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Hybrid Modelling of Energy Management System in Electric Traction

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Abstract— **The energy management system in electric traction is secured by DC-DC converters (boost and buck / boost). Modelling these converters has always been difficult due to the discontinuity of their differential equations. Indeed, in power electronics, switching circuits, by their nature, present a hybrid behaviour, which are a user discrete mode and a continuous mode. To describe jointly the two behaviours, the Matlab / Simulink environment allows us to obtain very precise models that help us in the study and design of such circuits. . The overall idea of this paper is to model the energy management system in both continuous and discreet modes. A hybrid model has been introduced and its simulation has been carried out.**

Keywords— **buck, boost converter, hybrid model, electrical traction**

I. INTRODUCTION

Nowadays, the electric vehicle has a promising solution for the use of clean energy. These vehicles are fully equipped with an electric propulsion, which is provided by one or more electric motors. A source of extra energy can perform the startup[6][10]. This paper is devoted to model the power management system in electric traction. Indeed, among the general issues of hybrid vehicles, a particularly critical point is the management of powers between the different components of the vehicle. This management is ensured mainly by DC-DC converters. Although, in recent decades we have seen a number of contributions in the field of modeling and control of the DC-DC converters like any other power electronics, their modeling and control has been a difficult task for researchers and engineers working in this field. Indeed, physical systems are often represented by a dynamic continuous model or a discrete event model.

The nature of each model is defined by the variables used to describe the state of the system and the variable characterizing the time [9]. It is important in many cases to use one of these two classes of models [11]. However, the majority of realistic complex systems mixing discrete and continuous categories can not be classified in either "continuous" or "discrete systems". It is then necessary to use hybrid models that can take into account both continuous and discrete variables and the interaction between them [1]. These DC-DC converters are switched systems whose structure changes over time. The nature of the switching of these systems makes them highly nonlinear. They thus form hybrid systems which include both continuous state variables and event variables as well as the interaction between them [3][4]. The system (fig .1) we will study is formed by a static DC-DC one-way converter-booster which raises the battery voltage, while the other DC-DC converter which is reversible operates on buck in case the electrical power is converted from the load to the super capacitor (when braking) and boost work otherwise (energy demand)[2].

The paper is organized as follows: a DC-DC (Buck and Buck/Boost) power converter is given in section 2. Section 3 deals with the hybrid modelisation of the system. In order to illustrate the effectiveness of the proposed method, simulations are made in section 3. Finally, a conclusion is provided in section 4.

II. ENERGY MANAGEMENT SYSTEM MODEL

The DC-DC converters are electronic switching systems, which allow to decrease (buck converter) or to increase DC voltage (boost converter) via a switching mechanism mainly based on IGBT. They are very used to build energy sources of electronic equipment because of their high efficiency and

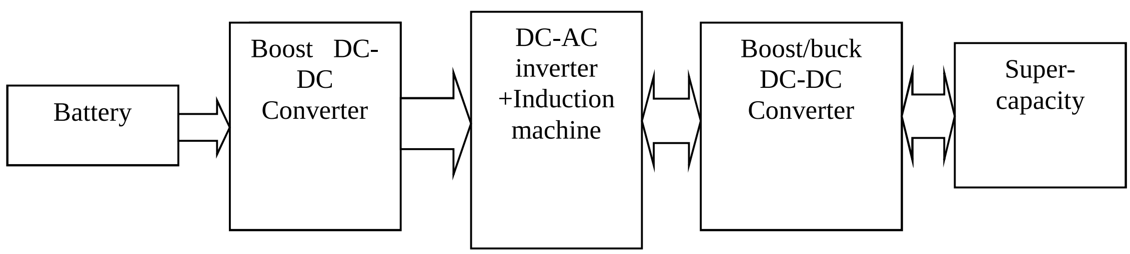

Figure 1

small size, as well as for the control of electric motors. These converters are modelled by hybrid systems[5], since they are formed by electronic components that function as switches that tell the diode and IGBT (discrete-time system) and electronics circuits (continuous-time system). In this paragraph, we present the model of boost and the buck/boost converter.

A. *BOOST Converter*

The main work of the boost converter is to elevate the voltage of the battery to have voltage of the DC bus sufficiently elevated.

