CHDN to Model Fuel Cell generator and Supercapacitors for Electrical Vehicle applications

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***Abstract*—The Component Hybrid Dynamic Nets CHDN is a graphic model for hybrid dynamic systems. The CHDN allows an individual representation of every component in the hybrid system. On the base of this methodology a software tool dedicated to the electrical engineering simulation has been developed. So, the aim of this paper is to present a brief review of model's structure and to describe the developed software which has been called SimRDH. In order to show the abilities of our tool, a motorisation device, including the use of the Fuel Cell and Supercapacitors hase been studied. The obtained results are encouraging especially in the development of simulator of E.V. areas.**

Index terms— Component Hybrid Dynamic Nets; PEM Fuel Cell; Supercapacitor; power converters; Electrical Vehicle simulators.

I. Introduction

Hybrid systems are natural models of complex interactive networks such as manufacturing, communication, power, and transportation systems. Hybrid systems are characterized by complex interactions between continuous dynamics and discrete events. Components such as generators, machines and loads have a continuous behavior, while other components such as tap-changing transformers, switched shunts, power switches, and protective devices contains some event-driven behaviors. The Component Hybrid Dynamic Nets is a graphic model for the hybrid dynamic systems introduced by Janah saadi in [1], [2]. In this model continuous components (resistor, inertia, tanks...) or switched ones (transistor, diodes, valves...) are explicitly and graphically developed. This model integrate also the topology of the total system what represents an important asset in simulation. In addition, this model uses the Petri Nets formalism very easy to integrate by beginners and largely used by discrete events community, more information about this model are given in [2]. In this paper, a brief review of this model is given at the beginning of the section II. Thus, the SimRDH software tool based on this model and allowing simulation of electro mechanical hybrid system is presented[3], [4]. So,the CHDN model developed for each component of the studied application is well described. Finally, the results of simulation using SimRDH and validated by Matlab are developed.
The studied application concerns a new device in wish the combination of the Fuel Cell [5], [6]with supercapacitors is

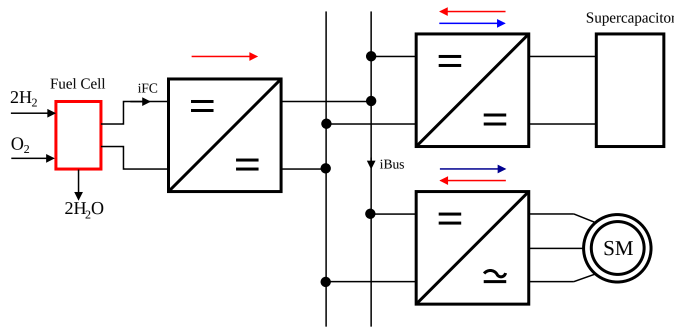


Fig. 1. The studied device

used to completely supply an electrical vehicle[7], seeg Fig 1. Only association of Fuel Cell and supercapacitors with DC Bus are studied here.

II. The CHDN Modeling and SimRDH

A. General presentation of the CHDN

Component Hybrid of Dynamic Nets (CHDN) is a graphic model allowing a unified representation for each component of a system and its structure. It is composed of two parts:

1) CCDN: Component Continuous Dynamic Nets allows a representation at the component level of continuous dynamic systems. So, the CCDN as Bond Graph [8], [9], allows a unified representation of dynamic systems (Electrical, Mechanical, Hydraulic...). Moreover, one may notice that the CCDN has an analogous presentation of continuous Petri nets [10] (Places - Transitions - weighted arcs) as shown at Fig.2.

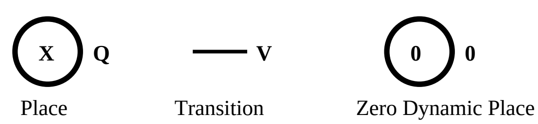


Fig. 2. The nodes of CCDN

- Places: two categories of places exist:
  - Dynamic places: to every one of these places is associated a marker representing one of the state variables weighted by a dynamic component of the system.

– Zero dynamic places: for which the marker is always zero (it is a particular case of the previous definition, for which the associated ponderation is equal 0).

- Transitions: the transitions are permanently validated; a firing variable is associated to them and can be proportional or independent of the state.
- Weighted arcs: they connect the places to the transitions. They are oriented in the direction of the positive flows. The weight of these arcs corresponds either to some constants or to some static components.

