Flatness Control of Batteries/Supercapacitors Hybrid Sources for Electric Traction

M. Benaouadj[1], A. Aboubou[1], R. Saadi[1], M.Y. Ayad[2], M. Becherif[3], M. Bahri[1] and O. Akhrif[4]
[1]MSE Laboratory, Mohamed Khider Biskra University, Algeria
[2]Industrial Hybrid Vehicle Applications, France
[3]FCLab FR CNRS 3539 FEMTO-ST UMR CNRS 6174, UTBM Belfort, France
[4]GREPCI Research Group, Ecole de Technologie Supérieure, Montréal, QC, Canada.
Email: m.benaouadj@mselab.org

Abstract—**Multi-source systems are the attractive solutions in transport applications like electric vehicles. These systems are often made of the assembly of clean energy sources such as fuel cells (FC), batteries (BAT), supercapacitors (SC) and photovoltaic systems.**

In this paper, a multi-sources system using lithium-ion batteries considered as the main source (energy source) and SCs considered as the auxiliary source (power source), are in charge of the vehicle traction.

The objective is to control the DC bus voltage by absorbing the excess or supplying the lack of power during the transient, satisfying the vehicle power requirement, and by recharge the supercapacitors.

A new nonlinear control strategy based on the differential flatness approach is applied to the BAT/SC hybrid source.

The advantage of this strategy is that the state and control variables are downright estimated by the flat outputs trajectories without the need to integrate any differential equation.

Keywords-*battery; electrical vehicle; energy management; flatness control; hybrid sources; supercapacitor.*

I. INTRODUCTION

For the last two centuries, emissions of certain polluting gases from human activities have intensified the phenomenon of greenhouse effect, and leads to warmer temperatures on Earth. Consequently, the international community is mobilized to limit atmospheric concentrations of greenhouse gases with the goal of halving global emissions by 2050 [1]. Several solutions have been proposed by researchers and the Electric Vehicle (VE) appears as the most promising alternatives.

Unlike the conventional vehicles on road today which are major consumers of fossil fuels like gasoline, the EV is a vehicle propelled by electricity which can be either produced outside the vehicle and stored in a battery or produced on board with the help of Fuel Cells (FCs).

Batteries of EV become, since few years, a very attractive research area both by car manufacturers and scientific researchers. To meet targets for reducing emissions, manufacturers are moving today to vehicle hybridization. The hybridization of battery with other sources and storage devices is considered in the literature as with SCs [2], [3], [4], with FCs [5], [6], [7], and with FCs/ SCs [8], [9],[10].

II. THE HYBRIDIZATION CONCEPT

The hybridization concept is to combine two or more electrochemical devices (at least one storage element) to obtain the respective advantages of each one while minimizing their disadvantages. For example, the hybridization of an electrochemical battery (or a fuel cell) with a supercapacitor can overcome problems of low specific energy.

The hybridization, which in principle, combines the advantages of both technologies: high specific energy and power available for significant periods during seconds, allows in particular separating dimensioning average and transient power. The main interest is the resulting gain in terms of volume and mass.

By connecting primary and auxiliary sources directly on the DC bus power, the easiest hybrid configuration is obtained. In [2], this configuration is studied using batteries considered as the main source and supercapacitors acting as auxiliaries (see figure 1); the studied application was an electric vehicle. This hybrid system has the advantage of simplicity and robustness, but has a number of drawbacks: it is necessary to adapt the nominal voltages of the main source and the storage organ eliminating then the system flexibility. In addition, the power flow cannot be actively controlled and the energy of the storage element is not used completely: the power flux between the main source and the storage organ is distributed passively.

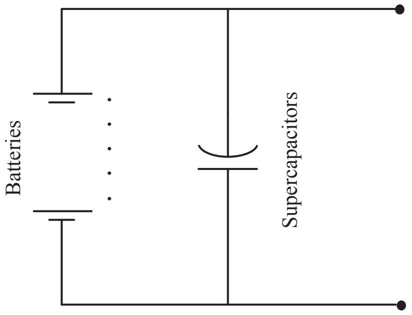

Figure 1. Direct and parallel connection of batteries and SC. [2]

Contrary to the precedent passive structure, it is possible to place a DC-DC converter between the main source and the storage element or through a DC bus. This design allows the main source and the storage element having a different

978-1-4673-6392-1/13/$31.00 ©2013 IEEE

voltage, power flow between them can be actively controlled and the energy of the storage device may be fully used.

