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Energy Management for Fuel Cells/Supercapacitor Power System

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***Abstract*— In this paper is proposed a management energy for fuel cells/supercapacitor hybrid power system sources. The management energy is based on a control strategy of flows energy. The energy flows are provided by the two DC/DC converters. The dc/dc boost converter allows a single direction of the energy flow, which is from the PEMFC to the DC bus, and fixes its voltage at a constant value required by the electrical load. The energy flows in both directions: from the SC to the DC bus and from the DC bus to the SC are provided by the DC/DC buck-boost converter. The control strategy is based on the determination of the references of the current in each source relative to the state of the electrical load (acceleration or braking) and also to the constraints on the PEMFC.**

***Keywords*—Fuel Cells, Supercapacitors, Hybrid System, Energy Management, Control.**

I. INTRODUCTION

To meet environmental standards, the electric vehicle has significant potential for development. A promising solution of using the Polymer Electrolyte Membrane Fuel Cell (PEMFC) because of its relatively lightweight and small size, ease of construction and low operating temperature. Moreover, on the technological aspect, these PEMFCs have yet to be improved on a number of points: lowering their cost, increasing their lifespan and using a quick start in very cold conditions [1, 2]. However, from a system point of view, the PEMFC generators have insufficient intrinsic characteristics (long start-up time, slow dynamics, reversible failures, etc.) and no reversibility in power, which do not allow them to meet the requirements directly automotive applications [3, 4]. It is therefore advisable to add to the generator PEMFC an auxiliary power source capable both of providing or recovering the impulse energy (acceleration, braking) and of avoiding the temporary failures of the PEMFC. At present, supercapacitors (SCs) have reached a stage of development (energy efficiency, long lifetime, high mass power, low cost) that enable them to meet the requirements of auxiliary storage in an automotive application, thereby opting for vehicle performance to PEMFC [5-7]. The PEMFC delivers the average power required for electric traction (vehicle autonomy), while starting, acceleration and regenerative braking, which involve high instantaneous power exchanges, are ensured with high efficiency by SCs, thus reducing stresses on the main energy source [6]. Depending on the association of the different constituents, the architectures of the hybrid system can be classified into three categories [8-10]: series, parallel and cascade. The parallel architecture is the most advantageous structure [9, 10], it has in particular lower constraints on the components, an ease of energy management and an increased reliability.

This paper discusses the parallel architecture for the hybridization of a PEMFC as a primary source and a SC module as a secondary source, each connected to a static converter. The proposed system is modeled and simulated under Matlab/Simulink package and obtained results are presented and commented to show the effectiveness of using hybrid PEMFC/SC system.

II. STRUCTURE AND MODELING OF HYBRID SYSTEM

A. *Structure of Hybrid System*

Referring to [11], Fig. 1 provides the structure of the proposed hybrid power system. The complete architecture is prepared in DC bus. Fuel cells (FCs) and SCs are the subsystems of DC bus. While the load is an electric vehicle system, and the power transfer happens between these components via an

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energy management, which based on control energy flows by controlling the DC/DC converters. The SC/Buck-Boost converter assembly is connected to the DC bus via inductor L_s, its function is to ensure that the current does not exceed the limit value, and not to allow the SC to reach the voltage of the DC bus [12].