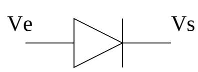
In every CCDN scheme as that shows on the Fig.2, the global marker of place P_i is called M_i and it is given as follows:

$$M_i = M(P_i) = Q_i \dot{X}_i \qquad (1)$$

where
X_i : The state variable associated to P_i
Q_i : The weighting associated to P_i

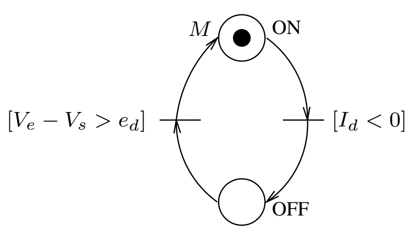
The weight and state variable of zero dynamic place is represented by a zero.

2) Petri Net: The discret part of component are modeled by Petri Net with variable topology. The CCDN and Petri Net can influence each other thanks to crossing influence functions. This influence may be applied at the level of the transitions as well as at the null dynamic places. The CHDN model of a diode, shown in Fig.3, illustrates these influences.

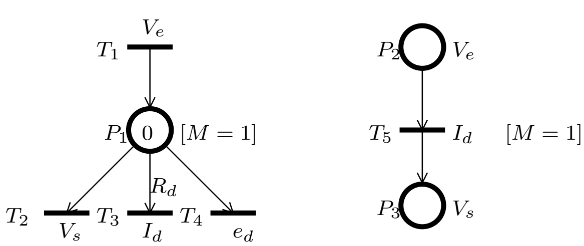


$V_e = V_s + e_d + R_d I_d$ if Diode is ON
$Id = 0$ else

(3-a) Diagram of a diode and continuous equation



(3-b) Petri Net of Diode



(3-c) CCDN model of Diode

Fig. 3. Diagram and electrical model of a diode in conduction

M : Number of mark in the place 'ON'
$[\ldots]$: Condition of crossing influence
T_i : The i^{th} transition
P_i : The i^{th} place

If M is equal to 1 (Diode is ON), the place P_1 and transition T_5 in CCDN are valid. The CCDN generate directly the dynamic equation of diode (3-a). If M is equal to 0 (Diode is OFF), the place P_1 and transition T_5 are inhibit. No equation are deducted from the CCDN, the flux of the diode is null (3-a).

3) Example : Model of system with discontinuities: The system represents a converter shown on Fig. 4. It presents the interactivity between the CCDN and Petri Nets. This example shows the functionality and the applicability of the CHDN.

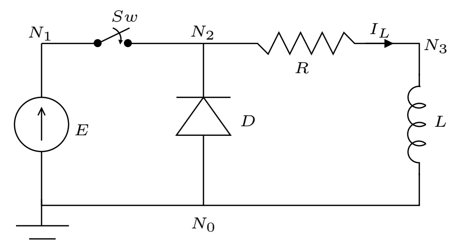


Fig. 4. Physical system with discontinuities

The CHDN model of the global system is deduced by composing each component CHDN as shown on the Fig. 5.

