Optimal Management of Electric Vehicles with a Hybrid Storage System.

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***Abstract*-This paper presents a comparison between two offline optimisation methods for energy management applied to electrical vehicle with one electrical machine and fed by a hybrid storage system composed of batteries and ultra-capacitors. After a short presentation of the two methods, they are applied and compared to the case of an electric micro bus.**

I. Introduction

Zero emission vehicles are an effective solution to reduce CO_2, pollutant and noise emissions. Lots of electrical vehicles are now available with different types of batteries. Nevertheless one of the key points is the relatively low lifetime of the battery. Their replacement after a few years (two to five years depending on battery type and use), leads to economical and ecological problems.

One solution to the battery ageing problem may be their association with Ultra-capacitors (UC). With a good management of the power share between these two electrical sources, the stress on the battery may be highly reduced.

Several rule based strategies have been developed in order to split the instantaneous power between the two sources [1]-[2]. Nevertheless their relevance can only be demonstrated regarding to theoretical optimal management laws.

Two direct methods of optimisation [3]-[4] are investigated and compared in this paper; dynamic programming and calculus of variation (i.e Pontryagin minimum principle).

In this paper, we propose to develop and compare these two methods to minimise the rms current in the battery pack for a given cycle.

Firstly the position of the problem is presented, then the formulation of the two optimisation methods applied to electrical vehicles with batteries and Ultra-capacitors are developed and compared in the case of a micro bus vehicle operating in electrical mode [5].

II. Optimisation method

A. The problem statement

The vehicle model is based on a systemic approach using energetic models for different subsystems.

Let us consider the electrical power-train architecture Figure 1. Optimisation methods use a backward approach [6]-[7] which is based on the knowledge of the driving cycle and the vehicle characteristics (inertia and resistant forces). Then one can easily calculate the wheel torque T_{wheel} with the vehicle speed and acceleration obtained by left derivative method, and go upstream from the wheels to batteries and Ultra-capacitors. The management law (rule based or optimal) determines the share of electrical power (P_{elec}) between batteries (P_{batt}) and UC (P_{uc}).

Note that if the driving cycle demand exceeds the capability of the powertrain, no solution is possible without decreasing iteratively the speed target. In this paper no vehicle speed decrease is tolerated.

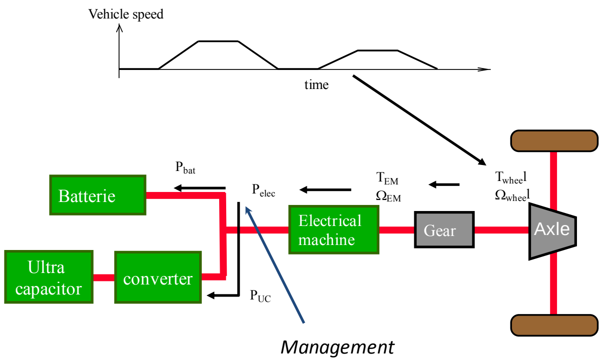

Figure 1 : backward approach of electrical vehicle

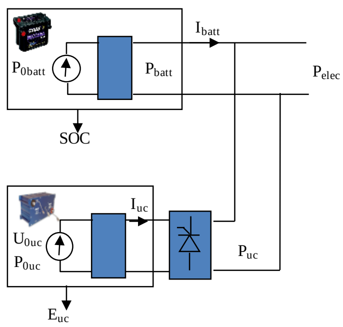

Figure 2 : Electrical scheme of power sources

Once the cycle is chosen then the optimisation problem can be mathematically formulated. In this paper we chose the RMS battery current as an objective to be minimised:

$$J = I_{batt\_RMS} = \sqrt{\frac{1}{T}\int_{t_0}^{t_f} I_{batt}^2 dt} \quad (1)$$

Under the constraint that the final UC open circuit voltage is imposed:

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$$\Delta U_{0uc} = U_{0uc\_final} - U_{0uc\_initial} = K \quad (2)$$

Where I_{batt} is the battery current, I_{batt_rms} is the root mean square current and U_{0uc} is the UC open circuit voltage.

Note that minimising I_{batt_rms} (1) is equivalent to minimising the integral square battery current:

$$J = \int_{t_0}^{t_f} I_{batt}^2 dt \quad (3)$$

This choice corresponds to a minimisation of the global stress of the battery and its heating during the use. Other criteria can be used using the proposed optimisation methods, for example an energy objective can be used (part IV.C).

