage of on-line methods [17], [18] is the reduced computational time, whereas the solution obtained using the instantaneous power load is sub-optimal.

Equivalent consumption minimization strategy (ECMS) [19], [20] and model predictive control [21] are among the on-line approaches that have been used for power management of electric or hybrid vehicle powertrain.

This article proposes a control structure that stabilizes the DC bus voltage and uses the information delivered by an energy management supervision system to regulate the FC power, which ensures the fuel consumption minimization over the whole driving cycle. Thus, the model of the FC/SC multi-source system is described in Section II. Section III presents the two-level control structure and the ECMS optimization problem formulation. In Section IV, simulation results are presented in order to evaluate the performances of the proposed control structure and the improvement of the hydrogen mass consumption due to the use of the supervision level. Finally, Section V presents conclusions and perspectives of this work.

II. POWER SUPPLY SYSTEM MODELING

A parallel architecture has been considered for the FC/SC multi-source system, which presents several advantages compared to the series or cascade architectures: more effective power distribution, high efficiency and DC bus voltage regulation [2]. The fuel cell is connected to the DC bus through a step-up (boost) DC/DC converter, that transforms the power supplied by the FC into DC bus power [22]. A bi-directional DC/DC power converter is used to interconnect the supercapacitor, which assists the SC charge/discharge processes when energy recovery or peak power is required [23]. The multi-source system architecture is illustrated in Fig. 1.

Thereafter, two models are presented: the static model of the fuel cell and the supercapacitor energy dynamics, used to elaborate the energy management strategy of the supervision system, and the system non-linear model employed for control design.

In this study, the proposed two-level control structure is evaluated using a static model of the fuel cell. Indeed, for practical implementation of this control structure, the energy management strategy and the control design should consider the dynamic model of the fuel cell.

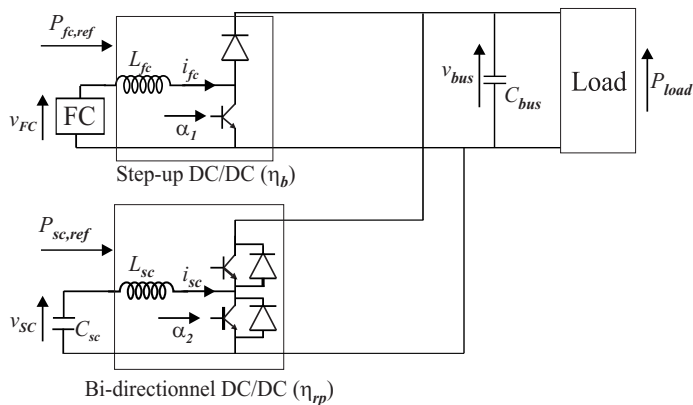


Fig. 1. Fuel cell/supercapacitor architecture

A. Energy management model

The fuel cell is an electrochemical device that produces electrical energy, water and heat as a result of the redox reaction between hydrogen and oxygen [24]. Generally, the FC is part of a fuel cell system composed by: stack, air compressor, fuel tank and humidifier [25]. In automotive applications, the stack is usually a polymer electrolyte membrane fuel cell (PEMFC), mainly for its convenient characteristics (high power density, small volume).

The fuel cell static model is given by the static output voltage (v_{fc}) - current (i_{fc}) characteristics, presented in Fig. 2. This characteristics is obtained by interpolation of different measured values of v_{fc} and i_{fc} and by approximation with a fifth order polynomial:

$$v_{fc} = a_5 i_{fc}^5 + a_4 i_{fc}^4 + a_3 i_{fc}^3 + a_2 i_{fc}^2 + a_1 i_{fc} + a_0 \quad (1)$$

where: $a_5 = -9.01 \cdot 10^{-8}$, $a_4 = 1.98 \cdot 10^{-5}$, $a_3 = -0.0016$, $a_2 = 0.0617$, $a_1 = -1.17$, $a_0 = 41.32$.