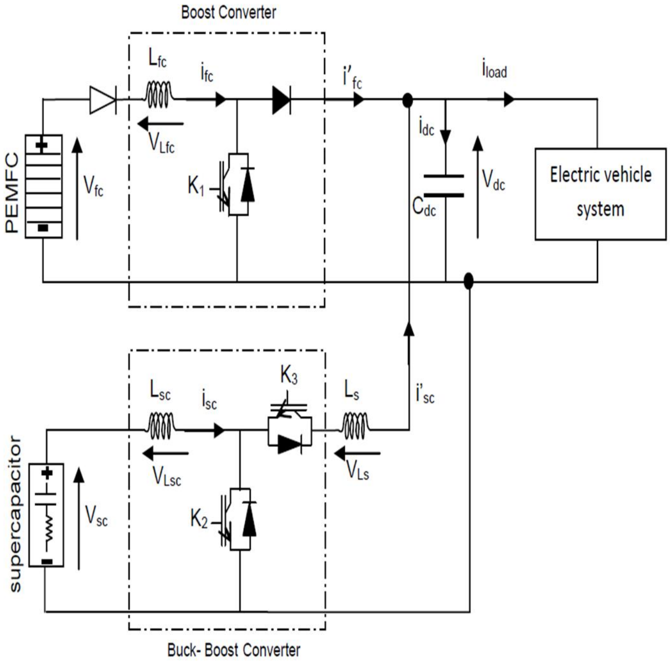

Fig. 1 Structure of the hybrid power system

B. Modelling of PEMFC

The model considered here is that of Chamberlin-Kim [13], which describes the cell voltage as a function of the current density (j), with five empirical parameters as indicated in equation [14]:

$$V(J) = E_0 - b \times ln(J) - R_s.J - m.\exp(n.J) \quad (1)$$

In this work a PEMFC of 1.2 kW nominal power is chosen and the simulation results of the characteristics (V-I) and (P-I) are presented in Fig. 2 and Fig. 3. The PEMFC parameters are given in Table 1.

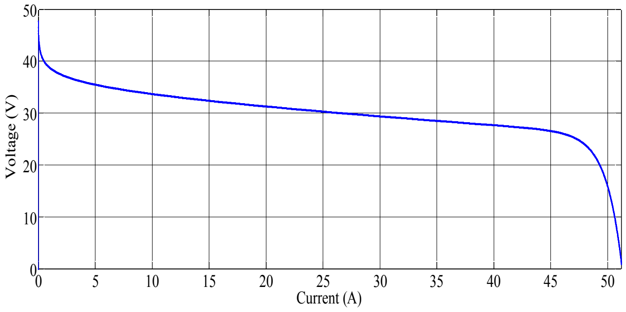

Fig. 2 Voltage-Current characteristic of PEMFC

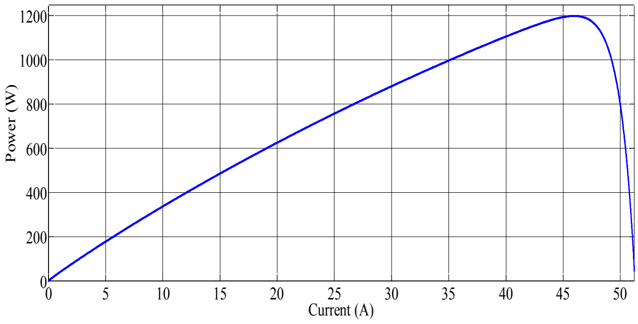

Fig. 3 Power-current characteristic of PEMFC

TABLE I

PEMFC PARAMETERS [2] [11]

Parameters	Values
Vaccum tension	45 V
Nominal voltage	26 V
Nominal current	46 A
Maximum current	50 A
Area	50 cm^2

C. Modelling of supercapacitor

The supercapacitor (SC) is also known as electrochemical double-layer capacitors, and it uses the double layer to store electric energy in both electrostatic storage and electrochemical storage [15]. The SC model is shown in Fig. 4, it's the most simplified and the model of the constructors [16]. The model includes a capacitor, an equivalent series resistance (ESR) representing the charging and discharging losses. The terminal voltage of the SC, v_{sc}, and the capacitor voltage, v_c, can be expressed as follow:

$$v_{sc} = v_c + R_s i_{sc} \quad (2)$$

$$v_c = \frac{1}{c}\int i_{sc} dt \quad (3)$$

Where:

i_{SC} is the SC current, V_{sc} is the SC voltage, C the SC capacitance which is equal to 2700F and R_s Equivalent Series Resistance (ESR) of the SC which is equal to 0.8 mΩ.

