Buck-Boost converters design for Ultracapacitors and lithium Battery mixing in Hybrid Vehicle Applications

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Abstract — **This paper presents a careful study related to a more efficient energy management between lithium battery (with rated voltage of 24V) and Ultracapacitors (UC) for Hybrid Electric Vehicle (HEV) applications. This association is due to the present trend in the field, knowing that the major drawback of the HEV is the autonomy problem. Thus, using the Hybrid energy source (such as UC + battery) and with a good energy management improves the HEV performances. In this paper, battery and Ultracapacitors (10 cells of 2.7V in series) are coupled to DC-bus using two buck-boost converters. The main contribution of this paper is focused on DC-bus voltage and currents control strategy based on polynomial (RST) controller. Through some simulations in MATLAB/Simulink software and experimental results, the authors present an improved energy management for HEV.**

Keywords- Lithium battery; ultracapacitors; polynomial control; hybrid electric vehicle.

NOMENCLATURE

V_{bat}	Battery's voltage
$V_{DC\text{-}bus}$	DC-bus voltage
V_{uc}	Ultracapacitors (*UC*) module voltage
I_{batin}	Battery's current
$I_{batinref}$	Battery's reference current
I_{Load}	Electric load current
I_{uc}	Ultracapacitors current
I_{ucref}	Ultracapacitors reference current
I_{out}	Converter output current in *UC* side
I_{bat}	Converter output current in battery side
α	Converter's duty cycles
M	Masse of the vehicle in [*kg*]
V	Vehicle's speed in [*m/s*]
g	Gravity acceleration
ρ_a	Air mass density
C_D	Aerodynamic drag coefficient of the vehicle
A_f	Front area of the vehicle in
σ	Rotational inertia factor
dV/dt	Acceleration of the vehicle in [*m/s^2*]
f_r	Rolling resistance coefficient
θ	Grade of the road in [*degree*]
f_d	Converter control frequency
L_1, L_2	I_{uc} and I_{batin} smoothing inductors
C_1, C_2	DC-bus capacitors

I. INTRODUCTION

TODAY, many researches are undertaken for Hybrid Electric Vehicle (HEV) applications. Generally, these vehicles combines in addition to its main energy sources (oil, gas), energy storage components such as: fly-wheel, ultracapacitors (UC) and battery. The HEV has the advantages of thermal vehicles (autonomy and flexibility in use) and electric ones (no pollution), but it is not the simple combination of these models, because the elements must be optimized.

Considering autonomy problem, the traction batteries used until now must be improved to satisfy the energy needs for future vehicles; if no, they must be dimensioned to satisfy the vehicle energy requested during transient states. This problem reduces drastically the battery lifetime.

A promising solution in the short time is based on the battery and Ultracapacitors combination. This affirmation is due to ultracapacitors dynamics behavior and their lifetime about 10 years. In terms of energy management the research teams are still trying to find the right solution which can assure an energetic autonomy to HEV [1] - [6].

In the case of HEV, the main subsystems include (see Figure.1): the electric source (lithium battery and ultracapacitors), the electric load emulator (Electric machine + Inverter) and the DC/DC converters for UC and lithium battery coupling.

The main goal of this paper is to present a new approach related to energy management in a HEV, through a control strategy of the currents and *DC-bus* voltage using polynomial controllers (*RST*).
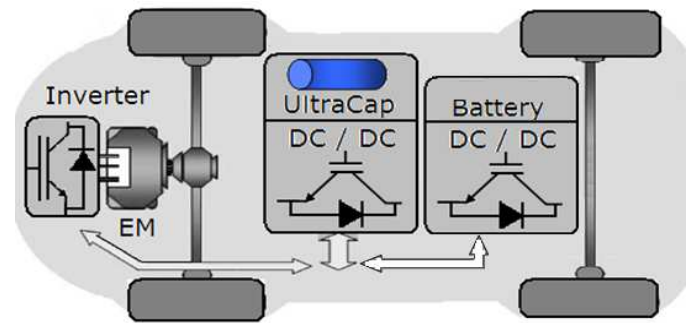

Figure.1: Controlling system layout.

