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Energy Management Algorithm for a Fuel Cell-Battery- and Ultra-capacitor in Electrical Hybrid Vehicle

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***Abstract*—This paper describes an energy management algorithm for an hybrid vehicle. The proposed hybrid vehicle presents a fuel cell as the primary energy source and (battery and ultra-capacitor) as the secondary energy sources. The main source is electrochemical energy conversion device which directly produce electricity, water and heat by processing hydrogen and oxygen. It must produce the necessary energy to the electrical vehicle. The secondary energy source produces the lacking power in acceleration, and absorbs excess power in braking operation. The addition of a supercapacitor and battery in fuel cell-based vehicles has a great potential because permits a significant reduction of the hydrogen consumption and an improvement of the vehicle efficiency. The electrical vehicle is composed of a traction motor drive, inverter, the energy sources and the power conditioning. The last is composed of three converters: a boost interfacing the fuel cell and two buck boost interfacing respectively the battery and the ultracapacitor. The energy management algorithm determines the currents of the converters in order to regulate accurately the power from the three electrical sources. In this paper, the proposed algorithm is evaluated for the New European driving cycle (NEDC).**

***Keywords*—Hybrid vehicle; Fuel cell; Battery; Ultra-capacitor; Converter; Energy management.**

I. INTRODUCTION

New zero emission vehicles are an attractive solution to reduce pollutant, noise and CO_2 emissions. Electric hybrid vehicles are proposed as an effective and potential solution to ensure environmentally friendly operation using clean energy sources as hydrogen [1]. Furthermore, hybrid vehicles take advantage of the higher energy efficiency of electrical traction systems [2]. Hybrid electric vehicles architecture includes two or more energy sources with their associated energy converters. Thus, there are a lot of electrical hybrid vehicles available now with different types of storage system. Typically, such these vehicles are equipped with a fuel cell, an electric motor and an electrical storage system, such as batteries or/and supercapacitors. Fuel cell (FC) is an energy source that converts the chemical energy into electrical energy. Actually, it becomes acknowledged as one of the most promising technologies to meet the energy requirements. However, this energy source has some known technical limitations. Indeed, it has a slow power transfer and a high cost per watt. Besides, it is characterized by a slow power transfer rate, especially, in transitory situations. For this reason, fuel cells do not be used alone in electrical traction to satisfy the load demands [3], [4]. Therefore, the automotive industry is undertaking to adapt to these constraints by using storage systems to satisfy with fuel cells the power demand in traction applications. Storage systems are usually used as secondary energy sources which produce the lacking power in acceleration, and absorb excess power in braking function. Commercially battery (BAT) presents many disadvantages when it is used alone as storage system in electric vehicle. Indeed, it presents long recharging time and a high time response in transient state [5]. Besides, battery performances may considerably be affected by significant current discharges. For this reason, we have associated to the battery a pack of super capacitors (SC) that can be used complementary to the battery and the fuel cell to satisfy the vehicle power requirement [5], [6]. Compared with fuel cell and battery, ultracapacitor presents a lower energy density and a higher power density. For a multi-source system, there are various converters connection topologies for combining the various elements of the power source and the load. The selected solution must be efficient, reliable, and compact and must have a low cost [3], [7]. To ensure a better energy management between the three energy sources, we proposed in this work an energy management algorithm for a hybrid vehicle. The energy management algorithm gives the currents of converters in order to regulate accurately the power from the three electrical sources. To distribute the energy between the two storage systems, we based on the limitation of battery current.

II. SYSTEM DESCRIPTION

Figure 1 shows the overall scheme of the studied hybrid system topology. This system is composed of three energy sources: fuel cell, battery and Supercapacitors. For the fuel cell, a DC / DC converter is associated therewith to increase the voltage level to the desired value and to keep it constant at its output. A DC/DC bidirectional current converter thus increases a constant voltage from a variable voltage is associated at the battery. Similarly for supercapacitors, they are associated with a reversible converter for transferring power in the both directions.

