INTERCONNECTION AND DAMPING ASSIGNMENT PASSIVITY BASED CONTROL FOR FUEL CELL AND BATTERY VEHICLE: SIMULATION AND EXPERIMENTATION

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***Abstract*— Due to the advantages and limitations on each particular source, the hybridization of sources and storage elements is becoming a necessity for embedded applications. This, in order to ensure particularly the continuity of service and the components lifespan. The hybrid electrical vehicle is the best example that uses the fuel cell as a primary source and the battery and/or supercapacitor as storage elements. Therefore, the energy management is a crucial question to be answered in order to satisfy different criteria and meet other objectives. In this paper, the considered energy chain is composed of a fuel cell as the main source and a battery as the secondary source. Each one of them is controlled using its own power converter to supply the load. The control of the energy distribution is achieved using the nonlinear control based on passivity method. The passivity control allows not only the energy management but also proves the system stability by making it passive which is an advantage compared to the classical controllers that show limitations in terms of the uses, saturation and the lack of stability prove. The obtained results prove the efficacy and the feasibility of the proposed approach for a real electrical vehicle. The results are experimentally validated.**

Key words—Energy management, hybrid system, fuel cell, battery, control based on passivity.

I. INTRODUCTION

The automobile transport is actually the sector responsible of the emission of greenhouse gases that are mainly responsible at their turn of climate warming. The hybrid electric vehicle represents a good alternative candidate to replace the internal combustion engine [1]. This system offers zero emission technology [2]. However, the control of the energy distribution between the embedded sources is an important task [3] [4][5]. This paper focalises on the control based on passivity approach of the hybrid system composed of FC as primary source and battery as the second source. This paper is organized as follows: the section 2 presents the description of the Interconnection and Damping Assignment-Passivity-Based Control (IDA-PBC) approach. The section 3 explains the hybrid structure and the modeling of hybrid system where the state space equations are given. In this section, the passivity control principle based on the IDA-PBC is also developed. In the section 4, the proposed scenario is given considering the role of different used sources. In the section 5, the obtained results from the simulation is presented and discussed. The experimental part is given in the section 6, where the test bench is presented and experimental results are shown and argued. The section 7 is dedicated to the conclusion.

II. PRINCIPAL OF IDA-PBC APPROACH STUDY

Equation of nonlinear system affine in control is given by:

$$\begin{gathered} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{gathered} \qquad (1)$$

Where $x \in \mathcal{R}^n$ is the state space vector, $y \in \mathcal{R}^m$ is the output vector, f(x), g(x) and h(x) are locally Lipschitz functions and $u \in \mathcal{R}^m$ is the control input vector.
A Port Control Hamiltonian (PCH) form of the equation system can be written by:

$$\begin{aligned} &\dot{x} = [J(x) - R(x)]\nabla H(x) + g(x)u \\ &y = g^{\perp}(x)\nabla H(x) \end{aligned} \qquad (2)$$

J(x) is an n×n skew symmetric matrix, R is a n×n positive semidefinite symmetric matrix and ∇H(x) is the gradient vector of the energy function H(x) of the system .

$$\begin{gathered} \nabla H(x) = \left[\frac{\partial H}{\partial x_1}(x)\frac{\partial H}{\partial x_2}(x)\dots.\frac{\partial H}{\partial x_n}(x)\right]^T \\ H((x) - H(x_0)) \leq \int_0^t u^T(s)y(s)ds \end{gathered} \qquad (3)$$

$g^{\perp}(x)$ is a full-rank left annihilator of g(x), that is $g^{\perp}(x)g(x) = 0$.
PCH system, with *H(x)* non-negative, is passive system. A recent and very interesting approach to solve these problems is the IDA-PBC approach which consists on identifying the natural energy function of the system called *H(x),* and then rewrite the nonlinear system versus the gradient of the energy function [18][6].

