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Fuzzy Logic and Passivity-Based controller applied to Electric Vehicle using Fuel Cell and Supercapacitors Hybrid Source

M. Mohammedi[a], O.Kraa[a], M.Becherif[b], A.Aboubou[a], M.Y.Ayad[c,*] and M.Bahri[a]

[a]Laboratory of Energy Systems Modeling, mohammedi_messaoud@yahoo.fr, Mohamed Kheider University, Biskra, Algeria
[b]FCLab FR CNRS 3539 FEMTO-ST UMR CNRS 6174, mohamed.becherif@utbm.fr, UTBM Belfort, France
[c]Industrial Hybrid Vehicle Applications, ayadmy@gmail.com, France

Abstract

Electric vehicles using Fuel Cell (FC), as a substitute for internal-combustion-engine vehicles, have become a research hotspot for most automobile manufacturers all over the world. Fuel cell systems have disadvantages, such as high cost, slow response and no regenerative energy recovery during braking; hybridization can be a solution to these drawbacks. This paper presents a modelling and control strategies of hybrid DC link which is equipped with a fuel cell system as a main source and a supercapacitor (SC) as an auxiliary power source as well. An energy management strategy based on passivity based control using fuzzy logic estimation, which is employed to control the power source, is described. This fuzzy estimation is capable to determine the desired current of SC according to the SC state of charge (SoC) and the FC remaining hydrogen quantity (QH_2). Finally, the computer simulation results under Matlab verify the validity of the proposed controller and demonstrate that the proposed controller provides robust dynamic characteristics.

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Keywords: Fuel cell, Supercapacitor, Passivity-Based Control, Energy Management, Fuzzy Logic Estimator, Hybrid Vehicle;

1. Introduction

Researches on the power propulsion system of EVs have drawn significant attention in the automobile industry and among academics. EVs can be classified into various categories according to their configurations of the used power sources e.g. pure EV or hybrid EV. On other hand, Fuel cell vehicles have been proposed as a potential solution in the case of automobiles but a fuel cell system alone, integrated into a vehicular power, is not always sufficient to supply propulsion power for a vehicle, because fuel cell systems have some deficiencies, such as high cost, slow response and no regenerative energy recovery during braking. Hybridization of a fuel cell system with energy storage devices

* Corresponding author. Tel: +33 (0) 3 84 58 33 46; fax: +33 (0) 3 84 57 00 32.
E-mail address: ayadmy@gmail.com

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can be a solution to these drawbacks [1]. One motivation for hybridization is that energy storage devices can provide instant peak power during transient conditions of vehicle operation and improve fuel economy by taking advantage of regenerative braking power; at the same time, hybridization can also be helpful in decreasing the cost of the vehicle because of the possibility to use a smaller fuel cell. 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 [1,2]. In this paper, a state-space model has been developed and used by authors for modelling the behaviour of electrical power source for hybrid vehicle applications. This hybrid DC link is equipped with a Proton Exchange Membrane Fuel Cell (PEMFC) as a main source and a supercapacitor (SC) as an auxiliary power source as well. The FC is supplying the mean energy to the load, whereas the storage device (SCs) is used to supply the load in the transient and steady states too in order to reduce the consumption of FC's H_2 quantity, contrary to hybrid systems that are studied in [3-5], where the authors used the SC to supply the load only in transient state. To achieve this goal, an effective energy management strategy is designed by authors, it is based on the Passivity Based Control (PBC) using a Fuzzy Logic estimation, which is capable to determine the desired supercapacitor current according to the SC state of charge (SoC) and the FC remaining hydrogen quantity (QH_2). The hybrid power source and proposed controller are simulated and validated under Matlab simulink.

2. Modelling of hybrid DC link

Fig. 1. (a) shows the scheme of the studied hybrid sources system. This system is composed of two sources, the first one is a FC and the second one is a SCs that are connected to the DC link through an unidirectional DC/DC and a current bidirectional DC/DC converters respectively. For reducing FC's H_2 quantity and improving the dynamic behaviour of studied hybrid system, the FC is supplying the mean energy to the load, whereas the storage device (auxiliary source) is used to supply the load in the transient and steady states too, contrary to the hybrid system in [4,6,10], where the SC has been used to supply the load only in the transient state.