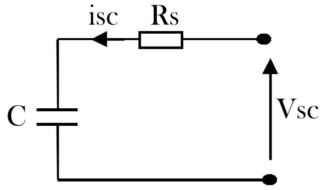

Fig. 4 Supercapacitor model

The SC model is implemented in Simulink. The charge and discharge current applied to the SC is shown in Fig.5. The result of the voltage response to the applied current is given in Fig.6.

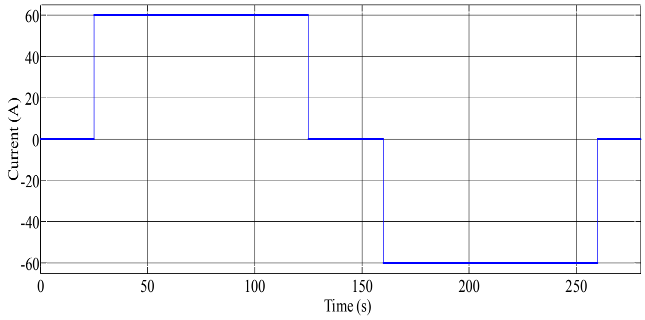

Fig. 5. Applied charge-discharge current waveform to the supercapacitor

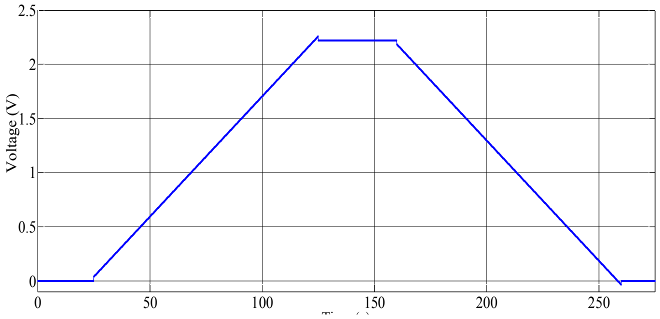

Fig. 5. Voltage response of the supercapacitor for applied current

D. *Modelling of the boost and buck-boost converters*

The PEMFC is connected to the DC bus by means of a unidirectional DC/DC converter, and the SC count to it is connected via a bidirectional DC/DC converter. The set can be modeled with the following equations:

$$C_{dc}\frac{dv_{dc}}{dt} = \left(1-d_{fc}\right)i_{fc} + (1-d_{sc})i_{sc} - i_{load} \quad (4)$$

$$L_{fc}\frac{di_{fc}}{dt} = v_{fc} - \left(1-d_{fc}\right)v_{dc} \quad (5)$$

$$L_{sc}\frac{di_{sc}}{dt} + L_s\frac{di'_{sc}}{dt} = v_{sc} - (1-d_{sc})v_{dc} \quad (6)$$

Where:

V_{dc} is the DC bus voltage, V_{fc}: is the PEMFC voltage, i_{load} is the load current, i_{fc} is the PEMFC current, i'_{sc}: is the SC current delivered by the buck-boost converter, C_{dc} is the DC bus capacitance, L_{fc} is the boost inductor and L_{sc} is the buck-boost inductor.

III. STRUCTURE MANAGEMENT AND CONTROL OF HYBRID SYSTEM

A. *Management of the Hybrid System*

The management strategy is based on the determination of the references powers in each source of the system. The reference power in the PEMFC is determined from the power profile of the load and taking into account the dynamic limit and maximum power of the PEMFC (Fig. 7.). The dynamic limit is represented by a transfer function of order 1, which τ is the time constant. The reference power in the SC is determined by subtracting the power profile of the load from the reference power of the PEMFC.

The references powers are then used to determine the reference currents: $i_{fc\text{-}ref}$ of the PEMFC, $i_{sc\text{-}ref}$ and $i'_{sc\text{-}ref}$ of the SC.

B. *Control of the Hybrid System*

To adapt the output voltage of the PEMFC to that imposed by the load chains for the DC bus, a boost DC/DC converter is used. The control is ensured with a proportional integral (PI) by regulation of the PEMFC's current (Fig. 8).

In addition, a feed-forward controller is employed, which will allow a good dynamic response of the system and an effective maintenance of the DC bus voltage at its reference.