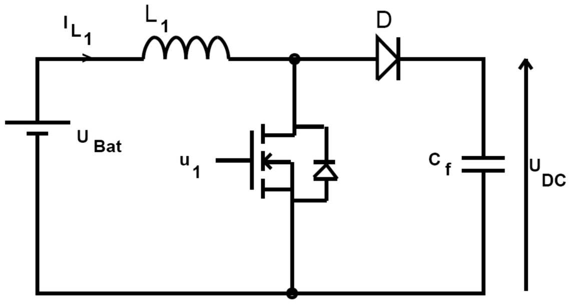

Figure 2: Boost Converter

The modelling of the converter passes through the analysis of different operating sequences which we assume with fixed time[7][8]. It appears that there are two sequences of functioning according to the state of the switch u_1, each can be represented by a differential equation.

<u>Case 1</u>:

The control of transistor $u_1 = 1$ then the diode D is blocked, this implies that the coil is charged by the battery all along the duration where the IGBT is commanded by the signal u_1. The equivalent circuit scheme is as follows:

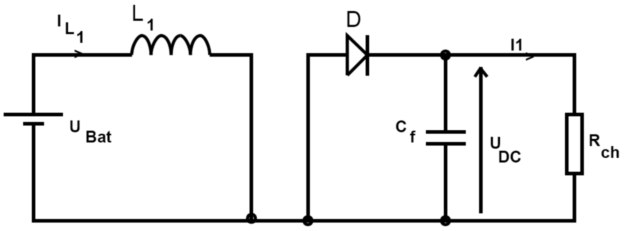

Figure 3: Boost scheme in first phase

The equations of the system are as follows:

$$\begin{cases} U_{Bat} = L_1 \dfrac{di_{L_1}}{dt} & (1) \\ 0 = C_f \dfrac{dU_{DC}}{dt} + I_1 & (2) \end{cases}$$

<u>Case 2</u>:

The control of the transistor $u_1 = 0$, which causes the discharge of the inductance in the capacitor and which fixes the output voltage is called the freewheel phase. Thus, the current driven by the coil will be shared between the capacity C_f and the current required by the DC bus I_1

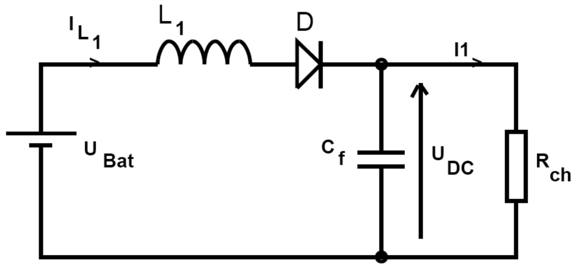

Figure 4: Boost scheme in the second phase

The equations of the system are as follows:

$$\begin{cases} U_{Bat} = L_1 \dfrac{di_{L_1}}{dt} + U_{DC} & (3) \\ i_{L_1} = C_f \dfrac{dU_{DC}}{dt} + I_1 & (4) \end{cases}$$

We can represent the converter by a single system of equations, which gives:

$$U_{Bat} = L_1 \frac{di_{L_1}}{dt} + (1 - u_1) U_{DC} \qquad (5)$$

$$i_{L_1}(1 - u_1) = C_f \frac{dU_{DC}}{dt} + I_1 \qquad (6)$$

with U_{Bat} : voltage of the battery (V)
U_{DC} : DC Bus voltage
I_{L1} : current driven by the coil L_1.
L_1 : Smoothing inductor.
C_f : filter capacitor.
u_1 : control signal of the transistor.
I_1 : current supplied by the converter.

B. *BUCK/BOOST Converter*

The buck / boost converter is a reversible current DC-DC which appears throughout the equations of the converter shown in (7) and (8). Two types of operations: Buck mode, when the supercapacitor receives power from the DC bus, and booster mode, when the supercapacitor provides power to the DC bus.

