Control Study of Fuel Cell and Supercapacitors System using Hybrid Dynamic Nets

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Abstract—Fuel cell with supercapacitors is a multi-physical system which, in association with converters, becomes hybrid. To model this complex system, different proposals have been made in literature. In this paper, Component Hybrid Dynamic Nets (CHDN) are used to model this system. CHDNs are a graphic model for hybrid systems, which allow each component of the hybrid system to be represented; moreover, a novel software for hybrid modelling, SimRDH, is presented which allows each component of the system to be well represented, no matter if it is continuous or discrete.

Index Terms — Fuel Cell; supercapacitors; modelling; sliding-mode; power converter; Component Hybrid Dynamic Nets; simulation.

I. INTRODUCTION

Nowadays fuel cells represent a promising new energy technology under development today. A fuel cell is a device that chemically combines hydrogen and oxygen to provide electrical energy without combustion. They produce electricity much like batteries do, but require such a steady supply of a hydrogen rich fuel as natural gas.

A great deal of studies have been undertaken throughout the world on fuel cells in many fields of physics. As for the fields of power electronics, a lot of work on distributed generation technologies using fuel cells has also been realised and a great number of command strategies dedicated to fuel cell systems have been studied [1]. Fuel cell represents a multi-physical system combining electrical, thermal and hydraulic components, thus requiring a multi-physical model. In addition, the study of the association of fuel cell to its environment like converters, leads to hybrid modelling. To study this multi-physical hybrid system, different models can be used, i.e. Bond Graph [2,3], REM [4] and CHDN [5]. In this paper, for the first time, Component Hybrid Dynamic Nets (CHDN) are used to model this system.

CHDNs are a graphical tool used to describe and model every hybrid dynamic component. This methodology can be used in hydraulics, mechatronics, thermodynamic and electrical systems. Actually CHDNs have proven effective for modelling and simulating multidomain systems, also for traction systems [6].

Dynamic models for each of the system components have already been presented, including fuel cell, supercapacitors, PI controllers, Transistors (Components used for power conversion).

CHDNs are used in the same way for modelling the global system as well as each component. Thus, it can be used in systemic modelling to simulate the system both in normal and degraded conditions. The model and control simulation in this paper is carried out by using the SimRDH (Simulateur à base des Réseaux Dynamiques Hybrides, Simulator with Hybrid Dynamic Nets), a software tool developed by using this model for extracting a set of linear equations for every configurations of the system [7].

II. DESCRIPTION OF THE APPLICATION

In this paper the hybrid system made up of the fuel cell and supercapacitors are described in the first part. The second part presents this model briefly and then it describes the software tool SimRDH. Finally the results of simulations using this software tool are shown.

The purpose of the studied applications is to present how the CHDN model can be used for modelling, controlling and simulating hybrid system and specifically those for the energy conversion.

In Fig. 1 the fuel cell and supercapacitors hybrid system

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The application in Fig. 1 presents the electrical scheme of an electrical vehicle power supply. The fuel cell is the main energy source in this application. In general one of the weakest points of fuel cell is its slow dynamics [8]. To solve this problem, the system has to be supplied with an auxiliary source, to supply high transient energy [9,10]. In this respect the very fast power response of supercapacitors can be exploited to complement the slower power output of the fuel cell to provide the necessary compatibility and performance characteristics required by a hybrid automotive system [11].

In Fig. 1 a first DC/DC power converter is used to increase the voltage level of the fuel cell stack up to that of the DC bus. Then, in order to adapt the supercapacitor pack voltage to the same DC bus and ensure the current reversibility, a second DC/DC power converter is also employed. The fuel...
cell and supercapacitor models are described in section 2.1 and 2.2 respectively.

A. Fuel cell model

Proposing a dynamical fuel cell model is quite a hard task. As a matter of fact a lot of different phenomena (electrochemistry, physical, thermodynamic, mechanical, etc) take place in fuel cell stacks. A solution for their dynamic modelling could be the use of an equivalent electrical model of the electrode. Different authors have proposed models based on the so-called Warburg impedance and the values of different electrical components have been mostly obtained considering the impedance spectrometry [8,12]. Figure 2 shows an equivalent electrical scheme of a fuel cell stack. The parameters of this model may be identified through experiment measurements.

