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Passivity Based Control and Fuzzy Logic Estimation applied to DC Hybrid Power Source using Fuel Cell and Supercapacitor

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Abstract— **Fuel Cells (FCs) are a good alternative for using clean energy in most of residential and industrial applications. Therefore, their slow dynamics and difficulty to respond to the abrupt changes of load leads to the preference or the adoption of the FC's association with one or more power sources of high dynamics, such as supercapacitors (SCs) or batteries. This paper presents the study of a hybrid power sources system using FC as a main source, a DC link and supercapacitor as an auxiliary power source as well. The whole system is modelled in state space equations. The energy management is reached by using passivity-Based Control (PBC). PBC is a very powerful nonlinear technique dealing with important system information like the system's total energy. A Fuzzy Logic System (FLS) is used in this work to estimate the immeasurable desired supercapacitor current which is necessary for controlling the studied system by PBC. Stability proof and simulation results are given.**

Index Terms—**Fuel cell, Supercapacitor, Passivity Based Control, Interconnection and damping assignment, Port Controlled Hamiltonian System, Fuzzy Logic System, Hybrid System.**

I. Introduction

The fuel cells advantages such as high efficiency, self-contained unit, modularity capability, being clean make them attractive to be used as autonomous DC power supplies in some applications. However, their slow dynamics (mainly due to their auxiliaries) and difficulty to cold start leads to prefer the association of a fuel cell with one or more power sources of high dynamics, such as supercapacitors or batteries [1].

This work displays a design of a hybrid DC power source using a Proton Exchange Membrane FC (PEMFC) as a main energy source and supercapacitor as auxiliary storage device [2-4]. Our interest is to control the system in such a way to converge to its desired equilibrium points. That means that, using our command, the controller is able 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.

Recently, a feedback control methodology has been developed which is aimed at modifying the closed loop energy dissipation and potential energy properties of nonlinear systems. This approach, passivity-based controllers design, has been successfully used in the control of Euler-Lagrange systems, such as robotic manipulators and electro-mechanical energy conversion devices [5].

Fuzzy logic systems (FLSs) have been credited in control system and applications as powerful tools capable of providing robust controllers for mathematically ill-defined systems that may be subjected to structured and unstructured uncertainties. The universal approximation has been another main driving force behind the increasing popularity of fuzzy logic controllers as it shows that fuzzy systems are theoretically capable of uniformly approximating any continuous real function to any degree of accuracy [6, 7]. FLS is much closer in spirit to human thinking and natural language [6], and preferred by control engineering practitioners. In this paper, FLS is only used to estimate the supercapacitor current I_{SC} which is employed to specify design requirements in PBC. This last, is able to cope with this unreliability, uncertainty and lack of information, this is the reason of their success in many works as in [8-10].

II. 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 had ever since drawn much attention in electrical, mechanical and electromechanical systems. 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 [4]. 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:

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

B. Structure of the Hybrid Power Source

The proposed 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 reference value V_d,

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and a storage device based on supercapacitor, which is connected to the DC link through a current bidirectional DC-DC converter, As shown in Fig. 1 [11, 12].

The role of the FC is to supply the mean energy to the load [1, 4], whereas the storage device (as an auxiliary source) is used to supply the load in the transient and steady state.

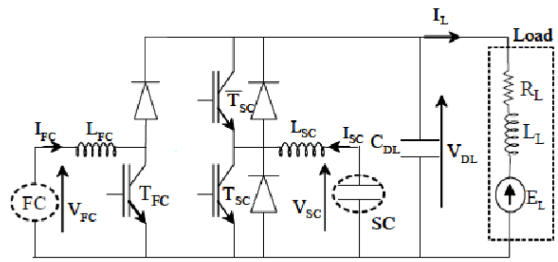

Figure 1. Structure of the hybrid source.