The constraint on the UC voltage allows the voltage sustaining and avoids the overuse of the UC. It allows also a fair comparison between strategies in an energetic point of view.

C. Calculus of variation

Principle [3]:

Considering a system defined by the state equation:

$$\dot{x}(t) = \frac{dx(t)}{dt} = a(x(t), u(t), t) \quad (4)$$

And the minimisation of a functional:

$$J(u) = \int_{t_0}^{t_f} g(x(t), u(t), t) dt \quad (5)$$

Where x (t) is the state variables vector, and u (t) the control variables vector.

If the final time and final state are imposed (which is our case) the Pontryagin's minimum [3]-[4] principle stipulates that if we define the augmented functional H, called Hamiltonian as:

$$H(x(t), u(t), p(t), t) = g(x(t), u(t), t) + p^T(t) \cdot a(x(t), u(t), t) \quad (6)$$

where $p^T(t)$ is the transposed matrix of p(t), usually called Lagrange multipliers and have to be determined in order to respect the constraint on the systems,

then, the necessary conditions for u* to be an optimal control are :

$$(i) \quad \dot{x}(t) = \frac{\partial H(x(t), u^*(t), p(t), t)}{\partial p}$$

$$(ii) \quad \dot{p}(t) = -\frac{\partial H(x(t), u^*(t), p(t), t)}{\partial x}$$

$$(iii) \quad \text{at each step of time and for all admissible control } u(t): \quad H(x(t), u^*(t), p(t), t) \le H(x(t), u(t), p(t), t) \quad (7)$$

Different points may be noted concerning these conditions:

- The first condition represents in fact the systems eq.(4)
- The second allows the determination of the Lagrange multipliers conjointly with the constraint of the system (see following part: determination of the Lagrange multiplier).
- The third condition may be explained as $\frac{\partial H(x(t), u(t), p(t), t)}{\partial u} = 0$ if the partial derivative along u exists. Nevertheless this condition expressed with inequality may be sufficient to be used. In this case, we can find the minimum of the function with an iterative numerical process for example.
- If the second partial derivative of H along u exist then $\frac{\partial^2 H(x(t), u(t), p(t), t)}{\partial u^2} > 0$ is sufficient to guarantee that u* causes a local minimum of H. Using (iii) expressed with inequality, the process to find the minimum of H has to ensure that it is a global minimum.

Note that this principle remains optimal only if the state and the control variable of the system are not saturated. In the case of saturation some method can be applied to improve the results [8], nevertheless it remains sub-optimal.

Application on an electrical vehicle:

We consider P_{uc} (UC electrical power, Figure 2) as the control variable and E_{uc} (the amount of the Energy stored in the UC) as the state variable. The Pontryagin's minimum principle for an electrical vehicle can be developed as follows:

$$J(P_{uc}) = \int_{t_0}^{t_f} I_{batt}^2(P_{uc}) dt \quad (8)$$

Where J is the objective function. Note that if P_{uc} is chosen as the control variable J does not depend on U_{0uc}.

The system state equation can be expressed as:

$$\dot{E}_{uc} = \frac{dE_{uc}}{dt} = P_{0uc}(E_{uc}, P_{uc}) \quad (9)$$

Where P_{0uc} is the electrical power on the perfect capacity C (Figure 3).

Applying the Pontryagin's minimum principle (8):

The Hamiltonian is defined as:

$$H(E_{uc}, P_{uc}) = I_{batt}^2(P_{uc}) + p(t) \cdot \dot{E}_{uc} \quad (10)$$

And

$$(iii) \quad \text{at each step of time and for all admissible control } P_{uc}(t) \quad H(E_{uc}, P_{uc}^*) \le H(E_{uc}, P_{uc})$$

$$(ii) \quad \dot{p}(t) = -\frac{\partial H(E_{uc}, P_{uc})}{\partial E_{uc}} = -p(t) \cdot \frac{\partial P_{0uc}(E_{uc}, P_{uc})}{\partial E_{uc}} \quad (11)$$

Determination of the Lagrange multiplier:

Considering the electrical model of the Figure 3 :

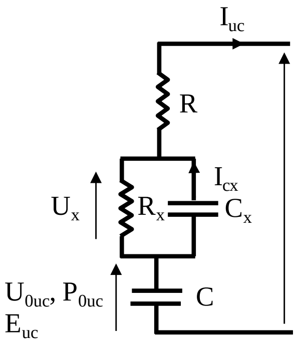

Figure 3 : Electrical model of the UC

And regarding (11), P_{0uc} has to be expressed in function of E_{uc} and P_{uc}.

