

The Use of the CHDN to Model a Permanent Magnet Synchronous Motor powered by ultracapacitors: Electrical Vehicle Application

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Abstract—The Component Hybrid Dynamic Nets (CHDN) is a graphic model for hybrid dynamic systems. The CHDN allow an individual representation of every component in the hybrid system. This paper presents a brief review of the structure of the model's structure and description of software (SimRDHC) based on this model. The software is used to simulate a permanent magnet synchronous motor supplied by a pack of ultracapacitors. Comparison with MATLAB simulations shows very good agreement.

Keywords- SimRDHC; electrical vehicle; ultracapacitor; DC-DC power converters

I. INTRODUCTION

Hybrid systems are natural models of complex interactive networks such as manufacturing, communication, power, and transportation systems. Hybrid systems allow interactions between discrete events and continuous dynamics. Power 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 exhibit an event-driven behavior. The Component Hybrid Dynamic Nets [1][2] is a graphic model for hybrid dynamic systems. In this model continuous components (resistor, inertia, tanks...) or switched ones (transistor, diodes, valves...) are explicitly and graphically developed. In this paper, a brief review of this model at the beginning of the section II. Then SimRDHC software tool [9] based on this model and allowing simulation of electro mechanical hybrid system is presented after. Section III describes the application presenting CHDN models of each component (Synchronous motor, ultracapacitor...). Results of simulation using SimRDHC and validated by Matlab are developed in section IV.

The study application concerns a new device in which the combination of the photovoltaic generator with ultracapacitors

is used to completely supply an electrical vehicle [7]. Only association of ultracapacitors and synchronous motor is studied here, see Fig. 1. The ultracapacitors have a very high energy density and can be released very quickly or rather more slowly with a lifetime up to one million cycles [6] [8]. Ultracapacitors characteristics make them more attractive than batteries to supply transient power demands during acceleration and deceleration. Onboard ultracapacitors pack is charged with a high current from another stationary ultracapacitor.

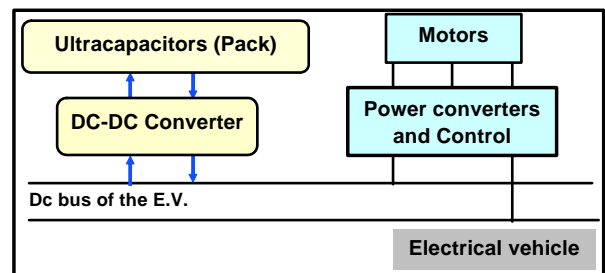


Figure 1. The modeled device

II. THE CHDN MODELING AND SIMRDHC

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:

a) CCDN : Component Continuous Dynamic Nets (CCDN) which allow a representation at the component level of continuous dynamic systems. The CCDN as Bond Graph [3][4], allows a unified representation of dynamic systems (Electrical, Mechanical, Hydraulic...etc). The CCDN has an analogous presentation of continuous Petri nets [5] (Places - Transitions – weighted arcs) as shown at fig. 2:

- Places: Two kinds 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: 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.

Fig. 2 shows the different nodes used for a CCDN. The global marker of place cP_i , is called M_i

$$M_i = M({}^cP_i) = Q_i \frac{dX_i}{dt} \quad (1)$$

where

X_i : The state variable associated to cP_i

Q_i : The weighting associated to cP_i

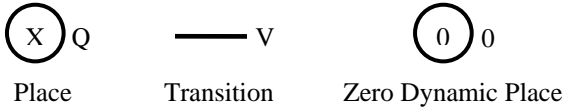
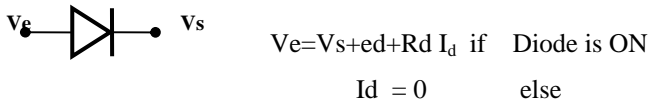


Figure 2. Nodes of a CCDN

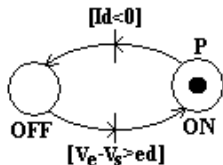
The weight and state variable of zero dynamic place is represented by a zero.

2) *Petri Net*: the switch state changes due to commutation conditions are modelised by Petri net. The switched components are modeled with variable topology.

