Fuel Cell,Ultracapacitor and Batteries Hybrid Sources using Sliding Mode Controller for Vehicle Applications

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Abstract—In this paper, the modeling and the control principles of two DC hybrid source systems have been presented. These systems are composed of a fuel cell source, Ultracapacitor source and with or without batteries on DC link. The state space models are given for both structures. These sources use the fuel cell as mean power source and Ultracapacitors as auxiliary transient power sources.

For the two hybrid structures, Sliding Mode Control principles have been applied in order to obtain a robustness control strategy. The sliding surface is generated as a function of multiple variables: DC link voltage and current, Ultracapacitors current and voltage, Load current. Ultracapactors allows recovering energy for the proposed structure supplying and absorbing the power peaks through many benefits can be expected. Finally, simulation results using Matlab are given.

Keywords— Fuel-cell, Battery, Ultracapacitor, Sliding Mode Controller.

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I. INTRODUCTION

Fuel Cells (FC) generate electrical energy from an electrochemical reaction between a fuel gas and an oxidant such as air or oxygen. They are high-current, and low-voltage sources. Their use becomes more remarkable when energy storage elements like batteries, with high specific energy and ultracapacitors (UC) with high specific power [2]. The permanent source which can either be FC's or batteries must produce the limited permanent energy to ensure the system dependence. In the transient phase, the storage devices produce the lacking power in acceleration function whereas it absorbs excess power in braking function. FC's, and due to its auxiliaries, have a large time constant to respond to an increase or decrease in power output. The UC's are sized for the peak load requirements. They are used for short duration load levelling events such as fuel starting, acceleration and braking.These short durations events are experienced thousands of times throughout the life of the hybrid source, which require relatively little energy but substantial power.
Three operating modes which are defined in order to manage energy exchanges between the different power sources are:
1st Mode:
The main source supplies energy to the storage device.

2nd Mode:
The primary and secondary sources are required to supply energy to the load.
3rd Mode:
The load supplies energy to the storage device.

We present in this work two hybrids DC power sources using SC as secondary storage device, a Proton Exchange Membrane-FC (PEMFC) as main energy source. The difference between the two structures is that the second contains a battery DC link. A single phase DC machine is connected to the DC bus and used as load. The general structures of the studied systems are presented and a dynamic model of the overall system is specified in a state space model. The control of the whole system is based on nonlinear sliding mode control for the DC-DC SC's converter and a linear regulation for the FC converter.

II. PRINCIPLE OF HYBRID STORAGE SYSTTEM

A. Fuel cells

A FC is an energy conversion device that converts the chemical energy of a fuel directly into electricity. The chemical reaction of a fuel (hydrogen) with the oxygen of air results in releasing of energy. The reaction occurs electrochemically and the energy is released as a combination of low-voltage DC electrical energy and heat. Types of FC's differ principally by the type of electrolyte they utilize (Fig. 1). The type of electrolyte, which is a substance that conducts ions, determines the operating temperature, which varies widely between types.

Proton Exchange Membrane (or "solid polymer") Fuel Cells (PEMFCs) are presently the most promising type of FCs for automotive use and have been used in the majority of prototypes built to date.

B. *Ultracapacitor*

Ultra-capacitor or Super-capacitor or Electric double-layer capacitor lies in capacitive properties of the interface between a solid electronic conductor and a liquid ionic conductor. ELDCS are electrical energy storage devices, which offer high power density, tremendously high cycling capability and mechanically robust. These properties lead to the possibility to store energy at solid/liquid interface. This effect is called electric double-layer, and its thickness is limited to some nanometers.

Energy storage is of electrostatic origin, and not of electrochemical origin as in the case of accumulators. So, supercapacitors are therefore capacities, for most of marketed devices. This gives them a potentially high specific power, which is typically only one order of magnitude lower than that of classical electrolytic capacitors.

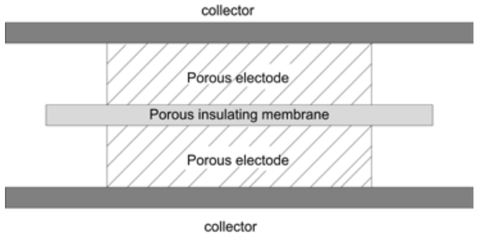

Fig.1.Assembly of Ultracapacitor

The dielectric function in UC’s is performed by the electric double-layer, which constitutes of solvent molecules. As shown in Fig.1,

- Two porous carbon electrodes impregnated with electrolyte,
- A porous insulating membrane, ensuring electronic insulation and ionic conduction between electrodes,
- Metallic collectors, usually in aluminium.