II. CONTROL STRATEGIES OF HYBRID SOURCES

With the insertion of a DC-DC converter between the principal source and the storage device: voltages can be different, power flows can be controlled, and the storage device energy maybe fully used.

Authors in [11] proposed to ensure the control of the FC/SC hybrid sources by a controller based on passivity. The objective was to control the DC bus voltage, maintain the average energy delivered by the FC at a constant value without significant peaks, and finally recharge the SC. The obtained results show that different variations of the required power cause a high terminal of the DC bus voltage. In addition, the low dynamic of the FC is not well compensated by the SC.

In another work, authors of [12] proposed a performance comparison based on two different control strategies, namely the flatness control and a classical PI controller, to ensure the control of the FC/SC hybrid sources. The objective was to control the DC bus voltage and the SC energy. The obtained results demonstrate that flatness control proves a good convergence of DC bus voltage to its desired reference of 42V.

From these conclusions, the flatness control is chosen to manage the energy flows between the BAT, SC and the load in a vehicle application.

III. FLATNESS CONTROL APPLIED TO BAT/SC HYBRID SOURCES

A. Definition of a flat system

The differential flatness was introduced by Michel Fliess [13], [14]. A system of ordinary differential equations is said to be differentially flat if there are variables such as [15]:

$$\dot{x} = f(x, u) \tag{1}$$

$$x = [x_1, x_2, \dots, x_n]^T \qquad x \in R^n \tag{2}$$

$$u = [u_1, u_2, \dots, u_m]^T \qquad u \in R^m \tag{3}$$

$$y = [y_1, y_2, \dots, y_m]^T \qquad y \in R^m \tag{4}$$

x is the vector of random variables, u is the control vector, y is the vector of flat outputs, and $(n, m) \in N$.

- The vector y can be written as function of x and u as follows:

$$y = \emptyset\left(x, u, \dot{u}, \dots, u^{(s)}\right) \tag{5}$$

s is the finite derivatives number.

- The vectors x and u can be expressed in terms of the vector of flat outputs y and a finite number of its derivatives as follows:

$$\begin{cases} x = \varphi\left(y, \dot{y}, \dots, y^{(r)}\right) \\ u = \Psi\left(y, \dot{y}, \dots, y^{(r+1)}\right) \end{cases} \tag{6}$$

r is the finite derivatives number.

- There is no differential equation of the form:

$$0 = \varsigma\left(y, \dot{y}, \dots, y^{(k)}\right) \tag{7}$$

k is the finite derivatives number.

The flat outputs y and their derivatives provide an alternate representation of the system dynamics such that if the flat output's profiles are known as a function of time, then one can obtain the profiles of all the system states and the corresponding inputs. This property is used to calculate the flat output's trajectories.

B. Structure of the hybrid source

As shown in figure 2, the studied hybrid source includes:

- A capacitive DC bus (C_{bus}),
- Lithium-ion batteries, considered as an energy source, of an output voltage v_{BV}, providing a power P_{BV} and connected to the DC bus via a DC-DC current bidirectional converter,
- Supercapacitors, considered as a power source, of an output voltage v_{SC}, providing a power P_{SC} and connected to the DC bus via a DC-DC current bidirectional converter,
- The group "inverter + permanent magnet synchronous machine" representing the load.

C. Modeling of the multi-sources system

For the sake of simplicity, it is assumed that the DC-DC converters are perfect. The equations governing the operation of the system can be written as follows:

- Currents i_{BV} and i_{SC}:

$$i_{BV} = \frac{P_{BV}}{v_{BV}} \tag{8}$$

$$i_{SC} = \frac{P_{SC}}{v_{SCBV}} \tag{9}$$

- The electrostatic energy y_{bus} stored in the DC bus:

$$y_{bus} = \frac{1}{2} C_{bus} v_{bus}(t)^2 \tag{10}$$

- The Power y_{bus} according to P_{BV}, P_{SC} and P_{LO}:

$$\dot{y}_{bus} = P_{BV} + P_{SC} - P_{LO} \tag{11}$$

Where:

$$\dot{y}_{bus} + P_{LO} = P_{BV} + P_{SC} \tag{12}$$

$$P_{BV} = i_{BV} . v_{BV} \tag{13}$$

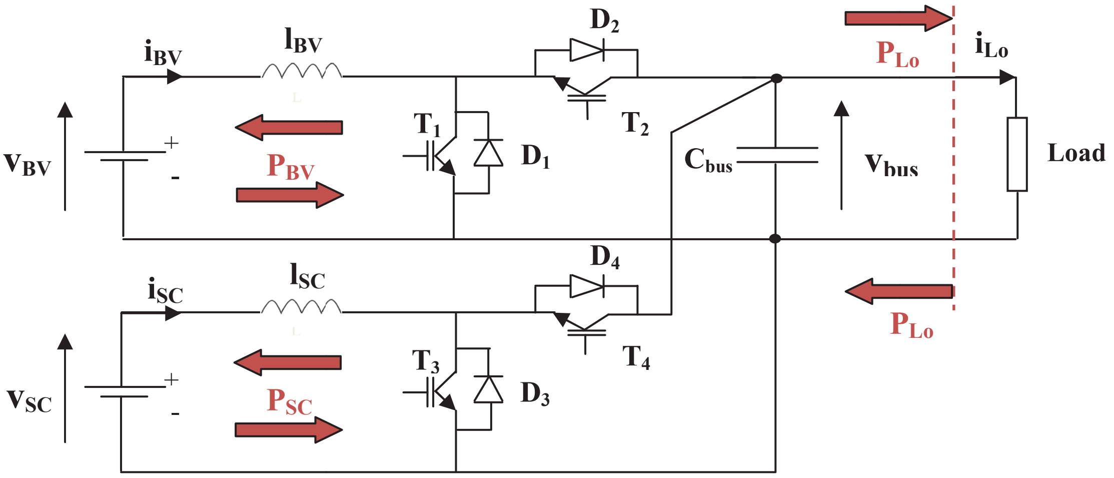

Figure 2. Structure of the multi-sources system.

$$P_{SC} = v_{SC}.i_{SC} = \sqrt{\frac{2y_{SC}}{C_{SC}}}.i_{SC} \qquad (14)$$

$$P_{LO} = v_{bus}.i_{LO} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{LO} \qquad (15)$$

- The supercapacitors energy y_{SC} is given by:

$$y_{SC} = \frac{1}{2}C_{SC}{v_{SC}}^2 \qquad (16)$$

D. Energy management and control laws

The proposed energy management is based on:

1) The use of supercapacitors to:
- Compensate the difference in power between the main source and the load power demand,
- Provide or absorb energy in order to regulate the voltage capacitive.

2) The use of lithium-ion batteries to:
- Provide or absorb the power demanded by the load,
- Absorb the energy necessary for the regulation of the capacitive voltage when SCs are fully charged.

E. Study of the flatness system

To demonstrate the flatness of the system, it is necessary to verify that it is always possible to express all the state and control variables according to the flat output variable and a finite number of its derivatives [12]. For that purpose, y_{bus} is defined as the flat output variable, P_{SC} as the control variable and v_{bus} as the state variable.

- From equation (10), the state variable v_{bus} can be written as follows:

$$v_{bus} = \sqrt{\frac{2y_{bus}}{C_{bus}}} = F_{v_{bus}}(y_{bus}) \qquad (17)$$

- From equations (12) and (15), the control variable P_{SC} can be written as follows:

$$P_{SC} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{LO} + \dot{y}_{bus} - P_{BV} = h_{P_{SC}}(y_{bus}, \dot{y}_{bus}) \qquad (18)$$

The system is flat:

$$v_{bus} = F_{v_{bus}}(y_{bus}) \text{ and } P_{SC} = h_{P_{SC}}(y_{bus}, \dot{y}_{bus})$$

F. Trajectory reference planning

One of the major advantages of the flatness is to plan the trajectory of the flat output variable. Knowing this trajectory and if the system modelling is without error, it is possible to know the evolution of the state and control variables without having to solve any differential equation [12].

Considering $y_{busréf}$ as the reference trajectory for the desired output flat variable y_{bus} (energy stored in the DC bus). The $y_{busréf}$ energy is given by:

$$y_{busref}(t) = \frac{1}{2}C_{bus}v_{busref}(t)^2 \qquad (19)$$

Fig. 3 shows in block diagram form, the generation of the reference trajectory $y_{busréf}$.