The hybrid system is simulated with MATLAB/Simulink Software and experimental control algorithm is implemented in PIC18F4431 microcontroller. The experimental data acquisition system is monitored using National Instruments Labview with *PXI-1002* Unit.

II. CONVERTERS MODELING AND CONTROL STRATEGY

The traction system of the Hybrid Electric Vehicle (in reduced scale) includes a module of Ultracapacitors (UC) with a maximum voltage of 27V, a source of energy (batteries) with rated voltage 54V, and 5kW power electronic load (as electrical machine + Inverter). The UC module and lithium batteries ones are coupled to DC-bus, through buck-boost converters, which ensure the energy exchange between the UC and the batteries as presented in Figure.2. The control of these converters is related to energy management strategy between the hybrid sources and the electric load (inverter + electric machine) [2]-[4].

A. Buck-boost converters modeling

To establish a general model of the buck-boost converter, it is necessary to analyze the buck and boost modes. During boost mode (Figure.2), K1 semiconductor is ON, and K2 is OFF. In this condition, the ultracapacitors module provides energy to the *DC-bus*. In buck mode, K2 is ON, and K1 pass in OFF mode, then the ultracapacitors receives energy from *DC-bus*. These sequences are same for buck-boost converter in battery side, i.e., if K3 is ON, and K4 is OFF, the second converter is in boost mode. When K3 is OFF, and K4 is ON, it becomes in buck mode.

The analytical model of the buck-boost converter (in ultracapacitors side) resulting from the sequences analyze is given in (1), where, k and α define the sign of the ultracapacitors current and the equivalent value of the duty cycle.

In lithium battery side, the converter average model obtained from the sequences analyzes is presented in (2), where δ and μ present the sign of the lithium battery current I_{batin}, and the equivalent value of the duty cycle.

$$\begin{cases} V_{L1} = L_1 \cdot \dfrac{d}{dt}(I_{uc}) = k \cdot (V_{uc} - \alpha \cdot V_{DC-bus}) \\ I_{ch} = I_{bat} + I_{out} \end{cases} \quad (1)$$

$$\begin{cases} V_{L2} = L_2 \cdot \dfrac{d}{dt}(I_{batin}) = \delta \cdot (V_{bat} - \mu \cdot V_{DC-bus}) \\ \mu = 1 - \alpha' \\ I_c = C_2 \cdot \dfrac{d}{dt}(V_{DC-bus}) = \mu \cdot I_{batin} - I_{bat} \end{cases} \quad (2)$$

These average models have a nonlinear behavior due to crosses between the control variables (α, μ) and the state variables (I_{uc}, I_{batin}, V_{DC-bus}). The following variables: V_{DC-bus}, V_{uc}, I_{Load}, and V_{bat} are likely to disturb the control.
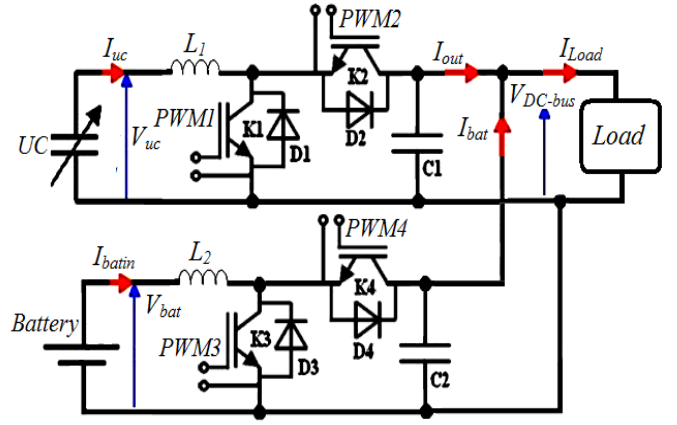

Figure.2: Converter topology

Theses last must be measured and used in control law estimation to ensure a dynamics of control [2], [4].