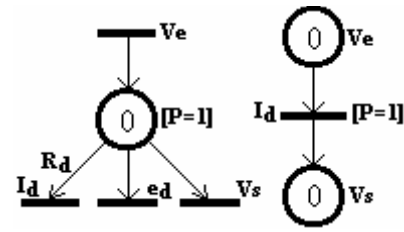
The two parts of the model can influence each other thanks to crossing influence functions. This influence can apply at the level of the transition as well as the null dynamic places. The model of a diode, shown in fig.3, illustrates these influences:



(3.a) Diagram of a diode and the mathematical equation



(3.b) Model of discrete part



(3.c) Model of dynamic part

Figure 3. Diagram and electric model of a diode in conduction

P: Mark in the place 'ON'

[...]: Condition of crossing influence.

B. SimRDHC

SimRDHC (*SIMulateur à base du Réseau Dynamique Hybride à Composants*) is simulation tool for hybrid systems, implemented in a Windows environment with the DELPHI programming language [9] [10]. The simulator uses an original approach to generate a global model of the system based on CHDN model. This model includes a topology representation of the system 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.

SimRDHC attempts to propagate known variable values (input, state and intermediate variables) through the model topology at each evaluation. These variables values can be visualized by a specific editor.

SimRDHC consists of three basic modules:

- Tschema: This module is a graphic user interface consisting 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 tests the switches (Petri Net part of the model) and builds the model of the system corresponding to this configuration. This model is then reduced by elimination of static equations. The optimal form obtained after reduction is then numerically solved by Range-Kutta algorithm with a fixed step. The methodology of simulation is shown at Fig.4.
- 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 can be 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].

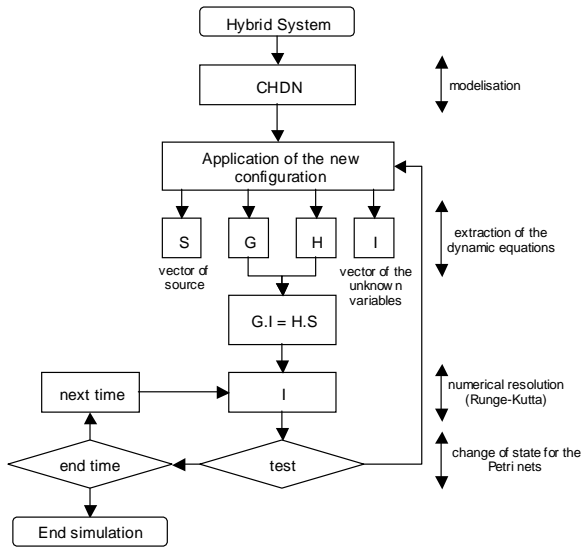


Figure 4. Flow chart for simulation in SimRDHC

III. DESCRIPTION OF THE APPLICATION

The application depicted in fig.1 represents an electrical vehicle powered by ultracapacitors feeding a reversible DC/DC power converters presented below in fig.5.

The ultracapacitor model is given section A and the motor model in section B.

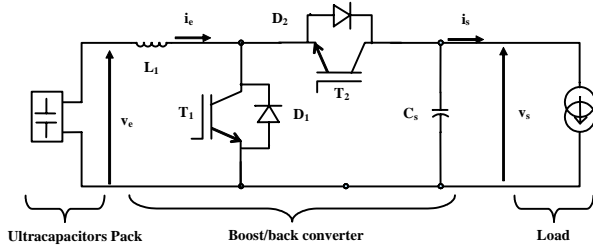


Figure 5. Ultracapacitors boost/buck converter

The complete ultracapacitors model [6] presented in Fig. 6 is very difficult to implement in simulation. Some assumptions are made in order to simplify the model size. The series inductances "L_{serie}", the leakage resistor "R_f" and the slow branch effect (R₁ & C₁) are neglected. This approximation is acceptable for charge-discharge cycles frequency varying from 1Hz to 100 kHz. Thus, the ultracapacitor element is assimilated to an ideal capacitor "C₀ + C_v × U" connected in series with the resistors "R₀".