Tow controllers proportional integral (PI) are used to ensure the regulation of the SC's currents (Fig.9.).

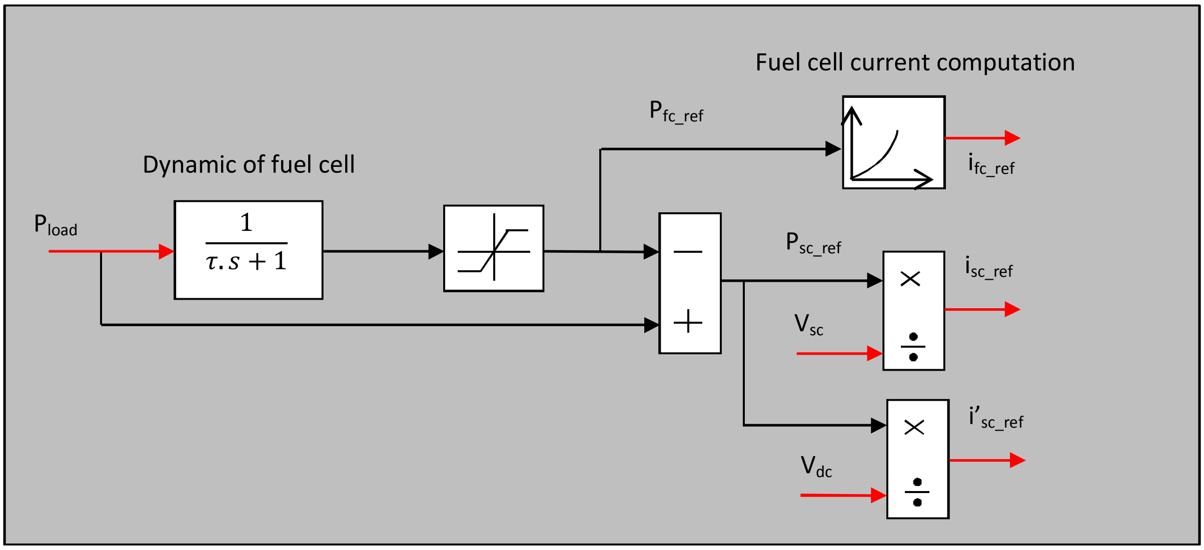

Fig. 7. Computation of powers and currents references of the PEMFC and the Supercapcitor.

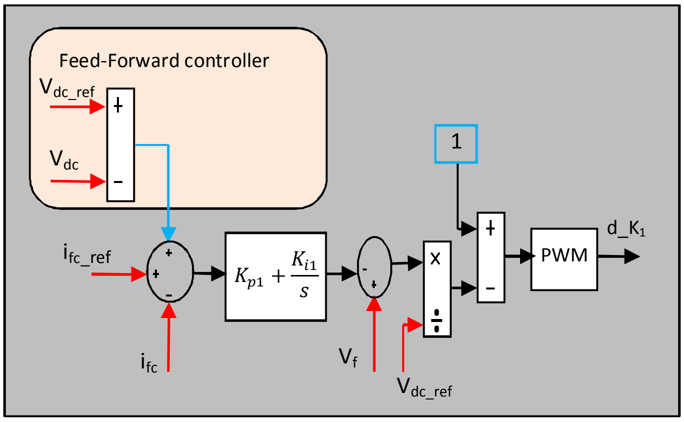

Fig. 8. Control loop of the DC/DC boost converter of the fuel cell.

