Energy Management of a Fuel Cell and Supercapacitors by Passivity-Based Control and Sliding Mode Control

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Abstract. Fuel cells are similar to batteries in that both produce a DC voltage by using an electrochemical process. Two electrodes separated by an electrolyte make up an anode and a cathode pair called a cell. Groups of cells are called stacks and produce useable voltage and power output. Unlike batteries, however, FCs do not release stored energy; instead they convert energy from hydrogen-rich fuel directly into electricity. They operate as long as they are supplied with fuel. Further, they have a large time constant to respond to an increase or decrease in power output. They are an environmentally clean, quiet, and an efficient method for generating electricity. They require some type of power conditioning circuit to be useful.
The use of supercapacitors as a storage system in DC hybrid sources, using fuel cell or batteries, is quite suitable, allows a peak load shaving, and compensates for the intrinsic limitations of the main source.
This paper deals with the conception of hybrid power sources using fuel cell as main source, a dc link and supercapacitors as transient power source. The proposed structure is presented with Passivity Based Controller and a Sliding Mode Controller.

Key words

Passivity-Based Control, Interconnection and Damping Assignment, Port Controlled Hamiltonian system, Sliding mode control, Fuel Cell, Supercapacitors

1. Introduction

Fuel cells (FCs) produce an electrical energy from an electrochemical reaction between a hydrogen-rich fuel gas and an oxidant (air or oxygen). The principal by-products are water, carbon dioxide, and heat. They are sources with high current and low voltage. Their use in embedded systems became interesting [1,5-6] when using storage energy element, like batteries with high specific energy, and supercapacitors (SCs), with high specific power [2-4,7].
In embedded systems, the permanent source, FC or batteries must produce the limited permanent energy to ensure the system autonomy.
In the transitory phases, the storage devices produce the lacking power in acceleration, and absorbs excess power in braking function [8-9]. FCs have a large time constant (several seconds) to respond to an increase or decrease in power output. The SCs are sized for the peak load requirements and are used for short duration load levelling events such as fuel starting acceleration and braking. These short duration events are experienced thousands of times throughout the life of the hybrid source and require relatively little energy, but substantial power.
We present in this work a conception of a hybrid DC power source using SC as auxiliary storage device, a PEMFC as main energy source [9,10]. The general structure of the studied system is presented and a dynamic model of the overall system is given. Two mode of control are presented and compared. The first is based on Passivity Based-Control (PBC). The system is written in a Port Controlled Hamiltonian (PCH) form where important structural properties are exhibited. The proof of global stability of the equilibrium with the proposed control laws is given. The second is based on nonlinear sliding mode control for the DC-DC supercapacitors converter and a linear regulation for the FC converter. Finally, simulation results using Matlab are given.

2. Structure of the hybrid power source

As shown in Fig. 1, the studied hybrid source comprises a DC link supplied by a FC and a no reversible DC-DC converter which maintains the DC voltage V_{DL} to its reference value, and a supercapacitive storage device, which is connected to the DC link through a current reversible DC-DC converter.

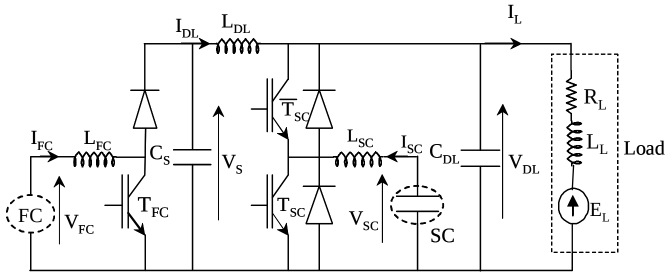

Fig. 1. Structure of the hybrid source

The role of FC is to supply mean power to the load, whereas the storage device is used as a power source: it supplies peak loads required during acceleration and braking.

The load consist of a resistor R_L an inductance L_L and an electromotive force E_L (single phase machine).

In order to manage energy exchanges between the DC link and the storage device, we define the operating modes:

- Normal mode, in which the main source supplies energy to the load,
- Charge mode, in which the main source supplies energy to the storage device,
- Discharge mode, in which the storage device supplies energy to the load,
- Recovery mode, in which the load supplies energy to the storage device.

