Advantages of variable DC bus voltage for Hybrid Electrical Vehicle

M. Becherif and M.Y. Ayad

Abstract. Most research paper on Hybrid vehicle or Hybrid Electrical vehicle propose electrical structures of a DC bus to supply the electrical motor (with or without recovering possibilities). The proposed DC bus has at the majority a constant voltage. As the electrical power is relatively high, it is reasonable to increase the DC bus voltage in order to decrease the current and consequently the Joules losses and to reduce also the sizing of the component and wires.

We show in this paper that a variables DC bus voltage is technologically feasible and economically interesting. In this purpose, we compare two different architectures. Both architectures were modelled and controlled (with the proof of stability) and finally the energy balance was proposed in order to compare the two structures and to exhibit the advantages of the variable DC bus voltage.

Index terms—hybrid vehicle, Fuel Cell, Supercapacitors, Batteries, Power converters, Energy conversion.

I. INTRODUCTION

Fuel-cell (FC) vehicles have the potential to revolutionize transportation. In particular, a FC vehicle, using a combined battery and supercapacitor (SC) energy storage system, can provide excellent fuel economy and performance while extending the battery life due to more frequent use of the SC. FCs are similar to batteries since they both produce a DC voltage by using an electrochemical process [1, 2]. Unlike batteries, FCs do not release storage of energy. FCs operate as long as they are supplied with fuel. Furthermore, they have a large time constant to respond to an increase or decrease in power output demand (mainly because of its auxiliaries) [3, 4]. The use of SCs [5, 6] as a storage system in DC hybrid sources, with FC or batteries, allows the peak load to be shaved and can compensates for the intrinsic limitations of the main source thanks to their suitable characteristics as a storage device; in addition they are easily controlled by power electronic conversion.

We present in this work two hybrids DC power sources using SC as auxiliary storage device, a Proton Exchange Membrane-FC (PEMFC) as main energy source [7, 8], with and without batteries on the DC link. A single phase DC machine is connected to the DC bus and plays the role of the load.

In this paper, the energy management means that the controller, instead of stabilizing the system towards its equilibrium, is sufficiently smart to decide, at each moment and according to the load power demand, which source has to supply or absorb the energy and eventually define the ratio of using of different sources in the same time. This goal is achieved by the choice of the adequate scenarios defining the giving system equilibriums which are function of the power/energy flow.

The authors uses the well known Passivity-Based Control (PBC) with the Port Controlled Hamiltonian (PCH) structure that allows exhibiting important structural properties like the total system energy, the Damping and the states interconnections. This paper is organized as follows: a brief introduction to PBC and PCH is giving. In section IV, the problem formulation is stated. In section V, the state space equations of the difference sources are given. In section VI, the PCH form of the whole system is developed and the control laws with the global stability proof are given. The simulations are presented in section VII with a change in the control laws that improve the control performances. Finally a conclusion can be found in section VIII.

In [8] and [9] a quite similar hybrid system are addressed but authors of those paper did not prove the stability of the system with the proposed PID controller. In addition, different PID where used for different subsystem (DC bus voltage loop in one hand and SCs voltage loop in another hand). The leitmotiv of this paper is firstly to have a state space equation of the whole system (without considering different subsystems) and secondly to use the PBC with PCH structure to proof the global asymptotic stability. Another important challenge of the authors of this paper is to measure only the SCs current and the FC voltage (for the first solution) and, in addition, the DC Bus voltage (for the second solution). The final purpose is to conclude with the advantages of variable DC Bus voltage for hybrid sources.

II. STRUCTURES OF THE HYBRIDPOWER SOURCES

As shown in Fig. 1, the studied hybrid power source include a DC link supplied by a FC and a unidirectional DC-DC converter which maintains the DC voltage V_{DL} to its desired value V_d, and a peak power unit based on electric double layer capacitors, which is connected to the DC link through a bidirectional DC-DC converter [12-13].

The role of the FC is to supply the mean energy to the load [14-17], whereas the peak power unit is used as a peak power source: is to supply peak power required during acceleration and can absorb peak power during braking [18-19].

In order to manage energy exchanges between the DC link and the peak power units, three operating modes can be defined:

- Charge mode, in which the main source supplies energy to the peak power unit,
- Discharge mode, in which the peak power unit supplies energy to the load,
- Recovery mode, in which the load supplies energy to the

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peak power unit.