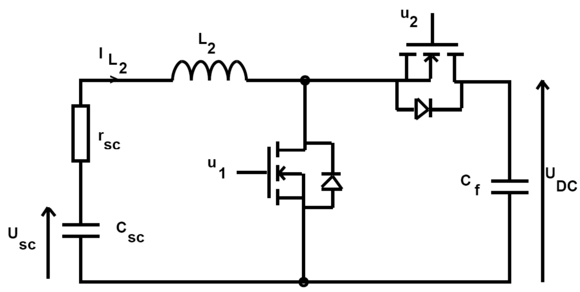

Figure 5: Buck/Boost converter

Remarque: The super capacitor is modelled by a constant value C_{sc} capacity in series with a low resistance.

Case 1:

The converter works as a boost mode so, it provides energy to the DC bus:

$$\frac{di_{L_2}}{dt} = \frac{R_{sc}}{L_2} i_{L_2} + \frac{1}{L_2} U_{sc} - \frac{1}{L_2} U_{DC} \quad u_1 \qquad (7)$$

Case 2:

The converter working as buck :

$$\frac{di_{L_2}}{dt} = \frac{R_{sc}}{L_2} i_{L_2} + \frac{1}{L_2} U_{sc} - \frac{1}{L_2} U_{DC} \quad (1-u_2) \qquad (8)$$

With: U_{SC}: voltage terminal of the capacitor of the super capacitor (V).
L_2: Smoothing inductor (H).
u_1, u_2 two commands of transistors.
R_{sc} : Internal resistance of the super capacitor pack
U_{DC} : DC bus voltage

C. Global system model

The overall model is formed by the two DC-DC converters super capacitor pack and a resistive load. The schema of the system in detail is presented in Figure 3

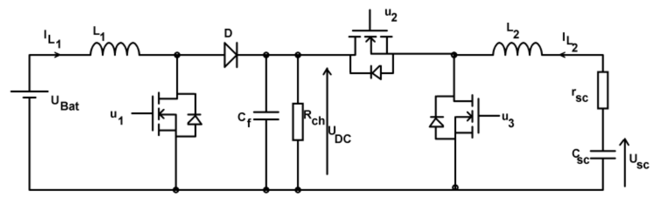

Figure 6: The global system scheme

The IGBT transistors are controlled by the command signals u_1 , u_2 and u_3.
With $I_{charge}=U_{DC}/R_{ch}$
Two cases will be presented:

Case 1 : the second converter (buck / boost) operates as BOOST then, the equations of the two converters are given by:

$$\frac{dI_{L_1}}{dt} = \frac{U_{Bat}}{L_1} - \frac{U_{DC}}{L_1} + \frac{u_1}{L_1} U_{DC} \qquad (9)$$

$$\frac{dI_{L_2}}{dt} = \frac{U_{sc}}{L_2} - \frac{R_{sc}}{L_2} I_{L_2} - \frac{U_{DC}}{L_2}(1-u_2) \qquad (10)$$

$$\frac{dU_{DC}}{dt} = \frac{I_{L_1}}{C_f}(1-u_1) + \frac{I_{L_2}}{C_f}(1-u_2) - \frac{U_{DC}}{R_{ch}C_f} \qquad (11)$$

Case 2: the second buck converter operates when the equations of the two converters are given by:

$$\frac{dI_{L_1}}{dt} = \frac{U_{Bat}}{L_1} - \frac{U_{DC}}{L_1} + \frac{u_1}{L_1} U_{DC} \qquad (12)$$

$$\frac{dI_{L_2}}{dt} = \frac{U_{sc}}{L_2} - \frac{R_{sc}}{L_2} I_{L_2} - \frac{U_{DC}}{L_2} u_3 \qquad (13)$$

$$\frac{dU_{DC}}{dt} = \frac{I_{L_1}}{C_f}(1-u_1) + \frac{I_{L_2}}{C_f}(1-u_2) - \frac{U_{DC}}{R_{ch}C_f} \qquad (14)$$

