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Hybrid Sources Control for Electric Drives Traction Applications

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Abstract— A judicious study with regard to a more efficient energy management on board of an electric vehicle (EV) is discussed in this paper. This analysis follows the present trend in the field, knowing that the major drawback of the EV is the autonomy problem. Thus, by using a hybrid energy source (formed by ultracapacitors and battery) and with a proper current control (of polynomial type) one can get the proper energy management which will increase the lifetime of the battery. Through numerical simulations and tests at a reduced scale, the authors present a successfully energy management with regard to the DC/DC – battery and DC/AC – electrical machine subsystems operation, used on board of an EV.

Index terms— battery, ultracapacitors, electrical machine, control, traction applications.

I. INTRODUCTION

For vehicle traction systems, three main components can be distinguished: the supplying source (fuel or/and battery), the traction engine (thermal, electric or hybrid ones) and the electric drive (DC/DC or/and DC/AC converters). Due to its poor efficiency and gas emission, the thermal engine will be shortly replaced by the electric car. First steps are already made, the automobile with hybrid motorization being present on the streets in our days. However, the total replacement of the fuelled motors will be certitude only when the supplying problems will be solved. In terms of energy management the research teams are still trying to find the right solution which can assure, to the electric vehicle (EV), autonomy comparable to the thermal vehicle [1]-[5].

In the case of an EV, the main subsystems are (see Fig. 1): the electric source (battery/ultracapacitors or fuel cells), the electric machine (working in motoring as well as in generating regime - for the last case, while recuperative braking occurs) and the control device (DC/DC and AC/DC converter).

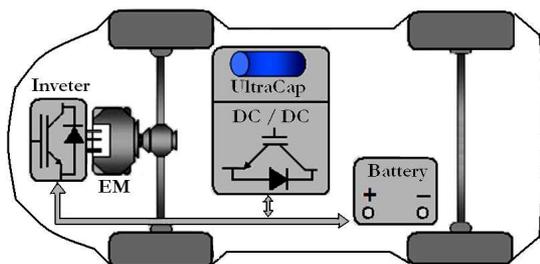


Fig. 1 Electric Vehicle components.

Having a reduced and compact structure, the electric motor placement under the hood can free the space to be used for electric sources (batteries) - even fuel cells can be employed, [6], but this increases the system's complexity and price (issue not discussed here). With regard to the battery, one of the causes which reduce its life time and finally the automobile autonomy is the transient states, due to starting or acceleration mode, where, in a short period of time, an important current is demanded. Thus, for many charging and discharging sequences the battery loses its operability. Therefore, the ultracapacitors (UC) have to be considered, [7], [9]. The UC can assure high currents for a reduced period of time, until the transient is surpassed (and after that it can be recharge).

The goal of this paper is to present a new approach with regard to the energy management on board of an EV. Through simulations, by using the numeric computation linked to the finite element method (FEM) analysis, the readers will see the control efficiency by using polynomial current controllers for the DC/DC converter and the pulse width modulation (PWM) current controllers DC/AC which will feed a load. The obtained results will clearly show that the polynomial and the PWM controllers give satisfactory results. Battery and ultracapacitors discharging states will be simulated numerically and tested on test bench. As a load, it will be considered an electrical motor, meaning a permanent magnet synchronous machine (PMSM) [10]-[12]. Finally, the two subsystems, *hybrid energy sources* and *the load* will be joined in order to simulate and test, at reduced scale, the EV behavior.

II. ULTRACAPACITORS-BATTERY ENERGY EXCHANGE

The traction chain of the electric vehicle (at reduced scale) comprises a module of ultracapacitors with a maximum voltage of 81 Vcc, a source of energy (batteries) with rated voltage 280Vcc, and a 4kW electrical machine as a load. The ultracapacitors module is coupled to DC-link by a buck-boost converter which assures the right/optimal energy repartition between the ultracapacitors and the batteries, Fig. 2. The control of these converters depends on the energy management strategy applied between the hybrid sources and the energy requested at the traction chain [7], [8], [10], [13].