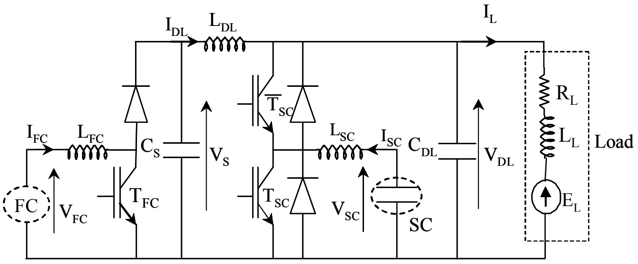


Fig. 1. Structure of the first hybrid source

As shown in Fig. 2 the second studied system comprises a DC link directly supplied by batteries, a PEMFC connected to the DC link by means of a Boost converter, and a supercapacitive storage device connected to the DC link through a current reversible DC-DC converter. The function of FC and the batteries is to supply mean power to the load, whereas the storage device is used as a power source: it manages load power peaks during acceleration and braking.

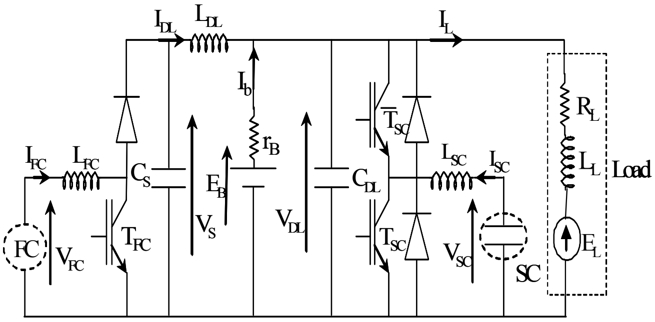


Fig. 2. Structure of the second hybrid source

The aim is to have a constant DC voltage and the challenge is to maintain a constant power working mode for the main sources (batteries and FC).

III. PASSIVITY BASED CONTROL OF THE SYSTEM

A. Port Controlled Hamiltonian System

PCH systems were introduced by van der Schaft and Maschke in the early nineties, and have since grown to become a large field of interest in the research of electrical, mechanical and electro-mechanical systems. A recent and very interesting approach in PBC is the Interconnection and Damping Assignment (IDA-PBC) method, which is a general way of stabilizing a large class of physical systems) (Ortega et al. 2002) (Becherif et al., 2005).

Some of the advantages of expressing systems in the PCH form are the fact that they cover a large set of physical systems and capture important structural properties. Consider the nonlinear system given by:

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

where $x \in R^n$ is the state vector, f(x) and g(x) are locally Lipschitz functions and $u \in R^m$ is the control input. A PCH form of the system (1) is given by:

$$\dot{x} = [\Im(x) - \Re(x)]\nabla H + g(x)u \tag{2}$$

where J(x) is an $n \times n$ skew symmetric matrix, R(x) is a $n \times n$ positive semi-definite symmetric matrix and ∇H is the gradient vector of the energy function H(x) of the system (1).

PCH systems, with H(x) non-negative, are passive systems.

A recent and very interesting approach to solve these problems is the Interconnection and Damping Assignment IDA-PBC method, which is a general way of stabilizing a large class of physical systems, see [10] and [11].

IV. PROBLEM FORMULATION

Both structures are feeding energy to the DC bus where a DC machine is connected. This machine plays the role of the load acting as a motor or as a generator when breaking.

The main purpose is to maintain a constant mean energy delivered by the FC, without a significant power peak, and the transient power is supplied by the SCs. A second purpose consists in recovering energy throw the charge of the SC. The regulation of the DC Bus voltage is asked. For the first structure this DC Bus voltage reference is variable and it is constant for the second structure and equal to the battery voltage.

After modeling, equilibrium points are calculated in order to ensure the desired behavior of the system. When steady state is reached, the load has to be supplied only by the FC source. So the controller has to maintain the DC bus voltage to a desired value and the SCs current has to be cancelled. During transient, the power delivered by the FC has to be as constant as possible (without a significant power peak), while the SCs deliver the transient power to the load. If the load provides current, the SCs recover this energy.

SC has to be charged when we have an excess of energy and at equilibrium the SC current has to be equal to zero.

In the next section, the controller will be designed and the system's stability will be investigated.

V. FC, SCs AND BATTERIES MODELING

A. Fuel cell model

The output voltage of FC "V_{FC}" can be defined by a static and nonlinear model as given in [2]:

$$V_{FC} = E_0 - A\log\left(\frac{i_{FC} - i_n}{i_0}\right) - \left\{ \begin{array}{l} R_m(i_{FC} - i_n) \\ + B\log\left(1 - \frac{i_{FC} - i_n}{i_{Lim}}\right) \end{array} \right\} \tag{3}$$

Hence $V_{FC} = f(i_{FC})$. E_0 is the reversible no loss voltage of the FC, i_{FC} is the delivered current, i_0 is the exchange current, A is the slope of the Tafel line, i_{Lim} is the limiting current, B is the constant in the mass transfer, i_n is the internal current and R_m is the membrane and contact resistances. In the sequel, V_{FC} will be considered as a measured disturbance, and from physical consideration, it comes that $V_{FC} \in [0; V_d[$, where V_d is the desired DC Bus voltage.