C. *Battery*

A battery is a device which converts chemical energy directly into electricity. It is an electrochemical galvanic cell or a combination of such cells which is capable of storing chemical energy. The first battery was invented by Alessandro Volta in the form of a voltaic pile in the 1800’s. Batteries can be classified as primary batteries, which once used, cannot be recharged again, and secondary batteries, which can be subjected to repeated use as they are capable of recharging by providing external electric current. Secondary batteries are more desirable for the use in vehicles, and in particular traction batteries are most commonly used by EV manufacturers. Traction batteries include Lead Acid type, Nickel and Cadmium, Lithium ion/polymer, Sodium and Nickel Chloride, Nickel and Zinc.

The battery for electrical vehicles should ideally provide a high autonomy (i.e. the distance covered by the vehicle for one complete discharge of the battery starting from its potential) to the vehicle and have a high specific energy, specific power and energy density (i.e. light weight, compact and capable of storing and supplying high amounts of energy and power respectively). These batteries should have a long life cycle (i.e. they should be able to discharge to as near as it can be to being empty and recharge to full potential as many number of times as possible) without showing any significant deterioration in the performance and should recharge in minimum possible time. They should be able to operate over a considerable range of temperature and should be safe to handle, recyclable with low costs. Some of the commonly used batteries and their properties are summarized in the Table 1.

	Lead Acid	***Ni-Cd***	***Ni-MH***	***Li-ion***	***Li-polymer***	***Na-NiCl2***	***Objectives***
Specific Energy (Wh/Kg)	35-40	55	70-90	125	155	80	200
Specific Power (W/Kg)	80	120	200	260	315	145	400
Energy Density (Wh/m3)	25-35	90	90	200	165	130	300
Cycle Life(No. of charging cycles)	300	1000	600	+600	+600	600	1000

Table 1. Comparison between different batteries technologies

A battery consists of one or more voltaic cell, each voltaic cell consists of two half-cells which are connected in series by a conductive electrolyte containing anions (negatively charged ions) and cations (positively charged ions). Each half-cell contains the electrolyte and an electrode (anode or cathode). The electrode to which the anions migrate is called the anode whereas the electrode to which cations migrate is called the cathode. The electrolyte connecting these electrodes can be either a liquid or a solid allowing the mobility of ions.

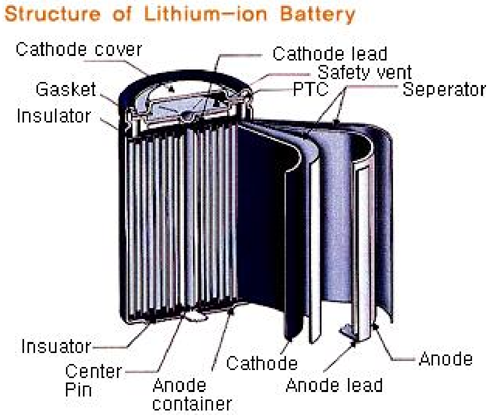

Fig 2. Structure of Lithium-ion Battery

An ideal battery has negligible internal resistance, so it would maintain a constant terminal voltage until exhausted, then dropping to zero. If such a battery maintained 1.5 volts and stored a charge of one Coulomb then on complete discharge it would perform 1.5 Joule of work.

Work done by battery (W) = - Charge X Potential Difference

III. CONTROL OF THE HYBRID SOURCES BASED ON FC, UC AND BATTERIES

A. *Structure of Hybrid Power Sources*

As shown in Fig. 3, the first hybrid source comprise a DC link supplied by a PEMFC and an irreversible DC-DC converter which maintains the DC voltage V_{DL} to its reference value, and a ultra-capacitor storage device, which is connected to the DC link through a current reversible DC-DC converter allowing recovering or supplying energy through UC.