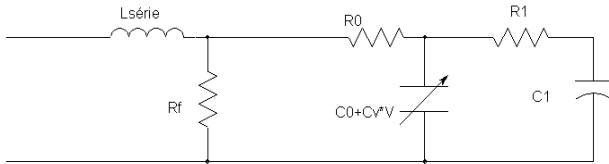


Figure 6. Three branches model of the ultracapacitor

A new model is useful for most of the studies and developments on the application side [7]. Such a model used in SimRDHC is presented in Fig. 7.

The capacitance of the ultracapacitor is not constant. It can be modeled as follows: $C = C_0 + \frac{KU}{C_u}$

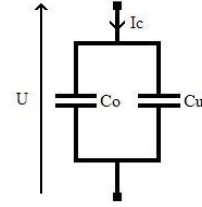
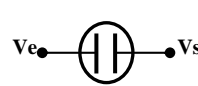


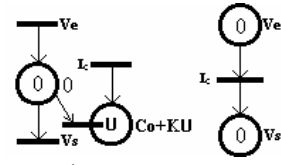
Figure 7. Equivalent circuit of an ultracapacitor used in SimRDHC



$$I_c = (C_0 + KU) \frac{dU}{dt}$$

$$U = V_e - V_s$$

(a) Diagram of ultracapacitor and the mathematical equation



(b) Model of dynamic part

Figure 8. CHDN model of ultracapacitor

A. Synchronous motor model

The equations below represents the synchronous motor model.

1) Dynamiques Equations:

a) Electrical equations:

$$\begin{cases} L_s \frac{dI_1}{dt} = V_1 - R_s I_1 + K\omega \sin(\theta_e) \\ L_s \frac{dI_2}{dt} = V_2 - R_s I_2 + K\omega \sin(\theta_e - 2\pi/3) \\ L_s \frac{dI_3}{dt} = V_3 - R_s I_3 + K\omega \sin(\theta_e - 4\pi/3) \end{cases} \quad (1)$$

b) Mecanichal equations:

$$J \frac{d\omega}{dt} = C_e - C_r \quad (2)$$

$$\frac{d\theta_e}{dt} = P \omega \quad (3)$$

c) Electromagnetic torque equation:

$$C_e = -KI_1 \sin(\theta_e) - KI_2 \sin(\theta_e - 2\pi/3) - KI_3 \sin(\theta_e - 4\pi/3) \quad (4)$$

where

I_k: stator current (k=1,2,3)

V_k: stator voltage (k=1,2,3)

ω : rotor speed

L_s, R_s, K, J, P : machine parametres

C_e : electromagnetic torque

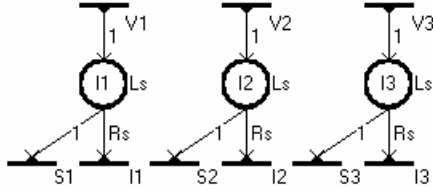
C_r : resistant torque

θ_e : electric angle

2) CHDN model:

The equivalent representation of equations (1) (2) (3) and (4) using CHDN models are given bellow:

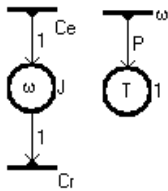
a) Electrical part :



where

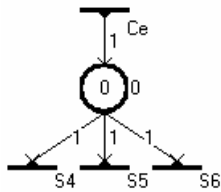
$$\begin{cases} S1 = -K\omega \sin(\theta_e) \\ S2 = -K\omega \sin(\theta_e - 2\Pi/3) \\ S3 = -K\omega \sin(\theta_e - 4\Pi/3) \end{cases} \quad (5)$$

b) Mecanical part :



T represents θ_e in (3).

c) Electromagnetical torque part :



where

$$\begin{cases} S4 = -KI_1 \sin(\theta_e) \\ S5 = -KI_2 \sin(\theta_e - 2\Pi/3) \\ S6 = -KI_3 \sin(\theta_e - 4\Pi/3) \end{cases} \quad (6)$$

3) CHDN dq model:

The equations (1) and (4) can be written in the dq plan (using park transformation) as follows:

a) Electric part :

$$\begin{cases} L_d \frac{dI_d}{dt} = V_d - R_s I_d - L_q P \omega I_q \\ L_q \frac{dI_q}{dt} = V_q - R_s I_q - L_d P \omega I_d - K\omega \end{cases} \quad (7)$$

b) Electromagnetic couple part :

$$C_e = \frac{3P}{2} (L_d - L_q) I_d I_q + \frac{3}{2} K I_q \quad (8)$$

where

I_d : d axis current.