B. Buck-boost converters control strategy

The converters control strategy is based in the polynomial dynamic control strategy for energy management between *DC-bus* and hybrid sources (batteries and ultracapacitors). This strategy includes two steps; the first is based on currents control (in UC side), and second is focused on *DC-bus* voltage control (in the lithium battery side). To manage the ultracapacitors current, the buck-boost converter control laws established from (1) are used as presented in (3) (buck mode), and (4) (boost mode).

$$\alpha = \alpha_{buck} = \frac{V_{uc} + V_{L1}}{V_{DC-bus}}, \ k = -1 \quad (3)$$

$$\alpha = 1 - \alpha_{boost} = \frac{V_{uc} - V_{L1}}{V_{DC-bus}}, \ k = 1 \quad (4)$$

That of the *DC-bus* voltage control, the boost converter control law, obtained from (2) is given in (5).In this case, two control loops are necessary, the first is the current feedback (inner loop) and the second is the voltage loop (outside loop).

$$\alpha' = 1 - \frac{V_{bat} - V_{L2}}{V_{DC-bus}}, \ \delta = 1 \quad (5)$$

The lithium battery and UC reference currents ($I_{batinref}$, and I_{ucref}) established from (2) is presented in (6), where I_{bat} presents the boost converter output current as showed in Figure.2, I_c is the capacitor's current.

$$\begin{cases} I_{batinref} = \dfrac{V_{DC-bus}}{V_{bat}}(I_{bat} + I_c) \\ I_{ucref} \approx \dfrac{V_{DC-bus}}{V_{uc}} \cdot I_{load} - \dfrac{V_{bat}}{V_{uc}} \cdot I_{batinref} \end{cases} \quad (6)$$

The electric load current [5], expressed as function of the HEV speed and technical parameters is presented in (7), where,

$$\begin{cases} I_{Load} = \dfrac{V}{V_{DC-bus}} \left(M \cdot g \cdot f_r + \dfrac{1}{2} \cdot \rho_a \cdot C_D \cdot A_f \cdot V^2 + \beta \right) \\ \beta = M \cdot \sigma \cdot \dfrac{d}{dt}(V) + M \cdot g \cdot \sin(\theta) \end{cases} \quad (7)$$

M is vehicle masse in [kg];
V is vehicle speed in meters per second;
g is gravity acceleration, *9.81m/s²*;
ρ_a is air mass density, *1.205kg/m³*;
C_D is the aerodynamic drag coefficient of the vehicle;
A_f is the front area of the vehicle in square meters;
σ is the rotational inertia factor;
dV/dt is the acceleration in meters per square second;
f_r is the rolling resistance coefficient *;*
θ is the grade of road.

In standard driving cycles, road is flat ($\theta=0$). These parameters are given in TABLE I. The UC current control strategy is illustrated in Figure.3, where Ultracapacitors module initial voltage is fixed at 23V. To improve the voltage control performances, ΔI_c current is estimated and injected in *DC-bus* voltage control loop as presented in Figure.4.a. The battery's current control diagram (inner loop) is illustrated in Figure.4.b.

$$\Delta I_c = \frac{\Delta I_{batinref} \cdot V_{bat}}{V_{DC-bus}} - I_{bat} \quad (8)$$

In goal to obtain a minimal static error with disturbance rejection, $R(z^{-1})$ and $S(z^{-1})$ polynomials are selected as expressed in (9). The choosing method is described in [2], [6], [7], where a similar polynomial control strategy was employed for current control in the parallel topology of the DC/DC converter. Here, this technique will be applied to the buck-boost converter for currents and *DC-bus* voltage management.

$$\begin{cases} S(z^{-1}) = 1 - z^{-1} \\ T(z^{-1}) = R(z^{-1}) = r_{0xx} + r_{1xx} \cdot z^{-1} \end{cases} \quad (9)$$

In this equation, *xx* index correspond to i_{uc} and i_{bat} (for *UC* current loop and battery's current loop), and *v* for *DC-bus* voltage control ones. The final coefficients obtained from closed loops analysis, in case of currents and voltage control are respectively expressed in (10) and (11), where C_2 is *DC-bus* voltage smoothing capacitor; L is current smoothing inductor; T_e is the sampling period; and ω_i is current control band-width. In case of the I_{uc} control, $L=L_1$; and $L=L_2$ for I_{batin}.