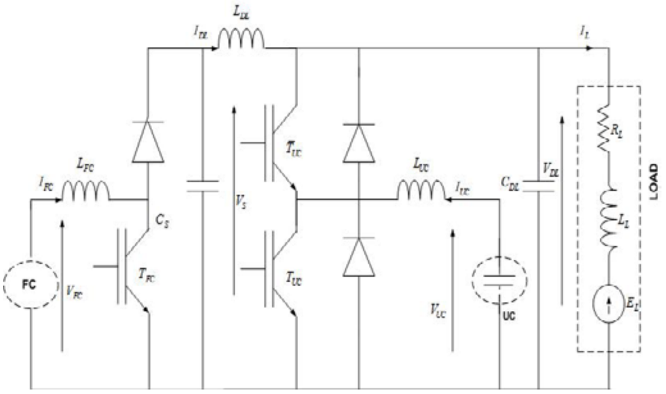

Fig.3.Structure of first Hybrid source

The second system, shown in Fig. 4, comprises of a DC link directly supplied by batteries, a PEMFC connected to the DC link by means of boost converter, and a ultra-capacitive storage device connected to the DC link through a reversible current DC-DC converter. The role of FC and the batteries is to supply mean power to the load, whereas the storage device is used as a power source: it manages load power peaks during acceleration and braking.

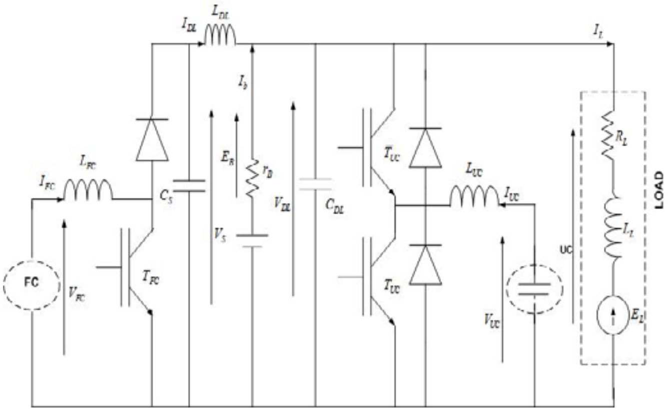

Fig.4. Structure of the second hybrid source

B. *Problem formulation*

Both structures are supplying energy to the DC bus where a DC machine is connected. This machine plays the role of the load acting as a motor or as a generator when braking.

The main purpose of the study is to present a control technique for the two hybrid source with two approaches. Two control strategies, based on sliding mode control have been considered, the first uses voltage controller and the second uses current controller. The second objective is to maintain a constant mean energy delivered by the FC, without a significant power peak, and the transient power is supplied by the SC's. A third purpose consists in recovering energy throw the charge of the SC.

After system modeling, equilibrium points are calculated in order to ensure the desired behavior 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 SC's current has to be cancelled. During transient, the power delivered by the DC source has to be as constant as possible (without a significant power peak), and the transient power has to be delivered through the SCs. The SCs in turn, recover their energy during regenerative braking when the load provides current.

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

C. *Sliding mode control of the hybrid sources*

Due to the weak request on the FC, a classical PI controller has been adapted for the boost converter. However, because of the fast response in the transient power and the possibility of working with a constant or variable frequency, a sliding mode control (Ayad et al., 2007) has been chosen for the DC-DC bidirectional SC converter. The management of charge-discharge cycles of the UC tank is possible due to the bidirectional property.

The current supplied by the FC is limited to a range [I_{MIN}, I_{MAX}]. Within this interval, the FC boost converter ensures current regulation (with respect to reference). Outside this interval, i.e. when the desired current is above I_{MAX} or below I_{MIN}, the boost converter saturates and the surge current is then provided or absorbed by the storage device. Hence 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: It is the mode 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 UC converter leads to the charge or the discharge of UC up to a reference voltage level V_{SCREF},

The discharge mode: It is the mode in 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 UC discharge,

The recovery mode: It is the mode in 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 UC charge.

D. Simulation results of the hybrid sources 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} = 131 W.
DC link parameters: V_{DL}= 24.2 V.
UC parameters: C_{UC} = 3500/6 F, V_{UC}^{*}=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 representing a single phase DC machine.

Figure 5 and 6 present the behavior of currents I_{DL}, I_L, I_{SC}, and the DC link voltage V_{DL} for transient responses obtained while moving from the normal mode to the discharge mode, using sliding mode control ∊. The test is performed by sharply changing the e.m.f load voltage E_L in the interval of *t [1.5s, 5s]*. The load current I_L changes from 16.8A to 24A. The current load I_L = 16.8A corresponds to a normal mode and the current load I_L = 24A to a discharge mode.