By making the following change of variables the two systems can be combined into one:

$$u_4 = (1-u_2)T + u_3(1-T)$$

Where k is a binary variable defined as:

$$\begin{cases} T=0 & \text{buck mode} \\ T=1 & \text{boost mode} \end{cases}$$

Which gives us: $T = buck \,.\, \overline{Boost}$

Both systems can be grouped into one. By combining the equations (9) with (10), (11) with (12) and (13) with (14), we obtain:

$$\frac{dI_{L1}}{dt} = \frac{U_{Bat}}{L_1} - \frac{U_{DC}}{L_1} + \frac{u_1}{L_1} U_{DC} \qquad (15)$$

$$\frac{dI_{L_2}}{dt} = \frac{U_{sc}}{L_2} - \frac{R_{sc}}{L_2} I_{L_2} - \frac{U_{DC}}{L_2} u_4 \qquad (16)$$

$$\frac{dU_{DC}}{dt} = \frac{I_{L_1}}{C_f}(1-u_1) + \frac{I_{L_2}}{C_f} u_4 - \frac{U_{DC}}{R_{ch}C_f} \qquad (17)$$

$$\frac{dU_{sc}}{dt} = -\frac{i_{L_2}}{C_{sc}} \qquad (18)$$

III Hybrid system

An autonomous hybrid system can be described as follows:

$$\dot{x}(t) = f(x(t), q(t)) \qquad x(t_0) = x_0$$

$$q(t))e(x(t), q(t-)) \qquad q(t_0) = i_0$$

Where $x(t) \in \Re^n$ is the continuous state vector, $q(t) \in Q = \{1, \ldots n_Q\}$, is the discrete state and $q(t-)$ is the discrete precedent state. The hybrid state space is $H = \Re^n \times Q.$

The function $e : \Re^n \times Q \rightarrow Q$ describes the change of discrete state. The change of a discrete state to another is called transition or switching. The transition between two states i and j is obtained when $x(t)$ reaches the switching section $S_{i,j} = \{x : e(x,i) = j\}$

Among the most important classes of hybrid systems found, are the piecewise linear systems, which are described by: $\dot{x}(t) = f_q(x) = A(q)x(t) + B(q)$

Where $A(q) \in \Re^{n\times m}$ and $B(q) \in \Re^{n}$ matrices are dependent on q.

By choosing the state variables as follows:
$x_1=I_{L1}$; $x_2=I_{L2}$; $x_3=U_{DC}$ and $x_4=U_{sc}$,The system can be presented as follows:

$$\dot{x}(t) = A_q x(t) + Bu(t) \quad (19)$$

$$y(t) = Cx(t) \quad (20)$$

With matrix A given in table 1:

	A_q	A_q
DC_convert_1:ON DC_convert_2:ON	A_1	A_4
DC_convert_1:OFF DC_convert_2:ON	A_2	A_3
DC_convert_1:OFF DC_convert_2:OFF	A_3	A_2
DC_convert_1:ON DC_convert_2:OFF	A_4	A_1
The second converter mode	BOOST	BUCK

Table 1: matrix A in buck and boost mode

Where

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -\frac{R_{sc}}{L_2} & 0 & \frac{1}{L_2} \\ 0 & 0 & -\frac{1}{R_{ch}C_f} & 0 \\ 0 & -\frac{1}{C_{sc}} & 0 & 0 \end{bmatrix} \quad A_2 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & -\frac{R_{sc}}{L_2} & 0 & \frac{1}{L_2} \\ \frac{1}{C_f} & 0 & -\frac{1}{R_{ch}C_f} & 0 \\ 0 & -\frac{1}{C_{sc}} & 0 & 0 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & -\frac{R_{sc}}{L_2} & -\frac{1}{L_2} & \frac{1}{L_2} \\ \frac{1}{C_f} & \frac{1}{C_f} & -\frac{1}{R_{ch}C_f} & 0 \\ 0 & -\frac{1}{C_{sc}} & 0 & 0 \end{bmatrix} \quad A_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -\frac{R_{sc}}{L_2} & -\frac{1}{L_2} & \frac{1}{L_2} \\ 0 & \frac{1}{C_f} & -\frac{1}{R_{ch}C_f} & 0 \\ 0 & -\frac{1}{C_{sc}} & 0 & 0 \end{bmatrix}$$

$$X = \begin{bmatrix} I_{L_1} \\ I_{L_2} \\ U_{DC} \\ U_{sc} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad u = \begin{bmatrix} u_1 \\ u_4 \end{bmatrix}$$

A hybrid automaton is a dynamical system that describes the evolution in time of the values of a set of discrete and continuous state variables.