Another function falling on the interface converter, that the levels voltage adaptation DC link (appreciably constant voltage value) and the storage element (voltage essentially variable).

The aim of the storage device is to supply power transient as well as peak load, the DC-DC FC converter output current I_{DL} being limited to a maximum value I_{DLmax}

3. Passivity Based Control of the Hybrid Source

A. Port Controlled Hamiltonian System

PCH systems were introduced by van der Schaft and Maschke in the early nineties [11]-[12] and had ever since drawn much attention in electrical, mechanical and electromechanical systems. Some of the advantages of expressing systems in 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:

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

where $\Im(x)$ is an $n \times n$ *skew symmetric* matrix, $\Re(x)$ 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[1] systems.

A recent and very interesting approach to solve these problems is the Interconnexion and Damping Assignment IDA-PBC method, which is a general way of stabilizing a large class of physical systems, see [11]-[12].

B. Equations of the system

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

$$x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \end{bmatrix}^T \tag{3}$$

With

$$x = \begin{bmatrix} V_S & I_{FC} & V_{DL} & I_{DL} & V_{SC} & I_{SC} & I_L \end{bmatrix}^T \tag{4}$$

The control vector is

$$\mu = \begin{bmatrix} \mu_1 & \mu_2 \end{bmatrix}^T = \begin{bmatrix} (1 - U_{FC}) & (1 - U_{SC}) \end{bmatrix}^T \tag{5}$$

or

$$U = \begin{bmatrix} U_{FC} & U_{SC} \end{bmatrix} \tag{6}$$

The 7th order overall state space model is then:

$$\begin{aligned}
\dot{x}_1 &= \frac{1}{C_S}\left[-x_4 + \mu_1 x_2\right] \\
\dot{x}_2 &= \frac{1}{L_{FC}}\left[V_{FC} - \mu_1 x_1\right] \\
\dot{x}_3 &= \frac{1}{C_{DL}}\left[x_4 - x_7 + x_6 \mu_2\right] \\
\dot{x}_4 &= \frac{1}{L_{DL}}\left[(x_1 - x_3)\right] \\
\dot{x}_5 &= \frac{-x_6}{C_{SC}} \\
\dot{x}_6 &= \frac{1}{L_{SC}}\left[x_5 - \mu_2 x_3\right] \\
\dot{x}_7 &= \frac{1}{L_L}\left[-R_L x_7 + x_3 - E_L\right]
\end{aligned} \tag{7}$$

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

PEMFC static model is given [2] as follow:

$$V_{FC} = E_0 - A\log\left(\frac{i_{FC} - i_n}{i_0}\right) - \left\{\begin{matrix} R_m(i_{FC} - i_n) \\ + B\log\left(1 - \frac{i_{FC} - i_n}{i_{Lim}}\right) \end{matrix}\right\} \tag{8}$$

Hence $V_{FC} = f(i_{FC})$. E_0 is the reversible no loss voltage of the Fuel cell, 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 $V_{FC} \in [0; V_d[$.

C. Equilibrium

After some simple calculations the equilibrium vector is:

$$\bar{x} = \begin{bmatrix} \bar{x}_1 & \bar{x}_2 & \bar{x}_3 & \bar{x}_4 & \bar{x}_5 & \bar{x}_6 & \bar{x}_7 \end{bmatrix} \tag{9}$$

$$x = \begin{bmatrix} V_d\,, & \frac{(V_d - E_L)V_d}{R_L V_{FC}}, & V_d\,, & \frac{V_d - E_L}{R_L}, & \bar{x}_5\,, & 0, & \frac{V_d - E_L}{R_L} \end{bmatrix}^T \tag{10}$$