1) Equations of the System: The energy management of this system needs to manage the energy used in the whole vehicle cycle. 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:

$$x = [x_1, x_2, x_3, x_4, x_5]^T = [I_{FC}, V_{DL}, V_{SC}, I_{SC}, I_L]^T \quad (3)$$

Let's have U_{FC} the control of the FC boost converter and U_{SC} the control of the supercapacitor buck-boost converter. Then the control vector is:

$$\mu = [\mu_1, \mu_2]^T = [(1 - U_{FC}), (1 - U_{SC})]^T \quad (4)$$

The fifth order overall state space model is then:

$$\begin{cases} \frac{dI_{FC}}{dt} = \frac{1}{L_{FC}}[-\mu_1 V_{DL} + V_{FC}] \\ \frac{dV_{DL}}{dt} = \frac{1}{C_{DL}}[\mu_1 I_{FC} + \mu_2 I_{SC} + I_L] \\ \frac{dV_{SC}}{dt} = \frac{1}{C_{SC}}[-I_{SC}] \\ \frac{dI_{SC}}{dt} = \frac{1}{L_{SC}}[-\mu_2 V_{DL} + V_{SC}] \\ \frac{dI_L}{dt} = \frac{1}{L_L}[V_{DL} - R_L I_L + E_L] \end{cases} \quad (5)$$

with $V_{FC} = V_{FC}(x_1)$, PEMFC static model is given as follows [13]:

$$V_{FC} = E_0 - A.\log\left(\frac{i_{FC} - i_n}{i_0}\right) - \{R_m(i_{FC} - i_n) + B.\log\left(1 - \frac{i_{FC} - i_n}{i_{Lim}}\right)\} \quad (6)$$

Hence $V_{FC} = f(i_{FC})$. E is the reversible no loss voltage of the fuel cell, E_0 is the measured open circuit voltage, 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.

2) Equilibrium: The equilibrium state space vector is:

$$\bar{x} = [\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4, \bar{x}_5]^T \quad (7)$$

At the equilibrium, the system of equations (5) becomes:

$$\begin{cases} \dot{\bar{x}}_1 = \frac{1}{L_{FC}}[-\bar{\mu}_1 \bar{x}_2 + V_{FC}] \\ \dot{\bar{x}}_2 = \frac{1}{C_{DL}}[\bar{\mu}_1 \bar{x}_2 + \bar{\mu}_2 \bar{x}_4 - \bar{x}_5] \\ \dot{\bar{x}}_3 = \frac{1}{C_{SC}}[-\bar{x}_4] \\ \dot{\bar{x}}_4 = \frac{1}{L_{SC}}[-\bar{\mu}_2 \bar{x}_2 + \bar{x}_3] \\ \dot{\bar{x}}_5 = \frac{1}{L_L}[\bar{x}_2 - R_L \bar{x}_5 + E_L] \end{cases} \quad (8)$$

After simple calculations, the equilibrium is defined as:

$$\bar{x} = [\bar{I}_{FC}, V_d, \bar{V}_{SC}, \bar{I}_{SC}, \frac{V_d - E_L}{R_L}]^T \quad (9)$$

The Fig. 2 shows the global structure of our system where the FC and SC supply the load and recover energy to charge the storage device (SC). Hence, the desired supercapacitor current $\bar{I}_{SC}$ is determined by fuzzy logic system as function of supercapacitor state of charge *SoC* and hydrogen quantity QH_2.

From the system (8), the equilibrium values of the control signals are calculated:

$$\bar{\mu}_1 = \frac{1}{V_d}(V_{FC} - L_{FC}\dot{\bar{x}}_1) \quad (10)$$

$$\bar{\mu}_2 = \frac{1}{V_d}(\bar{x}_3 - L_{SC}\dot{\bar{x}}_4) \quad (11)$$

where

$$\bar{\mu} = [\bar{\mu}_1, \bar{\mu}_2]^T = [(1 - \bar{U}_{FC}), (1 - \bar{U}_{SC})]^T \quad (12)$$

and

$$\bar{x}_3 = -\frac{1}{C_{SC}}\int \bar{x}_4 + \bar{V}_{SC0} \quad (13)$$

where $\bar{V}_{SC0} = \bar{V}_{SC}(t = 0) = 12V$.