B. Supercpacitors Model

The SC is then modeled by:

$$\begin{cases} \dfrac{dV_0}{dt} = \dfrac{1}{C_0 + kV_0} I_{SC} \\ V_{SC} = R_{sc} I_{SC} + V_0 \end{cases} \tag{4}$$

Where $C_0 + kV_0 > 0$

The differential capacitance is represented by two capacitors: a constant capacitor C_0 and a linear voltage dependent capacitor kV_0. k is a constant corresponding to the slope voltage.

C. *Battery model*

Many electrical equivalent circuits of battery are found in literature [12] [13]. In this work, The model of the battery is a simple model taking into account the internal resistance ($\boldsymbol{R}_{internal}$) in serial with an emf assumed to be constant throughout the process.

VI. PORT-CONTROLLED HAMILTONIAN REPRESENTATION OF THE SYSTEMS

A. *Equations of the first hybrid source*

The energy management of this system needs to manage the energy used in the whole vehicle cycle (In practice several minutes or hours). Hence, only the continuous main model of the different converters will be used. The overall model of the hybrid system is written in a state space model by choosing the following state space vector:

$$\begin{aligned} x &= [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7]^T \\ &= [V_S \quad I_{FC} \quad V_{DL} \quad I_{DL} \quad V_{SC} \quad I_{SC} \quad L_L]^T \end{aligned} \tag{5}$$

Let us put U_{FC} the control of the FC boost converter and U_{SC} the control of the SC buck-boost converter. Then the control vector is

$$\mu = [\mu_1 \quad \mu_2]^T = [(1-U_{FC}) \quad (1-U_{SC})]^T \tag{6}$$

where

$$U = 1-\mu = [U_{FC} \quad U_{SC}] \tag{7}$$

Equilibrium

After some simple calculations the equilibrium vector can be expressed as:

$$\bar{x} = [\bar{x}_1 \quad \bar{x}_2 \quad \bar{x}_3 \quad \bar{x}_4 \quad \bar{x}_5 \quad \bar{x}_6 \quad \bar{x}_7] \tag{8}$$

$$\bar{x} = \left[V_d, \quad \frac{(V_d - E_L)V_d}{R_L V_{FC}}, \quad V_d, \quad \frac{V_d - E_L}{R_L} \quad \bar{x}_5 \quad 0 \quad \frac{V_d - E_L}{R_L} \right]^T \tag{9}$$

Where V_d is the desired DC Bus voltage. An implicit purpose of the proposed structure is to recover energy to charge the SCs. Hence, the desired voltage $\bar{x}_5 = \bar{V}_{SC} = V_{SC}(t=0)$.

$$\bar{\mu} = [\bar{\mu}_1 \quad \bar{\mu}_2]^T = [(1-\bar{U}_{FC}) \quad (1-\bar{U}_{SC})]^T \tag{10}$$

where

$$\bar{U} = [\bar{U}_{FC} \quad \bar{U}_{SC}] = \left[1 - \frac{V_{FC}}{V_d} \quad 1 - \frac{\bar{x}_5}{V_d} \right] \tag{11}$$

The natural energy function of the system is

$$H = \frac{1}{2} x^T Q x \tag{12}$$

with

$$Q = diag\{C_S;\ L_{FC};\ C_{DL};\ L_{DL};\ C_{SC};\ L_{SC};\ L_L\}$$

is a diagonal matrix.

B. *Equations of the second hybrid source*

The overall model of the second hybrid system is written in a state space equation by choosing the following state space vector:

$$\begin{aligned} x &= [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7]^T \\ &= [V_S \quad I_{FC} \quad V_{DL} \quad I_{DL} \quad V_{SC} \quad I_{SC} \quad I_L]^T \end{aligned} \tag{13}$$

The output voltage of a single cell V_{FC} can be defined as the result of the following expression:

The control vector is:

$$\mu = [\mu_1, \quad \mu_2]^T = [(1-U_{FC}), \quad (1-U_{SC})]^T \tag{14}$$

where

$$U = [U_{FC}, \quad U_{SC}]^T \tag{15}$$

with $V_{FC}=V_{FC}(x_2)$

Equilibrium

After simple calculations the equilibrium vector is:

$$\bar{x} = [\bar{x}_1, \quad \bar{x}_2, \quad \bar{x}_3, \quad \bar{x}_4, \quad \bar{x}_5, \quad \bar{x}_6, \quad \bar{x}_7]^T$$

$$\bar{x} = \left[V_d, \quad \left(\frac{V_d}{V_{FC}} \left(\frac{V_d}{R_L} - \frac{E_B - V_d}{r_B} \right) \right), \quad V_d, \quad \frac{V_d}{R_L} - \frac{E_B - V_d}{r_B}, \quad V_{SC}(t=0), \quad 0, \quad \frac{V_d}{R_L} \right]^T \tag{16}$$

where V_d is the desired DC link voltage. The desired voltage $\bar{x}_5 = \bar{V}_{SC} = V_{SC}(t=0)$

$$\bar{\mu} = [\bar{\mu}_1, \quad \bar{\mu}_2]^T = \left[\frac{V_{FC}}{V_d}, \quad \frac{\bar{x}_5}{V_d} \right]^T \tag{17}$$

where

$$\bar{U} = [\bar{U}_{FC}, \quad \bar{U}_{SC}]^T = \left[1 - \frac{V_{FC}}{V_d}, \quad 1 - \frac{\bar{x}_5}{V_d} \right]^T \tag{18}$$

The natural energy function of the system is:

$$H = \frac{1}{2} x^T Q x \tag{19}$$

with

$$Q = diag\{C_S;\ L_{Fc};\ C_{DL};\ L_{DL};\ C_{SC};\ L_{SC};\ L_L\}$$

is a diagonal matrix.

In the following, a closed loop PCH representation is given. The desired closed loop energy function is:

$$H_d = \frac{1}{2} \tilde{x}^T Q \tilde{x} \tag{20}$$

Where $\tilde{x} = x - \bar{x}$ is the new state space defining the error between the state x and its equilibrium value $\bar{x}$.

The PCH form of the studied system with the new variable $\tilde{x}$ as a function of the gradient of the desired energy (19) (or (12)) is:

$$\dot{\tilde{x}} = [\Im(\mu_1, \mu_2) - \Re]\nabla H_d + A_i(\bar{x}, \mu) \tag{21}$$

With

$$\Im(\mu_1,\mu_2)-\Re=$$

$$\begin{bmatrix} 0 & \frac{\mu_1}{C_S L_{FC}} & 0 & \frac{1}{C_S L_{DL}} & 0 & 0 & 0 \\ \frac{-\mu_1}{C_S L_{FC}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{C_{DL}^2 r_B} & \frac{1}{C_{DL} L_{DL}} & 0 & \frac{\mu_2}{C_{DL} L_{SC}} & \frac{-1}{C_{DL} L_L} \\ \frac{1}{C_S L_{DL}} & 0 & \frac{-1}{C_{DL} L_{DL}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{C_{SC} L_{SC}} & 0 \\ 0 & 0 & \frac{-\mu_2}{C_{DL} L_{SC}} & 0 & \frac{1}{C_{SC} L_{SC}} & 0 & 0 \\ 0 & 0 & \frac{1}{C_{DL} L_L} & 0 & 0 & 0 & \frac{-R_L}{L_L^2} \end{bmatrix}$$

And

$$\nabla H_d = \begin{bmatrix} C_S \tilde{x}_1 \\ L_{FC} \tilde{x}_2 \\ C_{DL} \tilde{x}_3 \\ L_{DL} \tilde{x}_4 \\ C_{SC} \tilde{x}_5 \\ L_{SC} \tilde{x}_6 \\ L_L \tilde{x}_7 \end{bmatrix} \quad A_i(\bar{x},\mu) = \begin{bmatrix} C_S\left[-\bar{x}_4+\mu_1\bar{x}_2\right] \\ \frac{1}{L_{FC}}\left[V_{FC}-\mu_1\bar{x}_1\right] \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_{SC}}\left[\bar{x}_5-\mu_2\bar{x}_3\right] \\ 0 \end{bmatrix}$$

Where

$$\Im(\mu_1,\mu_2)=-\Im^T(\mu_1,\mu_2) \tag{22}$$

is a skew symmetric matrix defining the interconnection between the state space and $\Re = \Re^T \geq 0$ is a symmetric positive semi definite matrix defining the damping of the system.

With *r* is a design parameter, the following control laws are proposed:

$$\mu_1 = \bar{\mu}_1 \quad and \quad \mu_2 = \bar{\mu}_2 + r\tilde{x}_6 \tag{23}$$

Proposition 1: The origin of the closed loop PCH system (20), with the control laws (23) and (16) with the radially unbounded energy function (19), is globally stable.