Where Vd is the desired DC Bus voltage. An implicit purpose of the proposed structure is to recover energy to charge the SC. Hence, the desired voltage is:

$$\bar{x}_5 = \bar{V}_{SC} = V_{SC}(t = 0) = 12V\ .$$

$$\bar{\mu} = \begin{bmatrix} \bar{\mu}_1 & \bar{\mu}_2 \end{bmatrix}^T = \begin{bmatrix} (1 - \bar{U}_{FC}) & (1 - \bar{U}_{SC}) \end{bmatrix}^T \tag{11}$$

or

$$\bar{U} = \begin{bmatrix} \bar{U}_{FC} & \bar{U}_{SC} \end{bmatrix} = \begin{bmatrix} 1 - \frac{V_{FC}}{V_d} & 1 - \frac{\bar{x}_5}{V_d} \end{bmatrix} \tag{12}$$

The natural energy function of the system is

$$H = \frac{1}{2} x^T Q x \quad (13)$$

Where $Q = diag\{C_S;\ L_{FC};\ C_{DL};\ L_{DL};\ C_{SC};\ L_{SC};\ L_L\}$ is a diagonal matrix.

4. Problem Formulation

The main purpose of the study is to compare two control techniques of the hybrid source. The first is based on sliding mode control by using current controller, and the second based on PBC on voltage control. The second aim 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 third purpose consists in recovering energy throw the charge of the SC.

After system modelling, equilibrium points are computed in order to ensure the desired behaviour 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 constant value and the SCs current has to be cancelled. During transient, the power delivered by the DC source has to be the more constant as possible (without a significant power peak), so the SCs deliver the transient power to the load. If the load provides current, the SCs recover its energy.

At equilibrium, the SC has to be charged and then the current has to be equal to zero.

5. Port-Controlled Hamiltonian Representation

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

$$H_d = \frac{1}{2} \tilde{x}^T Q \tilde{x} \quad (14)$$

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

$$\begin{aligned}
\dot{\tilde{x}}_1 &= \frac{1}{C_S}\left[(1-U_{FC})(\tilde{x}_2+\bar{x}_2) - \tilde{x}_4 - \bar{x}_4\right] \\
\dot{\tilde{x}}_2 &= \frac{1}{L_{FC}}\left[V_{FC} - (1-U_{FC})(\tilde{x}_1+\bar{x}_1)\right] \\
\dot{\tilde{x}}_3 &= \frac{1}{C_{DL}}\left[(\tilde{x}_4+\bar{x}_4) - (\tilde{x}_7+\bar{x}_7) + (1-U_{SC})(\tilde{x}_6+\bar{x}_6)\right] \\
\dot{\tilde{x}}_4 &= \frac{1}{L_{DL}}\left[(\tilde{x}_1+\bar{x}_1) - (\tilde{x}_3+\bar{x}_3)\right] \qquad (15) \\
\dot{\tilde{x}}_5 &= \frac{-(\tilde{x}_6+\bar{x}_6)}{C_{SC}} \\
\dot{\tilde{x}}_6 &= \frac{1}{L_{SC}}\left[(\tilde{x}_5+\bar{x}_5) - (1-U_{SC})(\tilde{x}_3+\bar{x}_3)\right] \\
\dot{\tilde{x}}_7 &= \frac{1}{L_L}\left[(\tilde{x}_3+\bar{x}_3) - R_L(\tilde{x}_7+\bar{x}_7) - E_L\right]
\end{aligned}$$

The representation (15) in function of the gradient of the desired energy (14) is given by (16).

$$\dot{\tilde{x}} = \left[\Im(\mu_1 \mu_2) - \Re\right]\nabla H_d + A_i(\bar{x}, \mu) \quad (16)$$

with

$$\nabla H_d = \left[C_S \tilde{x}_1; L_{FC}\tilde{x}_2; C_{DL}\tilde{x}_3; L_{DL}\tilde{x}_4; C_{SC}\tilde{x}_5; L_{SC}\tilde{x}_6; L_L\tilde{x}_7\right]^T \quad (17)$$

and

$$A_i(\bar{x}, \mu) = \begin{bmatrix} \frac{1}{C_S}\left[-\bar{x}_4 + (1-U_{FC})\bar{x}_2\right] \\ \frac{1}{L_{FC}}\left[V_{FC} - (1-U_{FC})\bar{x}_1\right] \\ \frac{\bar{x}_4 - \bar{x}_7 + (1-U_{SC})\bar{x}_6}{C_{DL}} \\ \frac{\bar{x}_1 - \bar{x}_3}{L_{DL}} \\ -\frac{\bar{x}_6}{C_{SC}} \\ \frac{1}{L_{SC}}\left[\bar{x}_5 - (1-U_{SC})\bar{x}_3\right] \\ \frac{\bar{x}_3 - R_L\bar{x}_7 - E_L}{L_{DL}} \end{bmatrix} \quad (18)$$