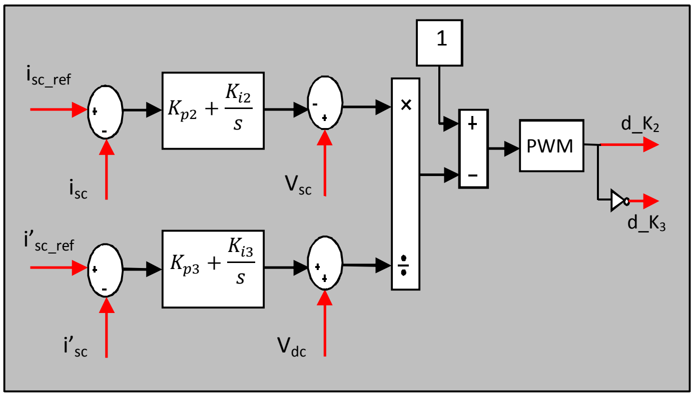

Fig. 9. Control loop of the DC/DC buck-boost converter of the Supercapcitor

The equations with the controllers are given as follow:

$$V_{m\_fc} = -\left(K_{p1} + \frac{K_{i1}}{s}\right)\left(i_{fc\_ref} - i_{fc}\right) + V_{fc} \qquad (7)$$

$$V_{m\_sc} = -\left(K_{p2} + \frac{K_{i2}}{s}\right)\left(i_{sc\_ref} - i_{sc}\right) + V_{sc} \qquad (8)$$

$$V'_{m\_sc} = \left(K_{p3} + \frac{K_{i3}}{s}\right)\left(i'_{sc\_ref} - i'_{sc}\right) + V_{dc} \qquad (9)$$

Where:

V_{m_fc} is the modulated voltage of the Boost converter, V_{m_sc} and V'_{m_sc} are the two modulated voltages of the Buck-Boost converter.

These modulated voltages serve to determine the duty cycles of the two converters. While the PWM generates the control signals d_K1, d_K2 and d_K3 of the IGBTs K1, K2 and K3 respectively, with the control signal d_K3 is the inverse of the control signal d_ K2.

IV. STRUCTURE MANAGEMENT AND CONTROL OF HYBRID SYSTEM

In this simulation part, a dynamic load is considered about 1800 W nominal power. It is represented Fig.10. This profile is chosen so as to have instantaneous power demanded by the load (through the various operating regimes: acceleration, deceleration and braking), which will make it possible to check the dynamics of the system.

In order to have a nominal voltage of the SC of 34V, serialization of several supercapacitors is necessary and the SC operating voltage is between 17V and 34V. At start-up, the SC voltage is charged at 26V and will oscillate without control around this value during the entire operating time of the system..

In acceleration the SC supplies energy, which makes its voltage decrease, in deceleration and braking the SC receives energy, which makes it possible to increase its voltage. The DC bus voltage V_{dc}, is well maintained at its reference of 48V (Fig. 11) despite significant and instantaneous variations in the power demanded by the load and even in braking regime. The use of SC decreases also the fluctuation of the DC bus voltage during the fast change of the load profile. The current in the PEMFC is represented in Fig.12. Two zooms (Figs.13 and 14) show that FC current follows its reference. SC current is illustrated in Fig.15.

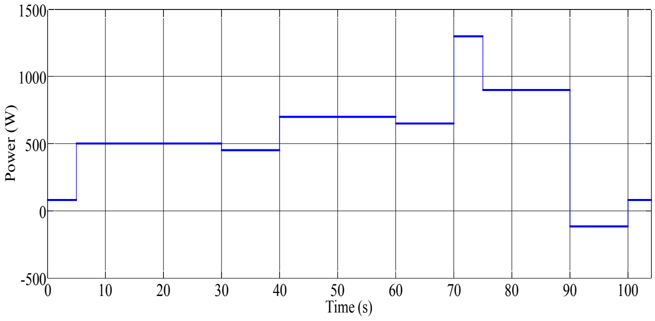

Fig. 10. Load power profile.