Proof: The closed loop dynamic of the PCH system (20) with the laws (23) and (16) with the radially unbounded energy function (26) is:

$$\dot{\tilde{x}} = \left[\Im(\mu_1,\mu_2)-\Re'\right]\nabla H_d \tag{24}$$

where

For the first hybrid source

$$\Re' = diag\left\{0;\ \ 0;\ \ 0;\ \ 0;\ \ 0;\ \ \frac{rV_d}{L_{SC}^2};\ \ \frac{R_L}{L_L^2}\right\} = \Re'^T \geq 0 \tag{25}$$

For the second hybrid source

$$\Re' = diag\left\{0;\ \ 0;\ \ \frac{1}{\left(C_{DL}^2 r_B\right)};\ \ 0;\ \ 0;\ \ \frac{rV_d}{L_{SC}^2};\frac{R_L}{L_L^2}\right\} = \Re'^T \geq 0 \tag{26}$$

The derivative of the desired energy function (19) (or (12)) along the trajectory of (24) is:

$$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = -\nabla H_d^T \Re' \nabla H_d \leq 0 \tag{27}$$

VII. SIMULATION RESULTS OF THE HYBRID SOURCES CONTROL

The whole system has been implemented in the Matlab-Simulink Software with the following parameters associated to the hybrid sources:

- FC parameters: P_{FC} = 400 W.

The supercapacitive power peak unit is obtained by a series association of six SCs of 3500 F. The rated voltage of theses components is 2.5V. The initial value of the supercapacitive power peak voltage is 12 V.

The results presented in this section have been carried out by connecting the hybrid source to a "R_L, L_L and E_L " load representing a single phase DC machine.

A. Passivity Based Control applied to the first hybrid source

The following simulations present the system response and control obtained with the proposed control laws. In this case, the load is considered to absorb power. To illustrate the controller efficiency, the DC bus voltage reference, the electromotive force (emf) and the resistance are modified (see Fig. 6 and Fig. 7). The DC bus voltage is initialized at 36V and the DC Bus voltage reference is set at 42V at the beginning.

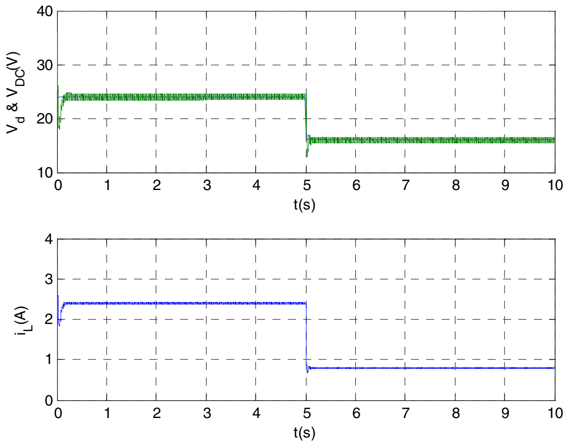


Fig. 3 (a) DC Bus voltage and its reference. (b) Load current.

Fig. 2 presents the system response to changes in the DC Bus voltage reference (V_d), emf (E), with E=E_L, and load current I_L. The DC Bus voltage tracks well the reference, a very low overshoot and no steady state error are observed.

Fig. 4 shows the FC voltage (V_{FC}) and current (I_{FC}). In our modelling, we assume that the DC source is ideal, thus V_{FC} stay at constant value regardless of the current I_{FC}. A smooth behaviour of the current is observed regarding the changes in V_d, E and R_L, because the SCs pack supply the transient power.

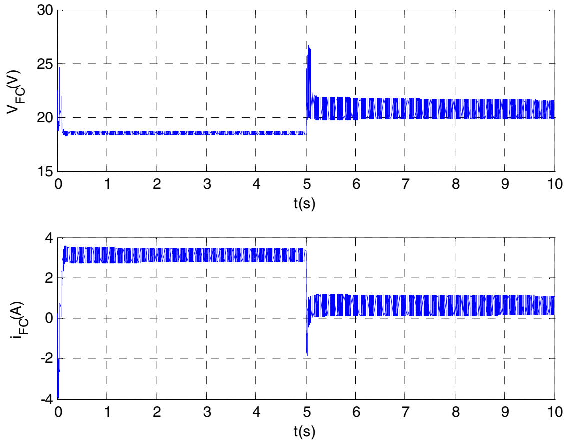


Fig. 4. (a) FC voltage. (b) FC current.

Figure 5 shows the SCs voltage and current responses. The SCs supply power to the load in the transient and in the steady state no power or energy is extracted since the current I_{SC} is zero. A positive value of I_{SC} means that the SCs supply power to the load and a negative value corresponds to the recover of energy by the SCs. At time $t = 4s$, the SCs absorb the current peak in response to quickly to the fast DC reference change.