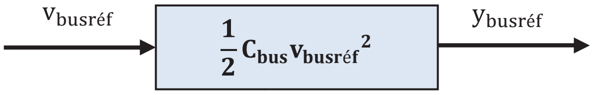

Figure 3 Generation of the trajectory reference $y_{busréf}$.

G. Control of the flat output variable towards its reference

To control the flat output variable y_{bus} to its reference $y_{busréf}$, the following behavioral law is used:

$$(\dot{y}_{bus} - \dot{y}_{busref}) + k_{11}(y_{bus} - y_{busref}) + k_{12}\int_0^t (y_{bus} - y_{busref})dt = 0 \qquad (20)$$

The choice of the coefficients of k_{11} and k_{12} is done by studying the roots of the characteristic equation as follows (roots placement):

$$s^2 + k_{11}s + k_{12} = 0 \qquad (21)$$

Those are written:

$$\begin{cases} k_{11} = 2\xi w_n \ [\mathrm{rad.s^{-1}}] \\ k_{12} = {w_n}^2 \ \ [\mathrm{rad.s^{-2}}] \end{cases} \qquad (22)$$

ξ and w_n are the desired dominant damping ratio and the natural frequency, respectively.

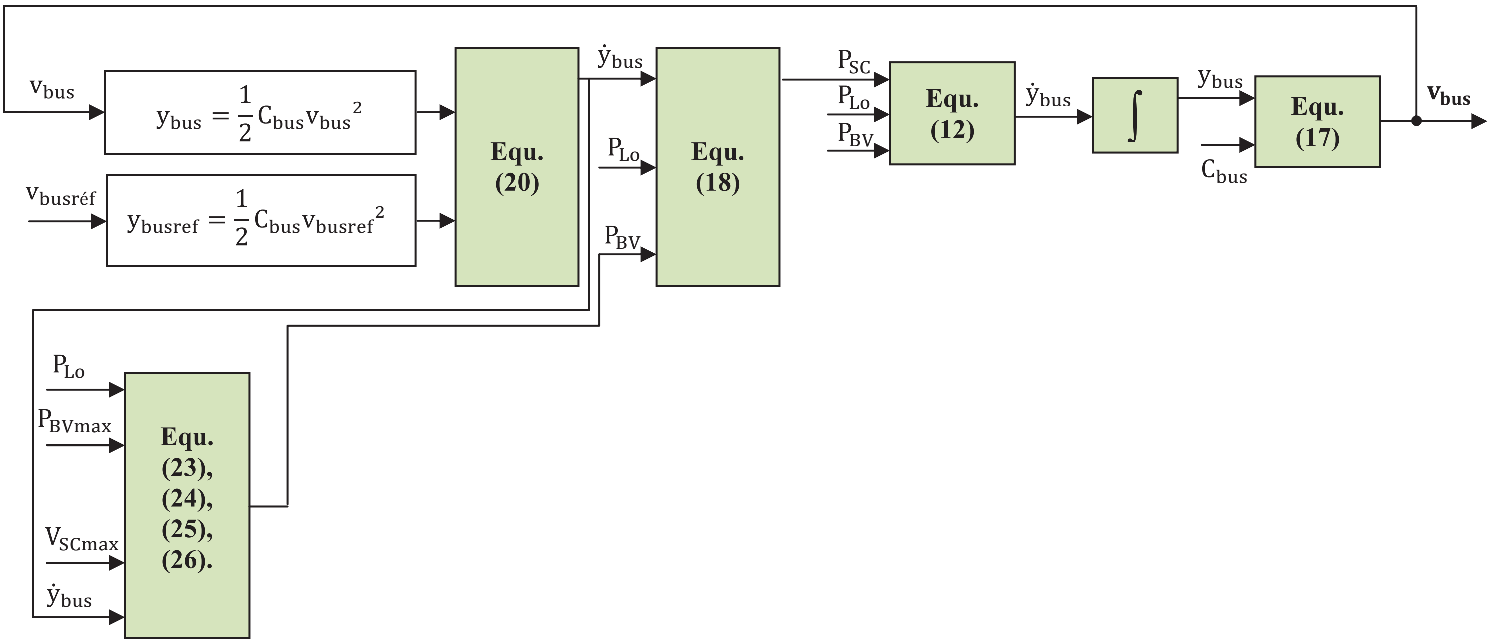

Figure 4. Control scheme for the Batteries/Supercapacitors hybrid sources.