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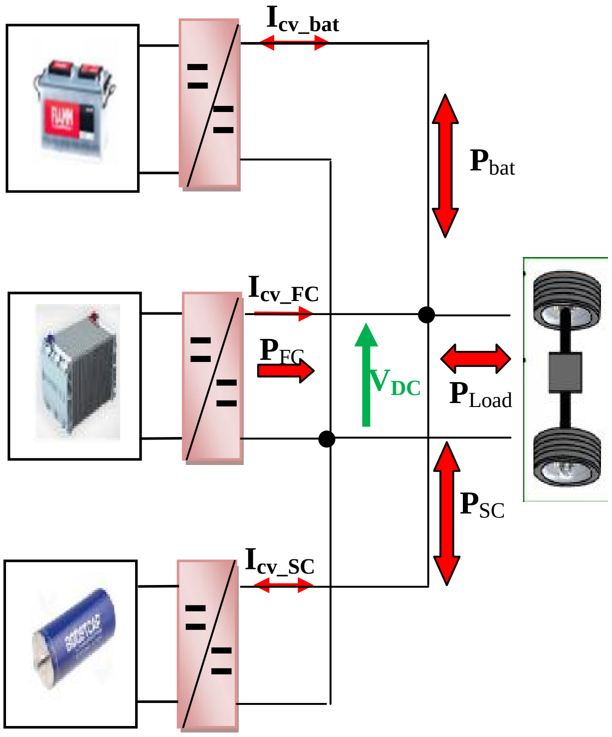

Fig. 1 Electrical system Scheme for hybrid vehicle

The load power is expressed by the following equation:

$$P_{Load} = (\frac{1}{2}\rho_{air} SC_x v^2(t) + MgC_r + M\frac{dv(t)}{dt})v(t) \qquad (1)$$

Where
M: is the vehicle mass.
v(t):vehicle Speed.
SC_x: Frontal area.
C_r: Rolling resistance coefficient.
ρ_{air} : Air Density.
g : gravitational constant.

III. ENERGY SOURCES

A. Fuel Cell Model

A fuel cell is an energy conversion system that converts chemical energy into electrical energy without any thermal or mechanical process. The operating principle of a fuel cell is described by a chemical reaction that reacted hydrogen and oxygen to produce electricity, heat and water, according to the chemical reaction given by (2), [8].

$$2H_2 + O_2 \rightarrow H_2O + electricity + heat \qquad (2)$$

There are many fuel cell models; each model has its own specificities and benefits, according to the phenomena studied. The chosen model should be simple and accurate. Indeed, this work presents an electrochemical model which can be used to predict the fuel cell behavior in static and dynamic conditions [9].

The fuel cell voltage depends on the partial pressures of hydrogen and oxygen, the chemical reaction temperature of the membrane hydration and the output current. It is defined by the following equation, [10].

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \qquad (3)$$

Where:

E_{Nernst} : the average thermodynamic potential of each unit cell. We can present it by (4), [10].

$$\begin{aligned} E_{Nernst} &= 1.229 - 0.85 \times 10^{-3}(T - 298.15) \\ &+ 4.3085 \times 10^{-5} T[\ln(P_{H_2}) + 0.5 \times \ln(P_{O_2})] \end{aligned} \qquad (4)$$

V_{act} : the activation voltage drop.

V_{ohmic} : the Ohmic voltage drop.

V_{con}: the concentration voltage drop .

Thus, we can define the voltage V_{stack} for N cells connected in series, forming a stack. V_{stack} is defined as following:

$$V_{stack} = N.V_{FC} \qquad (5)$$

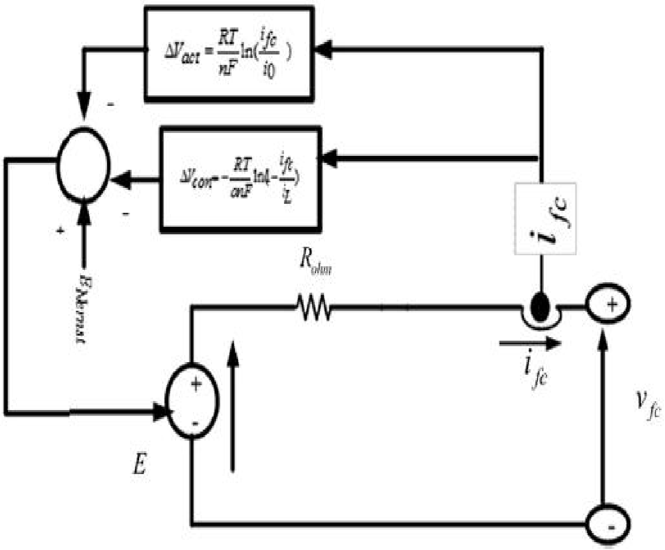

Fig. 2. Electrical model of a fuel cell.