$$\begin{cases} r_{0iuc,bat} = 2 \cdot (1 - \exp(-\omega_i \cdot T_e)) \cdot \dfrac{L}{T_e} \\ \omega_i \leq \dfrac{2 \cdot \pi \cdot f_d}{10} \\ r_{1iuc,bat} = (\exp(-2 \cdot \omega_i \cdot T_e) - 1) \cdot \dfrac{L}{T_e} \end{cases} \quad (10)$$

$$\begin{cases} r_{0v} = 2 \cdot (1 - \exp(-\omega_v \cdot T_e)) \cdot \dfrac{C_2}{T_e} \\ \omega_v = 100 \cdot \omega_i \\ r_{1v} = (\exp(-2 \cdot \omega_v \cdot T_e) - 1) \cdot \dfrac{C_2}{T_e} \end{cases} \quad (11)$$

These parameters are implemented in MATLAB/Simulink Software for Hybrid System simulations. The selected maximum frequency of the band-width is lower than (1/10) of the IGBT control frequency. The resulting parameters obtained from this condition are summarized in TABLE II.
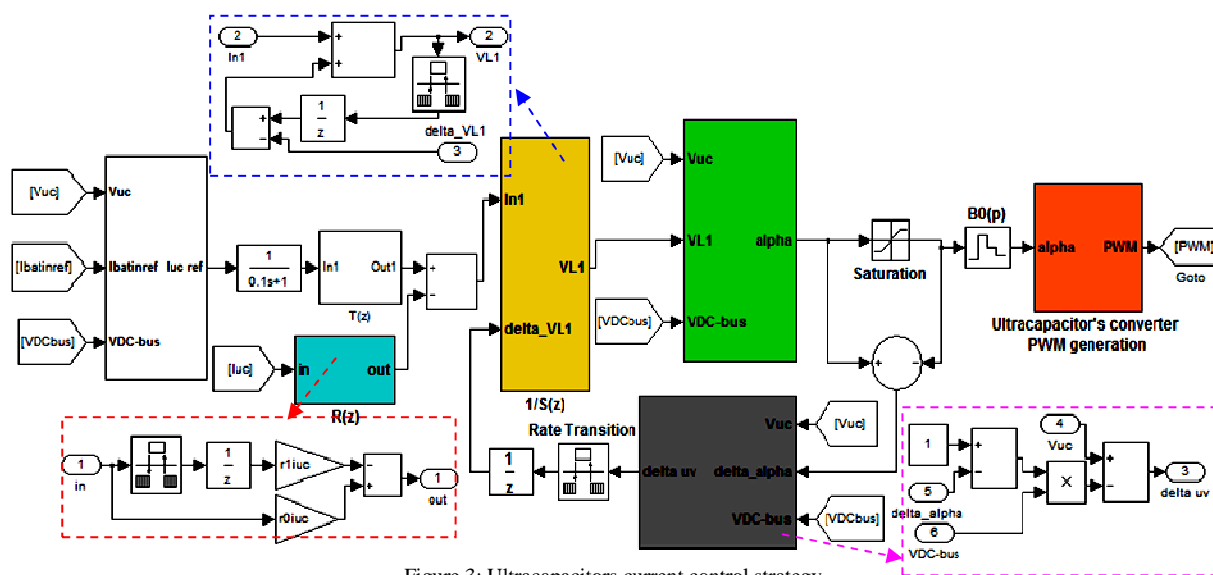

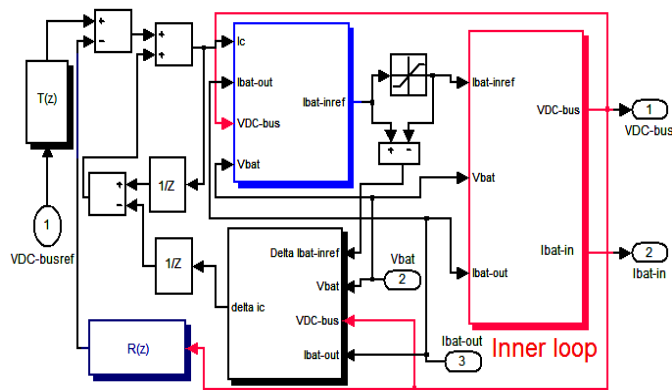Figure.3: Ultracapacitors current control strategy