Based on the previous static characteristics and on the hydrogen flow expression:

$$\phi_{H_2} = \frac{N_{cell} M_{H_2}}{n e_{-1} F} i_{fc}(P_{fc}) \quad (2)$$

with P_{fc} - the power produced by the FC [kW], N_{cell} - the cells number, M_{H_2} - the hydrogen molar mass [gram \cdot mol $^{-1}$], F - Faraday constant [C \cdot mol $^{-1}$], i_{fc} - the FC current [A], the instantaneous hydrogen flow values have been obtained for a FC power in the range of [0, 2.5] kW. Fig. 3 shows the static $\phi_{H_2} - P_{fc}$ characteristics obtained using a second order polynomial approximation:

$$\phi_{H_2} = b_2 P_{fc}^2 + b_1 P_{fc} + b_0 \quad (3)$$

where: $b_2 = 0.0018$, $b_1 = 0.0134$, $b_0 = 0.0001$. The hydrogen flow expression given in equation (3) is used in Section III to define an optimization problem, solved by the supervision system at each sampling time for fuel consumption reduction. Another objective of the energy management strategy is to assure a desired SC charge level at the end of the driving cycle.

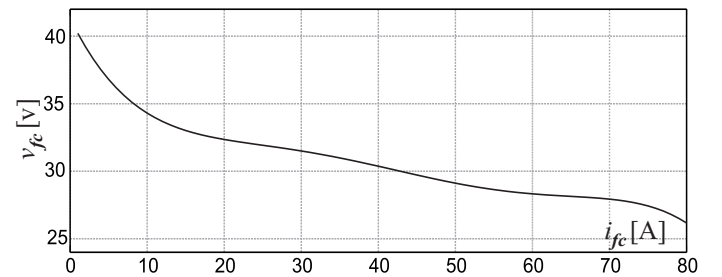


Fig. 2. Polynomial approximation of the static $v_{fc} - i_{fc}$ characteristics of the fuel cell.

Therefore, the scaled SC state of energy is defined as: $SoE(t) = \frac{E_{sc}(t)}{E_{sc,max}}$, where $E_{sc}(t)$ and $E_{sc,max}$ are the instantaneous and the maximum energy stored in the SC respectively. In addition to this, the multi-source system and the load are

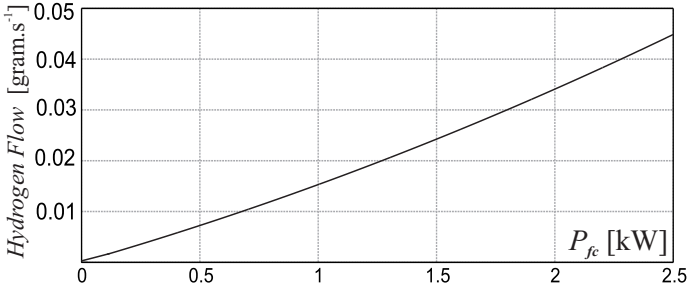


Fig. 3. Hydrogen flow ϕ_{H_2} polynomial approximation.

interconnected to the DC bus via a capacity C_{bus} [F]. Thus, the system power balance equation is the following:

$$P_{load}(t) + P_{C_{bus}}(t) = \eta_b P_{fc}(t) + \eta_{rp} P_{sc}(t) \quad (4)$$

with: η_b , η_{rp} - the efficiencies of DC-DC step-up and bi-directional power converters respectively, P_{load} - the power demand, P_{sc} - the SC power, $P_{C_{bus}}$ - the C_{bus} power.

The dynamics of the SC state of energy is defined in function of the power demand, FC and DC bus powers as follows:

$$\frac{dSoE}{dt}(t) = -\frac{P_{sc}(t)}{E_{sc,max}} = -\frac{P_{load}(t) + P_{C_{bus}}(t) - \eta_b P_{fc}(t)}{\eta_{rp} E_{sc,max}} \quad (5)$$

B. Control model

Let us consider the state-space vector $x(t) = (i_{fc}(t) \ i_{sc}(t) \ v_{sc}(t) \ v_{bus}(t))$ and the input vector $u = (\alpha_1 \ \alpha_2 \ v_{fc})$, with i_{fc} , i_{sc} - the fuel cell and supercapacitor currents, v_{fc} , v_{sc} , v_{bus} - the FC, SC and DC bus voltages, α_1 , α_2 - the duty cycles of the step-up and bidirectional power converters respectively.