Definition: A hybrid automaton H is a collection $H = (Q, X, f, Init, D, E, G, R)$, where:

$Q = \{q_1, q_2, ...\}$ *is a set of discrete states*

$X = \Re^n$ *is a set of continuous states*

$f(.,.): Q \times X \to \Re^n$ *is a vector field*

$Init \subseteq Q \times X$ *is a set of initial states*

$Dom(.): Q \to P(X)$ *is edges*

$G(.): E \to P(X)$ *is a guard condition*

$R(.,.): E \times X \to P(X)$ *is a reset map*

In our case eight discrete states are possible $Q = \{1,2,3,4,5,6,7,8\}$ and the edges are defined as following:

$$E = \left\{ \begin{array}{l} (q_1,q_2),(q_2,q_1),(q_1,q_4),(q_4,q_1),(q_2,q_3) \\ (q_3,q_2),(q_3,q_4),(q_4,q_3),(q_5,q_6),(q_6,q_5) \\ (q_5,q_8),(q_8,q_5)(q_6,q_7),(q_7,q_6),(q_7,q_8) \\ (q_8,q_7),(q_1,q_5),(q_5,q_1)(q_2,q_6),(q_6,q_2) \\ (q_3,q_7),(q_7,q_3),(q_4,q_8),(q_8,q_4) \end{array} \right\}$$

The guards are defined as follows:

The first case when the second converter works as a boost is defined by:

$G_{12} = G_{43} = \{x \in \Re^4,\ x_1 > Iref_1\}$

$G_{21} = G_{34} = \{x \in \Re^4,\ x_1 < Iref_1 - \Delta Iref_1\}$

$G_{14} = G_{23} = \{x \in \Re^4,\ x_2 > Iref_2\}$

$G_{41} = G_{32} = \{x \in \Re^4,\ x_2 < Iref_2 - \Delta Iref_2\}$

The second case when the second converter work as a buck we define:

$G_{56} = G_{87} = \{x \in \Re^4,\ x_1 > Iref_1'\}$

$G_{65} = G_{78} = \{x \in \Re^4,\ x_1 < Iref_1' - \Delta Iref_1'\}$

$G_{58} = G_{67} = \{x \in \Re^4,\ x_2 > Iref_2'\}$

$G_{85} = G_{76} = \{x \in \Re^4,\ x_2 < Iref_2' - \Delta Iref_2'\}$

And finally the second converter can change its mode function between boost and buck. So, we define the guard as follows: G_{15}, G_{26}, G_{37}, G_{48} WhenT=1 and G_{51}, G_{62}, G_{73}, G_{84} when T=0.

In boost mode, the Guard conditions for the first DC-Dc converter G_{12},G_{43} and G_{21},G_{34} are defined respectively as follows $i_{L1} \geq I_{ref1}$ and $I_{L1} \leq I_{ref1} - \Delta I_{ref1}$ at the same time for the second converter G_{14},G_{23} and G_{41},G_{32} are defined respectively as follows $i_{L2} \geq I_{ref2}$ and $I_{L2} \leq I_{ref2} - \Delta I_{ref2}$, These guards cause the system to remain in certain limits. Therefore, the load current and the voltage U_{DC} remain in a definite limit.

In figure 7, we have made the state chart when the second DC-DC converter is work as boost mode that is to say both DC-DC converter work as boost, the system initially starts with q = 1. Soon, as a condition is met, it switches to q = 2 if the current $I_{boost} > I_{ref}$ or it switches to q = 4 if the current $I_{boost2} > I_{ref}$.

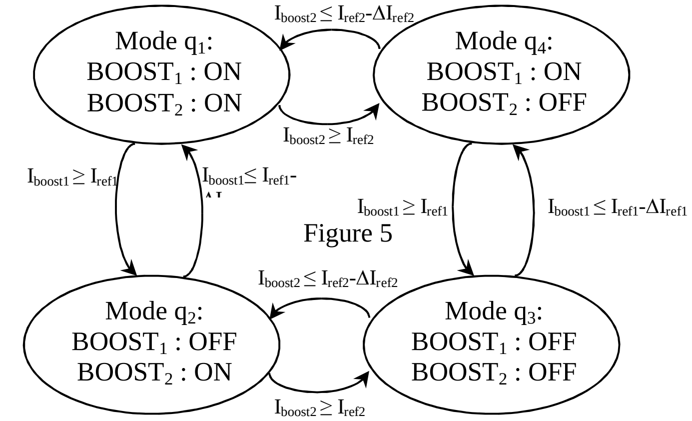

Figure 7

The second chart (figure 8) represent the second mode when the second converter work in buck mode.