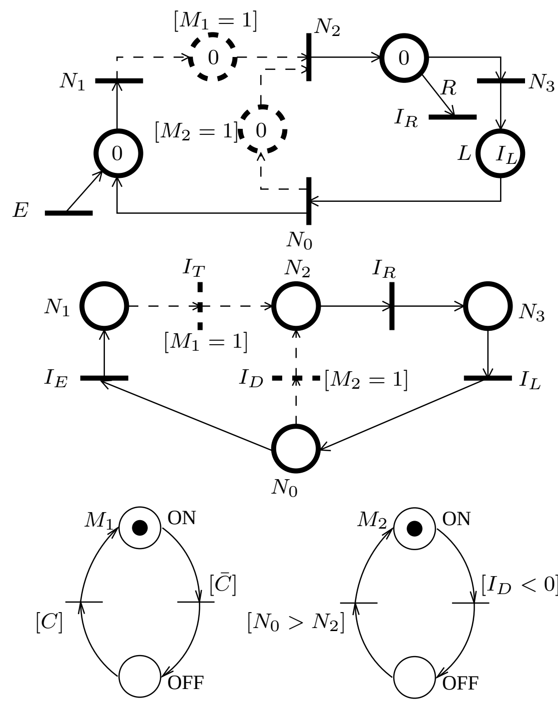
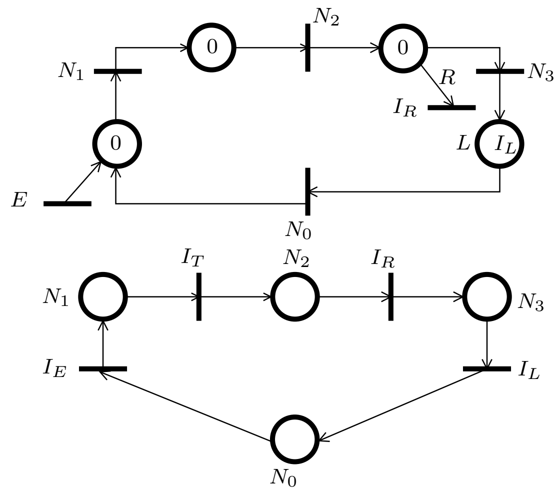
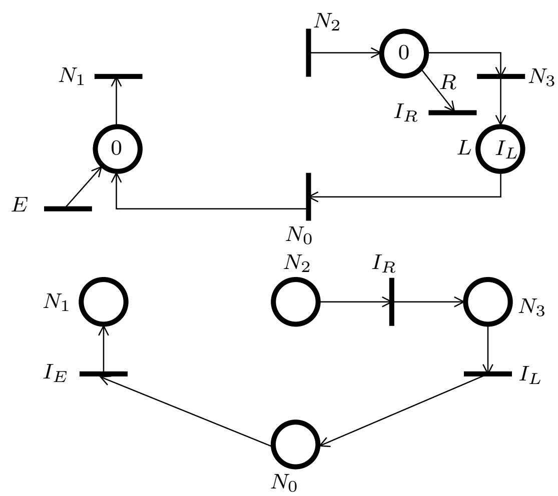


Fig. 5. Complete CHDN of system

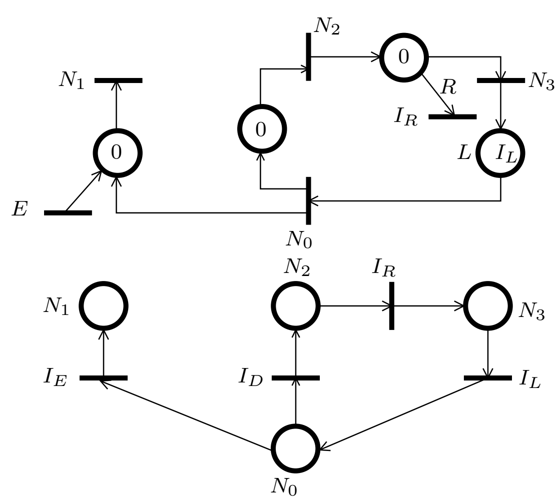
When the manual switch is closed, the inductor is connected to the source and builds up the flux. The diode is not active in this mode of operation (Fig 6-a). When the switch is opened, the current drawn by the inductor drops to 0, causing the instantaneously discharge(Fig 6-b). Because of the derivative nature, the result is the infinite derivative. The condition in Petri Net of diode $[N_2 = -\infty < N_0 = 0]$ is valid and the



(6-a) Switch on, Diode off



(6-b) Switch off, Diode off



(6-c) Switch off, Diode on

Fig. 6. Different function mode of the system

M_2 become equal to 1. The equivalents places and transitions become valid too (Fig 6-c). If the flux in the inductor become too low, the diode goes off instantaneously (Fig 6-a).

The use of CHDN is easy and permits using different level of component. It is integrate easily the default of discret component. This model includes a topology representation of the modelled device allowing a direct generation of the system equations by a simple evaluation of the whole system's places. This approach is original in the simulation of electrical systems. Using this model for simulation is too attractive.

B. SimRDH

SimRDH *(SIMulateur à base du Réseau Dynamique Hybride à composants)* is developed simulation tool for hybrid systems. It is implemented in a Windows environment with the DELPHI programming language [3], [4]. The simulator uses an original approach to generate a system of equations of the system using CHDN.
SimRDH attempts to calculate all variable values (state and intermediate variables)using trapezoidal algorithm. These variables values can be visualized by a specific editor.
SimRDH softawre may be presented by the bloc diagram of Fig. 7.