The natural energy function of the system is:

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

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

C. Problem Formulation

The main purpose of this work is the control of the hybrid source by PBC where the equilibrium points are computed as function of the desired supercapacitor current. The second aim is to determine the desired supercapacitor current by the fuzzy logic estimator FLE as function of supecapacitor state of charge *SoC* and the hydrogen quantity QH_2 in order to ensure the desired behaviour of the system. In the transient and steady state the load has to be supplied by the FC and SC sources according the desired supercapacitor current value. So the controller has to maintain the DC bus voltage to constant value and the SC current has to track its reference.

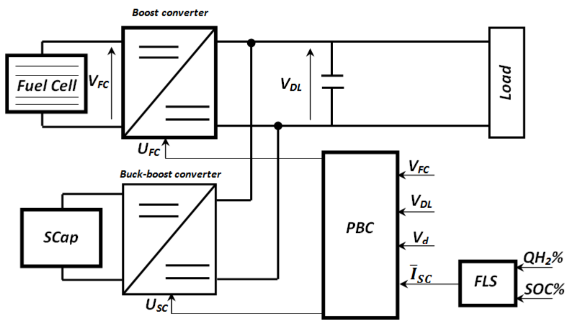

Figure 2. Global structure of the control system.

D. Port Controlled Hamiltonian Representation of the System

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

$$H_d = \frac{1}{2}\tilde{x}^T Q \tilde{x} \tag{15}$$

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

$$\begin{cases} \dot{\tilde{x}}_1 = \dfrac{1}{L_{FC}}[-\mu_1\tilde{x}_2 + (\bar{\mu}_1 - \mu_1)\bar{x}_2] \\ \dot{\tilde{x}}_2 = \dfrac{1}{C_{DL}}[\mu_1\tilde{x}_1 + \mu_2\tilde{x}_4 - \tilde{x}_5 + (\mu_1 - \bar{\mu}_1)\bar{x}_2 + (\mu_2 - \bar{\mu}_2)\bar{x}_4] \\ \dot{\tilde{x}}_3 = \dfrac{1}{C_{SC}}[-\tilde{x}_4] \\ \dot{\tilde{x}}_4 = \dfrac{1}{L_{SC}}[-\mu_1\tilde{x}_2 + \tilde{x}_3 + (\bar{\mu}_2 - \mu_2)\bar{x}_2] \\ \dot{\tilde{x}}_5 = \dfrac{1}{L_L}[\tilde{x}_2 - R_L\tilde{x}_5] \end{cases} \tag{16}$$

The error dynamic (16) as function of the gradient of the desired energy (15) and can be written as:

$$\dot{\tilde{x}} = [\Im(\mu) - \Re]\nabla H_d + A \tag{17}$$

with

$$\nabla H_d = [L_{FC}\tilde{x}_1; C_{DL}\tilde{x}_2; C_{SC}\tilde{x}_3; L_{SC}\tilde{x}_4; L_L\tilde{x}_5]^T \tag{18}$$

and

$$[\Im(\mu) - \Re] = \begin{bmatrix} 0 & -\frac{\mu_1}{C_{DL}L_{FC}} & 0 & 0 & 0 \\ \frac{\mu_1}{C_{DL}L_{FC}} & 0 & 0 & \frac{\mu_2}{C_{DL}L_{SC}} & -\frac{1}{C_{DL}L_L} \\ 0 & 0 & 0 & -\frac{1}{C_{SC}L_{SC}} & 0 \\ 0 & -\frac{\mu_2}{C_{DL}L_{SC}} & \frac{1}{C_{SC}L_{SC}} & 0 & 0 \\ 0 & \frac{1}{C_{DL}L_L} & 0 & 0 & -\frac{R_L}{L_L^2} \end{bmatrix} \tag{19}$$

$$A = \begin{bmatrix} \frac{1}{L_{FC}}[(\bar{\mu}_1 - \mu_1)\bar{x}_2] \\ \frac{1}{C_{DL}}[(\mu_1 - \bar{\mu}_1)\bar{x}_2 + (\mu_2 - \bar{\mu}_2)\bar{x}_4] \\ 0 \\ \frac{1}{L_{SC}}[(\bar{\mu}_2 - \mu_2)\bar{x}_2] \\ 0 \end{bmatrix} \tag{20}$$

Where $\Im(\mu_1, \mu_2) = -\Im^T(\mu_1, \mu_2)$ 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 [4], to introduce a parameter r in the damping matrix of the system:

$$\begin{cases} U_{FC} = \bar{U}_{FC} \\ U_{SC} = \bar{U}_{SC} - r\tilde{x}_4 \end{cases} \tag{21}$$

with r is a positive design parameter.