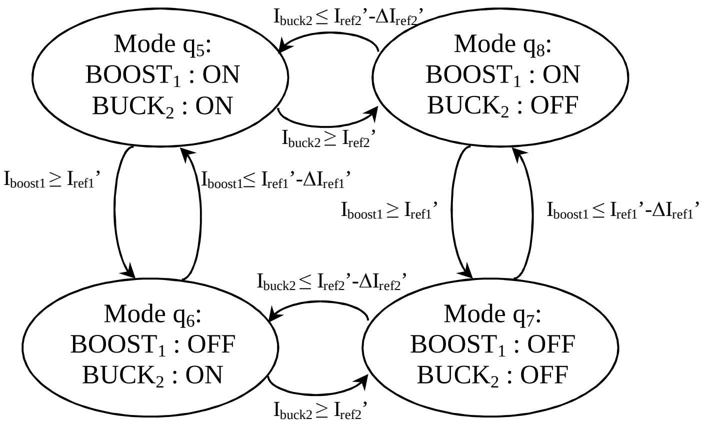

Figure 8

The passing between the two modes is conditioned by the value of T, if T = 1 we have $q \in \{1, 2, 3, 4\}$ and if T = 0 we have $q \in \{5, 6, 7, 8\}$

III. SIMULATIONS

We take the following values:

Compound	Value
L_1	330 mH
L_2	330 mH
C_F	800 µF
R_{sc}	0.001Ω
R_{ch}	100Ω
C_{sc}	70F

A. *The second DC-DC converter work as a boost:*

In this section, the second converter works in boost mode, both converters are current order. For the first boost current I_{L1} reference max and min is between 3.5A and 4A, while the second boost converter current value I_{L2} is between 1.5A and 2A. Figure 1 shows respectively the currents in the coils L_1 and L_2. We see that the two currents are positive and the super capacitor discharge because both converters work as boost.

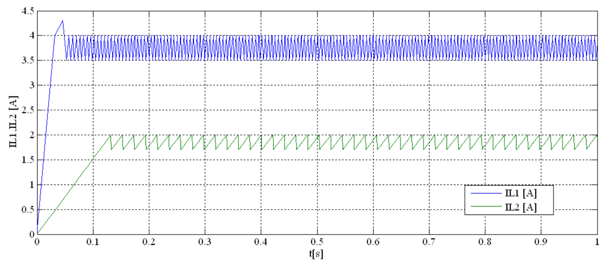

Figure 9: The I_{L1} and I_{L2} coil current

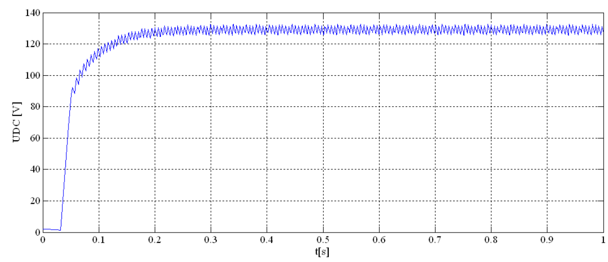

Figure 10: The U_{DC} DC voltage

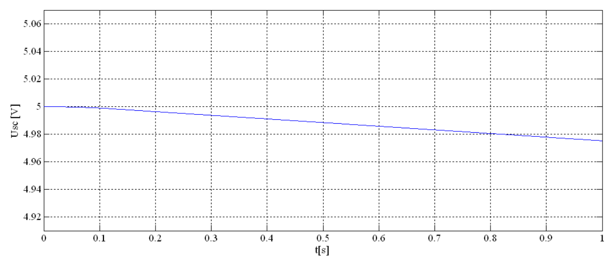

Figure 11: The U_{sc} Voltage of supercapacitor

In this case, the supercapacitor pack voltage decreases because the second converter works in boost mode. So, it provides the energy to the load (when it starts).