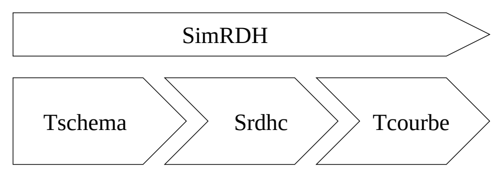


Fig. 7. Bloc diagram of the SimRDH Software

The functionalities of these blocs may be summarised as follows:

- Tschema: this module is a graphic user interface wish consists of a workspace and block diagram toolbox. Right clicking on an element brings up a pop-up menu with inputs that include the element name and its properties and its CHDN model.
- Srdhc: this module builds, in first, the global CHDN model. In the second, tests the switches (Petri Net part of the model) and deduces the system of equation corresponding to this configuration. This system is then reduced by elimination of static equations. The optimal form obtained after reduction is then numerically solved by Trapezoidal algorithm with a fixed step. The methodology of simulation is shown at Fig.8. The vector S represents the vector of source (effort and flow). The vector I represents all validate places variables and transitions variables of a global models. It can be written as follows:

$$I = \begin{pmatrix} \dot{X}(t) \\ Z(t) \end{pmatrix} \quad (2)$$

where

$X(t)$: State variables vector.
$Z(t)$: Intermediate variables vector.

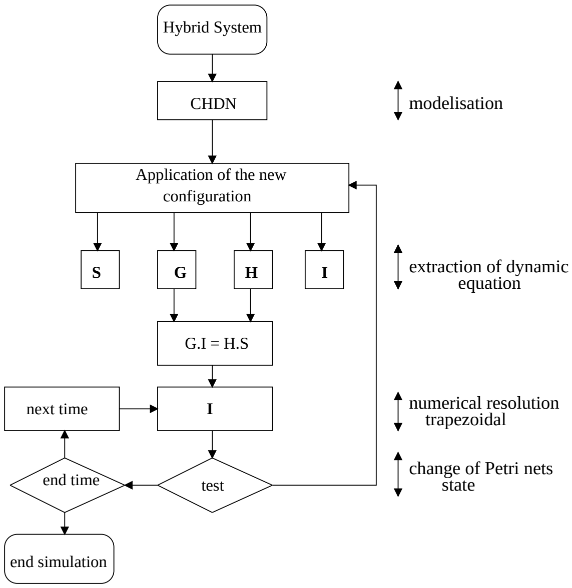


Fig. 8. Flow shart of simulation in SimRDH

The matrix G and H represent the penderation Q associated of all places and the weight of all arcs entering and outgoing of all places.

- Tcourbe: this module allows the user to have a graphic representation of the main variables composing the system. With some functions, such as data points on/off, auto scale, and a mouse driven zooming feature, user can also select maximal and minimal values for x-axis and y-axis separately. Furthermore data is written to a file in standard ASCII format, and can be plotted by more sophisticated plotters available in other software tools such as Matlab[11].

III. Description of the application

The application in Fig. 1 presents the electrical scheme of the power supply of an electrical vehicle. The feeding device of this vehicle is a combination of a Fuel Cell stack and a pack of supercapacitors which ensuring the current reversibility. A first DC/DC power converter is used to increase the voltage level of the fuel cell stack to the DC bus ones (Fig. 9). Furthermore, in order to adapt the supercapacitor pack voltage to the same DC bus, a second DC/DC power converter is used (Fig. 10). The supercapacitor and FC models are given in section III-A and III-B respectively.