Where $\Im(\mu_1, \mu_2) = -\Im(\mu_1, \mu_2)$ is a skew symmetric matrix defining the interconnection between the state space and $\Re = \Re^T \geq 0$ is symmetric positive semi definite matrix defining the Damping of the system.

The following control laws are proposed:

$$\begin{cases} U_{FC} = \bar{U}_{FC} \\ U_{SC} = \bar{U}_{SC} - r\tilde{x}_6 \end{cases} \quad (19)$$

where r is a design parameter.

Proposition 1: The origin of the closed loop PCH system (16), with the control laws (19) and (12) with the radially unbounded energy function (14), is globally stable.

Proof: The closed loop dynamic of the PCH system (16) with the laws (19) and (12) with the radially unbounded energy function (14) is:

$$\dot{\tilde{x}} = \left[\Im(\mu_1, \mu_2) - \Re'\right]\nabla H_d \quad (20)$$

where

$$\Re' = diag\{C_S; L_{Fc}; C_{DL}; L_{DL}; C_{SC}; L_{SC}; L_L\} = \Re'^T \geq 0 \quad (21)$$

The derivative of the desired energy function (14) along the trajectory of (20) is:

$$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = -\nabla H_d^T \Re' \nabla H_d \leq 0 \quad (22)$$

6. Sliding Mode Control of the Hybrid Source

Due to the weak request on the FC, a classical PI controller is adapted for the boost converter, and because of the fast response in the transient power and the possibility to work with a variable or a constant frequency, a non-linear sliding mode control [13-14] is chosen for the DC-DC bidirectional SC converter, that allows to manage the charge and the discharge of SC tank.

The current supplied by the FC is limited to an interval [I_{MIN}, I_{MAX}]. Within this interval, the FC boost ensures the regulation of this current to its reference. But, as soon as load current is greater than I_{MAX} or lower than I_{MIN}, the boost can no more regulate the desired current. The lacking or excess current is then provided or absorbed by the storage device, hence that the DC link current is kept equal to its reference level. Thus, three modes can be defined to optimize the functioning of the hybrid source:

-The normal mode, for which load current is within the interval [I_{MIN}, I_{MAX}]. In this mode, the FC boost converter ensures the regulation of the DC link current, and the control of the bidirectional SC converter leads to the charge or the discharge of SC up to a reference voltage level V_{SCREF},

-The discharge mode, for which load power is greater than I_{MAX}. The current reference of the boost is then saturated to I_{MAX}, and the FC DC-DC converter ensures the regulation of the DC link voltage by supplying the lacking current, through SC discharge,

-The recovery mode, for which load power is lower than I_{MIN}. The power reference of the FC boost converter is then saturated to I_{MIN}, and the FC DC-DC converter ensures the regulation of the DC link current by absorbing the excess current, through SC charge.

A. DC-DC boost FC converter control principle

Fig. 2 presents the synoptic control of the FC boost.

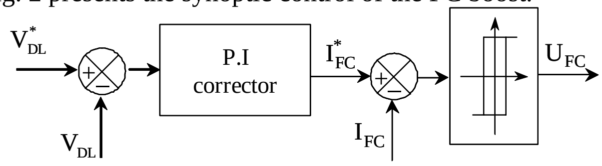

Fig. 2 Control of the FC converter

The FC current reference is generated by means of a PI voltage loop control on a DC link voltage and its reference:

$$I_{FC}^{*} = k_{Pf}\left(V_{DL}^{*} - V_{DL}\right) + k_{If}\int_{0}^{t}\left(V_{DL}^{*} - V_{DL}\right)dt \qquad (23)$$

With, k_{Pf} and k_{If} are the proportional and integral gains. The switching device is controlled by a hysteresis comparator.

