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Energy Management Using Fuzzy Logic, on HEV

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Abstract

On Hybrid Electrical Vehicles (HEV) the energy management becomes crucial, to increase the autonomy of the vehicle and decrease the costs. This paper presents a new approach, to manage the multiple electrical power sources, in front of variable user profiles and for many vehicle configurations. This new approach is based on the concept "adapt the sources type in front of the current profile on power bus". In this study the types of sources are "power" and "energy". The utilization rate of each source available is determined by the algorithm. The parameters used are kind of proprioceptive and exteroceptive the vehicle.

This paper focuses on adaptive methods using fuzzy logic at two levels: at first level will consider the proprioceptive variables (attached to the sources and energy available instantaneously), at second level will consider the exteroceptive variables (attached to the mission and road status, to minimize the consumption criteria). The benefits of this technology have been evaluated on mission profiles associated at the electric vehicles used for mail delivery.

Keywords: Control system, Energy recovery, Energy storage, HEV (hybrid electric vehicle), Power management

1 Introduction

To increase the electrical vehicles autonomy at reasonable costs, it is necessary to adapt the technology used for energy (continuous behaviour) or power (transients behavior), remaining consistent with the mission needs. On HEV (Hybrid Electrical Vehicles) two or more technologies are available[1] to produce energy/power (batteries, super-capacitors, fuel cells, solar panels…).

The major goal is to manage the power transient's present on power network with an optimal efficiency[2], while minimizing the batteries discharges on the overall mission.

Switching in real time to the best technology is conditioned by: 1) The ability to predict energy requirements, 2) The measurement of the energy available on different sources, 3) The capability to use this energy.

[1] A motor is also considered as an energy source in the phases of braking

[2] Using the adapted technology; Ex: Super-capacitors & revertible power converters

The first part of this paper presents the vehicle architecture and the technologies considered in our analysis. A focus will be made around multicellular reversible converters to manage the transfer of energy. The second part explains the Fuzzy Logic (FL) principles implemented and how to obtain an optimal energy management. The third part presents the test bench used in our analysis and the last part presents the experimental results obtained on a test bench[3].
A conclusion resumes the work done and the on-going work to implement this concept on a HEV used for mail delivery.

2 Description of the energy chain

In this study the energy chain of the vehicle consists of three energy sources (Fig.1). A battery pack connected to the distribution bus via a bidirectional converter, a subsystem PCube allowing assisting the battery pack in the management of energy transfer and a motor working as a generator in braking phases.
The PCube contains a pack of super-capacitors connected to the network via a bidirectional converter, several safety and measuring devices are used to control current limitations and measure the super-capacitor voltage. The load is represented by a powertrain, which provides positive power demand when the vehicle is in traction and negative power during braking phases.
The converter is a multiphase reversible power module, which delivers/absorbs current maintaining a regulated output voltage to respect Usc < Ubat. It is characterized by high efficiency from 93% up to 97% due to the high quality of power electronic components and internal control laws [0].

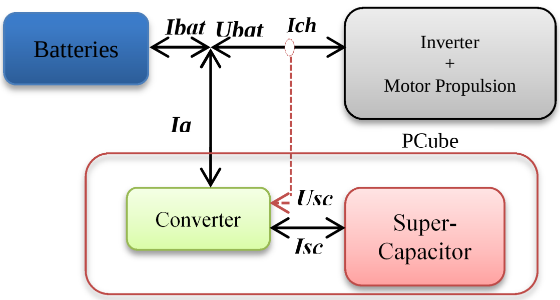

Figure 1: Vehicle Energy Chain.

[3] This test bench has the capability to reproduce the currents present on HEV power network for different mission profiles

2.1 Relevance and quality of the association

Hybridization batteries / super-capacitors can respond to mission profiles requiring "power" and "energy" while respecting cycling and economic criteria.
The combination of a super-capacitor with a battery improves power density, improves performance, and reduces stress on batteries. The direct association cannot be done because the voltage and current behavior are different; it is then necessary to use an indirect association via a converter. This association can be made according to several converter topologies. Topology "multicellular converter uncoupled, reversible current" used by Nexter Electronics, comes the best compromise cost / performance.
For the relevant hybridization, it is necessary that the transfer of bidirectional energy on the pair [super-capacitor + converter] is done with a better efficiency than with battery.
The converter must be designed to withstand the power's transient associated to the mission profiles. Figure 2 below shows the efficiency of a standard lead battery and efficiency curve for PCube [converter + super-capacitor].