In order to develop an energy management algorithm based on PBC of hybrid source used in the whole vehicle cycle, a dynamical modelling based on differential equations is used to describe the studied hybrid DC link. The following model is extended state-space model of the reduced model that has been developed by authors in [7] (in [7], the reduced model has five state variables). The seventh order overall state space model is written by the following expressions:

$$\begin{cases} \frac{dV_S}{dt} &= \frac{1}{C_S}[(1-U_{FC})I_{FC}-I_{DL}] \\ \frac{dI_{FC}}{dt} &= \frac{1}{L_{FC}}[-(1-U_{FC})V_S+V_{FC}] \\ \frac{dV_{DL}}{dt} &= \frac{1}{C_{DL}}[I_{DL}+(1-U_{SC})I_{SC}-I_L] \\ \frac{dI_{DL}}{dt} &= \frac{1}{L_{DL}}[V_S-V_{DL}] \\ \frac{dV_{SC}}{dt} &= \frac{1}{C_{SC}}[-I_{SC}] \\ \frac{dI_{SC}}{dt} &= \frac{1}{L_{SC}}[-(1-U_{SC})V_{DL}+V_{SC}] \\ \frac{dI_L}{dt} &= \frac{1}{L_L}[V_{DL}-R_LI_L-E_L] \end{cases} \tag{1}$$

The control vector μ is presented by:

$$\mu = [\mu_1, \mu_2]^T = [(1-U_{FC}), (1-U_{SC})]^T \tag{2}$$

with $V_{FC} = V_{FC}(x_2)$, PEMFC static model is given [8] as follow:

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

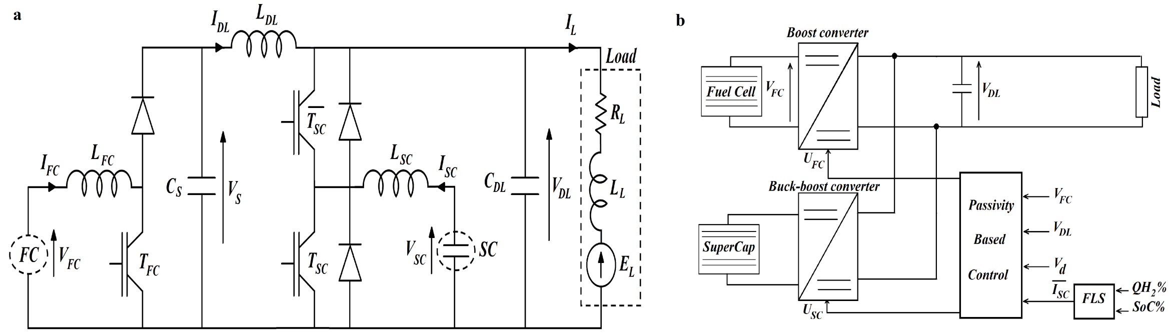

Fig. 1. (a) Structure of the studied hybrid source. (b) Global control system design.

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 link voltage.

3. Energy management based on PBC

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 SC current. The second aim is to estimate the desired SC current by the Fuzzy Logic according to the function of SCs *SoC* and QH_2 of FC, in order to ensure the desired behaviour of the system and to reduce the QH_2 consumption. In the transient and steady states the load is supplied by the FC-SCs hybrid sources and the controller has to maintain the DC link voltage to a constant value and the SC current has to track its reference.

3.1. Passivity based control

3.1.1. 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 [9]. Consider the non-linear system given by:

$$\dot{x} = f(x) + g(x)u \tag{4}$$

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:

$$\dot{x} = [\Im - \Re]\nabla H_d + g(x)u \tag{5}$$

The desired closed loop energy function are given by the following expression:

$$H_d = \frac{1}{2}\widetilde{x}^T Q \widetilde{x} \tag{6}$$

3.1.2. Reconstruction of the state model

It consists of determining the equilibrium values of state vector and building a system, whose inputs are u and Y and whose exit is a vector $\tilde{x}$, estimated from the state vector $\bar{x}$ of the source process. After some simple calculations, the equilibrium values of states $\bar{x}$ and control vector $\overline{\mu}$ can be expressed as:

$$\begin{cases} \bar{x} = [V_d, \bar{I}_{FC}, V_d, \bar{I}_{DL}, \overline{V}_{SC}, \bar{I}_{SC}, \frac{V_d - E_L}{R_L}]^T \\ \overline{\mu}_1 = \frac{1}{V_d}(V_{FC} - L_{FC}\dot{\bar{x}}_2) \\ \overline{\mu}_2 = \frac{1}{V_d}(\bar{x}_5 - L_{SC}\dot{\bar{x}}_6) \end{cases} \tag{7}$$

where

$$\overline{\mu} = [\overline{\mu}_1, \overline{\mu}_2]^T = [(1 - \overline{U}_{FC}), (1 - \overline{U}_{SC})]^T \tag{8}$$

After dynamic's error where $\tilde{x} = x - \bar{x}$, the new state-space model is:

$$\begin{cases} \dot{\tilde{x}}_1 = \frac{1}{C_S}[\mu_1\tilde{x}_2 - \tilde{x}_4 + (\mu_1 - \overline{\mu}_1)\bar{x}_2] \\ \dot{\tilde{x}}_2 = \frac{1}{L_{FC}}[-\mu_1\tilde{x}_1 + (\overline{\mu}_1 - \mu_1)\bar{x}_1] \\ \dot{\tilde{x}}_3 = \frac{1}{C_{DL}}[\tilde{x}_4 + \mu_2\tilde{x}_6 - \tilde{x}_7 + (\mu_2 - \overline{\mu}_2)\bar{x}_6] \\ \dot{\tilde{x}}_4 = \frac{1}{L_{DL}}[\tilde{x}_1 - \tilde{x}_3] \\ \dot{\tilde{x}}_5 = \frac{1}{C_{SC}}[-\tilde{x}_6] \\ \dot{\tilde{x}}_6 = \frac{1}{L_{SC}}[-\mu_2\tilde{x}_3 + \tilde{x}_5 + (\overline{\mu}_2 - \mu_2)\bar{x}_3] \\ \dot{\tilde{x}}_7 = \frac{1}{L_L}[\tilde{x}_3 - R_L\tilde{x}_7] \end{cases} \tag{9}$$

The global designed of control system is shown in Fig. 1. (b), the FC and SC supply the load and recover energy for charging the storage device (SC). Hence, the desired SCs current $\bar{I}_{SC}$ is estimated by fuzzy logic.

From the new system written by (9) and the function of the gradient of the desired energy given, the function (6) can be written as:

$$\dot{\tilde{x}} = [\mathfrak{I}(\mu) - \mathfrak{R}]\nabla H_d + A \tag{10}$$

with

$$\nabla H_d = [C_S\tilde{x}_1;\ L_{FC}\tilde{x}_2;\ C_{DL}\tilde{x}_3;\ L_{DL}\tilde{x}_4;\ C_{SC}\tilde{x}_5;\ L_{SC}\tilde{x}_6;\ L_L\tilde{x}_7]^T \tag{11}$$

and

$$[\mathfrak{I}(\mu) - \mathfrak{R}] = \begin{bmatrix} 0 & \frac{\mu_1}{C_S L_{FC}} & 0 & -\frac{1}{C_S L_{DL}} & 0 & 0 & 0 \\ -\frac{\mu_1}{C_S L_{FC}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_{DL} L_{DL}} & 0 & \frac{\mu_2}{C_{DL} L_{SC}} & -\frac{1}{C_{DL} L_L} \\ \frac{1}{C_S L_{DL}} & 0 & -\frac{1}{C_{DL} L_{DL}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_{SC} L_{SC}} & 0 \\ 0 & 0 & -\frac{\mu_2}{C_{DL} L_{SC}} & 0 & \frac{1}{C_{SC} L_{SC}} & 0 & 0 \\ 0 & 0 & \frac{1}{C_{DL} L_L} & 0 & 0 & 0 & -\frac{R_L}{L_L^2} \end{bmatrix} \tag{12}$$

$$A = \begin{bmatrix} \frac{1}{C_S}[(\mu_1 - \overline{\mu}_1)\bar{x}_2] \\ \frac{1}{C_{FC}}[(\overline{\mu}_1 - \mu_1)\bar{x}_1] \\ \frac{1}{C_{DL}}[(\mu_2 - \overline{\mu}_2)\bar{x}_6] \\ 0 \\ 0 \\ \frac{1}{L_{SC}}[(\overline{\mu}_2 - \mu_2)\bar{x}_3] \\ 0 \end{bmatrix} \tag{13}$$