For a given UC current I_{uc}, the current in C_x capacity is:

$$I_{Cx} = -(\frac{U_{x0}}{R_x} - I_{uc}) \cdot e^{-\frac{t}{\tau_x}} \qquad (12)$$

With I_{cx} the current in C_x capacity, U_{x0} the initial C_x voltage, and $\tau_x = R_x C_x$.

The power in the main capacity C:

$$P_{0uc} = U_{0uc} I_{uc} = -(P_{uc} + R I_{uc}^2 + \frac{U_x^2}{R_x} + U_x I_{cx}) \qquad (13)$$

Thus:

$$I_{uc} = -\frac{\sqrt{\frac{2E_{uc}}{C}} - U_{x0} \cdot e^{-t/\tau_x} - \sqrt{(\sqrt{\frac{2E_{uc}}{C}} - U_{x0} \cdot e^{-t/\tau_x})^2 - 4P_{uc}(R + R_x(1 - e^{-t/\tau_x})}}{2(R + R_x(1 - e^{-t/\tau_x}))} \qquad (14)$$

Using:

$$R_e = (R + R_x(1 - e^{-t/\tau_x}) \qquad U_{0uc} = \sqrt{\frac{2E_{0uc}}{C}} \qquad (15)$$

$\frac{\partial P_{0uc}}{\partial E_{uc}}$ can be expressed as :

$$\frac{\partial P_{0uc}}{\partial E_{uc}} = -\frac{1}{R_e C}(1 - \frac{U_{x0} e^{-t/\tau_x}}{2U_{0uc}} - \frac{U_{0uc}^2 - 2U_{0uc} U_{x0} e^{-t/\tau_x} - 2R_e P_{uc} - \frac{1}{2} U_{x0}^2 e^{-2t/\tau_x}}{\sqrt{U_{0uc}((U_{x0} e^{-t/\tau_x} - U_{0uc})^2 - 4R_e P_{uc})}}) \qquad (16)$$

Then using (11.ii) in discrete time:

$$\dot{p}(i) \equiv \frac{p(i) - p(i-1)}{T_s} \qquad (17)$$

Which leads to:

$$p(i) = \frac{p(i-1)}{(1 + \frac{\partial P_{0uc}(E_{uc}, P_{uc})}{\partial E_{uc}} T_s \quad)} \qquad (18)$$

Then, the Lagrange multiplier is defined iteratively along the cycle and only p(0) (initial value of p at instant 0) have to be fixed in order to respect the constrain on the UC open circuit voltage (2).

Note that a simple model of UC can be used with R_x=0 and C_x=0 which leads to:

$$\frac{\partial P_{0uc}}{\partial E_{uc}} = -\frac{1}{RC}(1 - \frac{E_{uc} - RCP_{uc}}{\sqrt{E_{uc}(E_{uc} - 4RCP_{uc})}}) \qquad (19)$$

D. Dynamic programming

Dynamic programming [4]-[9] is defined as a computer based method to solve an optimisation problem where the objective function is a sum of terms (20).

In this work the function to be minimised during a cycle of N sample time is the following:

$$J = \sum_{i=1}^{N} I_{bat}^2(i).T_e \qquad (20)$$

Note that, as in the calculus of variation formulation, the objective may be different (part IV.C).

In the optimisation problem we must consider the final UC voltage as a constraint. In order to control the UC voltage deviation, it is taken as the state variable of the problem and its evolution as a trajectory from the initial voltage to the imposed final voltage. The minimum of J is then obtained for the optimal trajectory of UC voltage.

In order to apply dynamic programming, the admissible UC voltage area is meshed with a given sample (Figure 4). Then all the connexion possibilities between points are calculated with the corresponding battery current square as the cost of each connexion.

Thus minimisation of (20) leads to the best strategy (instantaneous UC and battery currents) for a set of fixed initial and final UC voltage values (usually equal).

In order to find the optimal trajectory, a Bellman-Ford algorithm is applied.

As we mentioned at the beginning of this section, this method allows optimum calculation on a previously known driving cycle. Its application in real time is then impossible, but it is very useful to perform analysis and comparisons with rule based management laws.