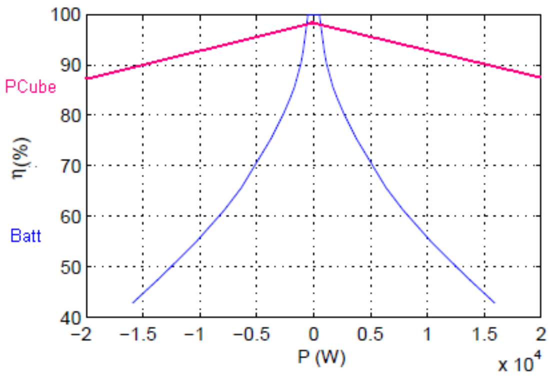

Figure 2: Battery and PCube efficiency

Neglecting the efficiency of the super-capacitor, the efficiency of PCube is the key point, because it occurs twice during storage and during the release of current transients.

3 Fuzzy Logic Method

The previous version of PCube implements an algorithm using a fix I_{ch} threshold to define in real time the battery assistance. The new Fuzzy Logic [1][2] algorithm modifies in real time this threshold, using different variables. Two phases are considered on this new algorithm:

- An “off-line” optimization phase will use genetic algorithms to extract the FL parameters in front of mission profile. More precisions on this are presented in [3].
- An “on-line” RT operation implementing the steps: fuzzification, rule engine, and defuzzification.

The fuzzification block consists in defining the linguistic variables used to describe situations. In our case, the variables are: the current required by the motor “**Ich**” and the voltage of the super-capacitor “**Usc**” representing the input variables, and the current supplied by the battery “**Ibat**” which corresponds to the output variable. Each one of these variables is represented by mathematical membership functions describing states and variation domain of the variable, and can be modeled under various forms (triangular, trapezoidal or Gaussian) as shown in Figures 3, 4, 5. The embedded application in the converter PCube used trapezoidal shape in order to reduce the on-line complexity.

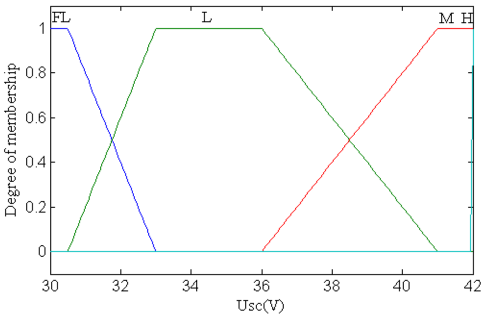

Figure 3: Super-capacitor voltage

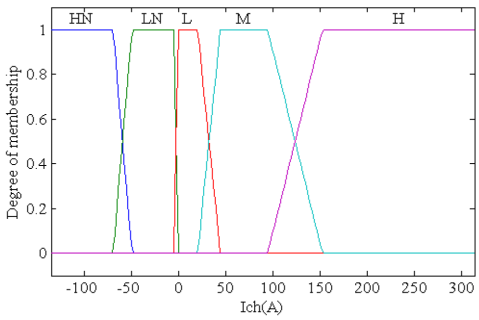

Figure 4: Demand of the powertrain

Table 1: Rules engine

(Ich,Usc)	**FL**	**L**	**M**	**H**
HN	**Z**	**Z**	**Z**	**HN**
LN	**Z**	**Z**	**Z**	**LN**
L	**L**	**L**	**Z**	**Z**
M	**M**	**L**	**L**	**Z**
H	**H**	**M**	**L**	**Z**