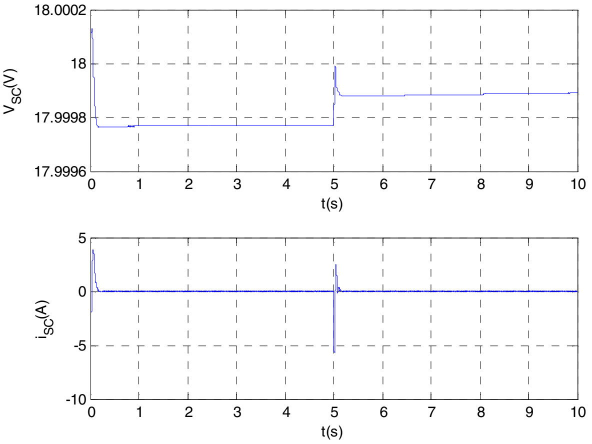


Fig. 5. (a) SCs voltage. (b) SCs current.

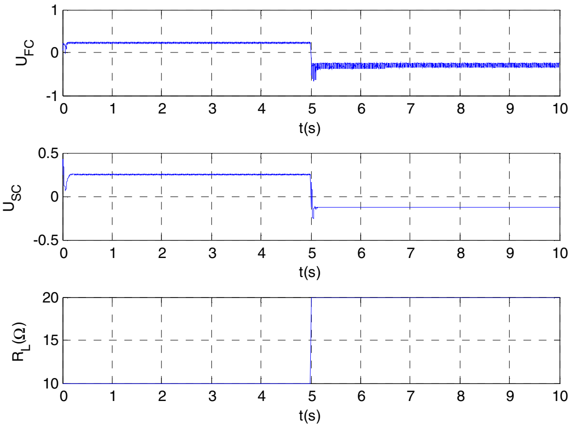
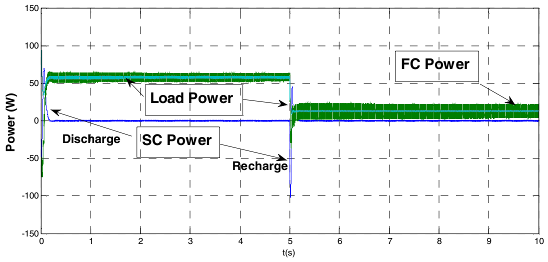


Fig. 6. (a) Source Boost control. (b) SCs converter control.

Fig. 6 and 7 present the network Boost controller, the SC bidirectional converter controller, the changes in the load resistance R_L and in emf. U_{FC} and U_{SC} are in the set [0, 1].

It can be seen from Figure 3 that the system with the proposed controller is robust towards load resistance changes and emf variations.



EL=353W; EFC=344W; ESCpos=7W; ESCneg=-5.7W

B. Passivity Based Control applied to the second hybrid source

Figure 8 shows the FC voltage and current. Figure 9 presents the SC voltage and current response. The SC supply power to the load in the transient and in the steady state no power or energy is extracted since the current $x_6 = I_{SC}$ is null.