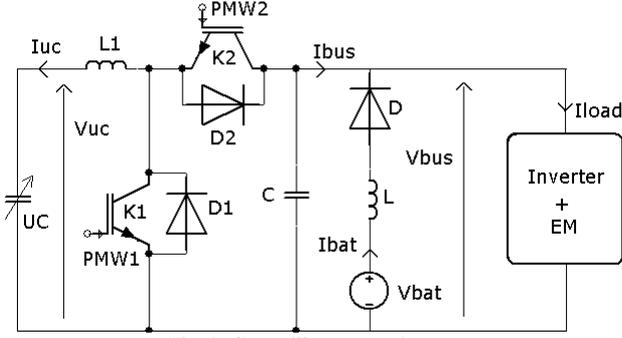


Fig. 2 Controlling system layout.

A. Bidirectional converter modeling

To establish a general model of the buck-boost converter, it is necessary to analyze the buck and boost modes. During the boost mode the K1 semiconductor is ON and the K2 is OFF and the ultracapacitors module provides energy to the DC-bus. In buck mode, the K2 is ON and the K1 become OFF. The ultracapacitors module receives energy from the batteries.

The general analytical model is given by (1), where k and α define the sign of the ultracapacitors current and the equivalent value of the duty cycle respectively.

$$\begin{cases} V_L = L \cdot \frac{d}{dt}(I_{uc}) = \frac{1}{k} \cdot (V_{uc} - \alpha \cdot V_{bus}) \\ I_{load} = I_{bat} + k \cdot I_{bus} \\ V_L = L \cdot \frac{d}{dt}(I_{bat}) = V_{bat} - V_{bus} \end{cases} \quad (1)$$

The converter average model has a nonlinear behavior because of crosses between the control variables (α_1, α_2) and the state variables (I_{uc}, V_{bus}). The $V_{bus}, V_{uc}, I_{load}$, and V_{bat} variables are likely to disturb the control. They must be measured and used for the control law estimation and to ensure a dynamics of control.

The bidirectional converter is in buck-mode for

$$\begin{cases} k = -1 \\ \alpha = \alpha_2 = \frac{V_{uc} + V_{L1}}{V_{bus}} \end{cases} \quad (2)$$

and it is in boost-mode for

$$\begin{cases} k = 1 \\ \alpha = 1 - \alpha_1 = \frac{V_{uc} - V_{L1}}{V_{bat} - V_L} \end{cases} \quad (3)$$

B. Buck-boost converter control strategy

The converter control strategy is based in the polynomial dynamic control strategy for energy management between batteries and ultracapacitors. The control strategy must be of current type because the DC-bus voltage level is imposed by the batteries.

The buck-boost converter control strategy presents two distinct phases, Fig. 3. The first phase ("1" in the

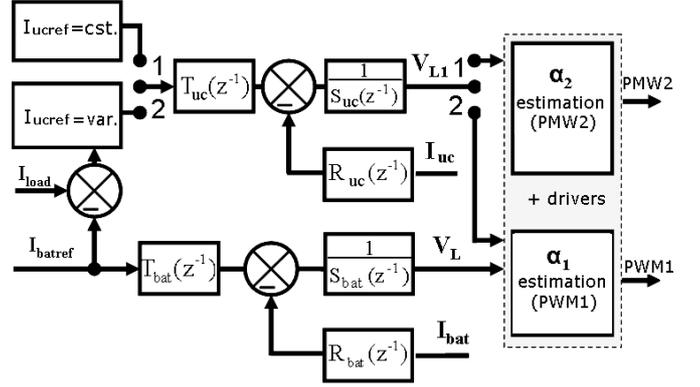


Fig. 3 Converter control strategy.

forementioned figure) is characterized by the charge of the ultracapacitors with constant current ($I_{uc_ref} = \text{constant}$). During this phase, the batteries current loop is not activated, so it can be said that only the PWM2 signal is activated. The second phase ("2" in the aforementioned figure) is characterized by the discharge of the UC with a variable current (4), where $0 < \eta \leq 95\%$ is the boost converter theoretical efficiency.