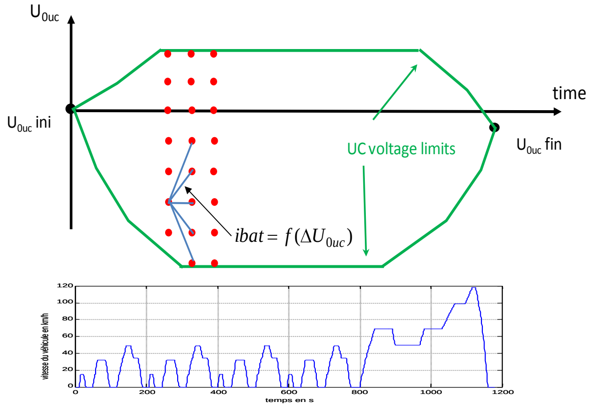

Figure 4 : Dynamic programming: meshed area.

IV. VALIDATION AND COMPARISON

A. Case Studies

In these part comparisons between the two methods are presented on the example of an electric micro bus [5].

The main electrical characteristics are the following:

Battery pack	32 NiCd elements in series 100 Ah, 7.2 V per element
UC Pack	60 UC elements in series 4500 F per elements

Table 1 : Electrical sources characteristics

B. Validation with two UC branches in parallel

As previously said, the pontryagine's minimum method is strictly optimal only if the state (for us the energy stored in the UCs) is not saturated. To avoid the UCs saturation and validate the two methods, a case with two parallel branches of 60 UCs elements serial connected is studied. The effects of saturation in the case of only one branch are presented in the next part.

Figure 6, shows the UCs voltage optimal trajectory for an ECE 15 cycle (Figure 5). It clearly appears that the two methods are perfectly equivalent.

Figure 7 and Figure 8 represent the battery Amps.hours classified in function of the current. For example, the bar labelled 12.5 represents the global Amps.hours discharged with a current between 0 and 25 A.

The Figure 7 represents the case without UCs; only the batteries provide the electrical power. The Figure 8 represents the case with two UCs branches. It proves that the two methods are really optimal as the current is in fact a constant equal to the mean current (40.9 A). Thus the rms current is also equal to the mean current which seems to be the optimal solution.

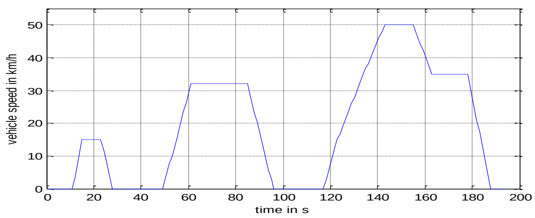

Figure 5 : ECE 15 cycle

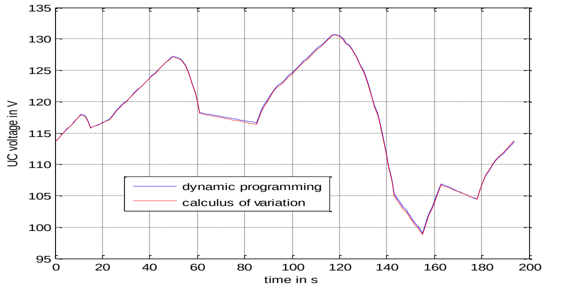

Figure 6 : UC open circuit voltage with two UC branches in parallel

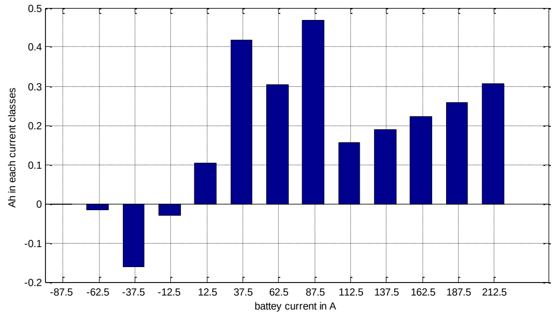

Figure 7 : Battery solicitation with no UC.

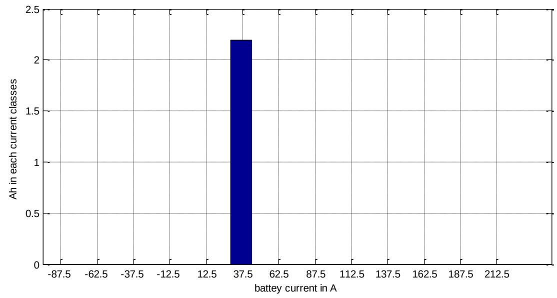

Figure 8 : Battery solicitation with two UC branches in parallel.

