PASSIVITY-BASED CONTROL OF HYBRID SOURCES APPLIED TO A TRACTION SYSTEM

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1. INTRODUCTION

In electric traction systems (like vehicles, elevators, ...), if the load is supplied using a single energy source, it has to answer to all solicitations of the load. Thus, the source has to supply or absorb the picks of power resulting from accelerations and braking. So, the source has to provide energy and power, this is strongly penalizing. In order to optimize the power transfer and to improve equipment lifetime, supercapacitors (SC) and different kind of DC sources can be hybridized. Then the SC supply or absorb power picks and the DC source provide the average power.

In this paper, a hybrid power source using DC source (obtained from network or from batteries alone or associated with photovoltaic panels) and SC supplying a load is proposed. In a first step, a dynamic modeling of the system is given. In a second step, this system is written in a Port Controlled Hamiltonian (PCH) form where important structural properties are exhibited. Then a Passivity-Based Control (PBC) of the system is presented proving the global stability of the equilibrium with the proposed control laws. Finally, simulation results using Matlab are given.

2. HYBRID DC SOURCE SYSTEM

2.1 Structure of the hybrid source

As shown in Figure 1, the studied system comprises a DC link supplied by a DC source and a no reversible DC-DC Boost converter which maintains the DC voltage V_{DC} to its reference value $\bar{V}_{DC}$ and a SC storage device which is connected to the DC link through a current reversible DC-DC converter. The load consist of a resitor R_L, a inductor L_L and an electromotive force (emf) E. This structure is used to model an electrical machine.

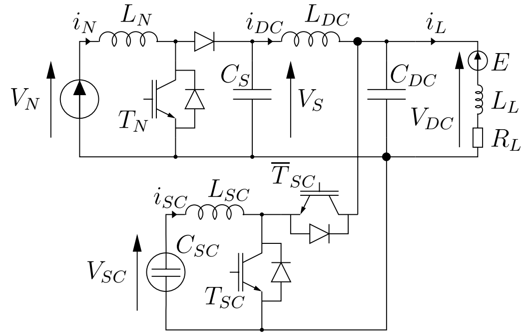

Fig. 1. System electrical model

The function of the DC source is to supply the mean power to the load, whereas the storage device is used as a power source: it supplies and absorbs peak loads required during acceleration and braking. In order to manage energy exchanges between the DC link and the storage device, three operating modes are defined:

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

2.2 *State space model of the system*

The model of the hybrid system can be written in a state space model by choosing the following variables:

$$x = \left[\, x_1,\, x_2,\, x_3,\, x_4,\, x_5,\, x_6,\, x_7 \,\right]^T = \left[\, V_S,\, i_N,\, V_{DC},\, i_{DC},\, V_{SC},\, i_{SC},\, i_L \,\right]^T$$

The control vector is:

$$u = \left[\, u_1,\, u_2 \,\right]^T = \left[\, u_N,\, u_{SC} \,\right]^T \tag{1}$$

where u_N and $u_{SC} \in [0, 1]$.
$u_i = 1$ means the associated transitor is closed and $u_i = 0$ means the associated transitor is opened (with $i = N$ or SC).

2.3 *Equilibrium*

After some simples calculations the equilibrium vector is:

$$\bar{x} = \left[\, \bar{x}_1,\, \bar{x}_2,\, \bar{x}_3,\, \bar{x}_4,\, \bar{x}_5,\, \bar{x}_6,\, \bar{x}_7 \,\right]^T = \left[V_d,\, \frac{(V_d - E)V_d}{R_L V_N},\, V_d,\, \frac{V_d - E}{R_L},\, \bar{x}_5,\, 0,\, \frac{V_d - E}{R_L} \right]^T \tag{2}$$

Where V_d is the desired DC Bus voltage. An implicit purpose of the proposed structure Figure 1 is to recover energy to charge the SC. Hence, the desired voltage $\bar{x}_5 = V_{SC}(t = 0) = 12V$.

$$\bar{u} = \left[\, \bar{u}_N,\, \bar{u}_{SC} \,\right]^T = \left[1 - \frac{V_N}{V_d},\, 1 - \frac{\bar{x}_5}{V_d} \right]^T \tag{3}$$

The natural energy function of the system is (where $Q = diag\{C_s; L_N; C_{DC}; L_{DC}; C_{SC}; L_{SC}; L_L\}$ is a diagonal matrix):

$$H = \frac{1}{2} x^T Q x \tag{4}$$

3. PROBLEM FORMULATION

The main purpose of the study is the control of the DC Bus voltage and consequently the load voltage by the mean of the control of the DC-DC converters. The second aim is to maintain a constant mean energy delivered by the DC source, without a significant power peak, and the transient power is supplied by the SC. A third purpose consists on recovering energy throw the charge of the SC.