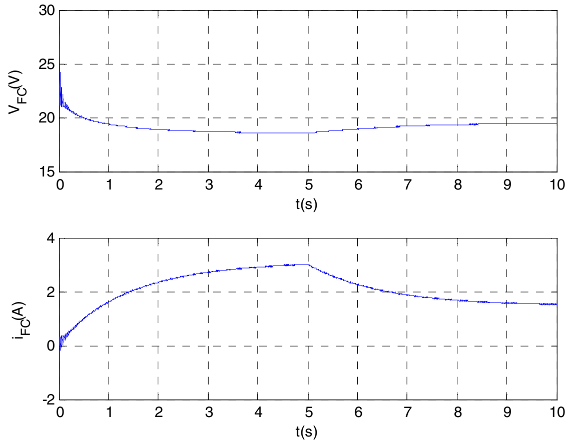


Fig. 7. FC voltage and FC current

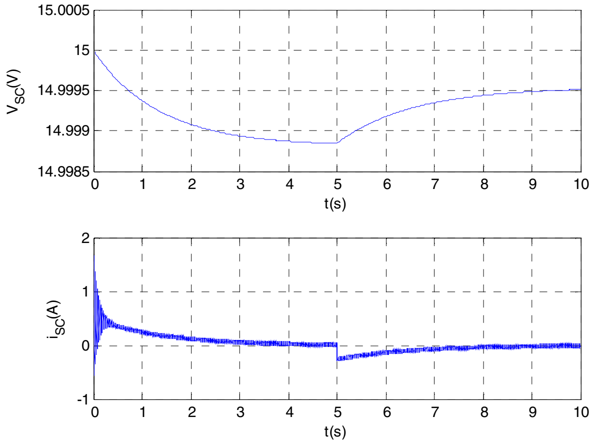


Fig. 8. SC voltage and SC current

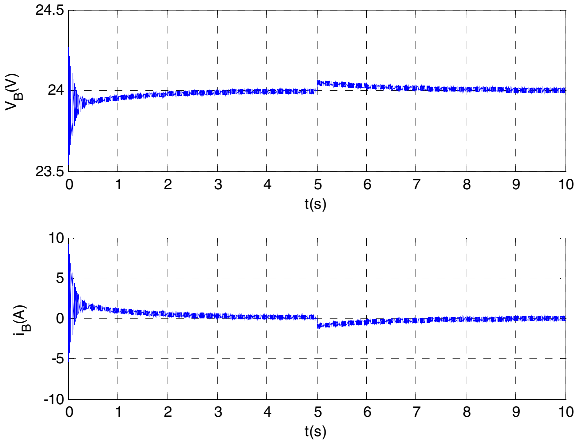


Fig. 9. Batteries voltage and batteries current

The positive sens of I_{SC} means that the SCs supply the load and the negative one corresponds to the recover of energy from the FC to the SC. Figure 10 presents the batteries voltage and its current. Figure 11 presents the response of the system to changes in the load current I_L. The DC Bus voltage tracks well the reference, i.e. very low overshoot and no steady state error are observed. It can be seen from this figure that the system with the proposed controller is robust towards load resistance changes. Figure 22 shows the FC Boost controller, the SC bidirectional converter controller and the changes in the Load resistance RL. U_{SC} and U_{FC} are in the set [0; 1].

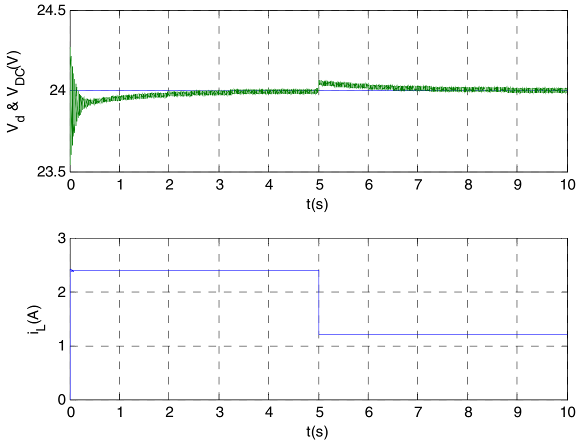


Fig.10. DC link voltage and load current

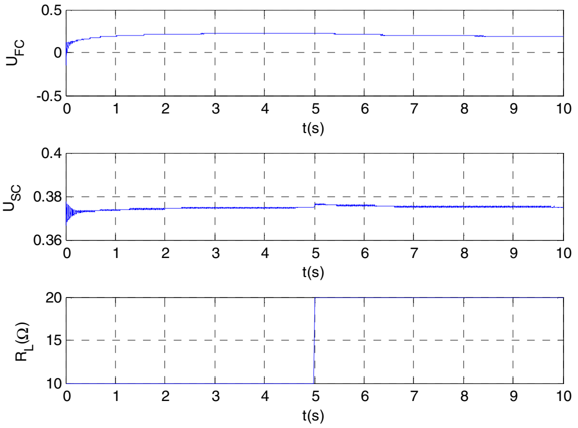
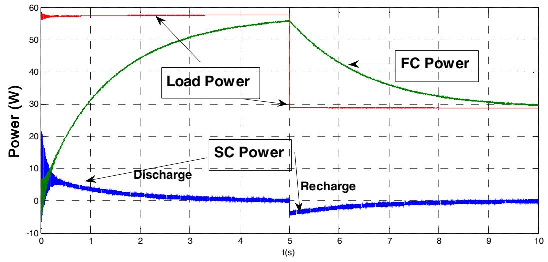


Fig. 11. (a) FC Boost control. (b) SC DC-DC (c) Load resistance change



EL=486W; EFC=437W; EBpos=89W; Ebneg=-47W; ESCpos=13W; ESCneg=-7W

VIII. CONCLUSION

In this paper, the modeling and the control principles of two DC hybrid source systems have been presented. These systems are composed of a FC source, supercapacity source and with or without batteries on DC link. The state space models are given for both structures. These sources use the FC as mean power source and SCs as auxiliary transient power sources.

For the two hybrid structures, Passivity Based Control principles have been applied.

The structure, without batteries on the DC link, permits to have a variable regulation of the DC link voltage in function of current of load. The batteries on the DC link can guarantees a constant voltage but with the applied controller the batteries delivery power can not controlled.