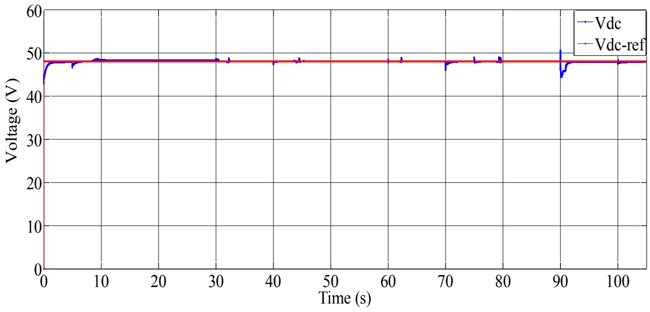

Fig. 11. DC bus voltage

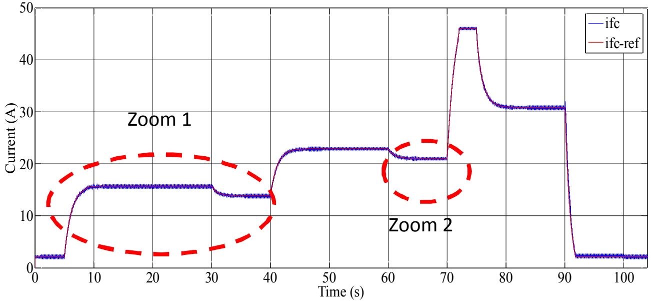

Fig. 12. PEMFC current.

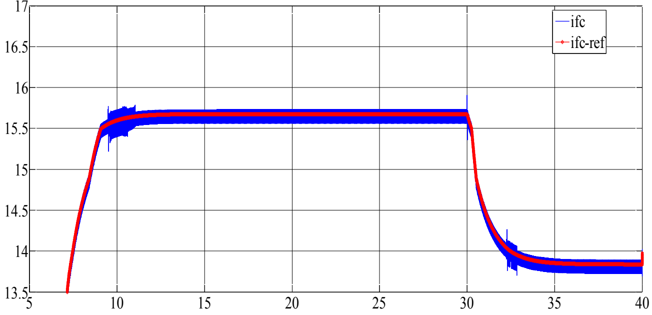

Fig. 13. Zoom 1 on PEMFC current.

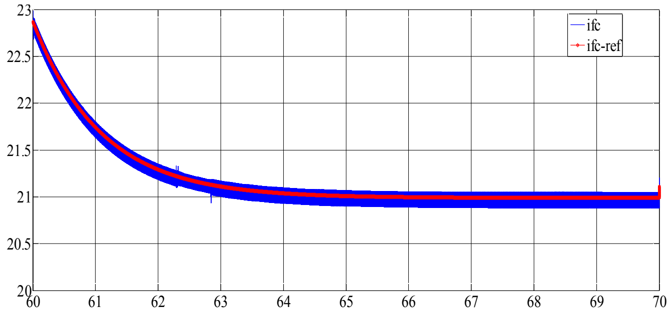

Fig. 14. Zoom2 on PEMFC current.

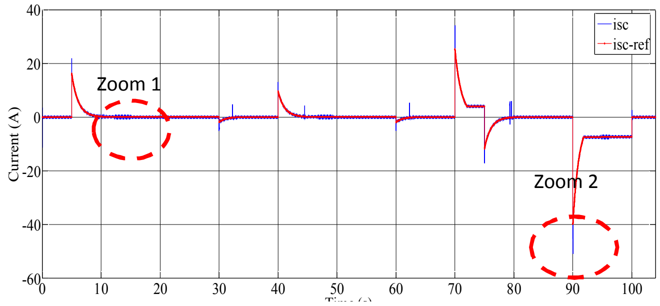

Fig 15. Supercapacitor current.

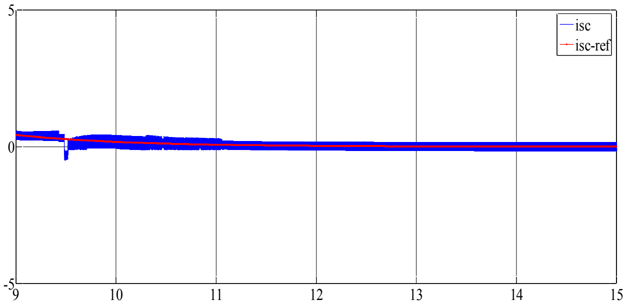

Fig. 16. Zoom 1 on Supercapacitor current.