4. PORT-CONTROLLED HAMILTONIAN REPRESENTATION OF THE SYSTEM

PCH systems were introduced by [1] and has 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 to solve these problems is the IDA-PBC method, which is a general way of stabilizing a large class of physical systems, see [2, 4].
The desired closed loop energy function is:

$$H_d = \frac{1}{2} \tilde{x}^T Q \tilde{x} \tag{5}$$

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 studied system with the new variable $\tilde{x}$ and in function of the gradient of the desired energy (5) is:

$$\dot{\tilde{x}} = \underbrace{\begin{bmatrix} 0 & \frac{1-u_1}{C_s L_N} & 0 & \frac{-1}{C_s L_{DC}} & 0 & 0 & 0 \\ -\frac{1-u_1}{C_s L_N} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_{DC} L_{DC}} & 0 & \frac{1-u_2}{C_{DC} L_{SC}} & \frac{-1}{C_{DC} L_L} \\ \frac{1}{C_s L_{DC}} & 0 & \frac{-1}{C_{DC} L_{DC}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{C_{SC} L_{SC}} & 0 \\ 0 & 0 & -\frac{1-u_2}{C_{DC} L_{SC}} & 0 & \frac{1}{C_{SC} L_{SC}} & 0 & 0 \\ 0 & 0 & \frac{1}{C_{DC} L_L} & 0 & 0 & 0 & \frac{-R_L}{L_L^2} \end{bmatrix}}_{\mathcal{J}(u_1,u_2)-\mathcal{R}} \underbrace{\begin{bmatrix} C_s \tilde{x}_1 \\ L_N \tilde{x}_2 \\ C_{DC} \tilde{x}_3 \\ L_{DC} \tilde{x}_4 \\ C_{SC} \tilde{x}_5 \\ L_{SC} \tilde{x}_6 \\ L_L \tilde{x}_7 \end{bmatrix}}_{\nabla H_d} + \underbrace{\begin{bmatrix} \frac{(1-u_1)\bar{x}_2 - \bar{x}_4}{C_s} \\ \frac{V_N - (1-u_1)\bar{x}_1}{L_N} \\ \frac{\bar{x}_4 - \bar{x}_7 + (1-u_2)\bar{x}_6}{C_{DC}} \\ \frac{\bar{x}_1 - \bar{x}_3}{L_{DC}} \\ \frac{-\bar{x}_6}{C_{SC}} \\ \frac{\bar{x}_5 - (1-u_2)\bar{x}_3}{L_{SC}} \\ \frac{\bar{x}_3 - R_L \bar{x}_7 - E}{L_L} \end{bmatrix}}_{A_i(\bar{x},u)} \quad (6)$$

where $\mathcal{J}(u_1, u_2) = -\mathcal{J}^T(u_1, u_2)$ is a skew symmetric matrix defining the interconnection between the state space and $\mathcal{R} = \mathcal{R}^T \geq 0$ is symmetric positive semi definite matrix defining the damping of the system.

The following control laws are proposed:

$$\begin{cases} u_N = \bar{u}_N \\ u_{SC} = \bar{u}_{SC} - r\tilde{x}_6 \end{cases} \quad (7)$$

where r is a design parameter ($r > 0$).

Proposition 1. The origine of the closed loop PCH system (6), with the control laws (7) and (3) with the radially unbounded energy function (5), is globally asymptotically stable.

Proof. The closed loop dynamic of the PCH system (6) with the laws (7) and (3) with the radially unbounded energy function (5) is:

$$\dot{\tilde{x}} = [\mathcal{J}(u_1, u_2) - \mathcal{R}'] \nabla H_d \quad (8)$$

Where $\mathcal{R}' = diag\{0; 0; 0; 0; 0; \frac{rV_d}{L_{SC}^2}; \frac{R_L}{L_L^2}\} = \mathcal{R}'^T \geq 0$. The derivative of the desired energy function (5) along the trajectory of (8) is:

$$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = -\nabla H_d^T \mathcal{R}' \nabla H_d \leq 0 \quad (9)$$

◁

5. SIMULATIONS

The following simulations present the system response and control obtained with the proposed control laws (7). To illustrate the controller efficiency, the DC bus voltage reference, the electromotive force (emf) and the resistance are modified. The DC bus voltage is initialized at 36 V.