Global asymptotic stability proofs are given and encouraging simulation results has been obtained.

Many benefits can be expected from the proposed structures such that supplying and absorbing the power picks by using SCs which also allows recovering energy.

References

[1] Y. Kishinevsky and S. Zelingher, “Coming clean with fuel cells,” IEEE Power & Energy Magazine, vol. 1, issue: 6, Nov.-Dec. 2003, pp. 20-25.

[2] J. Larminie and A. Dicks, Fuel cell systems explained, Wiley, 2000.

[3] M. Becherif, “Passivity-based control of hybrid sources: Fuel cell and Battery”. In 11th IFAC Symposium on Control in Transportation Systems (CTS’06), Netherlands, 2006

[4] J. M. Corrêa, F. A. Farret, J. R. Gomes, and M. G. Simões,“Simulation of fuel-cell stacks using a computer-controlled power rectifier with the purposes of actual high-power injection applications,” IEEE Trans. Ind. App., vol. 39, no. 4, pp. 1136-1142, July/Aug. 2003.

[5] M. Granovskii, I. Dincer, and M. A. Rosen, “Environmental and economic aspects of hydrogen production and utilization in fuel cell vehicles,” J. Power Sources, vol. 157, pp. 411-421, June 19, 2006

[6] F. Belhachemi, S. Rael and B. Davat “A Physical based model of power elctric double layer supercapacitors”, IAS 2000, 35th IEEE Industry Applications Conference, Rome, 8-12 October

[7] A. Rufer, P. Barrade, A supercapacitor-based energy-storage system for elevators with soft commutated interface, IEEE Transactions on Industry Applications 38/5 (September-October 2002) 1151-1159.

[8] P. Thounthong, S. Raël, and B. Davat, “A new control strategy of fuel cell and supercapacitors association for distributed generation system,” IEEE Trans. Ind. Electron, Volume 54, Issue 6, Dec. 2007 Page(s): 3225 – 3233

[9] P. Thounthong, S. Raël and B. Davat, “Utilizing Fuel Cell and Supercapacitors for Automotive Hybrid Electrical System,” in Proceedings of IEEE-APEC 2005 Conf., Texas-USA, March 6-10, 2005, pp. 90-96.

[10] R. Ortega, A.J. van der Schaft, B. Maschke and G. Escobar, Interconnection and damping assignment passivity–based control of port–controlled hamiltonian systems, Automatica, vol.38(4), pp.585–596, 2002.

[11] M. Becherif and E. Mendes, Stability and robustness of Disturbed-Port Controlled Hamiltonian system with Dissipation, 16th IFAC World Congress, Prague, 2005.

[12] M. Chen, A. Gabriel and Rincon-Mora, “Accurate Electrical Battery Model Capable of Predicting Runtime and *I–V* Performance”, *IEEE Trans. Energy Convers*, Vol. 21, No.2, pp.504-511 June 2006.

[13] Z.M. Salameh, M.A. Casacca and W.A. Lynch, “A mathematical model for lead-acid batteries”, *IEEE Trans. Energy Convers.*, vol. 7, no. 1, pp. 93–98, Mar. 1992.

[14] M. Becherif, M. Y. Ayad “Modelling and Passivity-Based Control of Hybrid Sources: Fuel cell and Supercapacitors” IAS 2006, USA. Volume 3, 8-12 Oct. 2006 Page(s):1134 - 1139

[15] M. Y. Ayad, S. Pierfederici, S. Raël, B. Davat, "Voltage Regulated Hybrid DC Source using supercapacitors", Energy Conversion and Management, Volume 48, Issue 7, July 2007, Pages 2196-2202

[16] S. Pischinger, C. Schönfelder, and J. Ogrzewalla, “Analysis of dynamic requirements for fuel cell systems for vehicle applications,” J. Power Sources, vol. 154, no. 2, pp. 420-427, March 2006.

[17] A. Rufer, D. Hotellier and P. Barrade, “A Supercapacitor-Based Energy-Storage Substation for Voltage - Compensation in Weak Transportation Networks,” IEEE Trans. Power Delivery, vol. 19, no. 2, April 2004, pp. 629-636.

[18] A. Rufer, D. Hotellier and P. Barrade, “A Supercapacitor-Based Energy-Storage Substation for Voltage - Compensation in Weak Transportation Networks,” IEEE Trans. Power Delivery, vol. 19, no. 2, April 2004, pp. 629-636.

[19] M. Y. Ayad, S. Pierfederici, S. Raël, B. Davat, "Voltage Regulated Hybrid DC Source using supercapacitors", Energy Conversion and Management, Volume 48, Issue 7, July 2007, Pages 2196-2202,