E. Stability Proof

Using the control laws (12), (21)

$$\dot{\tilde{x}} = [\Im(\mu) - \Re']\nabla H_d + A' \tag{22}$$

where

$$[\Im(\mu) - \Re'] = \begin{bmatrix} 0 & -\frac{\mu_1}{C_{DL}L_{FC}} & 0 & 0 & 0 \\ \frac{\mu_1}{C_{DL}L_{FC}} & 0 & 0 & \frac{\mu_2}{C_{DL}L_{SC}} & -\frac{1}{C_{DL}L_L} \\ 0 & 0 & 0 & -\frac{1}{C_{SC}L_{SC}} & 0 \\ 0 & -\frac{\mu_2}{C_{DL}L_{SC}} & \frac{1}{C_{SC}L_{SC}} & -\frac{rV_d}{L_{SC}^2} & 0 \\ 0 & \frac{1}{C_{DL}L_L} & 0 & 0 & -\frac{R_L}{L_L^2} \end{bmatrix} \tag{23}$$

and

$$\Re' = diag\left\{0; 0; 0; \frac{rV_d}{L_{SC}^2}; \frac{R_L}{L_L^2}\right\} = \Re'^T \tag{24}$$

$$A' = \begin{bmatrix} 0 \\ \frac{r\bar{x}_4\tilde{x}_4}{C_{DL}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{r\bar{x}_4}{C_{DL}L_{SC}} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \nabla H_d$$

$$A' = F\nabla H_d \tag{25}$$

$$[\Re' - F] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{r\bar{x}_4}{C_{DL}L_{SC}} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{rV_d}{L_{SC}^2} & 0 \\ 0 & 0 & 0 & 0 & \frac{R_L}{L_L^2} \end{bmatrix} \tag{26}$$

The derivative of the desired energy function (15) along the trajectories of (22) is non positive if and only if the following matrix is non negative definite. $[\Re' - F] \geq 0$ [14].

Proof:

$$\dot{\tilde{x}} = [\Im(\mu) - \Re']\nabla H_d + F\nabla H_d = \Im(\mu)\nabla H_d - [\Re' - F]\nabla H_d$$

$$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = \nabla H_d^T \Im \nabla H_d - \nabla H_d^T [\Re' - F] \nabla H_d$$

$$\dot{H}_d = \nabla H_d^T [F - \Re'] \nabla H_d \leq 0$$

$[F - \Re']$ is negative semi-definite if and only if all eigenvalues of $[F - \Re']$ are negative.

Mathematically, the eigenvalues of triangular matrices are the diagonal elements. In our case, $[F - \Re']$ is an upper triangular matrix so its eigenvalues are:

$$\left\{0; 0; 0; -\frac{rV_d}{L_{SC}^2}; -\frac{R_L}{L_L^2}\right.$$

Then the eigenvalues of $[F - \Re']$ are negative since r, V_d, L_{SC}, R_L and L_L are positive constants.

Hence, the derivative of the desired energy function (15) along the trajectories of (22) and the proposed control (21) is negative semi definite. Consequently, the origin of the closed loop dynamics (22) is stable.

III. Fuzzy Logic System

A FLS needs to define both input and output membership functions, fuzzication method, scaling factor values, type of membership, rules, rule processing (Mamdani, Sugeno), inference mechanism, t-norms, s-norms and defuzzication method. A typical block diagram of a fuzzy control system is detailed in [15].

A. Fuzzy Logic Estimator

The estimate function which is developed in the fuzzy logic rule base system is shown in table II. The fuzzy logic estimator input parameters are the supercapacitor state of charge (*SoC*) and the remaining quantity of H_2 (QH_2), the fuzzy output is the desired supercapacitor current $\bar{I}_{SC}$.The dynamic behavior of the input parameters is represented by the fuzzy logic membership functions.