The fuel cell/supercapacitor power system is represented by the following 4th order non-linear model:

$$\begin{cases} \frac{di_{fc}}{dt} = \frac{1}{L_{fc}}(v_{fc} - (1 - \alpha_1)v_{bus}) \\ \frac{di_{sc}}{dt} = \frac{1}{L_{sc}}(v_{sc} - (1 - \alpha_2)v_{bus}) \\ \frac{dv_{sc}}{dt} = -\frac{1}{C_{sc}}i_{sc} \\ \frac{dv_{bus}}{dt} = \frac{1}{C_{bus}}((1 - \alpha_1)i_{fc} + (1 - \alpha_2)i_{sc} - \frac{P_{load}}{v_{bus}}) \end{cases} \quad (6)$$

where L_{fc} , L_{sc} are the step-up and bi-directional converters inductances and C_{sc} , C_{bus} are the SC and DC bus capacities. The duty cycles α_1 , α_2 represent the control inputs to be computed while v_{fc} is determined at each instant using the polynomial approximation of the static $v_{fc} - i_{fc}$ characteristics of the fuel cell given in equation (1) and represented in Fig. 2.

C. Vehicle model

The power demand is determined using the vehicle dynamics [26], which depends on the velocity variation, the losses due to rolling and to aerodynamic frictions, and gravity:

$$P_{load} = V[0.5\rho_{air}V^2SC_x x + M(g \sin(\alpha) + \frac{dV}{dt} + gC_r \cos(\alpha))] \quad (7)$$

with: M - the vehicle mass, V - the vehicle velocity, S - the frontal surface, C_x - the drag coefficient, α - the road slope, ρ_{air} - the air density, g - the gravity acceleration, C_r - the vehicle rolling resisting coefficient.

In the literature, there exist different types of driving cycles which can be divided on standard profile or real-data driving cycles [1]. In this study, simulations of the proposed control strategy are done using Artemis cycle (real-world urban driving cycle) [27], which uses real measurements collected from vehicles in real driving conditions.

III. ENERGY MANAGEMENT CONTROL STRATEGY

The proposed two-level control structure is presented in Fig. 4. The high level includes an energy management supervision system. This system computes at each sampling time, the fuel cell and supercapacitor optimal powers ($P_{fc,optimal}$, $P_{sc,optimal}$) using an optimization strategy that minimizes the hydrogen mass consumption, with the aim of maximizing the system global performance. The supervisor takes into consideration the DC bus power variations during transients and the evolution of SC state of energy (SoE) that must reach the desired reference value (SoE_{ref}) at the end of the driving cycle. The reference FC current value ($i_{fc,ref}$) is then determined at each instant by using equation (2) and the polynomial approximation of the hydrogen flow ϕ_{H_2} introduced in equation (3). At low level, the two converters are controlled by fast inner current loops using classic PI controllers and PWM (pulse wave modulation) generators. The inner loops are designed to regulate the FC and SC currents (i_{fc} and i_{sc}) to their reference values $i_{fc,ref}$ and $i_{sc,ref}$ respectively. The bi-directional converter has to guarantee that the DC bus voltage (v_{bus}) is stabilized at the reference value ($V_{bus,ref}$). DC bus voltage regulation is done using a PI controller that generates the reference SC current value ($i_{sc,ref}$).

A. Equivalent consumption management strategy (ECMS)

The energy management strategy is employed to ensure an optimal power split between the fuel cell and the supercapacitor, by minimizing the fuel consumption while assuring the same charge level of the SC, at the beginning and at the end of the driving cycle. The approach adopted in this study is the equivalent consumption minimization strategy (ECMS), based on the concept of equivalent fuel consumption [28]. Therefore, the energy stored in the supercapacitor is transformed into fuel consumption using a conversion positive factor λ [gram \cdot J⁻¹]. Besides, ECMS represents an on-line optimization strategy, that relies only on the instantaneous power demand. For this reason, this energy management strategy can easily be applied to real-time applications due to its low computation time.