The electrical model of a fuel cell is given by Fig.2.

The polarization curve of a fuel cell is that which represents the battery voltage as a function of current output. This curve is presented for different temperature values. FC polarization curves increase with increasing of operating temperature such as shown in Fig.3.

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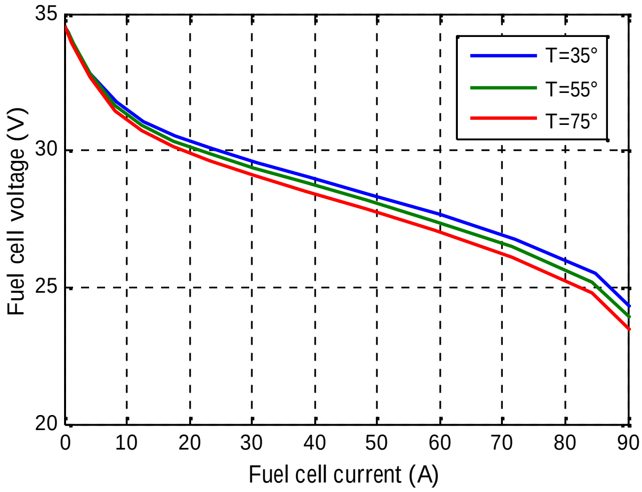

Fig. 3 Polarization curve at different temperatures.

B. Supercapacitor Model

Supercapacitors are one of the latest innovations for components dedicated to energy storage especially for embedded systems [11].

The SC electrical model is given by Fig.4. The model consists of a capacitance C_{sc} in series with an equivalent series resistance R_{sc} .

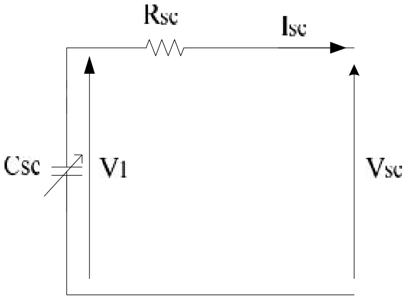

Fig. 4 Electrical model of a supercapacitor

Ultra-capacitor voltage V_{sc} is given, as function of SC current I_{sc} by the following equation:

$$V_{sc} = V_1 - R_{sc} I_{sc} = \frac{Q_{sc}}{C_{sc}} - R_{sc} I_{sc} \qquad (6)$$

Where Q_{sc} is the electricity quantity stored in a cell.

Ultracapacitor power is given by the equation (7).

$$P_{sc} = \frac{Q_{sc}}{C_{sc}} I_{sc} - R_{sc} I^2_{sc} \qquad (7)$$

Using ultracapacitors as a storage element in an electrical vehicle requires the realization of a stack consisting of several cells which N_s cells are connected in series and N_p cells are connected in parallel as presented in Fig. 5.

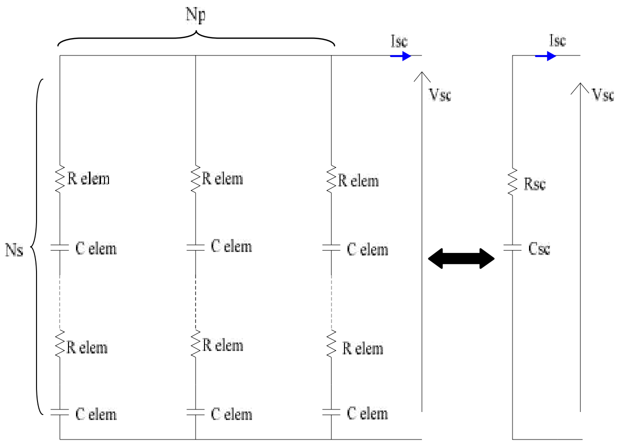

Fig. 5 Supercapacitor stack model .