I_q : q axis current.

V_d : d axis voltage.

V_q : q axis voltage.

IV. SIMULATION WITH SIMRDHC

A. Synchronous Motor simulation

1) Circuit presentation :

A DC/AC converter is used to supply the synchronous machine as shown in Fig. 9. A PI controller is used to control the speed. The command signal delivered by this controller is injected in the CTRL bloc. The motor is loaded 1 second after start time with 100 N.m.

The circuit is plotted using the graphic user interface of SimRDHC. OND and CTRL blocs are described respectively in fig. 10 and fig. 11.

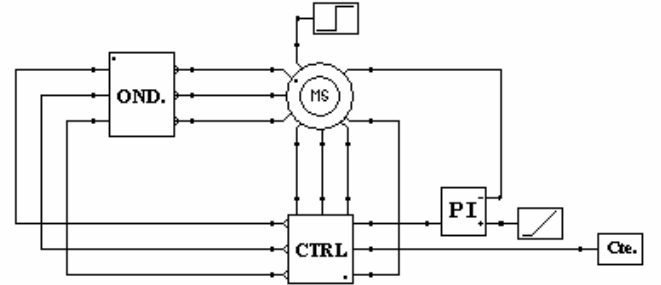


Figure 9. System description

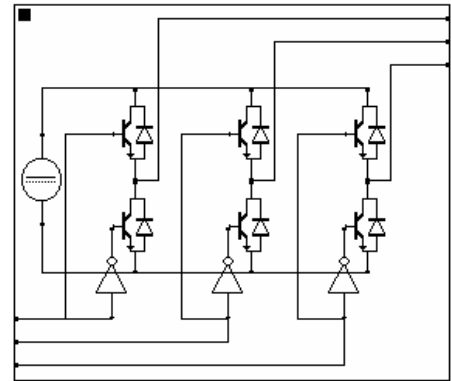


Figure 10. Details of 'OND.' bloc

The 'OND.' bloc presented in Fig. 10 is a DC/AC converter.

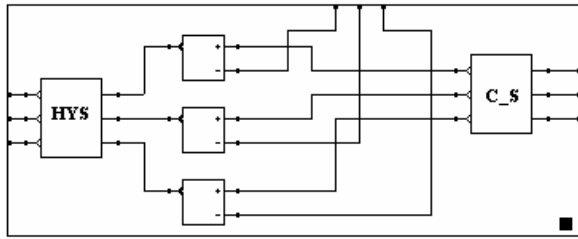


Figure 11. CTRL bloc details

The 'CTRL' bloc presented in Fig.11 is a PWM generator.

2) Simulation results and validations:

The whole application is simulated using SimRDHC software tool. Parameters of synchronous machine are given in Table.1.

TABLE I. PARAMETERS OF SYNCHRONOUS MOTOR

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

Figures 12 and 13 show the actual speed and reference speed simulation using respectively SimRDHC and Matlab.

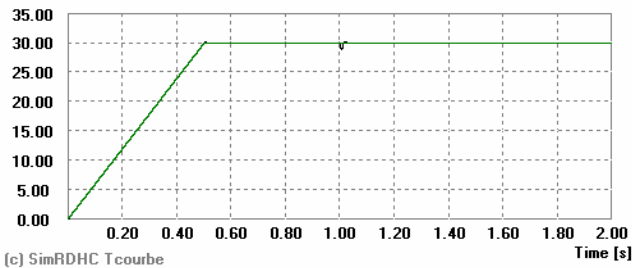


Figure 12. Result with SimRDHC, speed rotor(rd/s)

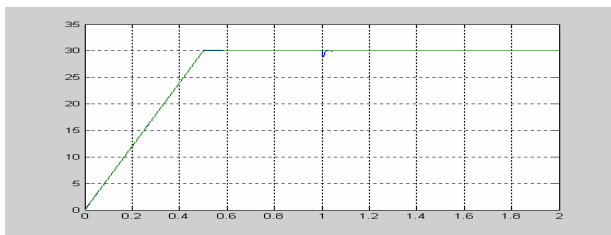


Figure 13. Result with Matlab, speed rotor(rd.s⁻¹/s)

Figures 14 and 15 present the electromagnetic and resistant torque simulation using respectively SimRDHC and Matlab.