Where $\Im(\mu) = -\Im(\mu)^T$ 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. The following control laws are proposed [4], to introduce a parameter r in the damping matrix of the system:

$$\begin{cases} U_{FC} = \overline{U}_{FC} \\ U_{SC} = \overline{U}_{SC} - r\widetilde{x}_6 \end{cases} \tag{14}$$

with r is a positive design parameter.

3.1.3. Stability proof

Using the control laws precedents (8), (14)

$$\dot{\tilde{x}} = [\Im(\mu) - \Re']\nabla H_d + A' \tag{15}$$

where $\Im(\mu)$ equals the same matrix given in (11), and:

$$\Re' = diag\left\{0;\ 0;\ 0;\ 0;\ 0;\ \frac{rV_d}{L_{SC}^2};\ \frac{R_L}{L_L^2}\right\} = \Re'^T \tag{16}$$

$$A' = \begin{bmatrix} 0 \\ 0 \\ \frac{r\bar{x}_6\widetilde{x}_6}{C_{DL}} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & \frac{r\bar{x}_6}{C_{DL}L_{SC}} & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \end{bmatrix} \nabla H_d = F\nabla H_d \tag{17}$$

$$A' = F\nabla H_d \tag{18}$$

$$[\Re' - F] = \begin{bmatrix} 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & -\frac{r\bar{x}_6}{C_{DL}L_{SC}} & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & 0 \\ 0\ 0\ 0\ 0\ 0 & \frac{rV_d}{L_{SC}^2} & 0 \\ 0\ 0\ 0\ 0\ 0 & 0 & \frac{R_L}{L_L^2} \end{bmatrix} \tag{19}$$

The derivative of the desired energy function (6) along the trajectories of (15) is non positive if and only if the following matrix is non negative definite, $[\Re' - F] \geq 0$ [10]. Proof:
$\dot{\tilde{x}} = [\Im(\mu) - \Re']\nabla H_d + F\nabla H_d = \Im\nabla H_d - [\Re' - F]\nabla H_d$
$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = \nabla H_d^T \Im \nabla H_d - \nabla H_d^T [\Re' - F]\nabla H_d$
$\dot{H}_d = \nabla H_d^T [F - \Re']\nabla H_d \leq 0$
$[F - \Re']$ 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: $[0,\ 0,\ 0,\ 0,\ -\frac{rV_d}{L_{SC}^2},\ -\frac{R_L}{L_L^2}]^T$. 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 (6) along the trajectories of (15) and the proposed control (14) is negative semi definite. Consequently, the origin of the closed loop dynamics (15) is stable.

3.2. Fuzzy logic estimator

The proposed SC current estimation is based on a classical Fuzzy Logic System which defined under Matlab toolbox . A FLS needs to define both input and output membership functions, fuzzification method, scaling factor values, type of membership, rules, rule processing (Mamdani, Sugeno), inference mechanism, t-norms, s-norms and defuzzification method [12,15]. A typical block diagram of a fuzzy control system is detailed in [13,14]. The FL estimator input parameters are the SC (SoC) and the remaining quantity of H_2 (QH_2), the fuzzy output is the desired SC current $\bar{I}_{SC}$. The dynamic behaviour of fuzzy estimation is defined by the rule base given in Table. 1.

Table 1. The Rule Base System of FLS.

	$SoC(Low)$	$SoC(Avg)$	$SoC(High)$
$QH_2(Low)$	0	*Positive Big*	*Positive Big*
$QH_2(Avg)$	*Negative*	*Positive*	*Positive*
$QH_2(High)$	*Negative Big*	0	0

Table 2. The Different Simulation Parameters.