1) Fuzzification Interface: In multi inputs and single output Mamdani type fuzzy inference system, the supercarpacitor *SoC*, is categorized into three different status called *SoC(Low)*, *SoC(Avg)* and *SoC(High)*. Similarly, the (QH_2) is assigned into three regions $QH_2(Low)$, $QH_2(Avg)$ and $QH_2(High)$. The non-fuzzy input space is mapped into the fuzzy set $U \in R^n$. Where U is the fuzzy set characterized by membership functions $\mu(SoC)$ and $\mu(QH_2)$.

2) Rule Base System: The fuzzy rule base is a set of linguistic rules defined with IF-THEN conditions. The rule base which has the M number of rules ($j = 1,2, ...,M$) is shown in (27) [16].

$$R^j: IF\ x_1\ is\ A_1^j\ and\ x_2\ is\ is\ A_2^j\ and\ ...\ x_n\ is\ is\ A_n^j$$
$$THEN\ z\ is\ B^j \quad (27)$$

$x_i(i = 1, 2, ..., n)$ are the fuzzy system input parameters and the fuzzy output variables is denoted as z. The membership functions $\mu_{Soc_i^j}(x_i)$ and $\mu_{QH_{2_i}^j}(x_i)$ are represented as the input linguistic term A_i^j. B_i^j is the linguistic term for thefuzzy output. Equation (28) shows the first rule assigned for the rule base system shown in TABLE II.

$$R^1: IF\ x_1\ is\ \mu_{SoC(Low)}\ and\ x_2\ is\ \mu_{QH_2(Low)}$$
$$THEN\ \bar{I}_{SC}\ is\ 0 \quad (28)$$

If the supercapacitor *SoC* and the quantity of H_2 are in low modes, then current of supercapacitor equals 0 mode. At this stage only the FC supplies the load.

$$R^2: IF\ x_1\ is\ \mu_{SoC(Avg)}\ and\ x_2\ is\ \mu_{QH_2(Low)}$$
$$THEN\ \bar{I}_{SC}\ is\ PosB^1 \quad (29)$$

At this stage the FC and SC simultaneously supply the load.

$$R^7: IF\ x_1\ is\ \mu_{SoC(Low)}\ and\ x_2\ is\ \mu_{QH_2(High)}$$
$$THEN\ \bar{I}_{SC}\ is\ NegB^2 \quad (30)$$

At this stage the FC supplies the load and charges the supercapacitor.

3) Fuzzy Inference Machine: The fuzzy inference machine is a decision making logic which converts the fuzzy rule base into the fuzzy outputs. The fuzzy output $\hat{I}_{SC}$ is decided by the rules assigned for *SoC* and QH_2.

4) Defuzzification Interface: In defuzzification interface, the fuzzy output value in the fuzzy inference machine is converted into a non fuzzy output value. The actual value of the desired supercapacitor current $\bar{I}_{SC}$ is obtained by centroid defuzzification method.

IV. Simulation Results of the Hybrid Source

The different simulation parameters are shown in TABLE I. The supercapacitive power peak unit is obtained by a series association of six supercapacitors *3500 F*. The rated voltage of these components is *2.5 V*. The initial value of the supercapacitive power peak voltage is *12 V*. A reference voltage that the DC link voltage must follow it is imposed. Fig.3 presents the system response to changes in the DC bus voltage reference V_d, and load current I_L. The DC bus voltage tracks well the reference, a very low overshoot and no steady state error are observed. Figs. 4 and 5 show the fuel cell V_{FC}, I_{FC} and the supercapacitor V_{SC}, I_{SC} responses successively. When the hydrogen quantity is decreasing, the supercapacitor supplies with the fuel cell power to the load in transient and steady state, if it is charged, by cons in the work [4], the SC supplies the load just in transient. The SC current I_{SC} tracks well its reference which is considered as the steady state of I_{SC} in PBC. Fig. 6 presents the network boost controller, the supercapacitor bidirectional converter controller. U_{FC} and U_{SC} are in the set [0,1]. Fig. 7 shows the variations of QH_2 and *SoC* according to the FC and SC powers provided to the load. At *5s* the load resistance makes change at *15* Ω as shown in Fig. 8. Fig. 9 shows the powers transfer of the system and the sum of the SC and FC powers given to the load power.