B. Case with one UC branch

This part present the results obtained with the effective parameters of the UCs pack installed in the micro-bus (only one branch of UCs). Figure 9 shows the UCs voltage optimal trajectory for an ECE 15 cycle. In this case the UCs are saturated especially between time 100s and 120s with the calculus of variation method. It appears, as previously said, that this method is suboptimal in this case. Nevertheless regarding table 1, Figure 10 and Figure 11 (representing the battery stress in A.h) compared to the Figure 7 (case with no UC), it is clear that the calculus of variation still gives good results. This is important as this method can be easily implemented in real time in the vehicle [10].

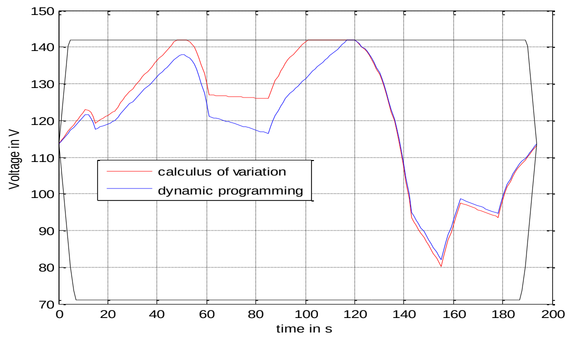

Figure 9 : UC open circuit voltage with one UC branch

	Mean current	RMS current
No UC	40.9	70.1
Dynamic programming	41.2	41.5
Calculus of variation	41.2	42.8

Table 2 : battery current characteristic

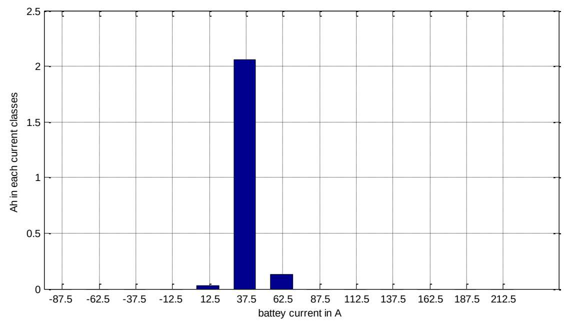

Figure 10 : Battery solicitation with one UC branch (calculus of variation)

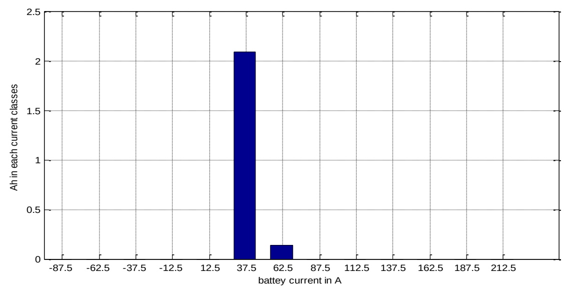

Figure 11 : Battery solicitation with one UC branch (dynamic programming)

C. Energetic consideration

As previously said, the objective function to be minimized is not necessarily the battery rms current. In order to minimize the electrical consumption, the battery energy can be chosen as the objective. This allows a comparison between the energy consumed for the two strategies (rms current or energy minimisation) and the case with batteries only.

Table 3 present the battery energy in Wh on ECE 15 cycle for the three cases. In fact the only difference in the energy consumption is due to the joules losses in battery and UC and the load of the vehicle (reduce by 60kg with no UC).

It is noted that the energy minimisation leads to a gain in terms of energy of only 2% (compared with the case with no UC). It presents a gain in terms of rms battery current of 35% but is 10% less efficient than rms current minimisation.

The relative small gain in terms of global energy consumption may be explained regarding the battery and UC respective resistor which is of the same order of size. The global resistor for 32 NiCd batteries is 0.096 Ω and that for 60 UC is 0.022 Ω. Moreover the potential gain is relatively small as joules losses represent only 5% of the global energy provided by the battery.

Finally it clearly appears that the addition of UC doesn't penalize too much the battery energy consumption: 1% increase regarding the consumption without UC.

ECE 15 cycle	Battery energy	Joules losses in battery	Joules losses in UC	Battery rms current
Battery rms current minimisation	429.8 Wh	7.3 Wh	15.8 Wh	41.5 A
Battery Energy minimisation	420.8 Wh	10.7 Wh	3.7 Wh	46.2 A
No UC	426.3 Wh	22.2 Wh	0	70.1A

Table 3 : Energetic balance ECE 15 cycle

V. Application on realistic cycle

As the microbus has been tested on a real mission [11] it becomes interesting to test the rms minimization method on this more realistic cycle (Figure 12).