D. DC-DC SC converter control principle

To ensure a proper functioning for the three modes, we use a sliding mode control for the DC-DC converter. Thus we define a sliding surface S as a function of the DC link voltage V_{DL}, its reference V_{DL}^{*}, the supercapacitors voltage V_{SC}, its reference V_{SC}^{*}, and the supercapacitors current I_{SC}:

$$S = \left(V_{DL} - V_{DL}^{*}\right) + k_c \cdot \left(I_{SC} - I\right) \qquad (24)$$

$$I = k_{ps}\left(V_{SC} - V_{SC}^{*}\right) + k_{is}\int_{0}^{t}\left(V_{SC} - V_{SC}^{*}\right)dt \qquad (25)$$

With, k_{ps} and k_{is} are the proportional and integral gains. When $S < 0$, we switch on $(T_{SC} = 1)$, we switch off $(\overline{T}_{SC} = 0)$. When $S > 0$, we switch on $(\overline{T}_{SC} = 1)$, we switch off $(T_{SC} = 0)$.

The FC PI controller ensures that I_{DL} tracks I_L. The SC PI controller ensures that V_{SC} tracks its reference V_{SC}^{*}.

k_C is the coefficient of proportionality, which ensures that the sliding surface equal zero by tracking the SC currents to its reference I when the FC controller can't ensure I_{DL} tracks I_L.

In steady state condition, the FC converter ensures that the first term of the sliding surface is null, and the integral term of equation (25) implies $V_{SC} = V_{SC}^{*}$. Then, imposing S = 0 leads to I_{SC} = 0, as far as the boost converter output current I_{DL} is not limited. So that, the storage element supplies energy only during power transient and I_{DL} limitation.

In the case of a variable frequency control, a hysteresis comparator is used with the sliding surface S as input. In the case of a constant frequency control, the general system equation can be written as:

$$\dot{X} = AX + BU + C + \xi \qquad (26)$$

with

$$X = \left[V_{DL}\ \ I_{SC}\ \ V_{SC}\ \ I\right]^{T} \qquad (27)$$

and

$$A = \begin{bmatrix} 0 & 1/C_{DL} & 0 & 0 \\ -1/L_{SC} & -r_{SC}/L_{SC} & 1/L_{SC} & 0 \\ 0 & -1/C_{SC} & 0 & 0 \\ 0 & -k_{ps}/C_{SC} & k_{is} & 0 \end{bmatrix}$$

$$B = \left[\frac{-I_{SC}}{C_{DL}}\ \ \frac{V_{DL}}{L_{SC}}\ \ 0\ \ 0\right]^{T}, U = U_{SC}$$

and $C = \left[\frac{(I_{DL} - I_L)}{C_{DL}}\ \ 0\ \ 0\ \ -k_{is}V_{SC}^{*}\right]^{T}$

If we note $G = \left[0\ \ k_C\ \ 0\ \ -k_C\right]$ (28)

the sliding surface is then given by

$$S = G \cdot \left(X - X_{ref}\right) \qquad (29)$$

with

$$X_{ref} = \left[V_{DL}^{*}\ \ 0\ \ 0\ \ 0\right]^{T}$$

In order to set the system dynamic, we define the reaching law

$$\dot{S} = -\lambda S - K sign(S) \qquad (30)$$

with

$$K = 0 \quad \text{if} \left\|S\right\| < \varepsilon \qquad (31)$$

and

$$K = n\lambda\varepsilon \quad \text{if} \left\|S\right\| > \varepsilon \qquad (32)$$

The linear term $-\lambda S(X)$ imposes the dynamic inside the error bandwidth ε. The choice of a high value of λ ($\le f_C/2$) ensures a small static error when $\left\|S\right\| < \varepsilon$. The non-linear term $-K.sign(S)$ permits to reject perturbation effects (uncertainty of the model, variations of the working conditions). This term allows compensating high values of error $\left\|S\right\| > \varepsilon$ due to the above mentioned perturbations. The choice of a small value of ε leads to high current undulation (chattering effect) but the static error remains small. A high value of ε obliges to reduce the value of λ to ensure the stability of the system and leads to higher static error.