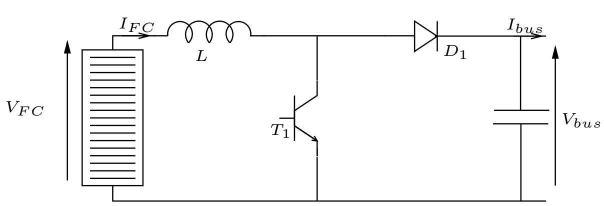


Fig. 9. Fuel Cell with boost converter

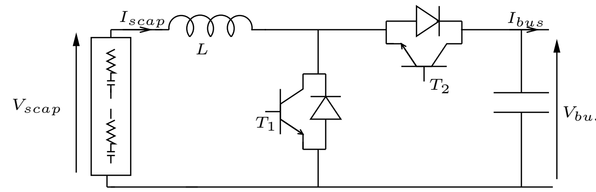


Fig. 10. Supercapacitor with buck/boost converter

A. Supercapacitor model

The complete supercapacitors model [12]presented in Fig.11 is not necessary to implement every time in simulations. Some assumptions may be made according to the needs of applications. Indeed, the series inductances L, the leakage resistor R_f and the slow branch effect R_2 et C_2 may be neglected in the case of E.V. applications. So, this approximation is acceptable for charge-discharge cycles frequency varying from 1Hz to 100 kHz. Thus, the supercapacitor element is assimilated to an ideal capacitor connected in series with the resistors R_1.

A new model is useful for most of the studies and developments on the application side. Such a model used in simulation is presented in Fig.12.

The capacitance of the supercapacitor is not constant. It can be modelled as follows : $C_1 = C_0 + \underbrace{C_v \cdot U}_{C_u}$

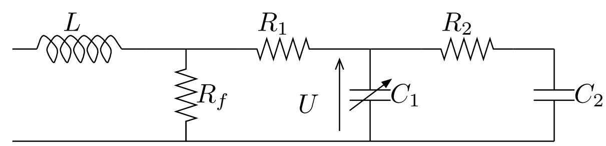
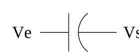
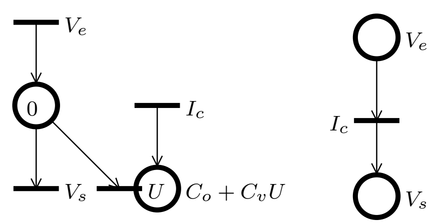


Fig. 11. Three branches model of supercapacitor



$$I_c = (C_o + C_v U)\frac{dU}{dt}$$
$$U = V_e - V_s$$

(12-a)Diagram of supercapacitor and the mathematical equation



(12-b)Model of dynamic part

Fig. 12. CHDN model of supercapacitor

B. Fuel Cell model

Firstly, it must be said that proposing a dynamical fuel cell model is far from easy. Indeed, many different kinds of phenomena (electrochemical, physical, thermodynamic, mechanical ...) are tacking place in fuel cell stacks. A solution for fuel cell dynamic modelling could be the proposition of an equivalent electrical model of an electrode. Different authors have proposed such models, based around a so-called Warburg impedance. Values of different electrical components are mostly obtained considering impedance spectrometry [5], [6], [13]. The figure 13 shows an equivalent electrical scheme of a fuel cell stack. The parameters of this model may be identified through experiment measurements.

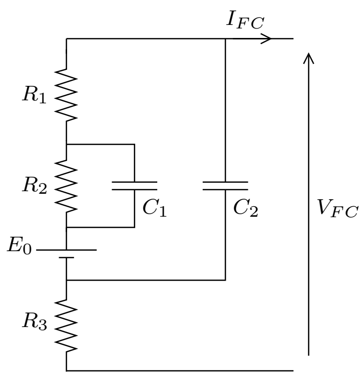


Fig. 13. The electrical model of Fuel Cell

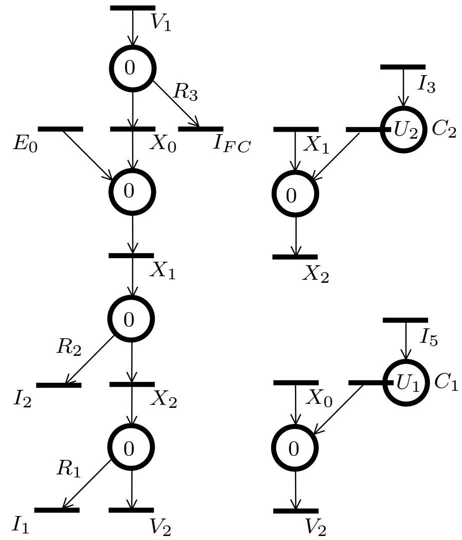
The Model CHDN of Fuel Cell is thus presented in Fig.14. Knowing that our software tool contains already the necessary electrical components i.e. (C, L, R), it has been so easy to bield the fuel cell equivalent scheme of Fig.13.