The capacity and the resistance of supercapacitor stack are defined respectively by equation (8) et (9).

$$C_{sc} = C_{elem} \frac{N_p}{N_s} \qquad (8)$$

$$R_{sc} = R_{elem} \frac{N_s}{N_p} \qquad (9)$$

The voltage and current of the stack are given, as function of the element voltage and the element current, by the following equations.

$$V_{sc} = N_s . V_{elem} \qquad (10)$$

$$I_{sc} = N_p . I_{elem} \qquad (11)$$

C. Battery Model

The battery is modeled using a simple controlled voltage source in series with a constant resistance as shown in Fig. 6 [12]. The battery voltage V_{bat} is described by equation (12).

$$V_{bat} = E - R_{bat} I_{bat} \qquad (12)$$

Where

R_{bat} : is the internal resistance (Ω)

I_{bat} : is the battery current (A)

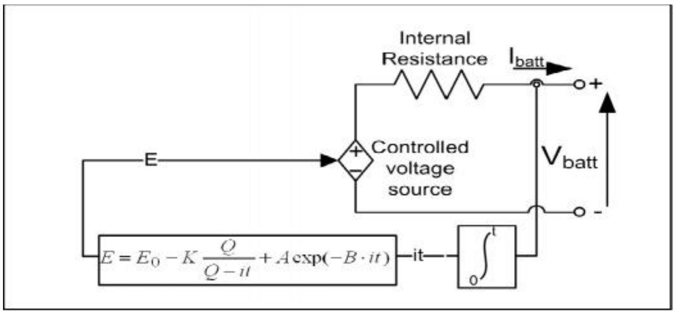

Fig. 6 Electrical Battery model

The controlled voltage source is given by (13).

$$E = E_0 - K\frac{Q}{Q_0 - \int i.dt} + A.\exp(-B\int i.dt) \qquad (13)$$

Where

E : is the no load voltage (V)

E_0 : is the battery constant voltage (V)

K : is the polarization voltage (V)

Q : is the battery capacity (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse $(\text{Ah})^{-1}$

The discharge characteristic of the battery is presented in Fig.7.

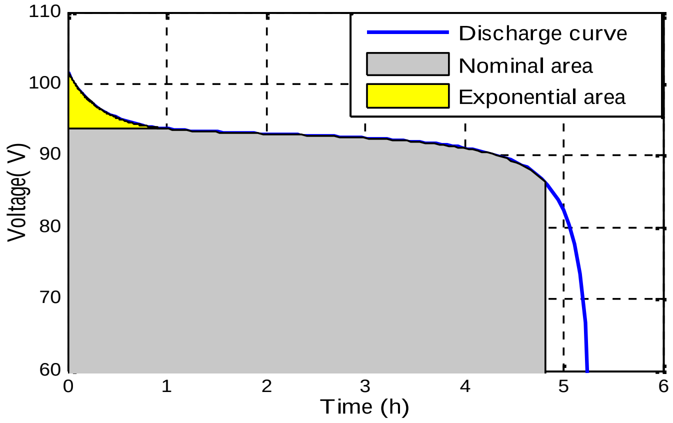

Fig. 7 Typical discharge curve of the battery.

IV. ENERGY MANAGEMENT ALGORITHM

In order to develop an energy management strategy in hybrid electrical vehicles, an approach based on the minimization of the battery current is proposed in this paper.

A. *Energetic Management Algorithm*

Energy management consists in finding the required powers values of the Fuel Cell P_{FC} , the battery P_{BAT} , and super-capacitors stack P_{SC} in order to satisfy the power demand P_d , without knowing future driving conditions.

This can be written as the following equation:

$$P_d = P_{FC} + P_{BAT} + P_{SC} \qquad (14)$$

In this paper, we proposed an energy management method whose main function is to distribute the energy flux between the three sources of the electric vehicle. The control of the energy flux between Fuel cell and storage system depends on the current demanded sign.

The rule on which we based is the limitation of the battery current. The SC provides, so, the difference between the current required by the vehicle and the sum of the current supplied by the battery, which is limited to an imposed value, and the current given by the FC such as given by equation (15). The adjustment variable will, in this case, the value of SC current.

$$I_{cv\_sc} = I_D - (I_{cv\_sc} + I_{cv\_bat\_\max}) \qquad (15)$$

The control of three converters is ensured by proportional integral regulators.