H. *Control of the batteries power*

Three modes can appear during the power exchange between the embarked batteries and the load:

- Discharge mode: In this mode, the power required by the load exceeds the maximum power (P_{BVmax}) that batteries can provide. The power P_{BV} is given by:

$$P_{BV} = P_{BVmax} \quad \text{if:} \quad P_{LO} \geq P_{BV\,max} \tag{23}$$

- Normal mode: In this mode, the power required by the load is positive and less than the maximum power ($P_{BV\,max}$) that can provide the batteries. The power P_{BV} is given by:

$$P_{BV} = P_{LO} \quad \text{if:} \quad 0 < P_{LO} < P_{BV\,max} \tag{24}$$

- Recovering mode: In this mode, the power required by the load is negative and must be absorbed by the various storage devices. The power P_{BV} is given by:

$$P_{BV} = 0 \qquad \text{if:} \quad P_{LO} < 0 \text{ and } v_{SC} < v_{SCmax} \tag{25}$$

Or:

$$P_{BV} = P_{LO} + \dot{y}_{bus} \quad \text{if:} \quad P_{LO} < 0 \text{ and } v_{SC} = v_{SCmax} \tag{26}$$

I. *Simulation results and discussion*

Parameters of the multi-sources system are shown in table I.

A profile based on sequences of powers is defined. This profile can ensure the hybrid requirement energy needs during running. This profile takes into account periods of acceleration, stopping and braking.

In this case, the following results present respectively the DC bus voltage and its reference, the power curves, the batteries and SCs voltages and states of charge.

The DC bus voltage, presented in figure 6, is well controlled and regulated to its reference. In fact:

TABLE I. PARAMETERS OF THE MULTI-SOURCES SYSTEM

Parameter	Value
Batteries maximum power	50 KW
Batteries nominal voltage	216 V
Batteries initial voltage	234 V
Batteries final voltage	201.6 V
Batteries initial state of charge	100 %
Batteries final state of charge	10 %
Supercapacitors maximum power	60 KW
Supercapacitors initial voltage	89 V
Supercapacitors final voltage	44.5 V
Supercapacitors initial state of charge	100 %
Supercapacitors final state of charge	0 %
DC bus reference voltage	300 V

- From t = 0 to t = 10 s: the load power is zero. In this case, no power is provided or absorbed by batteries and SCs. Hence, it is constancy between voltages and states of charge.
- From t = 10 to t = 70 s: batteries provide all the demanded power, and SCs supply the energy to regulate the one stored in the DC bus. Then, voltages and states of charge decrease.

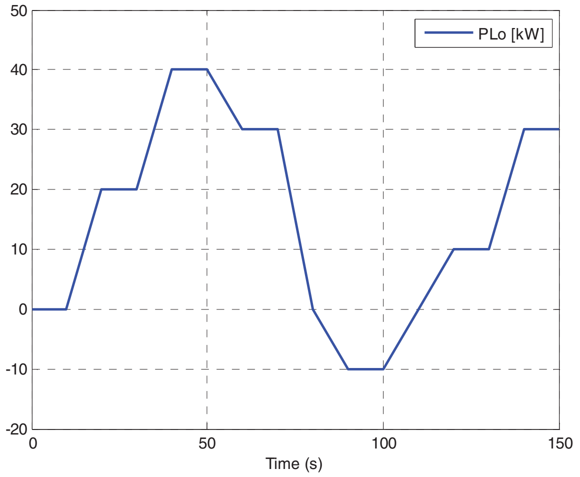

Figure 5. Load power profile.

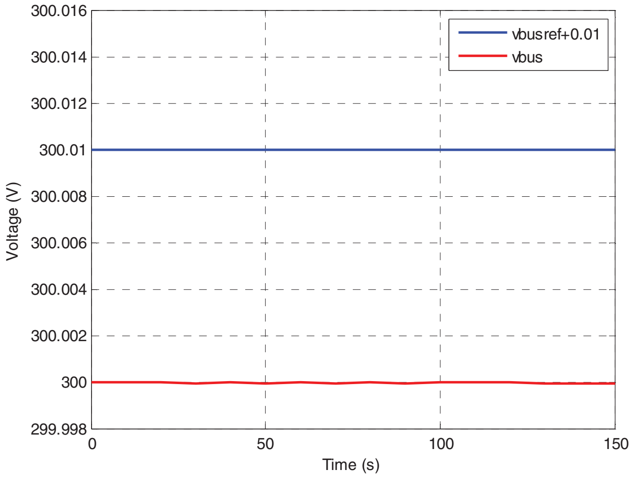

Figure 6. DC bus voltage and its reference.