Using the power balance equation (4) and considering:

$$P'_{sc} = P_{sc}(t) - \frac{P_{C_{bus}}(t)}{\eta_{rp}} \quad (8)$$

where $P_{C_{bus}}(t) = C_{bus}v_{bus} \frac{dv_{bus}}{dt}$, the cost function to be minimized is represented by the total fuel consumption $\gamma_{eq}(t)$:

$$\gamma_{eq}(t) = \phi_{H_2}(t) + \lambda P'_{sc}(t) \quad (9)$$

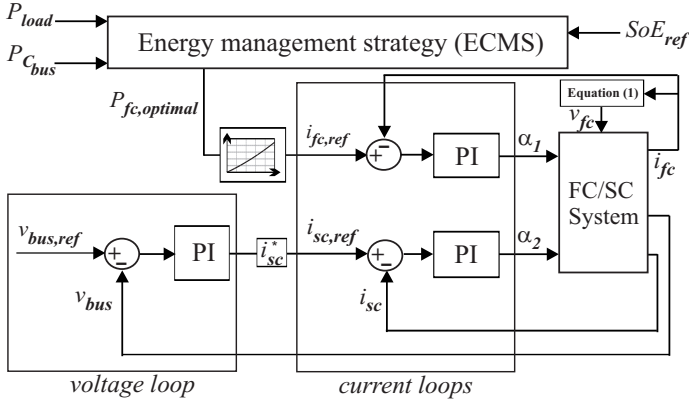


Fig. 4. Energy management control strategy.

By replacing the hydrogen flow expression (equation (3)) in the cost function equation (9), the following optimization problem must be solved in order to compute the instantaneous power $P'_{sc}(t)$:

$$\min_{P'_{sc}(t)} \beta_2 P'^2_{sc}(t) + \beta_1 P'_{sc}(t) + \beta_0 + \lambda(k) P'_{sc}(t) \quad (10)$$

with: $\beta_2 = b_2 \frac{\eta_{rp}^2}{\eta_b^2}$, $\beta_1 = -\frac{\eta_{rp}}{\eta_b} (2b_2 P_{load} + b_1)$ and $\beta_0 = \frac{b_2}{\eta_b^2} P_{load}^2 + \frac{b_1}{\eta_b} P_{load} + b_0$.

Once the solution of the optimization problem is found, the instantaneous optimal values $P_{sc,optimal}(t)$ and $P_{fc,optimal}(t)$ are determined using equations (8) and (4).

Then, the supervision system verifies *a posteriori* that the optimal power values respect the system physical limits. First of all, powers supplied by the fuel cell and the supercapacitor are bounded inside the intervals $[P_{fc,min}, P_{fc,max}]$ and $[P_{sc,min}, P_{sc,max}]$ respectively, where $P_{fc,min} (\geq 0)$, $P_{fc,max}$, $P_{sc,min}$, $P_{sc,max}$ are the minimum and maximum values of each power sources. Secondly, the scaled SC state of energy (SoE) is limited by its minimum and maximum values:

$$SoE_{min} \leq SoE(k) \leq SoE_{max} \quad (11)$$

The optimization problem (10) is solved using a conversion factor defined as a proportional controller $\lambda(t) = s_0 + s_1 (SoE_{ref} - SoE(t))$ [29], where s_0 and s_1 represent equivalence factors. s_0 and s_1 are chosen in order to guarantee the same SC state of energy at the beginning and at the end of the driving cycle ($SoE(T_{cycle}) = SoE(T_0)$). Their values influence the SC charge and discharge processes over the driving cycle and their tuning has to be adapted to driving conditions (road slope, acceleration and braking phases).

B. Current loops

Using the dynamic equations given in (6), the fuel cell and supercapacitor currents are:

$$I_{fc}(s) = \frac{V_{bus}(s)}{L_{fc}s} \alpha_1 + \frac{V_{bus}(s) - V_{fc}(s)}{L_{fc}s} \quad (12)$$

$$I_{sc}(s) = \frac{V_{bus}(s)}{L_{sc}s} \alpha_2 + \frac{V_{bus}(s) - V_{sc}(s)}{L_{sc}s} \quad (13)$$

To satisfy the imposed damping factors $\xi_{i_{fc}}$, $\xi_{i_{sc}}$ and the response time of each loop, two PI-controllers are designed with $H_{PI_i} = k_i (1 + \frac{1}{\tau_i s})$, $i = i_{fc}, i_{sc}$. These controllers are used for FC and SC current regulation respectively [11].