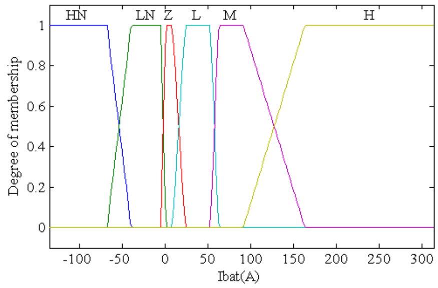

Figure 5: Battery current

For example, in our application, the different possible states to represent the super-capacitor voltage “**Usc**” are **{FL, L, M, H}** using the following notations: **HN** High Negative, **LN** Low Negative, **Z** Nil, **FL** Fairly Low, **L** Low, **M** Medium, and **H** High.
The second step is the rules engine, which permit the coordination between the variables using the operators IF, AND, OR to deduce conclusions about the battery current. All possible situations of the battery current are summarized in Table 1 according to the super-capacitor voltage and the powertrain demand variations. For each measurement (input value) of the super-capacitor voltage and the powertrain demand, the rules engine generates a maximum of four possible rules, because each input variable can belong to two functions simultaneously when the input value belongs to the fuzzy area. For example, by fixing (Usc=32V) and (Ich=112A), the fuzzification block deduces that the super-capacitor voltage membership degree is 50% FL and 50% L, and the membership degree of the powertrain demand is 75% M and 25% H. Now, it can be deduced the possible states of the current battery to supply, using rules engine as follows (see Fig.6):

- If (Usc = FL) and (Ich = M) then (Ibat = M) or
- If (Usc = FL) and (Ich = H) then (Ibat= H) or
- If (Usc = L) and (Ich = M) then (Ibat = L) or
- If (Usc = L) and (Ich = H) then (Ibat = M)

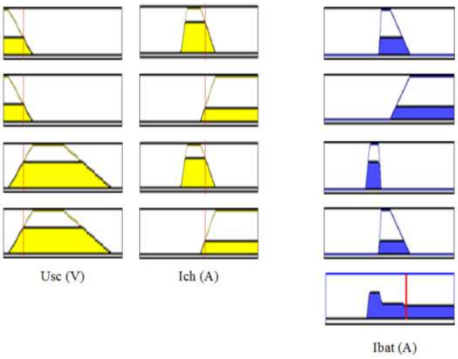

Figure 6: Possible states of the current battery

Finally, the defuzzification block allows deducing the battery current according to the information (value) on the input variables. It consists in computing the abscissa of the output variable "Ibat" using centroid method on the resulting fuzzy set. The decision surface (see Figure 7) gives the current battery necessary to feed the vehicle running on tested mission profile for each variation of input data.

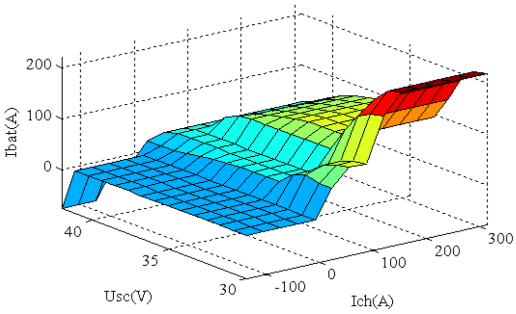

Figure 7: Decision surface

4 Test bench presentation

The test bench used in this study emulates the powertrain of an electric vehicle (inverter + motor) so as to test the complete power distribution part (batteries + PCube).

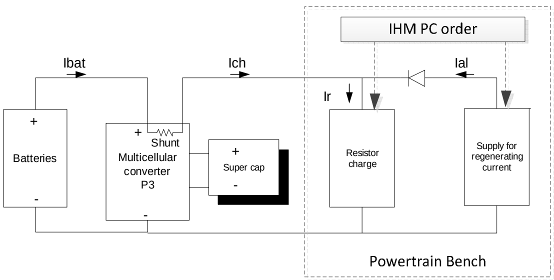

Figure 8: Test bench

This test bench includes:

- Battery pack,
- Super-capacitor,
- Multicellular converter that allows managing both energy sources,
- A shunt for current motor measurement,
- A Vehicle power network simulator including:
  - A computer controlling the current present on vehicle power bus.
  - A switchable resistor network simulating the motor in the acceleration phase. Network switch position is controlled by the simulator computer.
  - A controlled power supply delivering current on braking and deceleration phases.

5 Experimental results

A mission profile presented in Figure 8 is used for analysis. This profile corresponds to the instantaneous current demand of an electric vehicle[4] without any assistance. The implementation of the energy management strategy should minimize the battery discharge for such mission, while respecting and satisfying system constraints.