B. Supercapacitors model

The definition of a model for a supercapacitor has led to several studies, and depending on the approach, various models can be formalized. The complete supercapacitor model is presented in Fig.3 [13]. Where the capacitance C is not constant and it can be modelled as follows:

\[ C_1 = C_0 + C_v U \]  

where U represents the voltage variable capacitor.

III. THE CHDN MODELLING

A. General presentation of the CHDN

Component Hybrid Dynamic Nets (CHDN) are a graphic model allowing a unified representation for each component of a system and its structure [14]. It is composed of two parts, i.e. the CCDN and the Petri Nets. The CCDN (Component Continuous Dynamic Nets) is the part which allows a representation at the component level of continuous dynamic systems. In particular, the CCDNs are like Bond Graphs and permit a unified representation of dynamical systems (Electrical, Mechanical, Hydraulic...). Moreover, it should be remarked that CCDN have a similar representation as that of continuous Petri nets [15] as shown in Table 1.

The second part represents the discrete part of the components and is modelled by Petri Net with variable topology. The CCDN and Petri Net can influence each other because of crossing influence functions. This influence can be applied at the level of the transitions as well as at the zero dynamic Places. The methodology for extracting system equation is described in [7].

The CHDN can be generated from each CHDN component of the physical system.

B. The CHDN Component of simulated system

The CHDN model of Fuel Cell is presented in Fig.5. Since the software tool contains the necessary knowledge of the electrical components i.e. (C, L, R), it is easy to build the fuel cell equivalent scheme of Fig.2.

\[ V_1, V_2 : \text{Voltage of the fuel cell} \]
\[ X_1, X_2 : \text{Internal potential in the fuel cell} \]
\[ I_f C : \text{Current of the fuel cell} \]
\[ I_1, I_2 : \text{Internal currents in the fuel cell} \]
\[ R_{int} \parallel C : \text{Very simple model of the diffusion layer} \]

The CHDN model of the supercapacitor is presented in Fig.5.

\[ V_1, V_2 : \text{Voltage of the supercapacitor} \]
\[ X_1, X_2, X_3 : \text{Internal potential in the supercapacitor} \]
\[ I_f, I_f', I_1, I_2 : \text{Internal currents in the supercapacitor} \]
\[ R_f : \text{The equivalent parallel resistance} \]
\[ R_1, C_1 : \text{The main branch} \]
\[ R_2, C_2 : \text{The slow branch} \]

The CHDN model of a transistor is presented in Fig.6, where the transistor is modelled with a variable topology. If
M(ON) is equal to 1 (Transistor is ON), the Place $\mathcal{P}_1$ and Transition $\mathcal{T}_5$ in CCDN are valid (see Fig. 6), so the CCDN directly generates the first dynamic equation of the transistor. If $M(ON)$ is equal to 0 (Transistor is OFF), the Place $\mathcal{P}_1$ and Transition $\mathcal{T}_5$ are inhibited; the equation is inferred from the CCDN and the flux of the transistor is null.

![CHDN model of a transistor](image)

$Ve, Vs$: Voltages of the transistor
$Id$: Current of the transistor
$Rd$: Resistance conduction of the transistor
$C$: Command of the transistor
$M(pi)$: Number of global mark in the discrete Place $Pi$
$[\ldots]$ : Condition of crossing influence
$cTi$: The $i$th continue Transition
$cPi$: The $i$th continue Place

### IV. THE SIMRDH

SimRDH (SIMulateur à base du Réseau Dynamique Hybride à composants) (Simulator based on the Hybrid Dynamic Network of the component) is a simulation tool purposely developed for hybrid systems [14]. It is implemented in a Windows environment with the DELPHI programming language [16], and uses an original approach to generate a set of equations of the system by using CHDNs.

SimRDH attempts to calculate all variable values (state and intermediate variables) using different algorithm for integration i.e. (euler, trapezoidal, Runge Kutta). These variable values can be visualized by a specific editor.