Once the parameters (λ,K,ε) of the reaching law are determined, it is possible to calculate the continuous equivalent control, which allows to maintain the state trajectory on the sliding surface. We use the equations (26), (29) and (30), we find:

$$U_{SCeq} = (GB)^{-1}\begin{Bmatrix} -GAX - GC + GX_{ref} - \lambda GX \\ +\lambda GX_{ref} - Ksign(S) \end{Bmatrix} \quad (33)$$

Equations (26) and (33) give the equation:

$$A_{eq} = A - B(GB)^{-1}GA - B(GB)^{-1}\lambda G \quad (34)$$

This equation allows finding poles of the system during the sliding motion as a function of λ and k_C. The parameters k_{is} and k_{ps} are then determined by solving S = 0, equation justified by the fact that the sliding surface dynamic is hugely greater than supercapacitor voltage variation.

E. Stability

Consider the following Lyapunov function:

$$V = \frac{1}{2}S^2 , \quad (35)$$

With S is the sliding surface.

The derivative of the Lyapunov function along the trajectory of (26) in the closed loop with the control (33) gives:

$$\dot{V} = S\dot{S} = -\lambda S^2 - KSsign(S) \le 0 , \quad (36)$$

With $\lambda, K > 0$

Hence, the origin of the closed loop of the system (26) with the control (33) and the sliding surface (29) is asymptotically stable.

7. Simulation results of the hybrid source 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} = 130 W.
- DC link parameters: V_{DL}= 42 V.
- SC parameters: C_{SC} = 3500/6 F, $V^*_{SC} = 15V$.

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.

Figures 3 and 4 present the behaviour of FC, load and SCs currents: I_{FC}, I_L, I_{SC}; and the DC link voltage V_{DL} for a transition from the normal operating mode to the charging mode obtained by using sliding mode control,. The test is performed by changing sharply the e.m.f load voltage E_L from 20 V to 30 V in the interval of t∈[1s, 3s]. The e.m.f load voltage E_L = 20 V corresponds to a normal mode and the e.m.f load voltage E_L = 30 V to a charging mode.

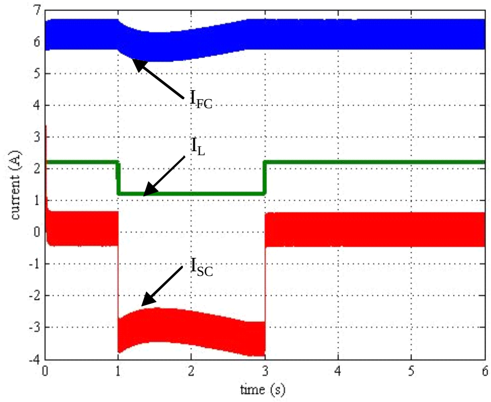

Fig. 3 Fuel cell, DC link currents and SC currents

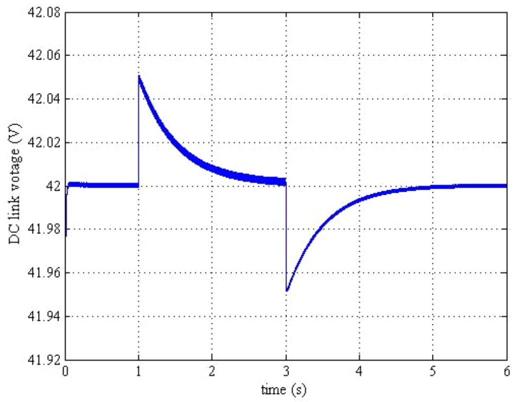

Fig. 4 DC link voltage

At the starting of the system, only the FC provides the mean power to the load. The storage device current reference is equal to zero, we are in normal mode. In the transient state, the load current I_L became lower than the DC link current I_{DL}. Then, the storage device current reference became negative thanks to controller which compensate this negative value by the difference between the SC voltage and its reference. We are in recovering mode. After the load variation (t > 3 s), the current in the DC link became equal to the load current. The SC current I_{SC} became null.