IV. Simulation with SimRDH

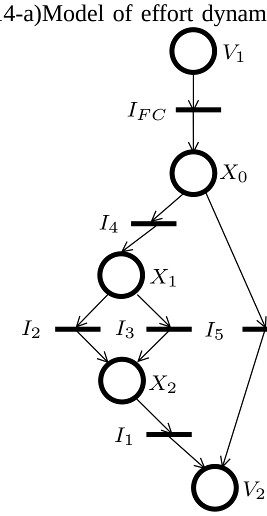
In order to show the abilities of our software, we use it in simulation of the different operating mode of the modeled device (Fig 1). When the E.V. energy is totally ensured by different DC power sources one finds tow principal modes of operating that is to say: The DC bus balancing is ensured through the use of a boost functionality either staring from the fuel cell neither from the super capacitors. The loads supplying is carried out by the way of a DC/AC converter, in the case of electrical motor feeding. In the next subsections, we expose the simulation of the both modes of operating.

A. Fuel Cell pack – DC bus simulation

1) Circuit presentation: This simulation presents only the behavior of two of the powertrain components (fuel cell generator, passive electrical load). Notice that the supercapacitors are assumed to be not present on the DC bus. This simulation highlights the fact that the fuel cell generator and its converter can well ensure the DC bus balancing. Figure 15 shows that the 540 V DC bus is supplied with a 40 A current load, delivering a DC power of 60 kW. The value of E_0 of the model is fixed at 350 V.
2) Simulation results and validations: Figure 16 shows the simulation results achieved with SimRDH. The first one present the DC bus voltage, the second present the fuel cell pack voltage.



(14-a)Model of effort dynamic part



(14-b)Model of flux dynamic part

Fig. 14. CHDN model of Fuel Cell

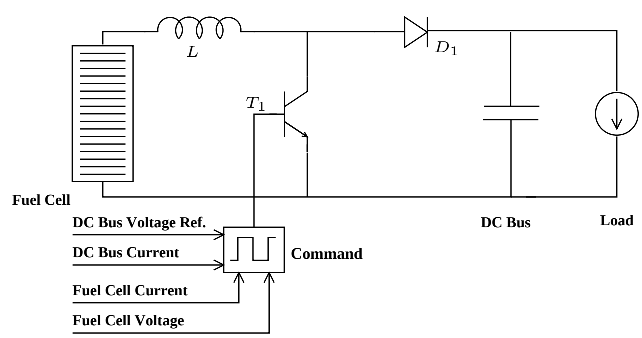


Fig. 15. SimRDH circuit description

B. Supercapacitor pack – DC bus simulation

In this simulation, the supercapacitors feed the DC bus of E.V. for which the load is modeled by a current source.

1) Circuit presentation: This simulation presents the behavior of the supercapacitor in charge and discharge. The

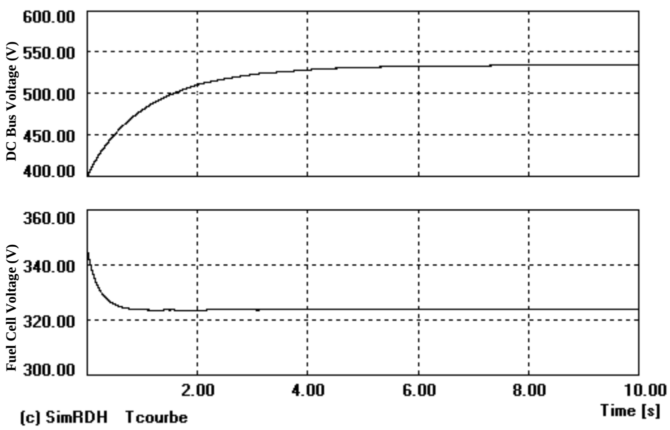


Fig. 16. Fuel Cell and DC Bus voltage

current in the bus takes two values during the cycle 40A and -40A (Fig. 17).