$$I_{uc_ref} = \frac{V_{bus}}{\eta \cdot V_{uc}} \cdot (I_{load} - I_{bat_ref}) = \frac{V_{bus}}{\eta \cdot V_{uc}} \cdot I_{bus_ref} \quad (4)$$

The ultracapacitors reference current (I_{uc_ref}) is obtained starting from the power management between batteries and ultracapacitors. During this phase the ultracapacitors and batteries current loops with PWM1 control signal are activated. PWM1 and PWM2 signals cannot be activated simultaneously. To obtain a minimal static error with disturbance rejection, the $R_{uc}(z^{-1})$, and $S_{uc}(z^{-1})$, polynomials of the equation (5) are selected.

$$\begin{cases} S_{uc}(z^{-1}) = 1 - z^{-1} \\ T_{uc}(z^{-1}) = R_{uc}(z^{-1}) = r_{0uc} + r_{1uc} \cdot z^{-1} \end{cases} \quad (5)$$

In [13] a similar polynomial control strategy was employed with regard to the parallel topology of the DC/DC converter. Here, this technique will be applied to the buck-boost converter.

The coefficients of these polynomials are given by (6), where L is the ultracapacitors current smoothing inductance, T_e is the sampling period and the ω_n is the control strategy band-width. The selected maximum frequency of the band-width is lower than (1/10) of the IGBT control frequency.

$$\begin{cases} \omega_n \leq \frac{2 \cdot \pi \cdot f_d}{10} \\ r_{0uc} = 2 \cdot (1 - \exp(-\omega_n \cdot T_e)) \cdot \frac{L_1}{T_e} \\ r_{1uc} = (\exp(-2 \cdot \omega_n \cdot T_e) - 1) \cdot \frac{L_1}{T_e} \end{cases} \quad (6)$$

C. Modeling of energy management with UC and battery

The hybrid system simulation parameters are presented in Table I and the simulations are carried out for boost converter state (PWM1=ON and PWM2=OFF), [8], [14].

TABLE I
HYBRID SYSTEM SIMULATION PARAMETERS

Symbol	Value	Name
f_d	10 kHz	IGBT control frequency
V_{bus1}	280 Vcc	DC-link maximal voltage
V_{uc}	81 Vcc	Super capacitors maximal voltage
η	86 %	Boost converter average efficiency
L	25 μ H	Maximal DC-link current
C	1500 μ F	DC-link voltage smoothing capacitance
L1	50 μ H	Ultracapacitors currents smoothing inductance

The boost converter simulation results are presented in Fig. 4-Fig. 9. The main goal is to maintain the battery current at a constant value (10 A) while the system (meaning the ultracapacitors, associate to its converter) will assure the surplus of demanded current.

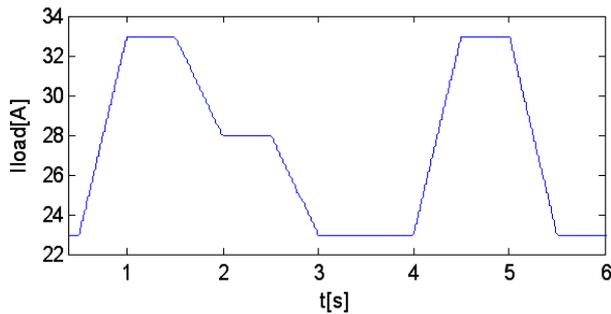


Fig. 4 Active load current profile.

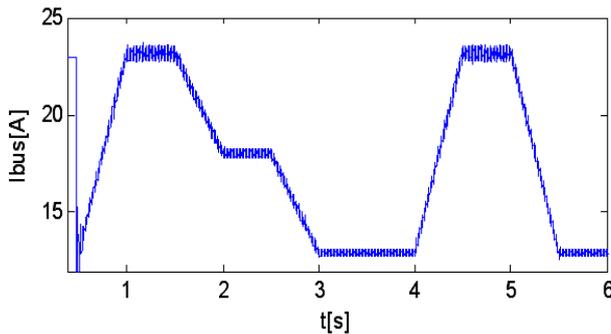


Fig. 5 DC-bus current control result.