Figure 13 shows the optimal strategy (UC open circuit voltage trajectory) for such a cycle. It appears that due to frequent acceleration/deceleration the UC is not too much saturated. And one branch of UC allows performing really good results taking into account that the battery rms current (36.8 A) cannot be smaller than the mean current (36.2 A).

Figure 14 and Figure 15 show the battery solicitation in case of optimal strategy (rms battery current minimization) and with no UC. The benefits of UC together with the optimization method clearly appear regarding the battery solicitation.

Finally, Table 14 shows that the addition of UC has small influence on the global vehicle energetic consumption (1% increase).

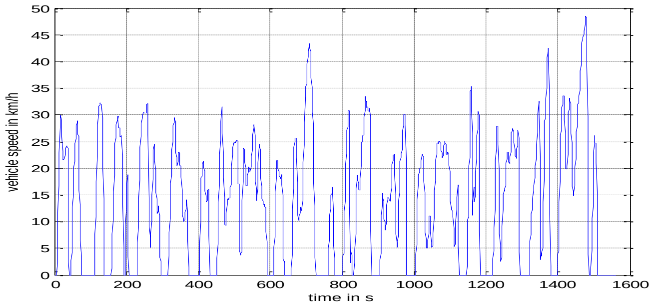

Figure 12 : Typical microbus mission.

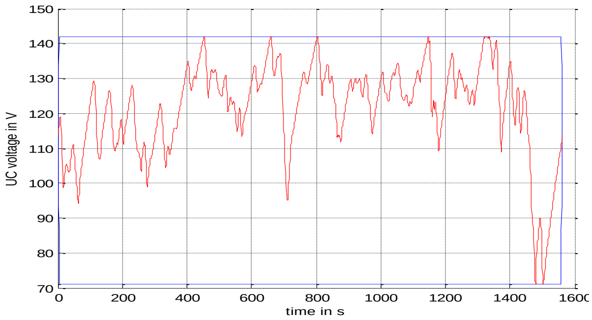

Figure 13 : UC optimal open circuit voltage.

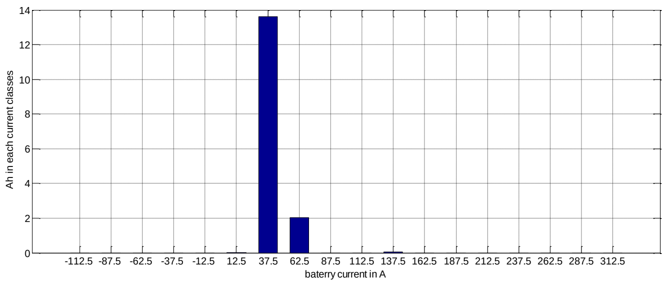

Figure 14 : battery solicitation with optimal strategy

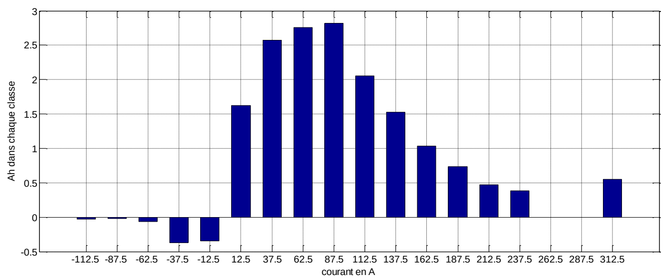

Figure 15 : battery solicitation with no UC

Urban microbus cycle	Battery énergie	Joules losses in battery	Joules losses in UC	Battery rms current
Battery rms current minimisation	3122 Wh	50 Wh	87 Wh	36.8 A
No UC	3093 Wh	145 Wh	0	62.3 A

Table 4 : Energetic balance urban microbus cycle

VI. CONCLUSION

Two methods of offline optimal management have been developed and tested in the case of electrical vehicle with a hybrid storage system. Validation of the two methods has been performed in case of non saturated UCs' open circuit voltage. Results of offline optimisation are presented in the case of an electric micro-bus in ECE 15 and actual drive mission.

The following step of this study is to investigate rule based management law and test it in vehicles. For that, result of optimisation will be really helpful to evaluate the relevance of these rule based laws.

Moreover, the variationnal method does not need a lot of resources and may be adapted and tested in real time.

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