Hence, the closed loops transfer functions are given as follows:

$$H_{i_{fc}} = \frac{1 + \tau_{i_{fc}} s}{1 + 2 \frac{\xi_{i_{fc}}}{\omega_{i_{fc}}} s + (\frac{1}{\omega_{i_{fc}}} s)^2} \quad (14)$$

$$H_{i_{sc}} = \frac{1 + \tau_{i_{sc}} s}{1 + 2 \frac{\xi_{i_{sc}}}{\omega_{i_{sc}}} s + (\frac{1}{\omega_{i_{sc}}} s)^2} \quad (15)$$

with $\tau_{i_{fc}} = \frac{2\xi_{i_{fc}}}{\omega_{i_{fc}}}$, $k_{i_{fc}} = \tau_{i_{fc}} \frac{\omega_{i_{fc}}^2 L_{fc}}{V_{bus}}$, $\tau_{i_{sc}} = \frac{2\xi_{i_{sc}}}{\omega_{i_{sc}}}$, $k_{i_{sc}} = \tau_{i_{sc}} \frac{\omega_{i_{sc}}^2 L_{sc}}{V_{bus}}$ and $\omega_{i_{fc}}$, $\omega_{i_{sc}}$ are the desired natural frequencies for each loop.

C. Voltage loop

Considering that the inner current loops are much faster than the voltage loop, the DC bus voltage regulation can be done using $i_{sc,ref}$ as control signal. Therefore, it can be considered that the SC current has already reached its steady state value ($i_{sc,ref}$). By defining the virtual control variable $I_{sc}^* = (1 - \alpha_2) I_{sc,ref}$ [3], the DC bus voltage dynamics is expressed as:

$$V_{bus}(s) = \frac{1}{C_{bus}s} ((1 - \alpha_1) I_{fc}(s) + I_{sc}^*(s) - \frac{P_{load}}{V_{bus}}) \quad (16)$$

A PI-controller, $H_{PI,v_{bus}} = k_{v_{bus}} (1 + \frac{1}{\tau_{v_{bus}} s})$, is designed to regulate V_{bus} to its reference value $V_{bus,ref}$. Then, the closed loop transfer function has the following form:

$$H_{v_{bus}} = \frac{V_{bus}}{V_{bus,ref}} = \frac{1 + \tau_{v_{bus}} s}{1 + 2 \frac{\xi_{v_{bus}}}{\omega_{v_{bus}}} s + (\frac{1}{\omega_{v_{bus}}} s)^2} \quad (17)$$

where $\tau_{v_{bus}} = \frac{2\xi_{v_{bus}}}{\omega_{v_{bus}}}$, $k_{v_{bus}} = C_{bus} \tau_{v_{bus}} \omega_{v_{bus}}^2$, $\xi_{v_{bus}}$ is the damping factor and $\omega_{v_{bus}}$ represents the closed-loop natural frequency.

IV. SIMULATION RESULTS

The two-level control structure is applied to a FC/SC multi-source system of an electric vehicle, and tested in simulation using the Artemis driving cycle shown in Fig 5. Vehicle parameters are shown in Table I, while the multi-source system and the DC bus parameters are given in Table II.

TABLE I
VEHICLE PARAMETERS

M [kg]	S [m ²]	ρ_{air} [kg · m ⁻³]	C_x	C_r	α [°]
700	1.8	1.225	0.3	0.01	0

The parameters of the PI controllers are tuned such that the current control loops are at least 10 times faster than the DC voltage control loop. Thus, for DC bus voltage regulation, the currents have already reached their steady state values. The following closed-loop time responses are