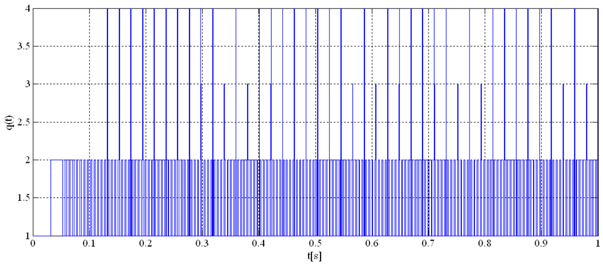

Figure 12: The q(t) Value (boost mode)

B. *The second DC-DC converter work as a buck:*

In this section, the second converter work in buck mode,. For the first boost current I_{L1} reference is between 3.5A and 4A, while the second buck converter current value I_{L2} is between -2A and -1.8A. Figure 1 shows respectively the currents in the coils L_1 and L_2. We see that the I_{L1} current is positive but I_{L2} current is negative and the super capacitor is charging.

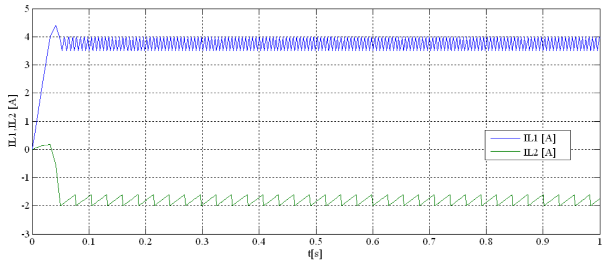

Figure 13: The I_{L1} and I_{L2} current

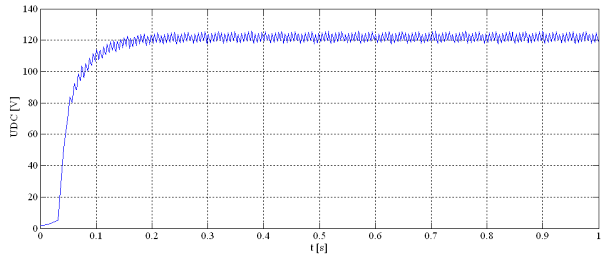

Figure 14: The U_{DC} DC voltage

U_{DC} voltage decreases compared with boost mode because the second converter recovered a part of the energy. Indeed, the current I_{L2} is negative which means that the super capacitor pack is being charged. So, the DC bus voltage also decreases.

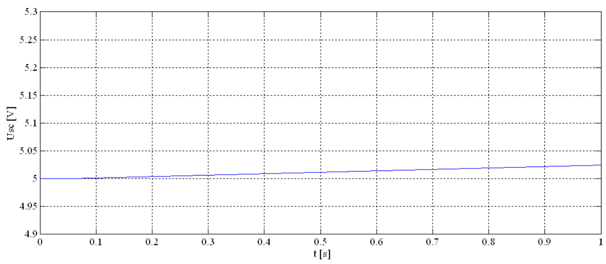

Figure 15: The U_{sc} Voltage of supercapacitor

In this case, the voltage supercapacitor pack increases because the second converter works in buck mode so it provides energy from the load (when braking).

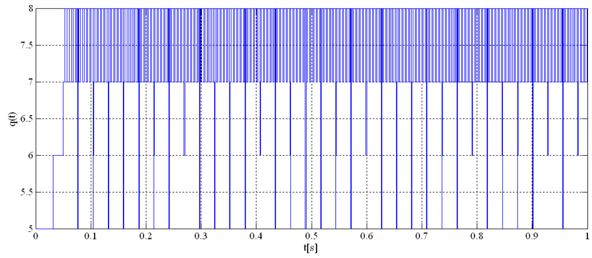

Figure 16: The q(t) Value (buck mode)

IV. CONCLUSION

In this paper, we have presented a hybrid modeling of the power management system for electric traction, essentially formed by two DC-DC converters (buck and buck / boost), which operates in several modes. Switching between these modes is defined by the current limits that guarantee that the DC bus voltage remains in a limit well determined. Finally, simulation and numeric applications, given the results obtained, show the validity of the approach used.

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