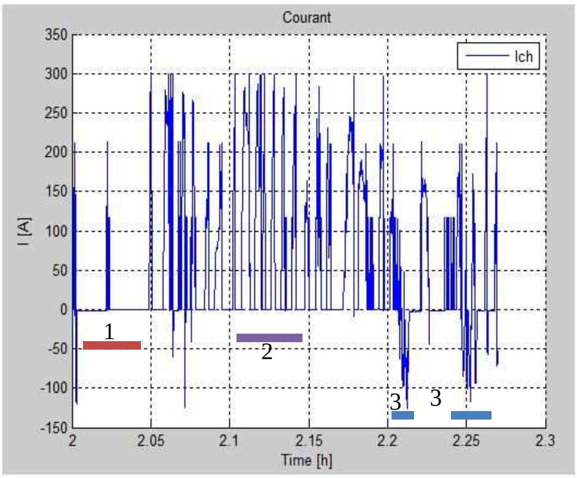

Figure 9: Nexter Electronics mission profile

5.1 Fuzzy parameters used for Nexter Electronics mission profile

The parameters configuration on FL depends on the mission profile. Because the use of genetic

[4] This profile was obtained by measurement on vehicle.

Table 2: Optimized fuzzy rules on Nexter Electronics mission profile algorithm [4] allows us to find (off-line) the optimized parameters for each mission profile while satisfying constraints.

Variable	Function	Parameters
Ich (A)	HN	-135.3 -135.3 -69.7 -49.7
	LN	-69.7 -49.7 -5.0 -1.0
	L	-5.0 -1.0 20.0 44.2
	M	20.0 44.2 94.2 152.4
	H	94.2 152.4 313.8 313.8
Usc (V)	FL	30.0 30.0 30.5 33.0
	L	30.5 33.0 36.0 41.0
	M	36.0 41.0 42.0 42.0
	H	42.0 42.0 42.0 42.0
Ich (A)	HN	-135.3 -135.3 68.0 40.0
	LN	-68.0 -40.0 -5.0 0.0
	Z	-5.0 0.0 8.5 23.0
	L	8.5 23.0 53.0 62.0
	M	53.0 62.0 91.2 123.2
	H	91.2 123.2 313.8 313.8

For tests in our mission profile, the rules presented in Table 1 are used and also the parameters presented in Table 2.

5.2 PCube operating modes

The different operating modes are:

- "Loading mode" which corresponds to the loading of super-capacitor by batteries in the low consumption phases of the motor.
  This charge is made to the max voltage of the super capacity.
- "Optimizer mode" corresponds to the phase where super-capacitor assists the batteries during the phases of high consumption of motor.
- "Power recovery mode" corresponds to the phase of feedback from the load current to charge the super-capacitors and batteries.
- "Stand-by mode" corresponds to the phase of maintaining the equilibrium voltages batteries and super-capacitor when there is no operating phase.

The different modes are present in Figures 10 and 11 below:

In Zone 1, the power demand is very low, and the batteries provide the power needed to charge the super-capacitor to its maximum voltage. Here is the "Loading mode".

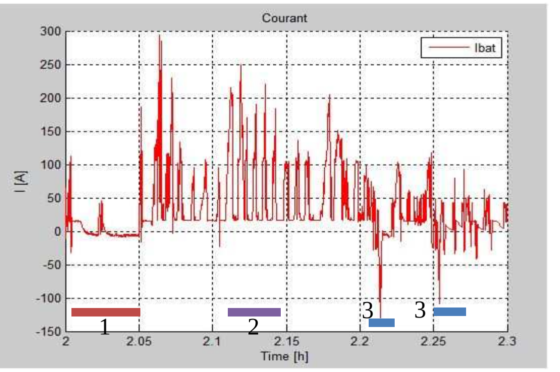

Figure 10: Current battery resulting fuzzy logic

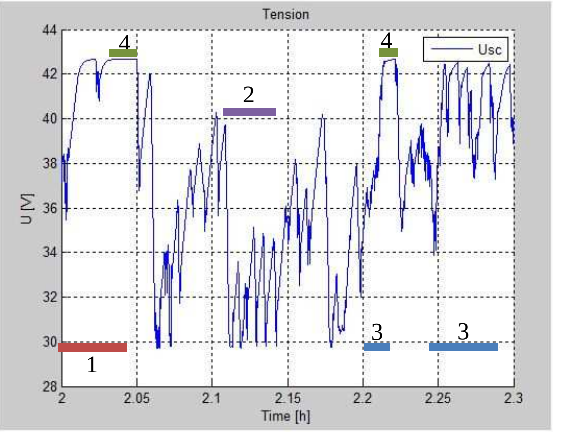

Figure 11: Super-capacitor voltage

Zone 2 corresponds at the high consumption phase of the motor, so we see well that the batteries (Fig.5) provide an average current equal to 200A instead of 300A as we can see in Fig.4 (which is the power demand of motor). So the compensation of this power demand is provided by super-capacitor (until minimum voltage) (Fig.6). Thus here is the phase where the super-capacitor assists the batteries: It is the "Optimizer mode".