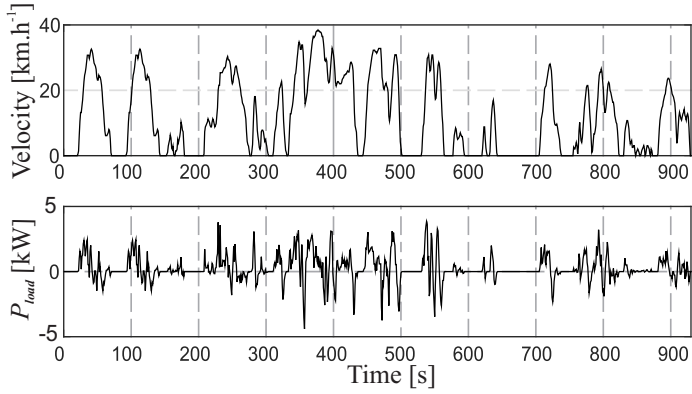


Fig. 5. Artemis driving cycle

TABLE II
MULTI-SOURCE SYSTEM AND DC BUS PARAMETERS

Multi-source system		DC bus
$L_{fc} = 2 \cdot 10^{-4}$ [H]	$\eta_b = 0.95$	$C_{bus} = 1.2 \cdot 10^{-3}$ [F]
$L_{sc} = 1 \cdot 10^{-4}$ [H]	$\eta_{rp} = 1$	$v_{bus,ref} = 50$ [V]
$C_{sc} = 130$ [F]	$SoE_{max} = 1$	
$P_{fc,max} = 3$ [kW]	$SoE_{min} = 0.2$	
$P_{fc,min} = 0$ [kW]	$E_{sc,max} = 20$ [kJ]	

used: $t_{res,i_{fc}} = t_{res,i_{sc}} = 0.5$ ms, $t_{res,v_{bus}} = 10$ ms and the damping factors are chosen such that the control loops are critically damped ($\xi_i = 0.7, i = i_{fc}, i_{sc}, v_{bus}$). Therefore, the PI-controllers parameters that ensure the previous specifications are: $k_{i_{fc}} = 5.83 \cdot 10^{-2}$, $k_{i_{sc}} = 2.92 \cdot 10^{-2}$, $k_{v_{bus}} = 1.03 \cdot 10^{-4}$, $\tau_{i_{fc}} = 1.4 \cdot 10^{-4}$, $\tau_{i_{sc}} = 1.4 \cdot 10^{-4}$, $\tau_{v_{bus}} = 0.0025$.

ECMS algorithm is applied using a sampling time of 1 s. The equivalent factors s_0 and s_1 are chosen in order to guarantee that the SC state of energy (SoE) stays inside the interval $[SoE_{min}, SoE_{max}]$ and that its values at the beginning and at the end of the cycle are equal. Fig. 6 illustrates the SoE evolution using $s_0, s_1 \in [1.4, 1.7] \cdot 10^{-5}$, values that have been tuned by multiple tests. A 2.5% error between the SoE initial and final values is observed. On the other hand, the fuel consumption over the driving cycle has been computed in two cases: for the considered FC/SC multi-source system and when only the fuel cell is connected to the DC bus, in order to show the supervision level contribution. The hydrogen mass consumption $m_{H_2} = 14.1$ g has been obtained, showing a fuel economy of 21%, compared to the use of only one power source.

Tacking into account the fuel cell slow dynamics, it is important to evaluate the system performance on the beginning of the driving cycle. Fig. 7 and Fig. 8 show the FC and the SC current regulation responses over the time intervals $t \in [20, 120]$ s. The reference current $i_{fc,ref}$ is computed at each sampling step by the supervision system and $i_{sc,ref}$ is determined by the DC voltage control loop. The simulation results show that the specified closed-loop response time is satisfied without steady state-error.

DC bus voltage evolution is illustrated in Fig. 9. The reference value of 50 V is maintained over the whole cycle, with voltage peaks during load variations. In Fig. 10, the power supplied by the FC/SC multi-source system is compared to the load power. The power demand is delivered in 20 ms with a maximum overshoot of 9%.

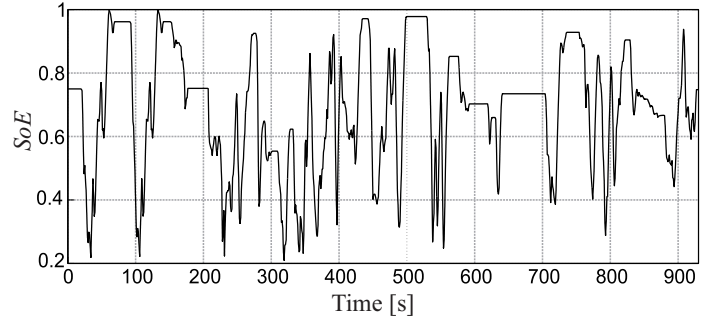


Fig. 6. Supercapacitor state of energy (SoE)