Parameter	$V_{SC}(V)$	$V_{DL}(V)$	$R_L(\Omega)$	$L_L(mH)$	$E(V)$	r	$C_{SC}(F)$	$C_{DL}(mF)$	$C_S(mF)$
Value	12, $at\ t=0$	60	10	10	10	0.01	584	15	300

4. Simulation and results discussions

The whole system has been implemented in the Matlab-Simulink Software, Table. 2 shows the parameters associated to the hybrid sources. The SC power peak unit is obtained by a series association of six SCs 3500F. The rated voltage of these components is 2.5V. The initial value of the SC power peak voltage is 12V. Fig. 2. (a) presents the behaviour of V_{DL}, its reference V_d and load current I_L. It is clear seen that V_{DL} tracks well its reference V_d without steady state error and with an acceptable small overshoot equals 3.33%. Fig. 2. (b) presents the signals control U_{FC} and U_{SC} of FC boost and the SC converters. Fig. 3. (a) and Fig. 3. (b) show the V_{FC}, I_{FC} and the V_{SC}, I_{SC} behaviours respectively.

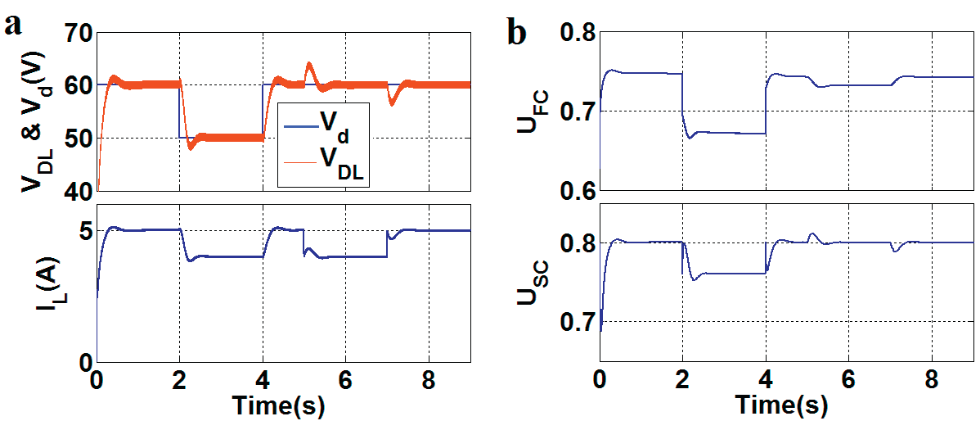

Fig. 2. (a) DC Link voltage and its reference; (b) FC boost control, SC converter control.

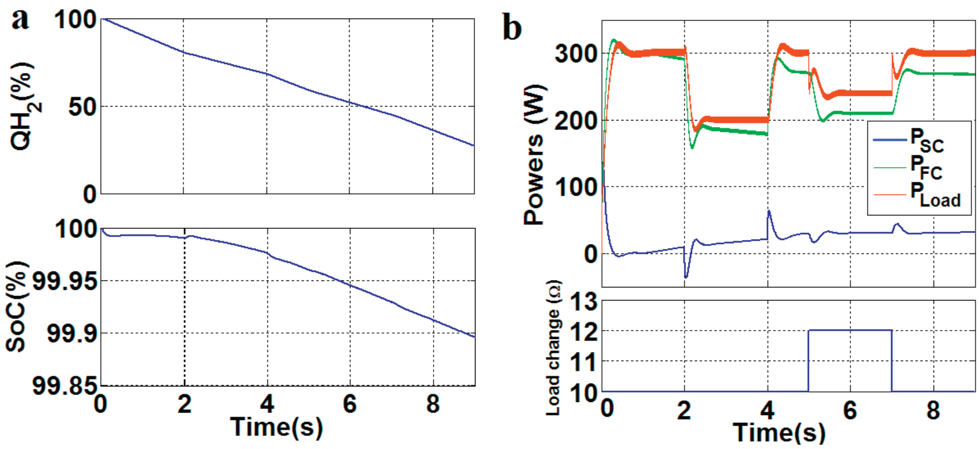

Fig. 3. (a) Fuel Cell QH_2 and Supercapacitor SoC; (b) Powers flow and Load resistance change.