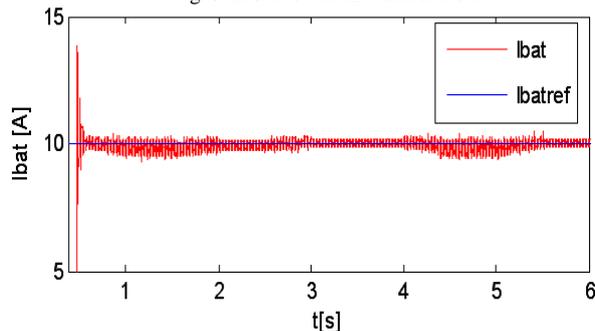


Fig. 6 Battery current control result

In order to verify the control of the boost converters, the battery reference current (I_{batref}) is fixed at 10 A. The active load current (I_{load}) profile is presented in Fig. 4. The simulation results plotted in Fig. 5 and Fig. 6 show that the boost converter control is satisfactory, except the instant around 0.5 second when the current loop do not have enough time to react.

The ultracapacitors module voltage (V_{uc}) is shown in Fig. 7 and its current (I_{uc}) control result is presented in Fig. 8. These results depict that the ultracapacitors current and its reference (I_{ucref}) are practically the same (a smooth control is employed). On the other hand, the DC-bus voltage (V_{bus}) shape obtained by coupling the battery and ultracapacitors cells (the hybrid source) is presented in Fig. 9.

The simulation results (the control which maintain constantly the battery current while the ultracapacitors covers the demand of peak current) give confidence for the implementation of the hybrid energy management system on test bench.

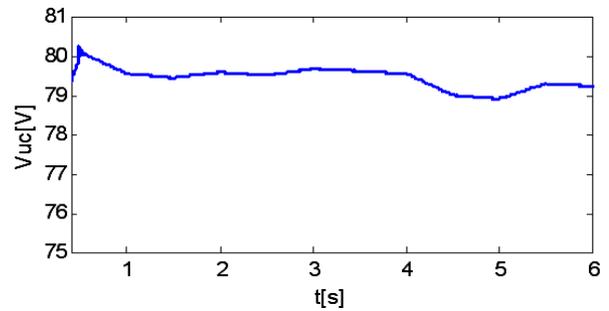


Fig. 7 Ultracapacitors module voltage

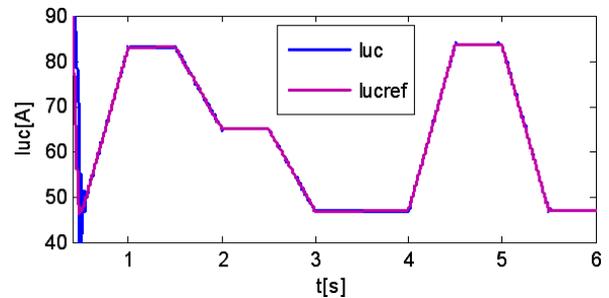


Fig. 8 Ultracapacitors current control result

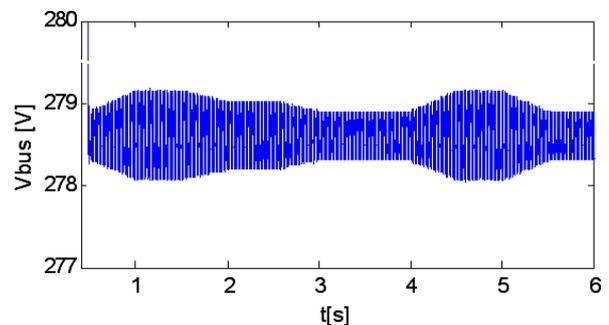


Fig. 9 DC-bus voltage

III. NUMERICAL CONTROL OF THE PMSM

In order to simulate the load, a permanent magnet synchronous machine (PMSM) is considered. Numerical