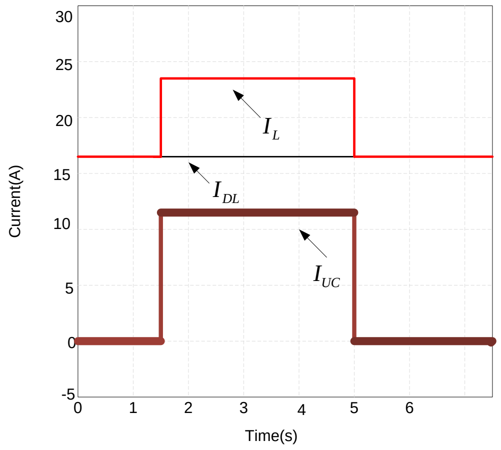

Fig.5. FC, UCs and load currents

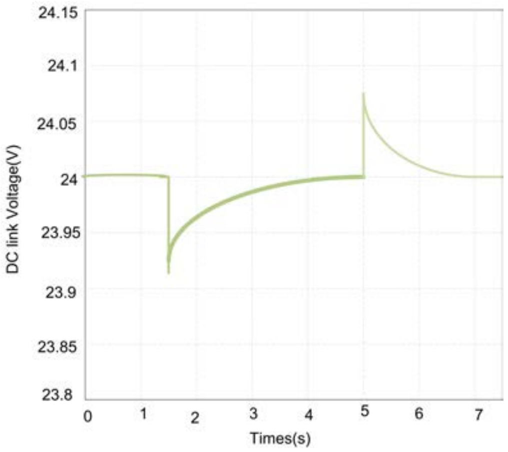

Fig.6.DC link Voltage

At the starting of the system, only FC provides the mean power to the load. The storage device current reference is equal to zero, when we are in normal mode. In the transient state, the load current IL becomes lower than the DC link current IDL. The DC link voltage reference is set at 24V. The DC link voltage tracks the reference well during the first second, after which, a very small overshoot is observed when the load current becomes negative. Then, the storage device current reference becomes negative because the controller compensates the negative load current value by the difference between the UC voltage and its reference. This is the recovering mode. After the load variation (t > 5s), the current in the DC link becomes equal to the load current. The UC current I_{UC} becomes null.

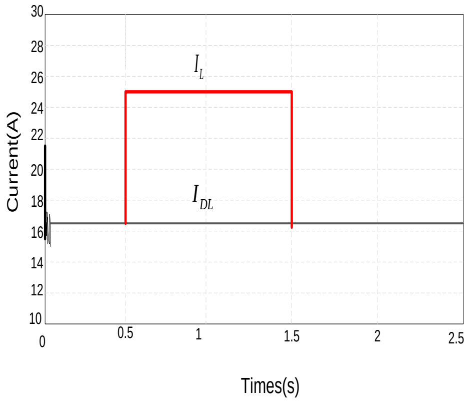

Fig.7.Load and DC link currents

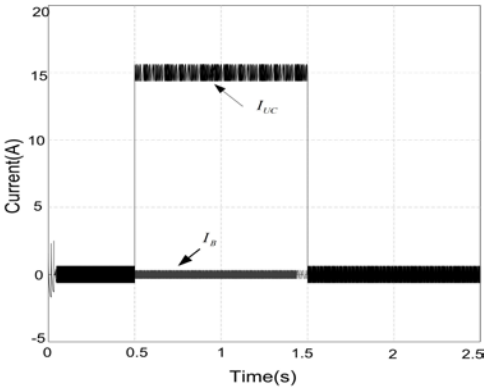

Fig.8.UC and batteries currents

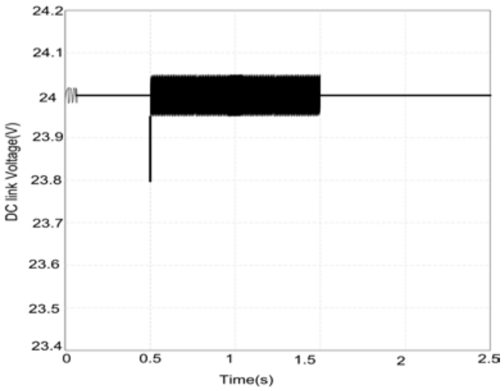

Fig.9.DC link voltage

IV. CONCLUSION

In this paper for the two hybrid structures, Sliding Mode Control principles have been applied in order to obtain a robustness control strategy. The sliding surface is generated as a function of multiple variables: DC link voltage and current, ultracapacitors current and voltage, Load current.

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

Many benefits can be expected from the proposed structures such as supplying and absorbing the power peaks by using ultracapactors which also allows recovering energy.

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