The DC link voltage reference is set at 42V. The DC link voltage tracks well the reference during the first second, then a very small overshoot is observed when the load current becomes negative.

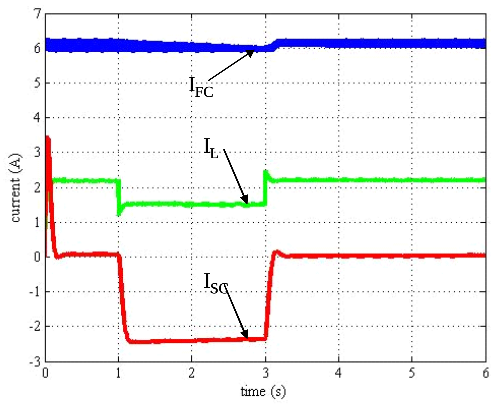

Fig. 5 Fuel cell, DC link currents and SC currents

Figures 5 and 6 present the system response, by using passivity based control, when the load is considered as a generator. So, the proposed control laws can be tested

during recovery mode (between t=1s and t=3), only the electromotive force (emf) is modified for these simulations.
Figure 5 shows the behaviour of currents I_{FC}, I_L, I_{SC}. A smooth behaviour of the current is observed regarding the changes in E_L, this is because the SCs supply the transient power. When the load provides energy, all goes to the SC because FC with the boost converter are not reversible. All the current provided by the load is absorbed by the SC during the recovery mode. The SC supply power to the load in the transient. The SC voltage increase when the load works as a generator.

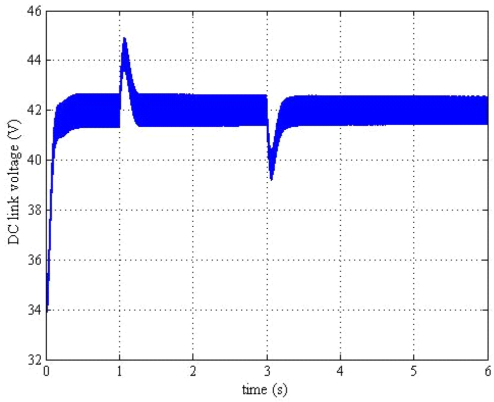

Fig. 6 DC link voltage

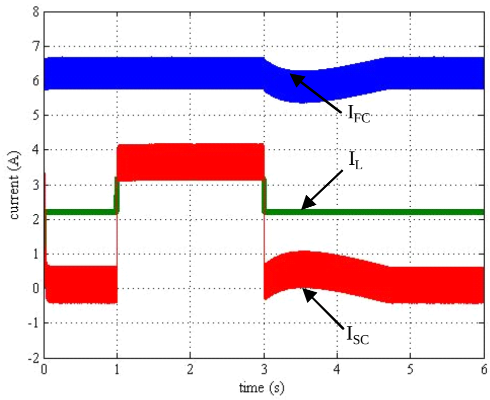

Fig. 7 Fuel cell, DC link currents and SC currents

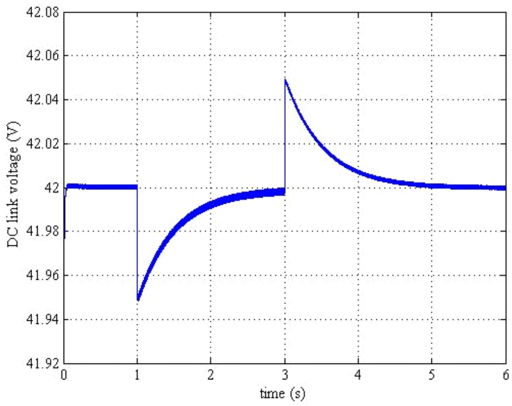

Fig. 8 DC link voltage

The DC link voltage reference is set at 42V. The DC link voltage tracks well the reference during the first second, then a small overshoot is observed when the load current becomes negative.