- At t = 80 s: the required power decrease from 30 kW to 0 kW. No power is provided by the batteries and the SCs absorb the energy to regulate DC bus voltage.
- Therefore, the batteries voltage and state of charge remain constant, while those of the SCs increase to full recharge.
- From t = 90 to t = 100 s: the absorbed power is negative (braking of the vehicle). At this time, SCs are fully charged, and the batteries absorb two energies, one resulting from braking and the other is needed to regulate the energy stored in the DC bus. Thus, the SCs voltage and state of charge remain constant, while those of the batteries increase.
- At t = 110 s: the demanded power is zero, and SCs are fully charged. In this case, the batteries absorb only the energy needed to regulate the energy stored in the DC bus. As a result, the SCs voltage and state of charge remain constant, while those of the batteries increase.
- From t = 120 to t = 150 s: batteries provide all of the absorbed power, and SCs provide the energy to regulate the DC bus voltage, which explains the decrease of voltages and states of charge.

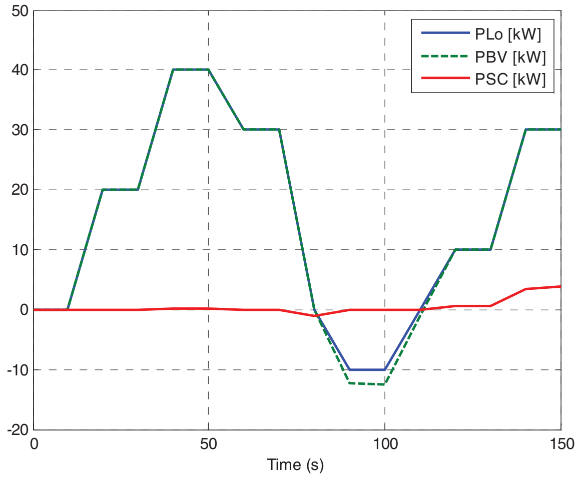

Figure 7. Power curves.

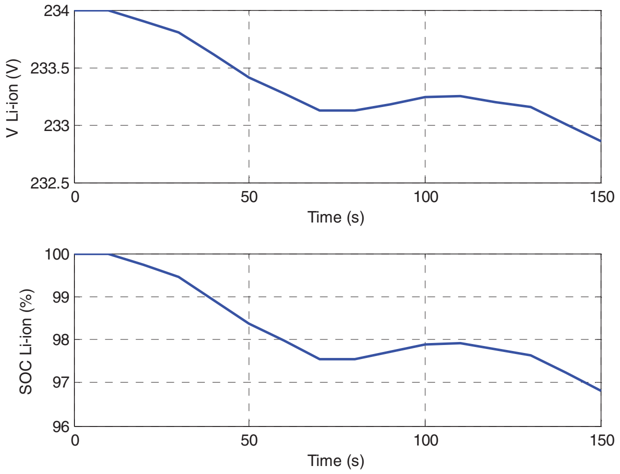

Figure 8. Batteries voltage and state of charge.

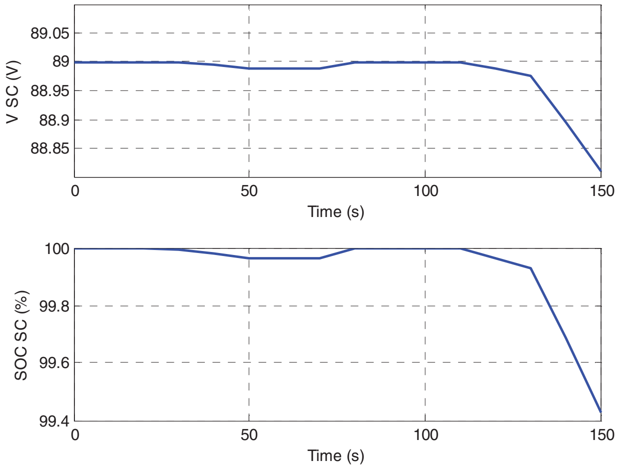

Figure 9. SCs voltage and state of charge.