Figure 2 presents the system response to changes in the DC Bus voltage reference (V_d), emf (E) and load current i_L. The DC Bus voltage tracks well the reference, i.e. very low overshoot and no steady state error are observed.

Figure 3 shows the source voltage (V_N) and current. In our modeling, we assume that the DC source is ideal, thus V_N stay at constant value regardless of the current i_N. A smooth behavior of the current is observed regarding the changes in V_d, E and R_L, this is because the SC supply the transient power.

Figure 4 shows 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 i_{SC} is nul. The positive sens of i_{SC} means that the SC supply the load and the negative one corresponds to the recover of energy by the SC. At time ($t = 4s$), the SC absorb the current pick to respond quickly to the fast DC reference change.

Figure 5 present the network Boost controller, the SC bidirectional converter controller, the changes in the load resistance R_L and in emf. U_N and U_{SC} are in the set $[0, 1]$.

It can be seen from Figure 2 that the system with the proposed controller is robust towards load resistance changes and emf variations.

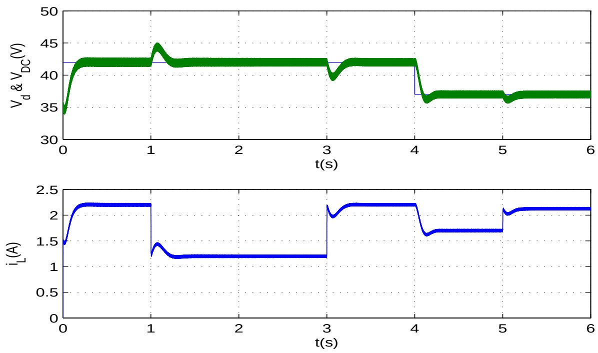

Fig. 2. (a) DC Bus voltage and its reference. (b) Load current.

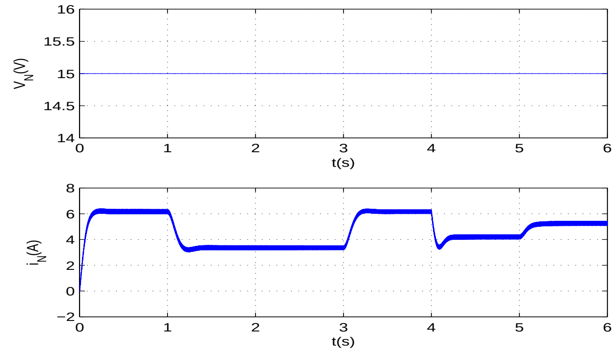

Fig. 3. (a) DC source voltage. (b) DC source current.

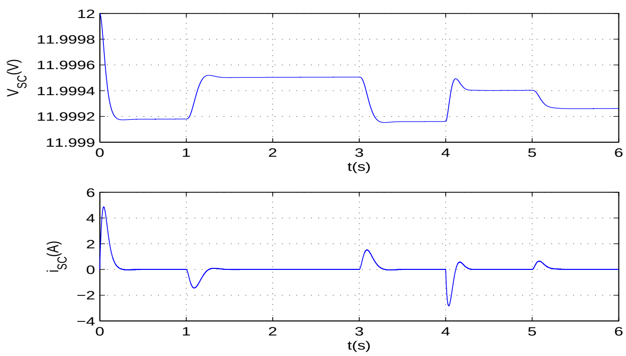

Fig. 4. (a) SC voltage. (b) SC current.

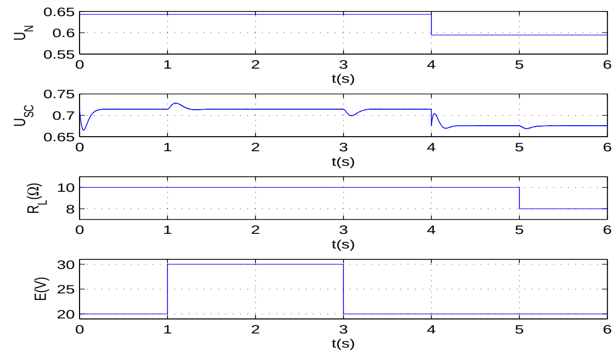

Fig. 5. (a) Source Boost control. (b) SC DC-DC converter control. (c) Load resistance change. (d) Load emf change.

6. CONCLUSION

A modeling of hybrid sources system composed of a DC energy source and SC power source is presented. 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 controller based on an IDA-PBC approach. An important property has to be underline, only i_{SC} measure is needed for the controller. Many benefits can be expected from the proposed structure such that supplying and absorbing the power picks by using SC which also allow recovering energy. Global Stability proof is given and encouraging simulation results has been obtained.

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