Figures 7 and 8 present the behaviour of currents I_{FC}, I_L, I_{SC} and the DC link voltage V_{DL} in a transient from the normal operating mode to the recovery mode, obtained by using sliding mode control. The test is performed by changing sharply the e.m.f load voltage E_L from 20 V to 10 V in the interval of $t \in [1s, 3s]$. The e.m.f load voltage E_L = 20 V corresponds to a normal mode and the e.m.f load voltage E_L = 10 V to the discharging mode.
At the starting of the system, only the FC provides the mean power to the load. The storage device current reference is equal to zero, we are in normal mode. In the transient state, the load current I_L became greater than the DC link current I_{DL}. The storage device current reference became positive thanks to the controller which compensate this positive value by the difference between the SC voltage and its reference. We are in discharging mode. After the load variation (t > 3 s), the current in the DC link became equal to the load current. The SC current I_{SC} became null.
The DC link voltage reference is set at 42V. The DC link voltage tracks well the reference during the first second, then a very small overshoot is observed when the load current becomes positive.
Figures 9 and 10 present the system response, by using PBC, when the load is considered as a receiver. So, the proposed control laws can be tested during discharging mode (between t=1s and t=3s), only the electromotive force (emf) is modified for these simulations.

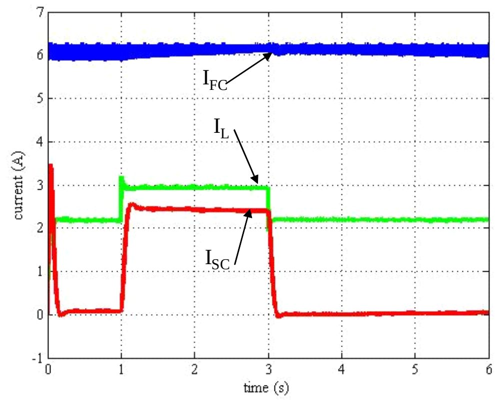

Fig. 9 Fuel cell, DC link currents and SC currents

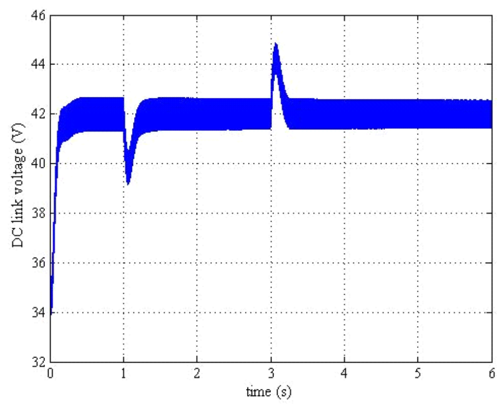

Fig. 10 DC link voltage

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A very low overshoot and no steady state error are observed. 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 null. The positive sense of I_{SC} means that the SCs supply the load and the

negative one corresponds to the recovery of energy by the SC. At time t = 3s, the SC absorb the current pick to respond quickly to the fast DC reference change. The power pick are absorbed or supplied by SC, thus a smooth power is provided by the DC source. This can reduce significantly the harmonics on the line. It can be seen that the system with the proposed controller is robust towards load resistance changes and emf variations.

The DC link voltage reference is set at 42V. The DC link voltage tracks well the reference during the first second, then a small overshoot and a steady state error are observed when the load current becomes negative. This is a 7% error which is acceptable in most of the case

8. Conclusion

In this paper, a modelling and the control principles of a DC hybrid source system, composed of a FC source and a SC source, have been presented. This source uses the fuel cell as mean power source and supercapacitors as auxiliary transient power source.

Sliding Mode Control and Passivity Based Control principles have been applied, with stability proof, and validated by simulation results.

PCH structure of the overall system is given exhibiting important physical properties in terms of variable interconnection and damping of the system. The problem of the DC Bus Voltage control is solved using simple linear controllers based on an IDA-PBC approach.

With the sliding mode principle control, we have a robustness control. But the sliding surface is generated in function of multiple variables: DC link voltage, supercapacitors current and voltage.

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

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

Many advantages follow from the energy storage principle in electric double layer supercapacitors technology.

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