computation through electrical-mechanical equations gives satisfactory results for specific problems; here, generally, the saturation and losses, as well as electromagnetic parameters variation, are neglected. By taking into account the electric circuit and all the electromagnetic phenomena, and using the finite element method (FEM) computation one can achieve very accurate simulation results which can give confidence for the future tests of the hybrid energy system control for vehicle application. Even if it is time consuming, this analysis is necessary with respect to the estimation of the real MSMP performances; also, some measurements issues can be predicted and operation faults avoided.

The numerical analysis by FEM is implemented on Flux2D software. Moreover, the system control is realized through Matlab/Simulink, thus the real operation conditions are very well fulfilled [1].

The load current profile (from Fig. 4) is the reference current in the modeling system. With a current control strategy, based on pulse width modulation (PWM) technique, one can simulated the system behavior. It is about of 180° current open-loop control strategy (sinusoidal currents feeding the armature windings). Thus, the control is viewed from the absorbed current (and finally mechanical torque) point of view, meaning that for a constant speed the load varies.

The system is employed in Simulink. The inverter (Fig. 10a - left) controls the feeding of the PMSM

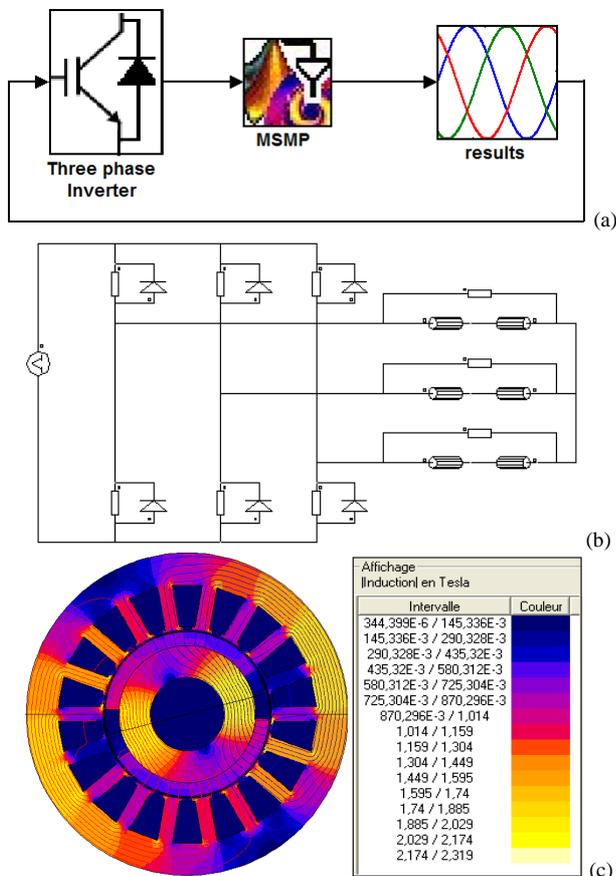


Fig. 10 Numerical analysis of the PMSM: (a) Simulink control system coupled with Flux2D; (b) three phase inverter; (c) field lines and flux density repartition.