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After this step, the passivity command called IDA (Interconnection and Damping Assignment) is used. Consider the system (1), assumes that matrices $J_d(x) = -J_d^T(x)$, $R_d(x) = R_d^T(x) \geq 0$ are the desired matrices, $g^{\perp}(x)$ and function $H_d(x)$: $\mathcal{R}^n \longrightarrow \mathcal{R}$ that verify the partial differential equation.

$$g^{\perp}(x)f(x) = g^{\perp}(x)[J_d(x) - R_d(x)]\nabla H_d \qquad (4)$$

∇H_d is such that

$$\bar{x} = argmin(H_d(x)) \qquad (5)$$

Where $\bar{x}$ is a desired equilibrium to be stabilized, taking the control u as:

$$u = [g^T(x)g(x)]^{-1}g^T(x)\{[J_d(x) - R_d(x)]\nabla H_d - f(x)\} \qquad (6)$$

Then the closed-loop dynamic takes the form:

$$\dot{x} = [J_d(x) - R_d(x)]\nabla H_d \qquad (7)$$

$\bar{x}$ is then a stable equilibrium. It will be asymptotically stable if in addition, $\bar{x}$ is an isolated minimum of H_d(x) and the largest invariant set under the closed-loop dynamics (7) contained in

$\{x \in \mathcal{R}^n, \nabla \mathrm{H}_d^T\, R_d(x)\, \nabla H_d = 0\}$

III. HYBRID FC SYSTEM STRUCTURE

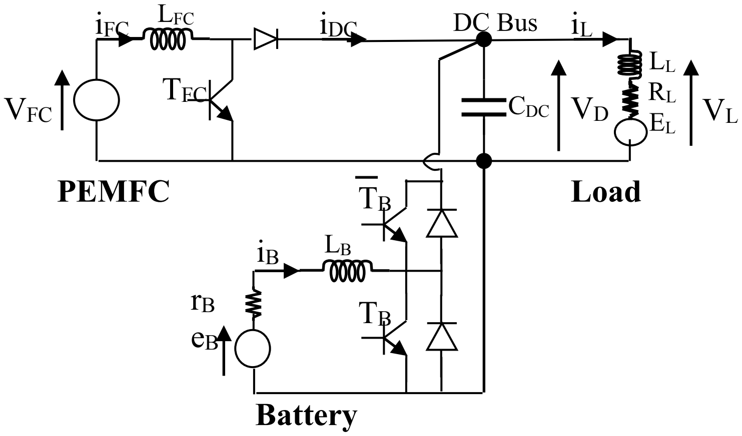

Fig.1: hybrid system structure

The complete model of the hybrid system can be written by the following state space equations:

$$\begin{aligned}
\dot{x}_1 &= \frac{1}{L_{FC}}\,[V_{FC} - \mu_1 x_2] \\
\dot{x}_2 &= \frac{1}{C_{DC}}\,[\mu_1 x_1 - x_4 + \mu_2 x_3] \\
\dot{x}_3 &= \frac{1}{L_B}\,[e_B - r_B x_3 - \mu_2 x_2] \\
\dot{x}_4 &= \frac{1}{L_L}\,[E_L - R_L x_4 + x_2]
\end{aligned} \qquad (8)$$

Where:

$x = [x_1, x_2, x_3, x_4]^T = [i_{FC}, V_{DC}, i_B, i_L]^T$

μ_1, μ_2 are the control of the FC boost converter, and the battery control of the buck-boost converter, respectively.

The natural energy function is:

$$H = \frac{1}{2}x^T Q x \qquad (9)$$

With matrix Q= diag(L_{FC}, C_{DC}, L_B, L_L).

$\bar{x} = [\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4] = [\bar{x}_1, V_d, I_{ref}, \bar{\iota}_L]$

- If $I_{ref} = 0$, the controls law at the equilibrium are:

$$\bar{\mu}_1 = \frac{V_{fc}}{\bar{x}_2} \quad ; \quad \bar{\mu}_2 = \frac{e_B}{\bar{x}_2} \qquad (10)$$

- If $I_{ref} \neq 0$, the controls law are:

$$\bar{\mu}_1 = \frac{V_{fc}}{\bar{x}_2} \quad ; \quad \bar{\mu}_2 = \frac{e_B - r_b I_{ref}}{\bar{x}_2} \qquad (11)$$

In the following, the model is written using the new state space $\tilde{x}$, which is defined as the error between the state and its equilibrium value

$\tilde{x} = x - \bar{x}$.