[1] PosB: Positive Big

[2] NegB: Negative Big

TABLE I. THE DIFFERENT SIMULATION PARAMETERS

Initialization, RLE load and controller parameters					
$V_{SC}(V)$	$\boldsymbol{V_{DL}}(V)$	$\boldsymbol{R_L}$ (Ω)	$\boldsymbol{L_L}(mH)$	$E(V)$	r
12, at t = 0s	*42*	*10*	*10*	*20*	*0.01*

TABLE II. THE RULE BASE SYSTEM

	SoC(Low)	*SoC(Avg)*	*SoC(High)*
$QH_2(Low)$	*0*	*PosB*	*PosB*
$QH_2(Avg)$	*Neg*	*Pos*	*Pos*
$QH_2(High)$	*NegB*	*0*	*0*

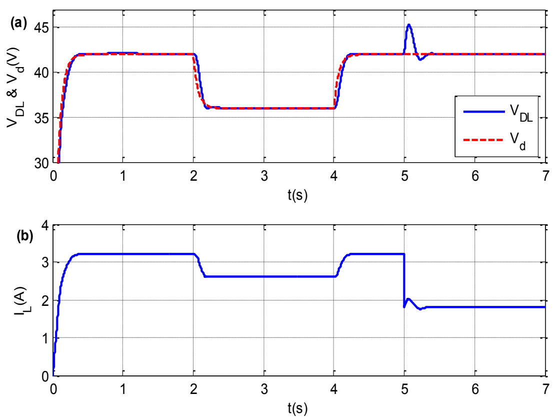

Figure 3. (a) DC Link voltage and its reference. (b) Load current

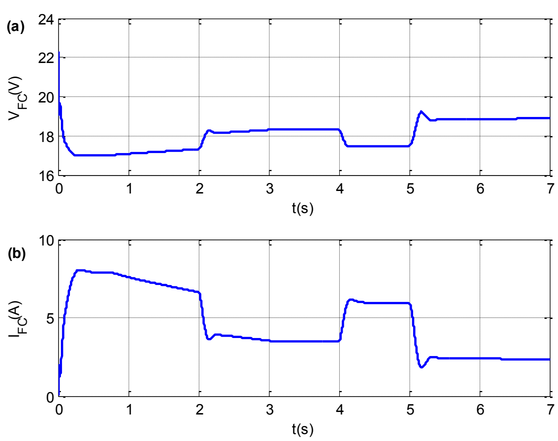

Figure 4. (a) FC Voltage. (b) FC current.

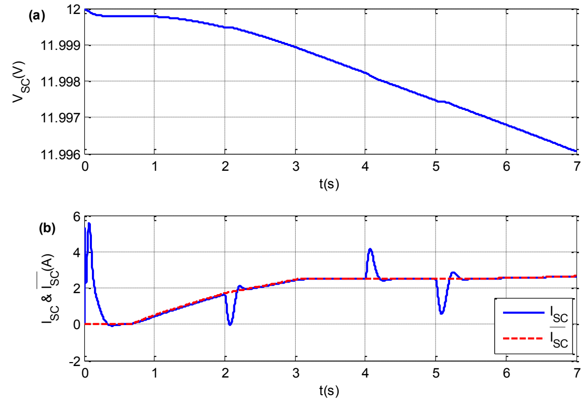

Figure 5. (a) SC Voltage. (b) Reference and SC currents.

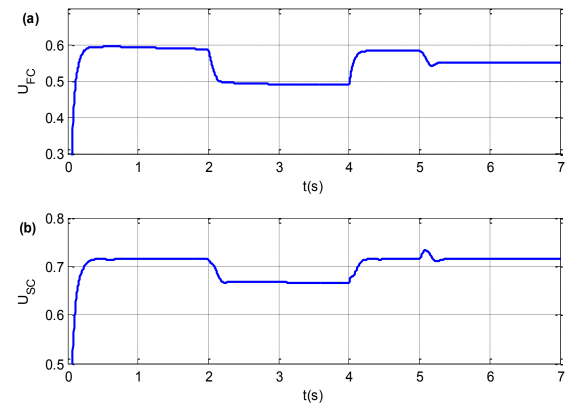

Figure 6. (a) FC boost control. (b) SC converter control.