IV. CONCLUSION

In this work, a nonlinear control strategy is presented to manage the flow of energy in a hybrid vehicle combined two sources: a lithium-ion batteries, used as energy source, and supercapacitors used as power source.

The adopted strategy based on flatness principle consists on generating reference trajectories for the electrostatic energy contained in the capacitor of the hybrid source. These trajectories are used to define the evolution of all variables without having to solve any differential equation.

Through different results, it is found that:

- The power demand is satisfied.
- The DC bus voltage is well controlled and regulated to its reference.
- SCs are recharged when the vehicle brakes.

The control laws illustrate how to use supercapacitors to compensate the low dynamic of lithium-ion batteries. Therefore, the hybrid source lifetime is theoretically increased.

REFERENCES

[1] S. Kermani, ‘‘Gestion énergétique des véhicules hybrides: de la simulation à la commande temps réel’’, PhD thesis, Valenciennes and Hainaut Cambrésis University, September 2009.

[2] M. Ehsani, Y. Gao, S.E. Gay, A. Emadi, ‘‘Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design’’, CRC PRESS, 2005.

[3] M.Y.Ayad, S.Raël, B. Davat, ‘‘Hybrid power source using supercapacitors and batteries’’, Proc. EPE 03, Toulouse (France), September 2003.

[4] C.R. Akli, X. Roboam, B. Sareni, A. Jeunesse, ‘‘Energy management and sizing of storage devices of a hybrid locomotive’’, in 12th Europ. Conf. on Power Elec. And Appl. (EPE07), Aalborg, Denmark, 02-05 September 2007.

[5] Z. Jiang, L. Gao, R.A. Dougal, ‘‘Flexible Multiobjective Control of Power Converter in Active Hybrid Fuel Cell/Battery Power Sources’’, IEEE Transactions on Power Electronics, vol. 20, 2005, pp. 244-253.

[6] M. Nadal, F. Barbir, ‘‘Development of a hybrid fuel cell/battery powered electric vehicle’’, International Journal of Hydrogen Energy, vol. 21, no. 6, June 1996, pp. 497-505.

[7] T.A. Nergaard, J.F. Ferrell, L.G. Leslie, J.S. Lai, ‘‘Design considerations for a 48V fuel cell to split single phase inverter system with ultracapacitor energy storage’’, Proc. of IEEE-PESC02, Queensland, June 2002.

[8] J. Bauman and M. Kazerani, ‘‘A comparative study of fuel-cell–battery, fuel-cell–ultracapacitor, and fuel-cell–battery–ultracapacitor’’, IEEE Trans. Veh. Technol., vol. 57, no. 2, pp. 760-769, March 2008.

[9] P. Thounthong, S. Raël, and B. Davat, ‘‘Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications’’, J. Power Sources, vol. 193, no. 1, pp. 376-385, August 2009.

[10] 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.

[11] M.Y. Ayad, M. Becherif, A. Henni, A. Aboubou, M. Wack, S. Laghrouche, ‘‘Passivity-Based Control applied to DC hybrid power source using fuel cell and supercapacitors’’, Energy Conversion and Management 51, Elsevier, 2010, pp. 1468-1475.

[12] P. Thounthong, S. Pierfederici, J.P. Martin, M. Hinaje, B. Davat, ‘‘Modeling and Control of Fuel Cell/Supercapacitor Hybrid Source Based on Differential Flatness Control’’, IEEE Transactions on Vehicular Technology, 2010.

[13] M. Fliess, J. Lévine, P. Martin, and P. Rouchon, ‘‘Flatness and defect of nonlinear systems. Introductory theory and examples’’, Int. J. Control, 61(6), pp. 1327-1361, June 1995.

[14] M. Fliess, J. Lévine, P. Martin and P. Rouchon, ‘‘A Lie-Bäcklund approach to equivalence and flatness of nonlinear systems’’, IEEE Trans. Automat. Control 61, pp. 1327-1361, 1999.

[15] Ph. Martin, R. Murray and P. Rouchon, ‘‘Flatness Based Design’’, Control Systems, Robotics and Automation, vol. XIII.