The energy management algorithm is presented in Fig. 8

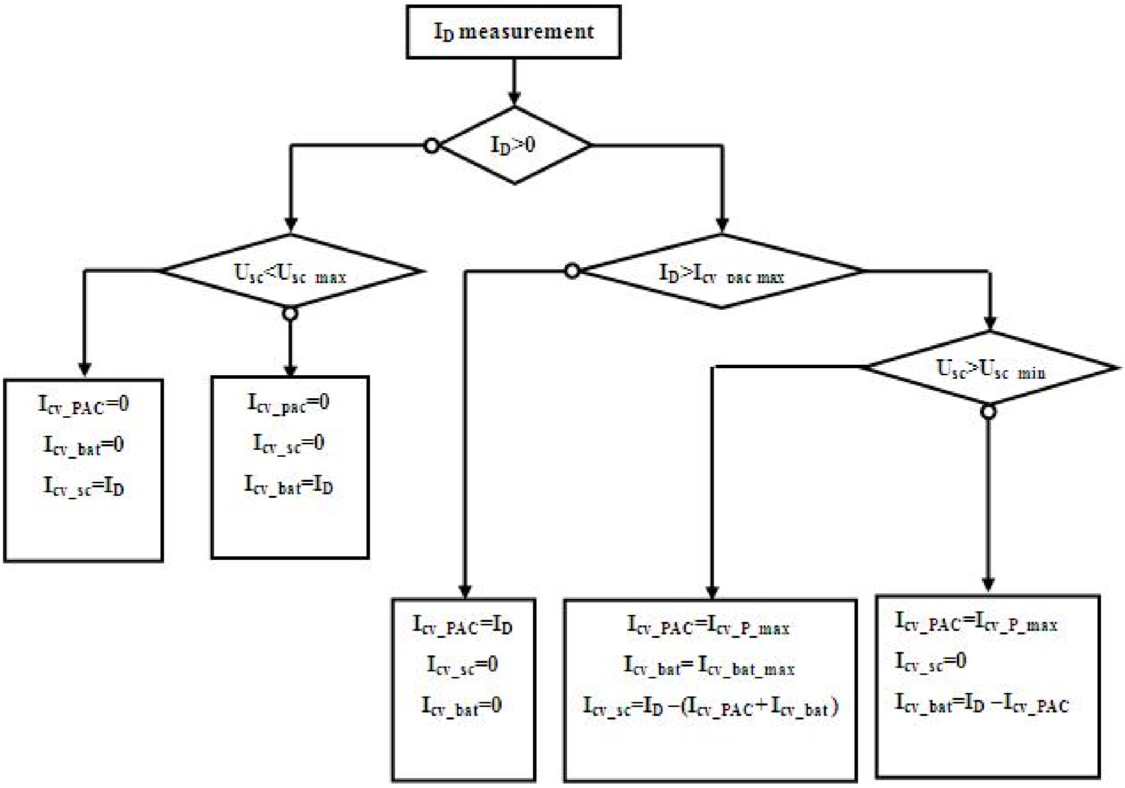

Fig. 8 The energy management algorithm.

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B. *Simulation Results*

In order to prove the proposed algorithm, some simulations were done. For this reason, a detailed model, whose parameters are given in table I, was developed using MATLAB/Simulink and mathematical models of the described system.

TABLE I
MODEL PARAMETER

Parameter	Value	Parameter	Value
M	800Kg	R_{sc}	$7.5e^{-3}\Omega$
SC_x	$1.75m^2$	R_{FC}	0.0012Ω
C_r	0.009	R_{bat}	0.0018462Ω
R_{air}	$1.2Kg/m^3$	Q	6.5Ah
g	$9.81m.s^2$	E	1.2V
C_{sc}	90F	E_0	1.4136 V

Simulation results are given in the following figures.

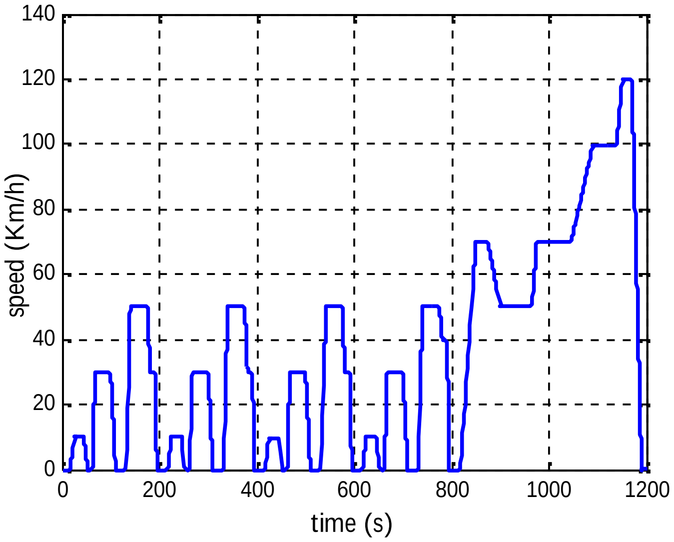

Fig. 9 Driving cycle NEDC.