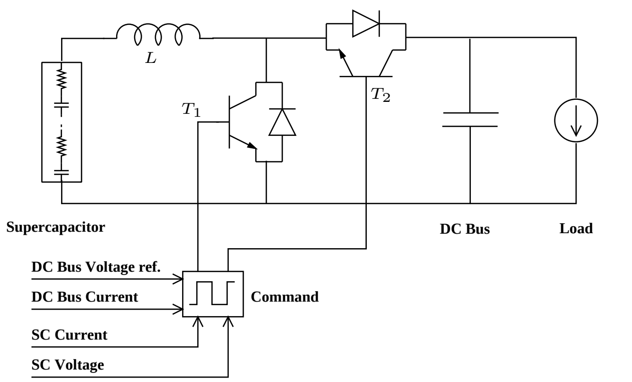


Fig. 17. SimRDH circuit description

2) Simulation results and validations:

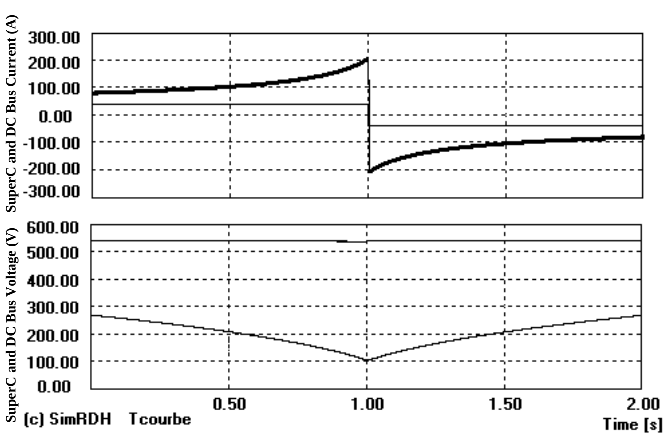


Fig. 18. System responses in charge discharge cycle

Figure 18 shows the simulation results with SimRDH. The first one presents the smoothness of the DC bus voltage and supercapacitor pack charge-discharge cycle. The second presents the DC bus and supercapacitors current. It may be clearly seen that the supercapacitors ensures well the current reversibility: between 0 and 1 seconds the supercapacitors supplies the DC bus, so, the current of the load is positive, in the second part of the simulation period (1 to 2 seconds), the load gives a negative current which charges the supercapacitors. Thus by, neglecting the circuit losses, the theoretical study shows that most of the given energy may be recovered. So, the global efficiency is improved.

C. SM machine – DC bus simulation

A DC/AC converter is used to supply the synchronous machine as shown in Fig. 19. A PI controller is used to control the speed. The command signal delivered by this controller is injected in the command bloc. The motor is loaded at start time with 100 N.m.

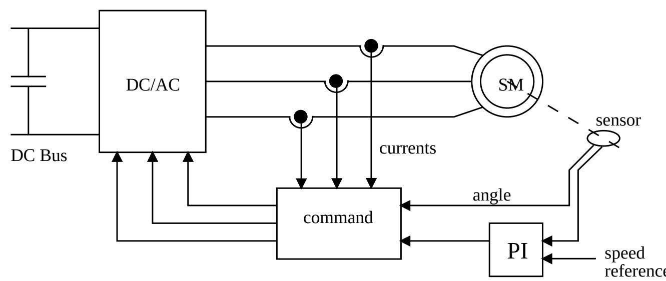


Fig. 19. SimRDH circuit description

The whole application is simulated using SimRDH software tool. Parameters of synchronous machine are given in Table.I.

Parameters	Value
Ls(Stator cyclic inductance)	10.4 mH
Rs(Rsistance)	0.15 Ω
K(EMF constant)	5.318 $V/rd/s$
J(Inertia)	0.2 $Kg.m^2$
P(Number of poles)	16

TABLE I
PARAMETERS OF SYNCHRONOUS MOTOR

Figure 20 presents the electromagnetic torque simulation (N.m).

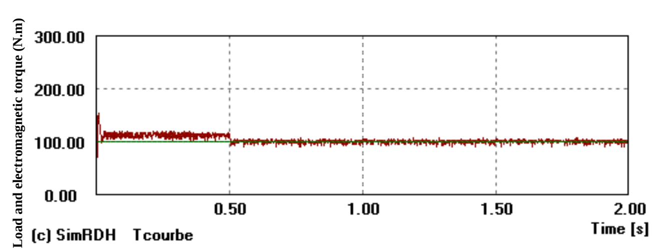


Fig. 20. Electromagnetic torque of synchronous motor (N.m)

Figure 21 presents the three phases currents of synchronous motor(A).