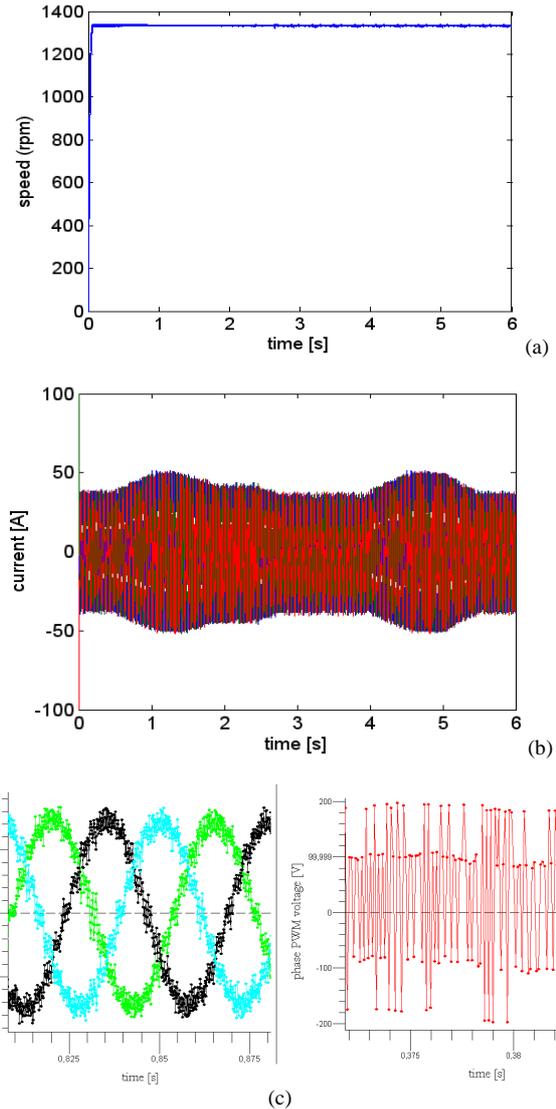


Fig. 11 Results from numerical analysis of the PMSM: (a) the motor speed; (b) the three phase currents; (c) zoom on PWM voltage and current.

(Fig. 10a - middle) which is employed in Flux2D, as well as the inverter circuit, Fig. 10b (here, the resistances of $1e6\Omega$ simulate the voltmeter behavior, or the on/off state of the switches). Among the results, the rotor position is computed and used as loop-parameter, (Fig. 10a - right).

As a sample on the magnetic behavior in the PMSM active parts, one can see the field lines and flux density repartition in Fig. 10c.

More simulated results are given in Fig. 11. Here the speed (Fig. 11a) remains constant, while the current (Fig. 11b) varies with the reference current, I_{load} (see Fig. 4). For a more clear view on the current control due to the PWM voltage one can see a zoom of these waves in Fig. 11c.

IV. TESTS

(Due to some material problem - a non sufficient number of UC cells - the PMSM was replaced by a resistive charge. Consequently, the battery voltage is of 100Vcc.)

The experimental test bench (Fig. 12) includes two series connected inductances of $25\mu\text{H}$ (L_1 in Fig. 2) used to filter the ultracapacitors current, a pack of ultracapacitors of 30 cells in series connexion to a maximum voltage of 81V_{cc} (UC), a battery package of total of 100V_{cc} with 13Ah , a buck-boost converter, a capacitor (C) of $6,8\text{mF}$ for filtering of the DC-bus voltage, an inductance for smoothing the battery current (L in Fig. 2) of $25\mu\text{H}$, and the load. The whole system is controlled by a microcontroller of PIC18F4431 type.

The boost converters tests are carried out in the following conditions: during the ultracapacitors discharge, the batteries current reference (I_{batref}) is fixed at 6A so that, the ultracapacitors modules provide hybrid vehicle's power request for transient states. For these tests, the hybrid vehicle request (I_{load}) was fixed at 21A .

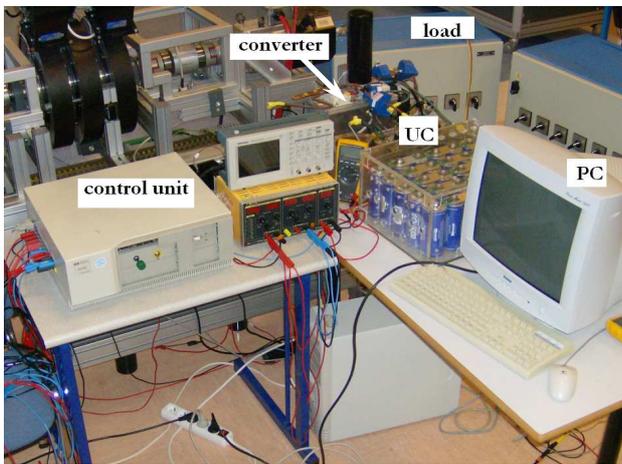


Fig. 12 Experimental setup for UC-battery energy management.