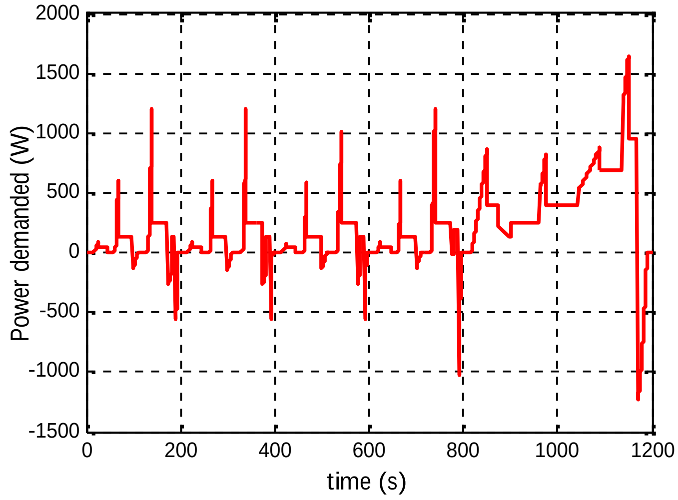

Fig. 10 Required Power.

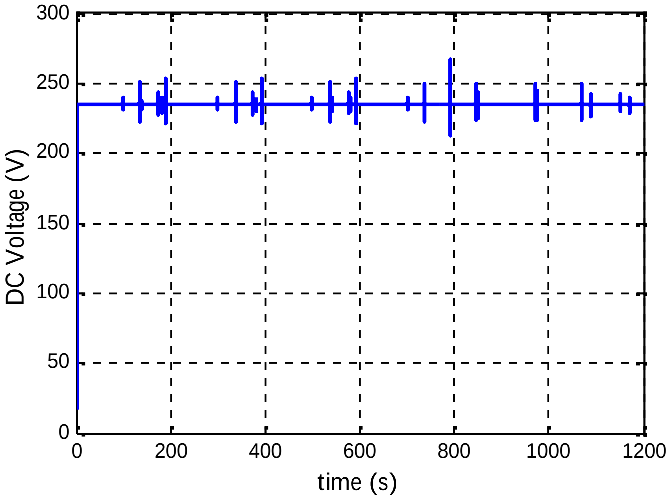

Fig. 11 DC bus Voltage.

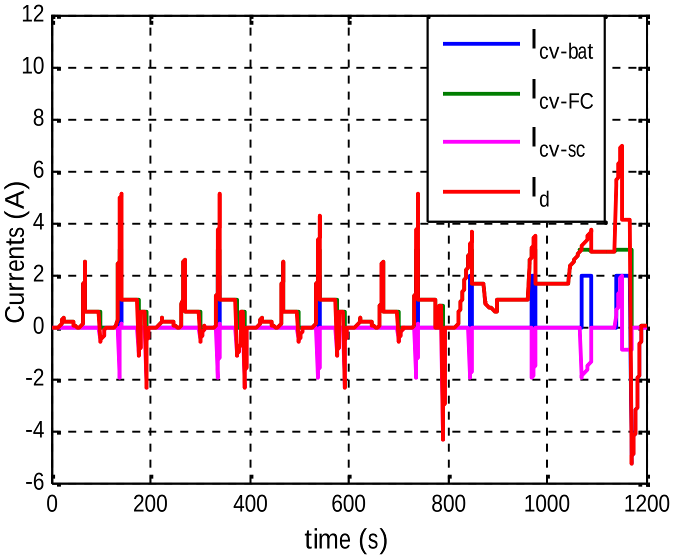

Fig. 12 Required current, Supercapacitor current, fuel cell current and battery current.