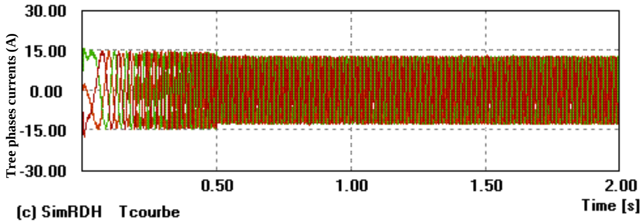


Fig. 21. Three phases currents of synchronous motor

Figure 22 presents the actual and reference speed of rotor(rd/s).

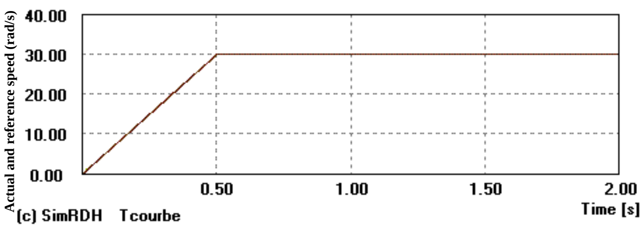


Fig. 22. Actual and reference speed of rotor

V. Conclusion

We have proposed, throughout this work, a new tool of modelling and simulation for the hybrid systems. This tool allows a representation of every component of the system, either continuous or discrete. SimRDH is a general simulation tool for electromechanical hybrid systems; it permits several level of precision in the simulation also to integrate defaults on components. In this paper we prove that this tool can be easily used to simulate electrical vehicle applications. An application to permanent magnet synchronous motor feed by a converter using Fuel Cell pack was studied showing the autonomy of the pure electrical running mode of the vehicle.

References

[1] J. Saadi. *Diagnostic et modélisation de défauts au sein d'une association convertisseur - machine*. PhD thesis, Mohamed V University, Casablanca, Maroc, 1994.

[2] J. Saadi, T. Bennani, and H. Alla. Component hybrid dynamic nets. In *IFAC/IFIP Conference on Management and Control of Production and Logistics*, pages 211–216, Septembre 1997.

[3] M. Chami and J. Saadi. Logiciel de simulation des convertisseurs statiques sans a priori. In *CD ROM Proceedings of the Fourth International Conference on Applied Mathematics and Engineering Sciences (CIMASI 2002)*, Casablanca, Morocco, Octobre 2002.

[4] M. Chami, A. Djerdir, J. Saadi, and A. Miraoui. The use of the CHDN to model a permanent magnet synchronous motor powered by ultracapacitors : Electrical vehicle application. In *CD ROM Symposium IEEE Vehicle Power and Propulsion*, Paris, France, Octobre 2004.

[5] J. Larmine and A. Dicks. *Fuel Cell Systems Explained*. J. Wiley and Sons, isbn 0471 490261 edition, 2000.

[6] A. Djerdir and All. Pem fuel cell and supercapacitor sizing for the power supply of a heavy duty aecv. In *CD ROM, All Eectric Combat Vehicle Conference*, London, UK, 2003.

[7] A. Djerdir, K. Elkadri, and A. Miraoui. Electrical vehicle feeding by association of ultracapacitors and photovoltaic generators. *Electromotion*, 2003.

[8] P. C. Breedveld. Multibond graph elements in physical systems theory. *Journal of Franklin Institute*, 1:1–36, January/February 1985.

[9] P. J. Mosterman, J. O. Campbell, A. J. Broderson, and J. R. Bourne. Design and implementation of an electronics laboratory simulator. *IEEE Transactions on Education*, 39(3):309–313, August 1996.

[10] R. David and H. Alla. Continous petri nets. In *8th European conference on theory and applications of Petri nets*, pages 275–294, Saragosse, Espagne, June 1987.

[11] B. R. Hunt, R. L. Lipsman, and Jonathan M. Rosenberg. *A Guide to MATLAB: for Beginners and Experienced Users*. Cambridge University Press, October 2001.

[12] L. Zubieta and R. Bonert. Characterization of double-layer capacitors (dlcs) for power electronics applications. *Industry Applications Conference, Thirty-Third IAS Annual Meeting. The 1998 IEEE*, 2:1149–1154, 1998.

[13] D. Candusso. *Hybridation du groupe lectrogne pile combustible pour l'alimentation d'un vhicule lectrique*. PhD thesis, Institut National Polytechnique de Grenoble, France, June 2002.