Figure.4.a: Voltage control loop (outside)
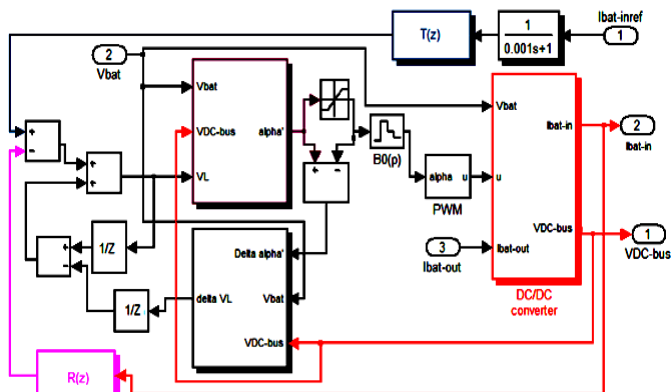
Figure.4.b: Battery's current control loop (inner loop)

TABLE I:
COMPONENTS NOMENCLATURE

SYMBOL	NAME	VALUE
$L_1=L_2$	Currents smoothing inductances	200 µH
C_1	DC-bus capacitor	1500 µF
C2	DC-bus capacitor	6800 µF
M	Vehicle masse	1250kg
C_D	Aerodynamic drag coefficient	0.3
A_f	Front area	2.2m^2
σ	Rotational inertia factor	1.05
f_r	Rolling resistance coefficient	0.3
fd	control frequency	10kHz

TABLE II:
VOLTAGE AND CURRENTS control loops PARAMETERS

SYMBOL	INPUT PARAMETERS	NOMENCLATURE
V_{uc}	13.5 V-27 V	UC module voltage
$Te=1/fd$	100µs	Sampling period
ω_i	6283 rad/s	Currents loops band-width
$r_{0iuc} + r_{1iuc}.z^{-1}$	$0.7654 - 0.3993.z^{-1}$	I_{uc} control polynomial
$r_{0ibat} + r_{1ibat}.z^{-1}$	$0.7654 - 0.3993.z^{-1}$	I_{bat} control polynomial
$r_{0v} + r_{1v}.z^{-1}$	$33.20 - 16.60.z^{-1}$	V_{DC-bus} control polynomial

III. HYBRID SYSTEM SIMULATION RESULTS

Lithium battery and UC models used for Hybrid Electric Vehicle (HEV) behavior simulation are described in previous papers [2], [4]. In this paper, *DC-bus* voltage reference is fixed at constant value so that, the UC module provides HEV energy request during the transient states. This reference is filtered by using low pass filter with constant time of $\tau=0.1s$. The load current (I_{Load}) profile is generated from HEV speed as expressed in (7).

For hybrid system simulations, the HEV speed profile plotted in Figure.5 is used. Figure.6 presents the ultracapacitors voltage. This curve shows that, the ultracapacitors pass in charge mode and discharge as function of I_{uc} courant sign. UC current control result corresponding to this strategy is plotted in Figure.7. This last shows that the proposed control strategy is satisfactory for HEV behavior simulations [8]-[14].

To illustrate *DC-bus* voltage control performances, the reference values of this voltage are fixed at 54V (from 0 to 2 s and 6 to 8 s) and 100V (from 2 to 6 s). *DC-bus* voltage control result obtained from this strategy is presented in Figure.8. The measured voltage and current on lithium battery module are respectively illustrated in Figure.9 and Figure.10. Load current profile estimated from hybrid electric vehicle speed in [*km/h*] as presented in (7) is plotted in Figure.11. This current is shared between Ultracapacitors and batteries as illustrated in Figure.12 and Figure.13.
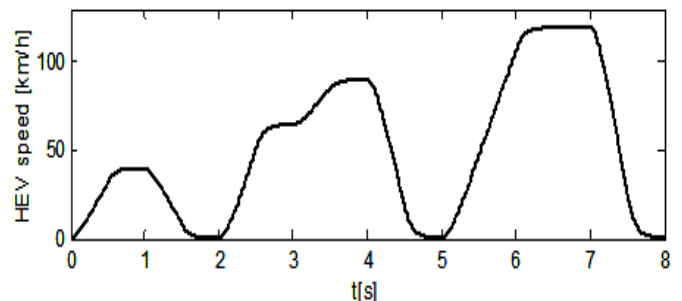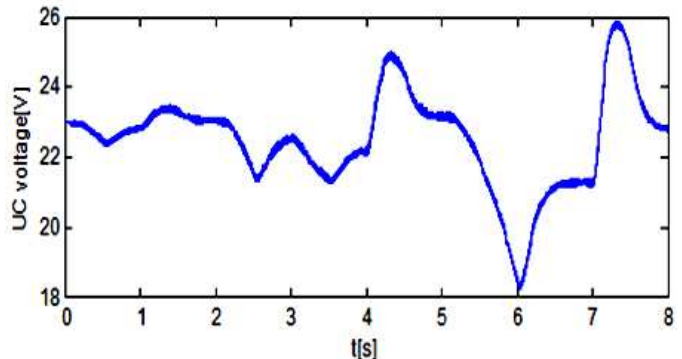