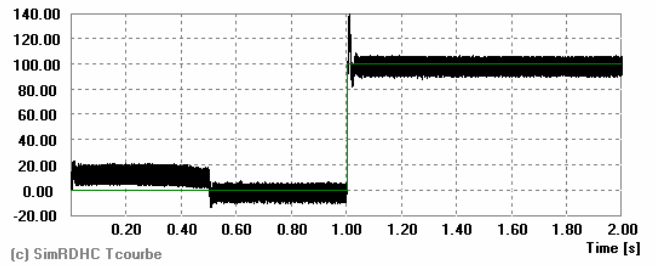


Figure 14. Result with SimRDHC, torque (N.m)

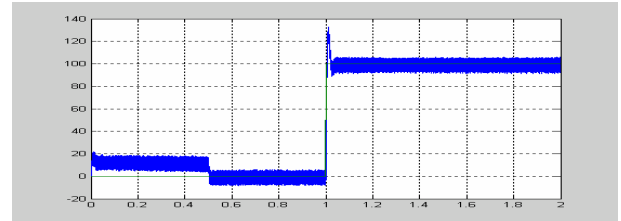


Figure 15. Result with Matlab, torque (N.m)

Figures 16, 17, 18, 19 present the three phases currents simulation using respectively SimRDHC and Matlab.

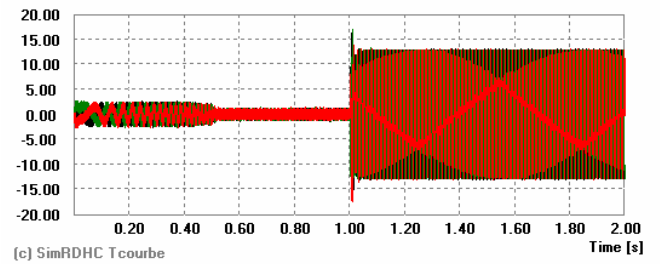


Figure 16. Result with SimRDHC, currents (Ampere)

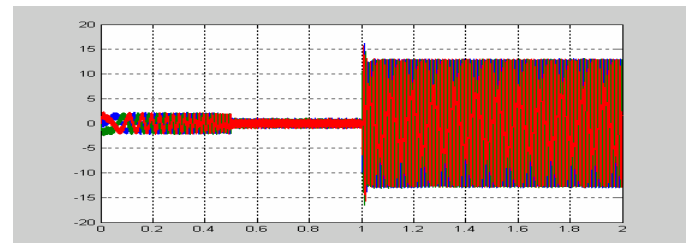


Figure 17. Result with Matlab, currents (Ampere)

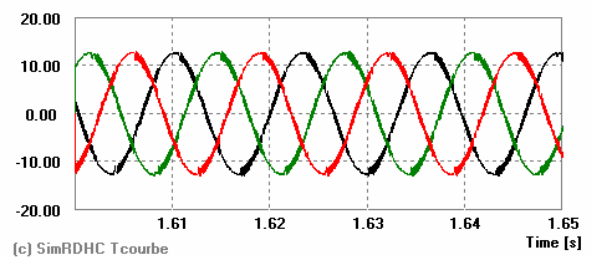


Figure 18. zoom : Result with SimRDHC (Ampere)

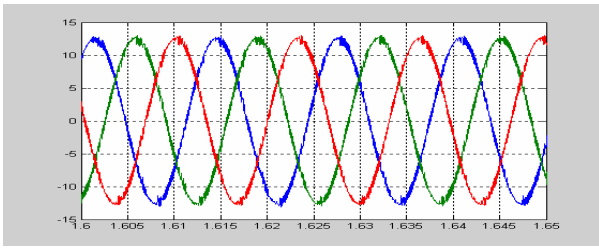


Figure 19. zoom : result with Matlab (Ampere/s)

B. Ultracapacitors pack –DC/DC converter-DC bus simulation

1) Circuit presentation :