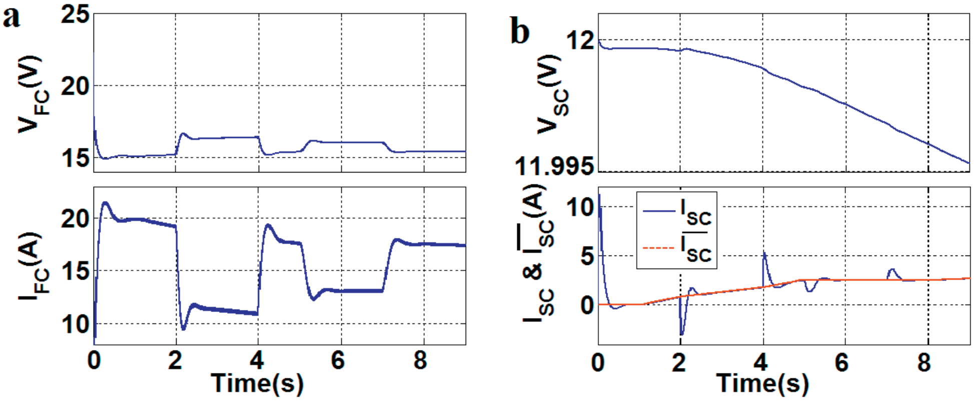

Fig. 4. (a) FC voltage and current; (b) SC voltage and current with its reference.

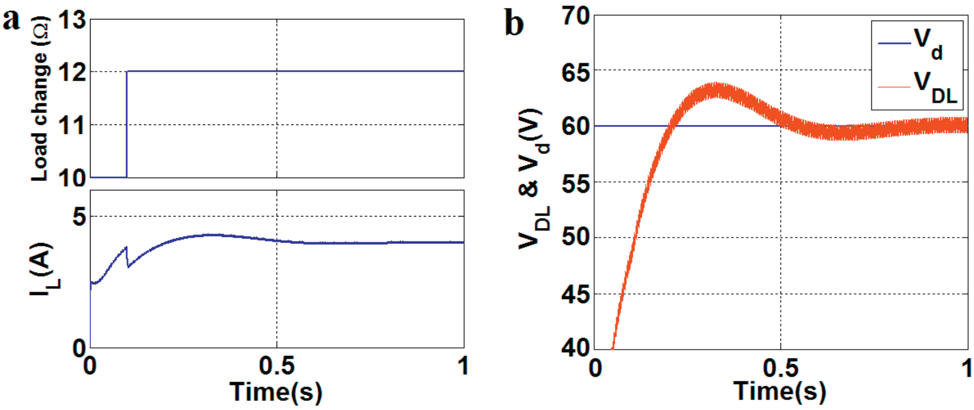

Fig. 5. (a) Load resistance and current change; (b) DC link voltage and its reference.

When the hydrogen quantity is decreasing, the SC supplies with the fuel cell the power to the load in transient and steady state. The I_{SC} tracks well its estimated reference $\bar{I}_{SC}$ which is considered as the equilibrium state of I_{SC} in PBC. Fig. 4. (a) shows the variations of QH_2 and SoC according to the FC and SC powers provided to the load. The required power of the load is obtained from the hybrid system by the sum of the SC and FC powers. In order to test the robustness of proposed controller, a perturbation is imposed in the simulation. This test is performed by sharply changing the R_L in the interval of t $[5s, 7s]$ in the steady and transient states of system (Fig. 3. (b) and Fig. 5. (b)). Because of the perturbation, very small overshoots of V_{DL} are observed but the controller shows a good robustness and the V_{DL} re-tracks its reference V_d quickly after the perturbation without a steady error. Finally, these simulation results demonstrate the robustness and the dynamic performance of the proposed controllers applied to the FC-SC hybrid source and show an efficient energy management strategy based on PBC using a fuzzy estimation which allow to the SC supplying the load with the FC in the steady state to save and to reduce FC's hydrogen consumption.

5. 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. The energy management technique has to govern the operative way chosen, in particular by regulating the energy flow between sources and load. This can be executed by controlling both the unidirectional and bidirectional DC/DC converters. A 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 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.

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