Figure.5: Hybrid Electric Vehicle Speed in [km/h]

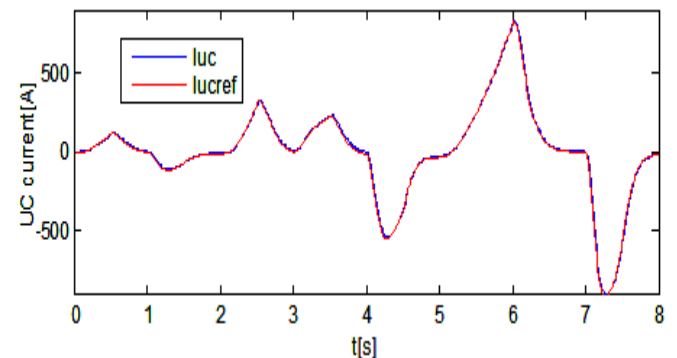Figure.6: Ultracapacitors module voltage

Figure.7: Ultracapacitors current control result

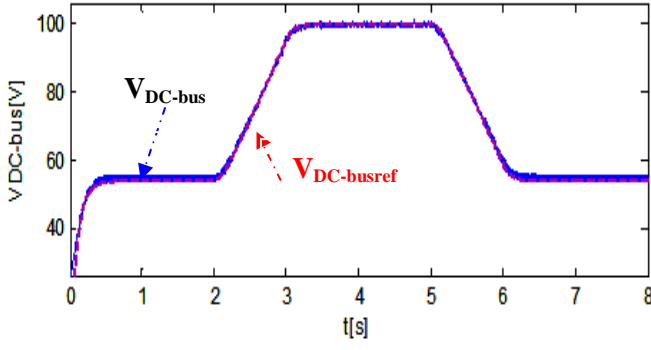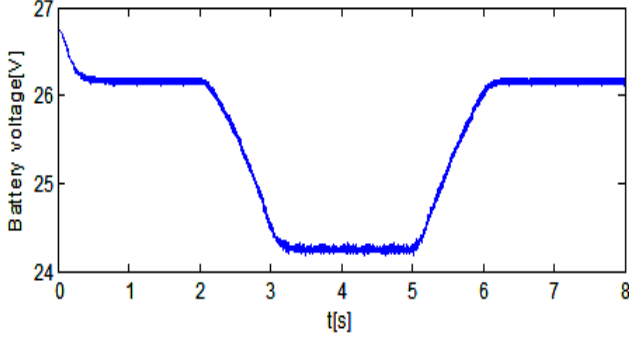Figure.8: DC-bus voltage control result
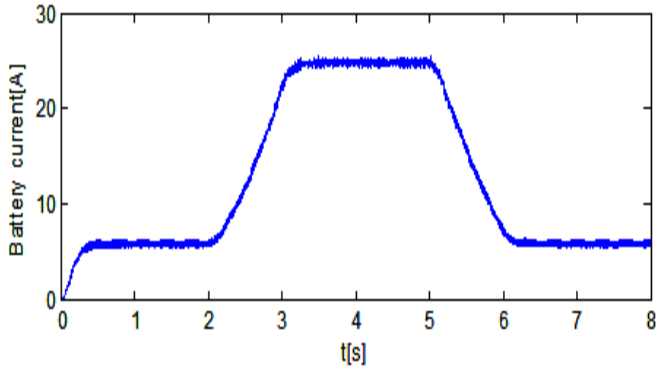