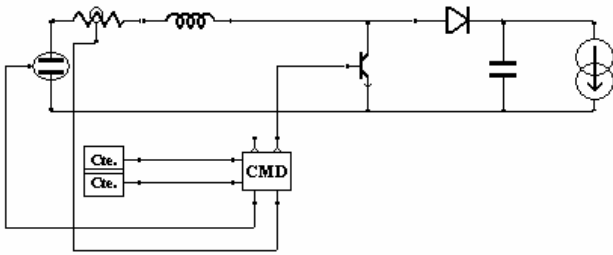


Figure 20. System description

Only boost converter is used in this simulation. The converter represented in fig.17 is plotted using the graphic user interface of SimRDHC. In the circuit CMD bloc is the control bloc of the transistor.

2) Result of simulation with SimRDHC:

The pack is initially charged at 270 V, the nominal voltage of the DC bus is 540 V. The pack is discharged in DC bus though the converter DC-DC. Fig. 21 and 22 shows respectively the currents and the voltages of the pack. The effect of load variation (fig. 23) on the DC bus voltage is negligible fig. 24.

This simulation is achieved in a goal of validation of our tool. Results hardly prove to be optimal, an optimization of parameters is obligatory.

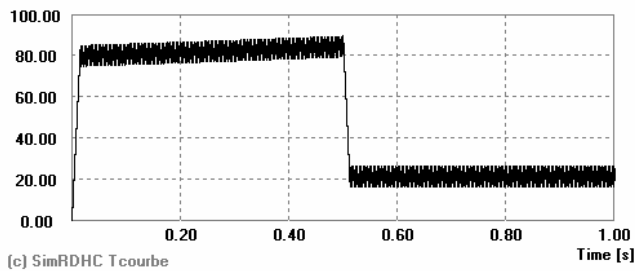


Figure 21. Ultracapacitor pack current variations (Ampere)

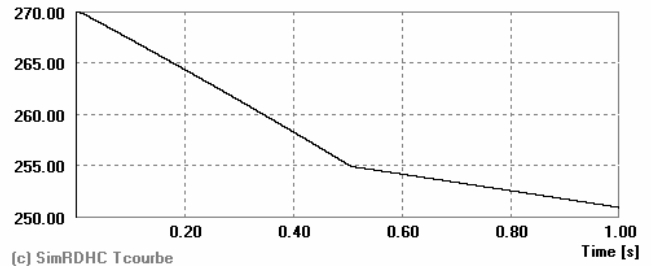


Figure 22. Voltage variations of pack(Volt)

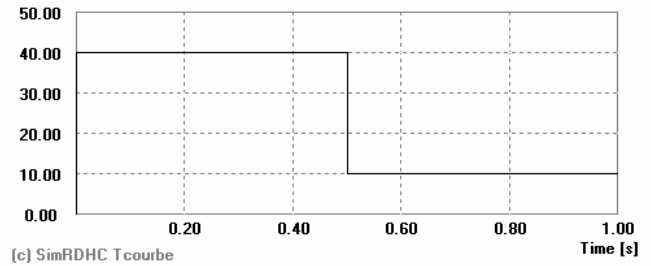


Figure 23. Current of the Dc bus during a load cycle(Ampere)

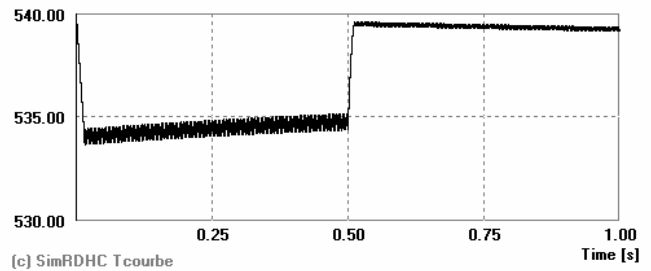


Figure 24. Voltage variations of DC bus(Volt)

V. CONCLUSION:

We have proposed, throughout this work, a new tool of modeling and simulation for the hybrid systems. This tool allows a representation of every component of the system, either continuous or discrete. SimRDHC 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 ultra capacitors was studied showing the obvious contribution of the ultracapacitors to smooth the bus voltage variations.

All the results are validated with Matlab (Simulink).

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