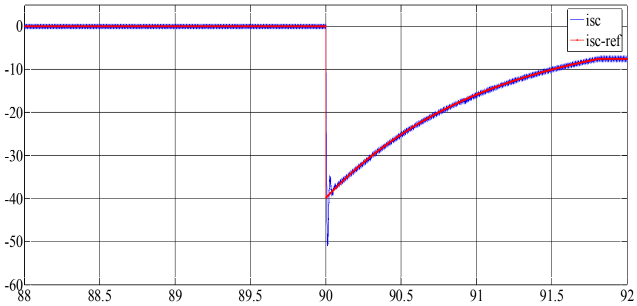

Fig. 17. Zoom 2 Supercapacitor current.

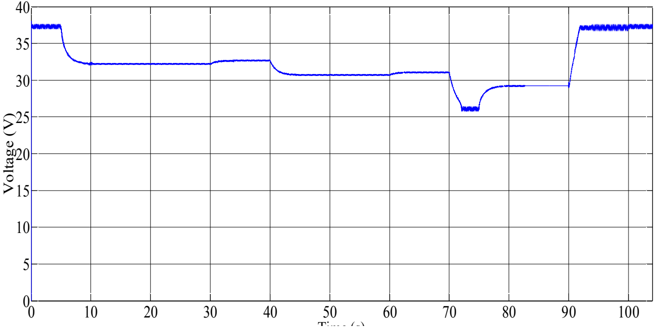

Fig. 18. PEMFC voltage

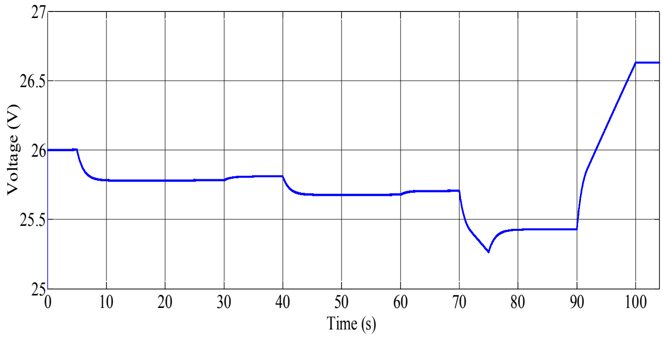

Fig. 19. Supercapacitor voltage.

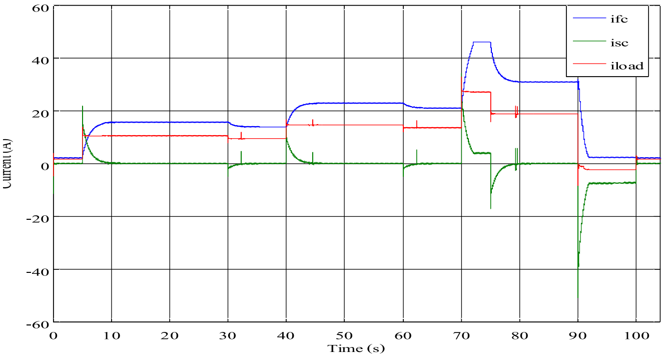

Fig. 20. Currents waveforms

It is observed that during rapid variation (Figs. 16 and 17), the current follows rapidly its reference. PEMFc and CS voltages are also given in Figs 18. and 19. It is noticed that current follows its references well, which makes it possible to have stable and small oscillations of the voltages in the SC and in PEMFC, which leads to conclude on the good efficiency of the used control for the two currents (SC and PEMFC).

V. CONCLUSIONS

In this article, an energy management strategy for FC/SC power system has been proposed. Among the various existing structures, we have opted for the parallel structure due to the advantages that it presents. The control technique used is based on the regulation of the currents in the two energy sources, and the regulators used are simple proportional integral (PI). The load is dynamic (electric vehicle system) and the power profile is chosen to study the three speeds: acceleration, deceleration and braking. The system simulation program is implemented in Matlab/Simulink. The simulation results clearly showed a good dynamic response and a stability of the system, which means that the control used is efficient and allows the flow of energy appropriately and thus a good operating of the studied system.

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