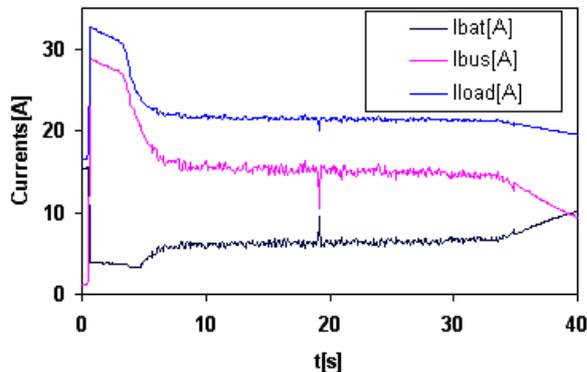


Fig. 13 DC-bus and battery current control result

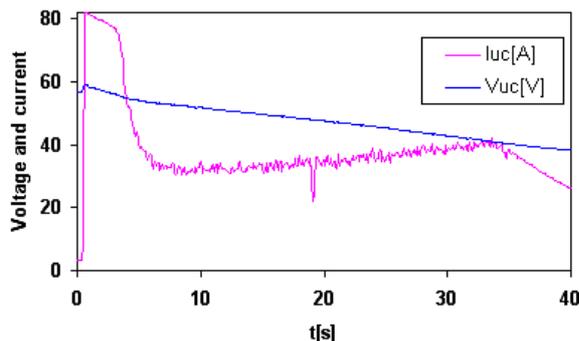


Fig. 14 Ultracapacitors voltage and current

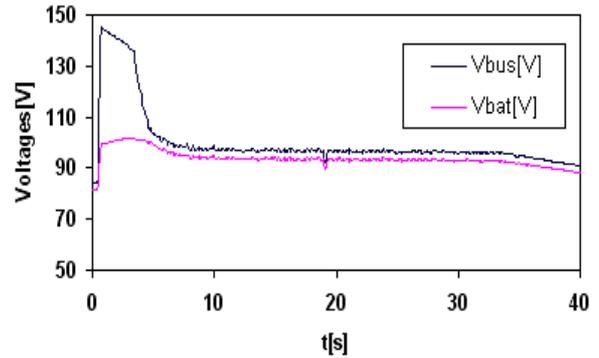


Fig. 15 DC-bus and battery voltages

The Fig. 13 presents the DC-bus current (I_{bus}), battery current (I_{bat}) and the active load current (I_{load}) experimental performances. These results show that the ultracapacitors module assure a current of 15A (for I_{bus}) to the hybrid sources DC-bus, and 6A only is provided by the battery. (The time elapsed at the beginning of the control process involves the peak of currents and voltages, until the battery are introduced in the electric circuit).

The ultracapacitors current (I_{uc}) and voltage (V_{uc}) experimental results are showed in Fig. 14. It can be seen that when the voltage decreases, the current increases in order to maintain constantly the absorbed power, up to 35 seconds, when the UC are no longer useful.

Moreover, experimental results of DC-bus and battery voltages are presented in Fig. 15. Here one can see that the battery voltage is maintained constant up to 35 seconds, until the UC cannot assure, any longer, the necessary absorbed power.

V. CONCLUSIONS

This paper presents the energy management study for an electric vehicle traction application. The *ultracapacitor-battery* energy exchange intermediated through a DC/DC converter, and the battery-electrical machine electric power management through a DC/AC converter are studied analytically, numerically (by finite element method) and on the test bench. With a complete experimental setup (at reduced scale) and by employing a current controllers strategy (polynomial controller) it were obtained successfully results in terms of energy management.

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