Figure.9: Lithium battery voltage

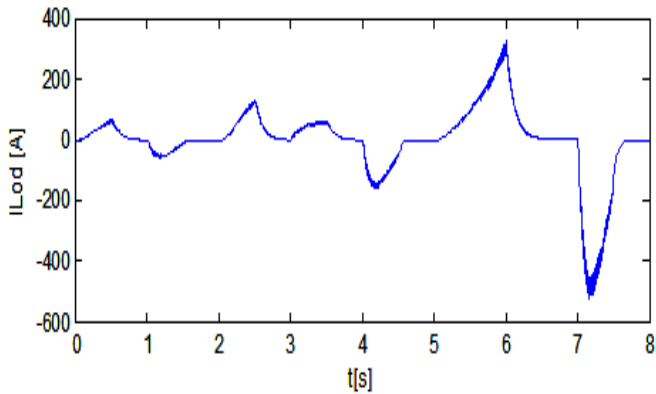Figure.10: Lithium battery current

Figure.11: Load current estimated from HEV speed in [km/h]
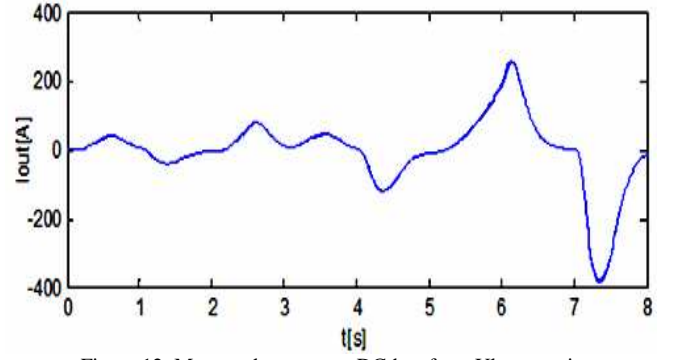

Figure.12: Measured current on DC-bus from Ultracapacitors
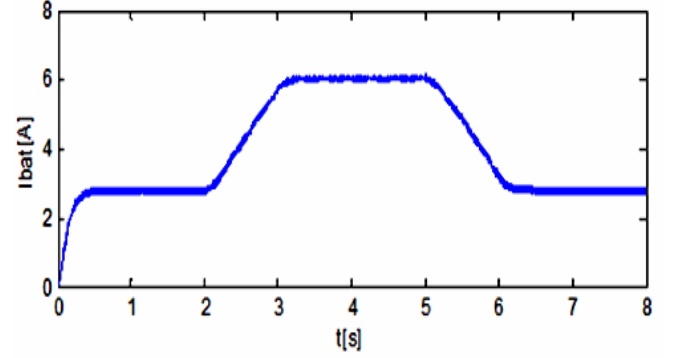

Figure.13: Measured current on DC-bus from battery

These curves show that, the main contribution of the sources is ensured by the Ultracapacitors module. These simulation results enable to conclude that, the polynomial control is very interesting in Hybrid Electric Vehicle behavior simulation. This strategy is implemented in PIC18F4431 microcontroller for experimental test bench control in reduced scale.

IV. EXPERIMENTAL SETUP AND RESULTS

An experimental test bench is designed in reduce scale to validate the proposed strategy outlined above. The experimental test bench presented in Figure.14 includes a module of ultracapacitors (10 cells in series with a maximum voltage of 27V); a lithium battery module (four elements of 12V with 92Ah, in series); two buck-boost converters; and power electronics load.

The described control of the buck-boost converters integrating the *UC* voltage limitation algorithm is implemented in Microchip's microcontroller (PIC18F4431).