The desired closed loop energy function is given by:

$$H_d = \frac{1}{2}\tilde{x}^T Q \tilde{x} \qquad (12)$$

The error dynamic equations are expressed using the gradient of the desired energy as follows:

$$\dot{\tilde{x}} = [J - R]\nabla H_d + \xi \qquad (13)$$

The desired equilibrium are noted as following:

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$$\underbrace{\begin{bmatrix} 0 & \frac{-\mu_1}{L_{fc}C_{DC}} & 0 & 0 \\ \frac{\mu_1}{L_{fc}C_{DC}} & 0 & \frac{\mu_2}{L_B C_{DC}} & \frac{-1}{L_L C_{DC}} \\ 0 & \frac{-\mu_2}{L_B C_{DC}} & \frac{-r_B}{L_B^2} & 0 \\ 0 & \frac{1}{L_L C_{DC}} & 0 & \frac{-R_L}{L_L{}^2} \end{bmatrix}}_{J-R} \underbrace{\begin{bmatrix} L_{fc}\tilde{x}_1 \\ C_{DC}\tilde{x}_2 \\ L_B\tilde{x}_3 \\ L_L\tilde{x}_4 \end{bmatrix}}_{\nabla H_d} + \underbrace{\begin{bmatrix} \frac{1}{L_{fc}}(\bar{\mu}_1-\mu_1)\bar{x}_2 \\ \frac{1}{C_{DC}}[(\mu_1-\bar{\mu}_1)\bar{x}_1-(\mu_2-\bar{\mu}_2)\bar{x}_3] \\ \frac{1}{L_B}(\bar{\mu}_2-\mu_2)\bar{x}_2 \\ 0 \end{bmatrix}}_{\zeta}$$

$\nabla H_d = [L_{FC}\tilde{x}_1, C_{DC}\tilde{x}_2, L_B\tilde{x}_3, L_L\tilde{x}_4]^T$

$J(\mu) = -J^T(\mu)$ is a skew symmetric matrix defining the interconnection between the variables and $R = R^T \geq 0$ is symmetric positive semi definite matrix defining the damping of the system.

With control laws which are chosen as:

$$\begin{cases} \mu_1 = \bar{\mu}_1 \\ \mu_2 = \bar{\mu}_2 - r\tilde{x}_3 \end{cases} \qquad (15)$$

Where r is a positive design parameter.

IV. PROPOSED SCENARIO

The major objectives to achieve are:

- Voltage control of the load and therefore the voltage of DC bus through the command of the two DC-DC converters.
- Ensure that the battery provides the power required during the transient phases.
- Supply the load by the battery when the FC is not able, for example in the system start up or under limitation.
- The energy management strategy is based on the control of the battery current to a desired battery current reference.
- This reference can be imposed regarding different criteria (battery SOC, FC state of heath, hydrogen level, start-up, load transient power,…).

The control objective is to control the battery current to its reference. In this work, a power source is used to emulate the FC role.

V. SIMULATION RESULT

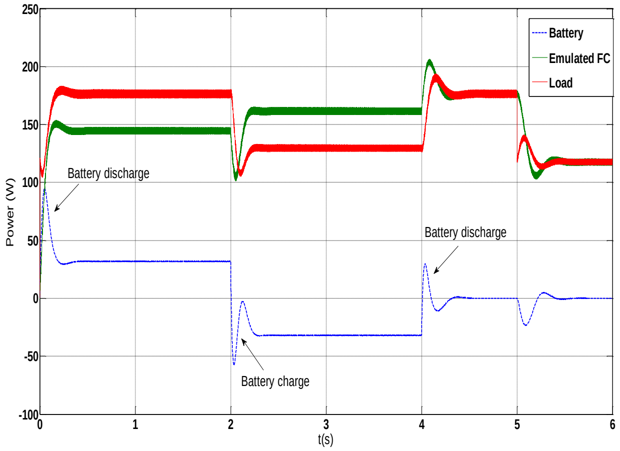

Fig. 2. Powers of different HEV source.

VI. EXPERIMENTAL RESULT

The test bench is developed at State Key Laboratory of Industrial Control Technology, Zhejiang University (Hangzhou, China). The experimental is illustrated in the Fig.3 and the objective is to valid the correct operation of the chosen control strategy, study the role of used sources and the distribution control of the power between different elements in real time.