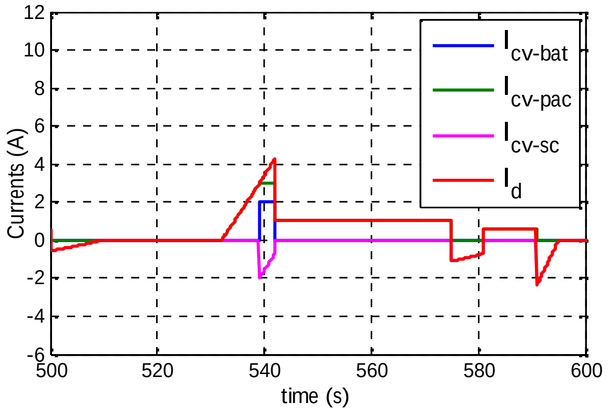

Fig. 13 Zoom in currents.

When the vehicle is braked (negative current demanded), the fuel cell is stopped. The fuel cell current is equal to zero.

The recovered energy is used to charge the storage system which is formed of two elements: battery and super-capacitors. Energy storage in these two elements must be done by a suitable energetic management. The adopted strategy is proposed to share the energy in the storage electric system between the super-capacitor and the battery in depending on the value of the super-capacitor voltage such as presented in the algorithm given by fig.8.

When the Vehicle accelerates, it demands higher power. The FC generates its maximum power and the storage system supplements to FC producing the rest of power required by the vehicle during the acceleration phase. The rule on which we based is the limitation of the battery current. The SC provides, so, the difference between the current required by the vehicle and the sum of the current supplied by the battery, which is limited to an imposed value, and the current given by the FC.

For a DC bus voltage maintained constant such as given in Fig. 11, the different currents curves, presented in Fig.12 and Fig.13, satisfy, always, the equation (14).

V. CONCLUSION

This paper has presented an algorithm to manage the power flow between different elements in an electrical hybrid power source used for electric vehicular applications. The energy source is composed of a fuel cell and a storage system which is composed by : Battery and Supercapacitor. The main advantage of the proposed control algorithm lies in the fact that it allows for managing the energy in the vehicle without algorithm commutations. The simulation results obtained, for the New European driving cycle (NEDC), had showed the efficiency of the energy management strategy adopted in this work.

REFERENCES

[1] M. Zandi, A. Payman, J. P. Martin , S. Pierfederici and B. Davat "Energy Management of a Fuel Cell/Supercapacitor/Battery Power Source for Electric Vehicular Applications''*IEEE Trans Veh. Technol.*, vol. 60, no.2, pp. 433–443, Feb. 2011.

[2] Y. Wu and H. W. Gao, "Optimization of fuel cell and supercapacitor for fuel-cell electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1748–1755, Nov. 2006.

[3] A. Payman, S. Pierfederici, and F. Meibody-Tabar, "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Convers. Manage.*, vol. 49, no. 6, pp. 1637–1644, Jun. 2008.

[4] M. C. Kisacikoglu, M. Uzunoglu, andM. S. Alam, "Fuzzy logic control of a fuel cell/battery/ultracapacitor hybrid vehicular power system," *in Proc. IEEE VPPC*, pp. 591–596, 2007.

[5] J. Bauman and M. Kazerani, "An analytical optimization method for improved fuel cell–battery–ultracapacitor powertrain," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3186–3197, Sep. 2009.

[6] J. Bauman and M. Kazerani, "A comparative study of fuelcell–battery, fuel-cell–ultracapacitor, and fuel-cell–battery–ultracapacitor vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 760–769, Mar. 2008.

[7] M. Amirabadi and S. Farhangi, "Fuzzy control of a hybrid power source for fuel cell electric vehicle using regenerative braking ultracapacitor," in *Proc. IEEE EPE*, pp. 1389–1394, 2006.

[8] J.M. Lee and B.H. Cho, "A dynamic model of a PEM cuel cell System," *IEEE Transactions on Applied Power Electronics Conference and Exposition* , pp 720-724, 2009.

[9] P. Buasri, and Z. M. Salameh, "An Electrical Circuit Model for A Proton Exchange Membrane Fuel Cell (PEMFC)," Power Engineering Society General Meeting, *IEEE* 2006.

[10] X. Qingshan, W. Nianchun, K. Ichiyanagi, K. Yukita, "PEM Fuel Cell modeling and parameter influences of performance evaluation", *IEEE* 2008.

[11] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, Sep. 2008.

[12] O. Tremblay and A. Dekkiche, "A generic battery model for the dynamic simulation of hybrid electric vehicles, " *IEEE Transactions* Vehicle Power and Propulsion Conference, pp. 284-289, 2007.