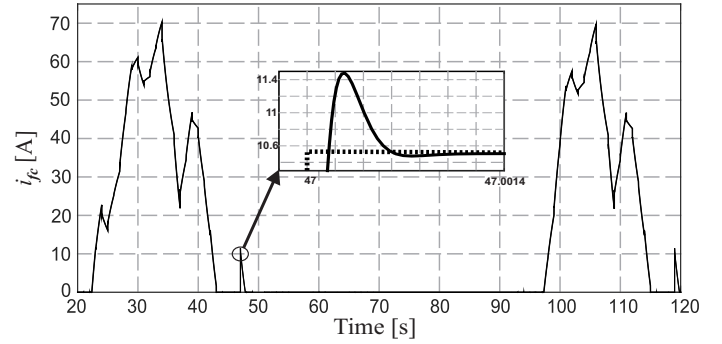


Fig. 7. Fuel cell current (solid line), fuel cell reference current (dash-dot line).

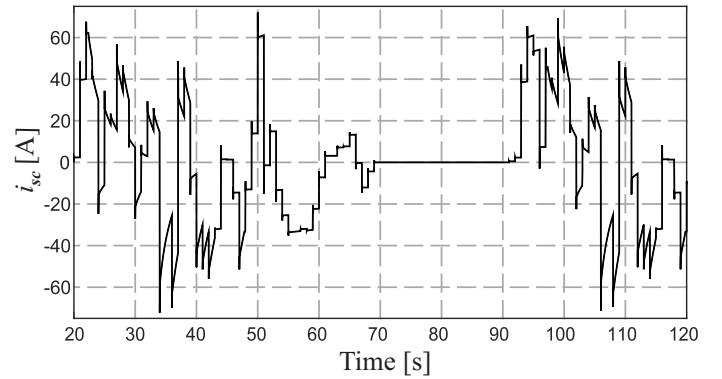


Fig. 8. Supercapacitor current (solid line), supercapacitor reference current (dash-dot line).

V. CONCLUSIONS

A two-level control structure has been elaborated for electric vehicles, which assures the DC bus voltage regulation while optimizing the system global efficiency by minimizing the hydrogen mass consumption. The simulation results illustrate

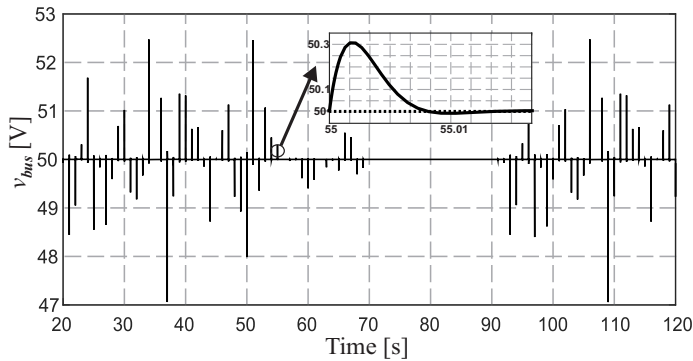


Fig. 9. DC bus voltage (solid line), DC bus reference voltage (dash-dot line).

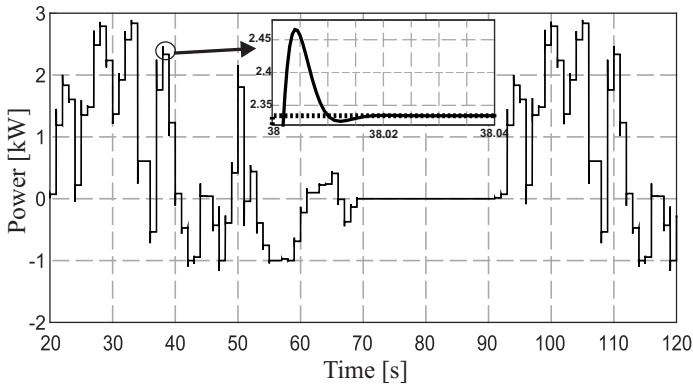


Fig. 10. Power supplied by the multi-source system (solid line), power demand (dash-dot line)

good performances of the control loops and a significant fuel economy due to supervision system based on equivalent consumption strategy.

As perspectives of this work, the equivalent consumption minimization strategy could be improved in order to simplify the equivalence factors tuning for different driving cycles. Also, the supervision level could consider the fuel cell dynamics by using a dynamic model of the FC. Besides this, a different on-line optimization-based method could be employed, such as model predictive control. Finally, the energy management control system could be implemented and evaluated on an embedded system.

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