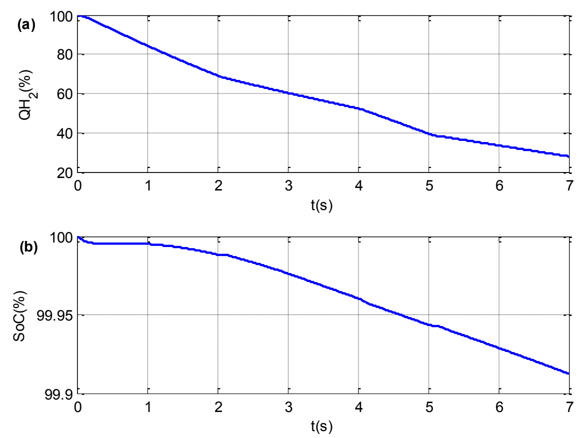

Figure 7. (a)Fuel Cell QH_2. (b) Supercapacitor *SoC*.

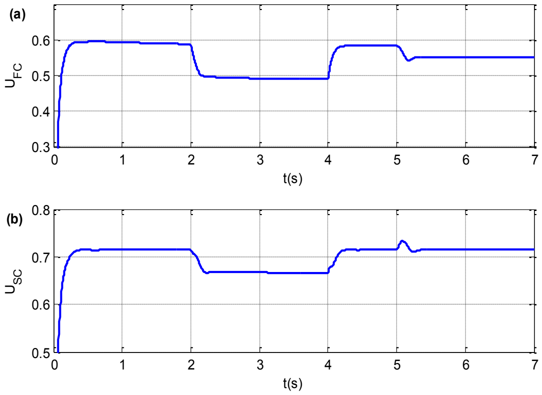

Figure 8. (a) FC boost control. (b) SC converter control.

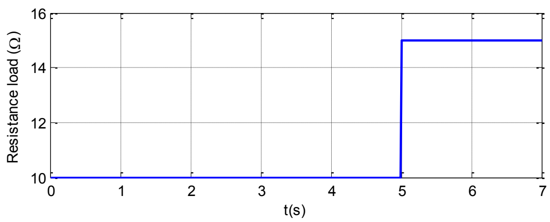

Figure 9. Load resistance change.

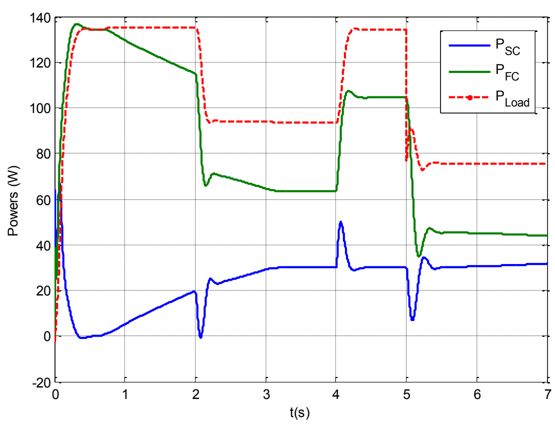

Figure 10. Powers flow.

V. Conclusion

In this paper, a modelling and the control principles of a DC hybrid sources system, composed of a FC and a SC sources, have been presented. This system uses the fuel cell as mean power source and the supercapacitor as auxiliary power source which supplies the load in transient and steady state as function of *SoC* and QH_2. 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. An intelligent Fuzzy Logic Estimation is adopted to determine the desired supercapacitor current used in PBC. Global Stability proofs are given and encouraging simulation results have been obtained. Many advantages can be expected from the proposed structure such that supplying the power peaks in the transient and the steady state by using SCs. Many advantages follow from the energy storage principle in electric double layer supercapacitors technology.