The methodology of simulation is shown in Fig. 7. The vector $S$ represents the vector of source (effort and flow), while the vector $I$ represents all validated Place variables i.e. (state variable) and transition variables of a global models i.e. (intermediate variable). The matrix $G$ and $H$ represent the weight $Q$ associated to all Places and the weight of all arcs incoming and outgoing of all Places.

### V. SIMULATION WITH SIMRDH

#### A. Description of the system

To show the ability of this software, it has been used to simulate the three operating modes of the modelled device (Fig. 8):

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

![Simulated system](image)

The aim of the storage device is to supply power transients as well as peak loads, under the constraint that the DC/DC fuel cell converter output current $I_{FC}$ is limited to a maximum value $I_{FC}^{\text{max}}$. The schematic of the control is described in Fig. 9. The output of the voltage loop gives the reference active power which has to be provided by the rectifier to control the DC bus voltage at its rated value.

![Control of the fuel cell converter](image)

Sliding-mode control is introduced to control the DC/DC converter connected to the supercapacitor. Consequently a sliding-mode surface $S$ is defined as a function of the DC bus voltage $V_{bus}$, its reference $V_{bus}^*$, the supercapacitors voltage $V_{sc}$, its reference $V_{sc}^*$ and the supercapacitors current reference $I_{sc}$:

$$S = k_p \left( V_{bus} - V_{bus}^* \right) + k \int \left( V_{bus} - V_{bus}^* \right) dt + k_c \left( I_{sc} - I \right)$$  \hspace{1cm} (2)

With
\[ I = k_p (V_{sc} - V_{sc,ref}) + k_i \int_0^t (V_{sc} - V_{sc,ref}) dt \]  

(3)

During discharge and recovery modes, the regulation of the DC bus voltage with no static error has ensured. During normal operating mode, the supercapacitors voltage to the reference \( V_{sc}^* \) has regulated. The control law has been reduced to \( S = 0 \) that is to say:

\[ I_{sc} = I - \frac{k_p (V_{bus} - V_{bus}^*) + k_i \int_0^t (V_{bus} - V_{bus}^*) dt}{k_i} \]  

(4)

The association of the equations (3) and (4) allows the design of the controller described in Fig 10.

The tests presented in this section have been carried out by connecting the hybrid source to a load with adquat value in the three modes (i.e. normal mode, recovery mode and discharge mode).

1) Transition from the normal mode to the recovery mode:

The figures 11 and 12 present the behavior of currents \( I_{bus}, I_{sc}, I_{fc} \), the DC bus voltage \( V_{bus} \) and finally the supercapacitors voltage \( V_{sc} \). The test is performed by changing sharply the load current \( I_{bus} \) from 6 A (normal mode) to -6 A (recovery mode).

At starting of the system, only the fuel cell provides the mean power to the load. The storage device current reference is equal to zero, this is the normal mode. In the transient state, the storage device current reference became negative thanks to control function which compensate this negative value by the difference between the supercapacitors voltage and its reference. This is the recovering mode.

2) Transition from the normal mode to the discharge mode:

The figures 13 and 14 present the behavior of currents \( I_{bus}, I_{sc}, I_{fc} \), the DC bus voltage \( V_{bus} \) and finally the supercapacitors voltage \( V_{sc} \). The test is performed by changing sharply the load current \( I_{bus} \) from 6 A (normal mode) to 13 A (discharge mode).

At starting of the system, only the fuel cell provides the mean power to the load. The storage device current reference is equal to zero (normal mode). In the transient state, the storage device current become positive thanks to control function which compensate this positive value by the reference between the supercapacitors voltage and its reference (discharging mode).

VI. CONCLUSION

A sliding mode control has been developed and simulated for a hybrid power sources. The system is composed by the fuel cell as average power generators and supercapacitors as auxiliary transient power sources. The simulation results
validate the suggested system. This paper shows also that the SimRDH tool can be easily used to simulate hybrid power sources. This tool allows each component of the system to be well represented, either if it is continuous or discrete. SimRDH is a general simulation tool for electromechanical hybrid systems; it permits to get several levels of precision in simulation and it is also able to take into account any components faults.

Fig. 14. DC bus, fuel cell and supercapacitors voltage

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