In this paper, only the boost converter mode (PWM2 and PWM4 are in OFF mode) is tested because the used electronics load is no bidirectional. For this raison, it is no possible to do the HEV current profile as presented in (7). For these experimental tests, the UC module voltage is limited at 18V (for low level) and 27V (for high level). The hybrid vehicle request current I_{Lod} is fixed at 25A; and lithium battery current is limited at 5A as plotted in Figure.15. These curves show that control strategy of the Ultracapacitors current and that of the battery are satisfactory. The Ultracapacitors voltage and current corresponding to this test are showed in Figure.16. The experimental *DC-bus* voltage obtained from described strategy in above (Figure.4.a) is plotted in Figure.17.
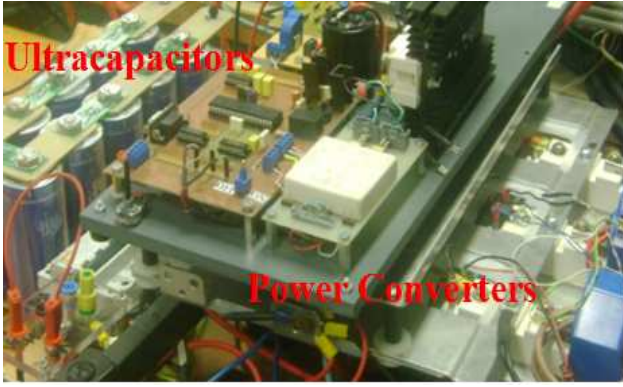
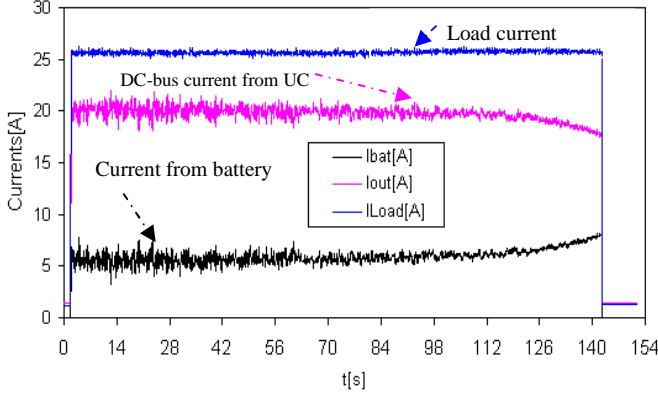Fig. 14: Experimental setup for UC-lithium battery energy management.
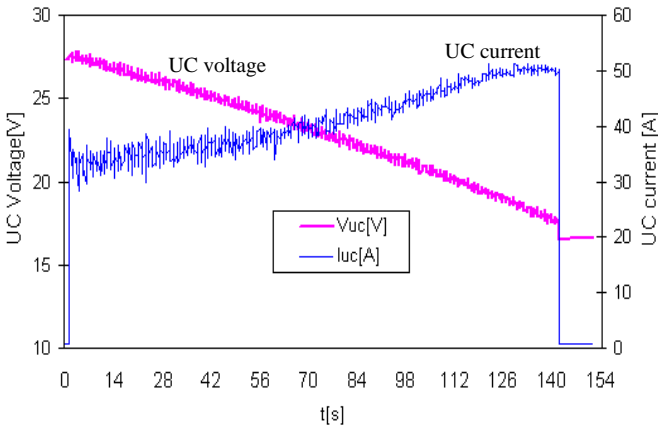

Figure.15: Measured current on DC-bus

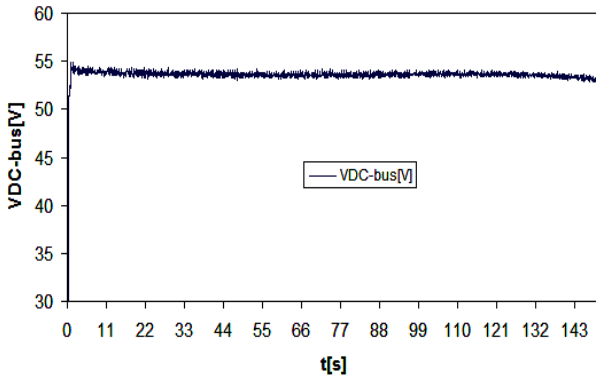Figure.16: Ultracapacitors module voltage (V_{uc}) and current (I_{uc})

Figure.17: DC-bus voltage control result

V. CONCLUSION

This paper presents the *DC-bus* voltage and currents management for Hybrid Electric Vehicle traction applications. The *Ultracapacitors - Lithium battery* energy exchange through two buck-boost converters is simulated, and experimented. Complete simulation, and experimental results based on polynomial controller's techniques are presented and analyzed in this paper. Through the simulation results, the performance in terms of the voltage control and the currents are illustrated.

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