References

[1] A. Payman, S. Pierfederici, F. Meibody-Tabar and B. Davat, “Flatness Based Control of a Fuel Cell-Supercapacitor Multi Source/Multi Load Hybrid system”, *13th European Conference on Power Electronics and Applications, EPE ’09.* , 2009, pp. 1-10.

[2] P. Thounthong, S. Raël and B. Davat, “Control Strategy of Fuel Cell and Supercapacitors Association for Distributed Generation System”, *IEEE Transactions on Industrial Electronics*, 2007, pp. 3225-3233.

[3] P. Thounthong, P. Sethakul, S. Ra¨ el and B. Davat, “Performance Investigation of Fuel Cell/Battery and Fuel Cell/Supercapacitor Hybrid Sources for Electric Vehicle Applications”, *4th IET Conference on Power Electronics, Machines and Drives*, 2008, pp. 455-459.

[4] M.Y. Ayad, M. Becherif, A. Henni, A. Aboubou, M. Wack and S. Laghrouche, “Passivity-Based Control applied to DC Hybrid Power Source using Fuel Cell and Supercapacitors”, *Energy Conversion and Management, Elsevier*, 2010, pp. 1468-1475.

[5] H. Sira-Ramirez and R. Ortega, “Passivity Based Controllers for the Stabilization of DC-to-DC Power Converters”, *Proceedings of the 34th IEEE Conference on Decision and Control*, Vol. 4, 1995, pp. 3471-3476.

[6] L. Huang, S.S. Ge and T.H. Lee, “Fuzzy Unidirectional Force Control of Constrained Robotic Manipulators”, *Fuzzy Sets and Systems, Elsevier*, Vol. 134, Issue 1, 16 February 2003, pp 135-146.

[7] L.X. Wang, Adaptive Fuzzy Systems and Control, Design, and Stability Analysis, Prentice Hall, Englewood Cliffs, NJ; 1994.

[8] S. Caux,W. Hankache, M. Fadel and D. Hissel, “On-line Fuzzy Energy Management for Hybrid Fuel Cell Systems”, *International Journal of Hydrogen Energy, Elsevier*, Vol. 35, Issue 5, March 2010, pp. 2134-2143.

[9] D. Gao, Z. Jin and Q. Lu, “Energy management strategy based on fuzzy logic for a fuel cell hybrid bus”, *Journal of Power Sources, Elsevier*, Vol. 185, Issue 1, 15 October 2008, pp. 311-317.

[10] Ö. Gündogdu, K. Erentürk, “Fuzzy Control of a DC Motor Driven Four-Bar Mechanism”, *Mechatronics, Elsevier*, Vol. 15, Issue 4, 2005, pp. 423-438.

[11] M.Y. Ayad, M. Becherif and A. Miraoui, “Sliding Mode Control of DC Bus Voltage of a Hybrid Sources using Fuel Cell and Supercapacitors for Traction System”, *IEEE International Symposium on Industrial Electronics, ISIE*, 2007, pp. 383-388.

[12] M.Y. Ayad, M. Becherif, D. Paire, A. Djerdir and A. Miraoui, “Passivity-based control of hybrid power sources using fuel cell, supercapacitors, and batteries on the dc link for energy traction system”, *Electric Machines & Drives Conference, IEMDC’07. IEEE International*, Vol. 1, 2007, pp. 453-458.

[13] J. Larminie, A. Dicks, *Fuel Cell Systems Explained*, Wiley New York, 2000.

[14] M. Becherif, M.Y. Ayad and M. Wack, “Control study of Fuel Cell, Battery and Solar Hybridization Power Sources”, *Industry Applications Society Annual Meeting (IAS), IEEE*, 2010, pp. 1-8.

[15] J.M. Mendel, *Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions*, Prentice-Hall, Upper-Saddle River, NJ, 2001.

[16] L. Karunarathne, J.T. Economou and K. Knowles, “Model Based Power and Energy Management System for PEM Fuel Cell/Li-Ion Battery Driven Propulsion System”, *5th IET International Conference on Power Electronics, Machines and Drives, PEMD*, 2010, pp. 1-6.