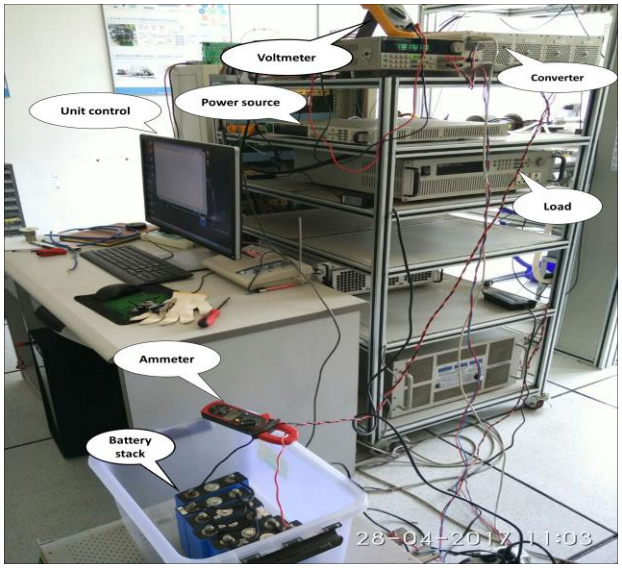

Fig. 3. Powers of different HEV source

The used test bench in this study has been built by authors (see Fig.3).

This test bench makes it possible to emulate energy exchanges within a vehicle on a reduced scale. Comparing to the classical regulators, the used strategy is suitable for nonlinear systems, i.e. no needs to linearize around operating point. And the stability is over all real set.

The test bench is composed of:

- Power source emulating a FC role.

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- Battery stack consists of 6 cells of 3.2 V connected in series (36Ah each).
- An electrical charge emulating the power demand.
- Two DC / DC converters for the power source and the battery.
- Ammeters to measure the current
- Voltmeters to measure the voltage.
- LabVIEW software with DAQ MAX Acquisition system.

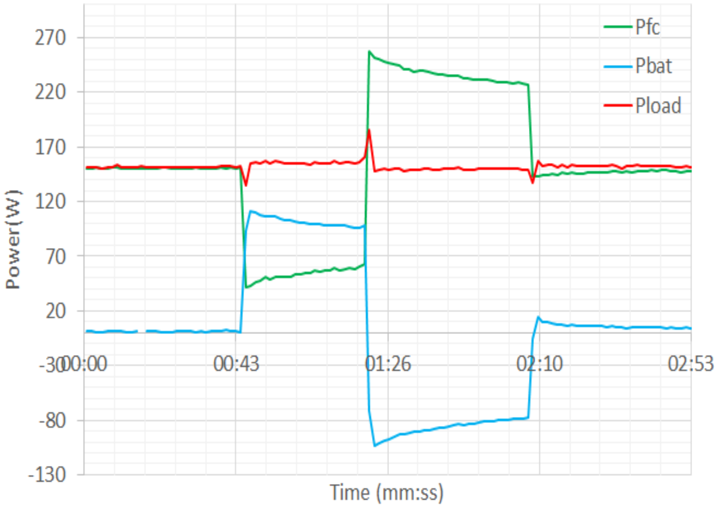

Fig. 4. Experimental results of powers using IDA-PBC technique.

VII. CONCLUSION

A studied hybrid system is composed of a power source emulating the FC as primary source and battery. A control strategy along with the energy management is developed using the passivity control. For this purpose, this paper introduces the system mathematical modeling. The IDA-PBC is used to design a smart nonlinear energy management control. The experimental and simulation results show the correct and the efficacy of the proposed control. This is clearly demonstrated in the obtained curve through the simulation and practical results. The obtained results reflect exactly the proposed scenario. The other results will be given in an extended journal version.

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Parameters	Definition
L_{FC}	FC inductance
V_{FC}	FC voltage
V_d	Desired DC bus voltage
C_{DC}	Converter capacity
L_B	Battery inductance
I_{ref}	Battery current reference
e_B	f.e.m of battery
r_B	internal resistance of battery
L_L	load inductance
E_L	f.e.m of load
R_L	resistance of load
r	damping parameter
P_{FC}	FC power
P_{Batt}	battery power
P_{load}	load power

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