In zone 3, the power demand of motor is negative (Fig.4) so we are in the phase of braking. During this phase, we notice that the motor recharges the super-capacitor until the maximum voltage (Fig.6) and recharges also the batteries with a low current. This phase corresponds to the "Power recovery mode".

Zone 4, in Fig.11, represents the "Stand-by mode", because when the super-capacitor reaches its maximum voltage the batteries provide a low current for maintain super-capacitor voltage.

5.3 Tests in progress

After verification by simulation, the energetic relevance of this new algorithm and its robustness regarding different user profiles, tests are ongoing with the test bench presented in Figure 8. These tests will permit to confirm or refute the results obtained by simulation done by LAAS/LAPLACE laboratories. The first results obtained by simulation are very encouraging [3].

The powertrain emulator on this test bench has good precision (better as 5%). The emulated current domain is -330A / +800A over 48VDC.
For the study two types of user profiles are analyzed:

- Short cycle, repetitive user profile, (similar as standard UDC[5])
- Long cycle user(s) profile(s) (Fig. 9).

The first type of user profile was employed to integrate and validate the FL algorithm on Pcube. The second type was used to correlate the results obtained with the FL algorithm implemented on PCube and the simulation results.

The first results of this correlation show that the proprioceptive parameters of the components in the energy chain, and in particular the evolution of the battery efficiency, affect the determination of fuzzy parameters in off-line. This battery efficiency is easy to characterize at constant current discharge, but when the current varies greatly, as the case in the user profile of Figure 9, the non-linear behavior and hysteresis appear. Technics for dynamic characterization of battery efficiency (considering electrochemical relaxation at different temperatures and different states of charge) must be considered [6][7][8][9] to re-estimate membership functions presented in Figure 5. This characterization work is in progress.

5.4 Next steps

On Table 2, the SoC[6] parameter is not considered as fuzzy parameters.
The battery SoC is considered in the off-line part as an input parameter to obtain fuzzy parameters optimized [10].

[5] Urban Drive Cycle

[6] Battery state of charge

The dynamic battery characterization process will deliver the influence of this parameter on FL approach. Result of this analysis will be considered on the next version of FL algorithm implemented on PCube.
Work will be continued until mid-2014 focusing on the following aspects:

- Pursuit the test, using the test bench, for different user profiles, to conclude on the:
  - improvement of energy efficiency introduced by the use of FL, for different user profiles,
  - Sensitivity of the fuzzy rules to classify the user profiles on defuzzification phase,
- Tune the sources models used on data inputs for optimal behavior on each user profile. Introduce the constraints of the hardware implemented in PCube.
- Test campaign on urban mail delivery vehicle, to conclude on energy efficiency. For this, the vehicle will be instrumented with means for recording.

The last point in the study considers the opportunity to introduce a fuzzy swithing between specific fuzzy rules to commute in real time between different rules engines (each associated at a specific mission profile). Major parameters used for this function are exteroceptive to the vehicle [11].

6 Conclusions

This paper has presented the study, in progress, about the energy efficiency optimization on a HEV, using the fuzzy logic to tune the current assistance level off batteries by super-capacitors.

The presented concept is easily extrapolated to platforms using other types of energy sources instead of batteries, such as a fuel cell. The use of a reversible current converter to connect the ultra-capacitor on power network remains necessary.

For an optimal approach of this concept, the performance of PCube (reversible current power converter + super-capacitor) should be better than that of the power source.[7]

[7] Our technology is challenged by the improvements expected on the next decade on batteries and in particular on LTO: Lithium Titanate.

The concept presented to dissociate the "on-line" real-time phase from the "off-line" phase permits to embed this concept in vehicles using standard low cost processors.

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