FUZZY-LOGIC SUPERVISION STRATEGY FOR BATTERY-POWERED ELECTRIC VEHICLES

Ştefan BREBAN[1], Mircea RĂDULESCU[2]

Battery-powered electric vehicles are becoming a viable alternative to gasoline- or diesel-powered vehicles. Four main factors are contributing to this evolution: oil price, pollution, greenhouse effect and advances in electrochemical energy storage. All major car manufacturers are developing projects in this area. Until now, the battery-powered electric vehicles available on the market have autonomy of about 100 to 150 km, limited by the energy stored in the electrochemical battery. The battery is the most expensive part of the electric vehicle and has also a limited lifetime. To increase the lifespan of the electrochemical battery a well-known solution is to use an energy buffer, the electric double-layer capacitor (ultracapacitor). This paper proposes a new fuzzy-logic-based supervision strategy aiming at increasing the lifespan of the electrochemical battery.

Keywords: battery-powered electric vehicle; embedded electrical power system; energy storage; ultracapacitor; fuzzy-logic supervision

1. Introduction

Numerous arguments to increase efficiency on every level of energy consumption are well known by all: exhaustible raw material for energy generation, high costs of exploitation, pollution agents due to burning of carbon based fuels and the famous CO2 green gas effect that concerns us maybe the most nowadays. All these issues are pushing researchers to find more ways to reduce consumption by increasing efficiency. One of the solutions is to electrify the transportation sector, being considered among the biggest consumer and polluter of our planet. Electrification in this area has its advantages: greater efficiency, increased reliability, better dynamics and sometimes smaller costs [1].

One of the most important elements of an embedded electrical power system is the energy storage device. This element plays different roles depending on the application: main power source, auxiliary power source, power leveling or power peak shaving [2]. Battery-powered electric vehicles (BEVs) are using different types of batteries as main power source. A supervision strategy for an ultracapacitor (UC) that complements an electrochemical battery (EB) will be presented in the next sections. The aim of this study is to limit the number of

[1] Technical University of Cluj-Napoca, Romania, e-mail: Stefan.Breban@emd.utcluj.ro
[2] Technical University of Cluj-Napoca, Romania, e-mail: Mircea.Radulescu@emd.utcluj.ro

charge/discharge cycles (CDCs) and also the power fluctuations that an EB has to support during BEV operation. This will be achieved using a new fuzzy-logic supervision strategy.

The most common energy storage system used to power the electric vehicles consists of an EB and a UC [3-7]. This is due to the well-known complementarity of these two elements. The EB has a high energy capacity and the UC, a high power capacity. Many papers are treating this combined energy storage system. The UC has usually the role to reduce the stress on the EB, by power peak shaving and braking energy recovering. In reference [3], a comparison between "current/voltage/power profiles of the batteries with and without UCs indicated the peak currents and thus the stress on the batteries were reduced by about a factor of three using UCs. This reduction is expected to lead to a large increase in battery cycle life". The authors of reference [4] are proposing a strategy to design and supervise the battery and UC on a fuel-cell hybrid electric vehicle. The proposed strategy uses low-pass filters and some logical operations. In reference [5], a fuzzy-logic strategy is presented, aiming at reduction of power peaks on the electrochemical battery with the help of a UC. In [6], a fuzzy-logic control method is utilized to design an energy management strategy that enhances the fuel economy, and increases the mileage of a vehicle by means of a hybrid energy storage power system consisting of fuel cell, EB and UC. The authors of reference [7] are proposing a new battery/UC configuration that allows a reduced-size power converter. The braking energy is completely stored in the UC, having an important capacity of almost 1200 kJ. In spite of the common knowledge of EBs, the authors of reference [8] are stating that for some LiFePO4 batteries "the cycle depth of discharge and relative fraction of low-rate galvanostatic cycling vs. acceleration/regenerative braking current pulses are not important even over thousands of driving days"; thus, they are not affecting significantly the lifetime of the batteries, the only important factor being the energy processed. In this study, the authors are estimating an approximate capacity lost per normalized Wh of about -6 x 10-3% for Plug-in Hybrid Vehicle use and -2.7 x 10-3% for vehicle to grid use, due to more rapid cycling found in driving conditions.

Considering all these elements stated in the scientific literature, this article proposes a novel fuzzy logic supervision aimed to reduce the capacity decrease of the battery by reducing the number of CDCs and the energy processed, using UCs.

2. Power System under Study

In Fig. 1, the simplified diagram of the on-board power system under study is presented. The main power source consists of an EB that can be connected to the loads directly [5] or by means of a power converter [4]. The UC usually is connected through a buck-boost (DC/DC) converter to the DC-link, due to low voltage operation [4, 5]. The electric motors are supplied through power inverters (DC/AC converter).

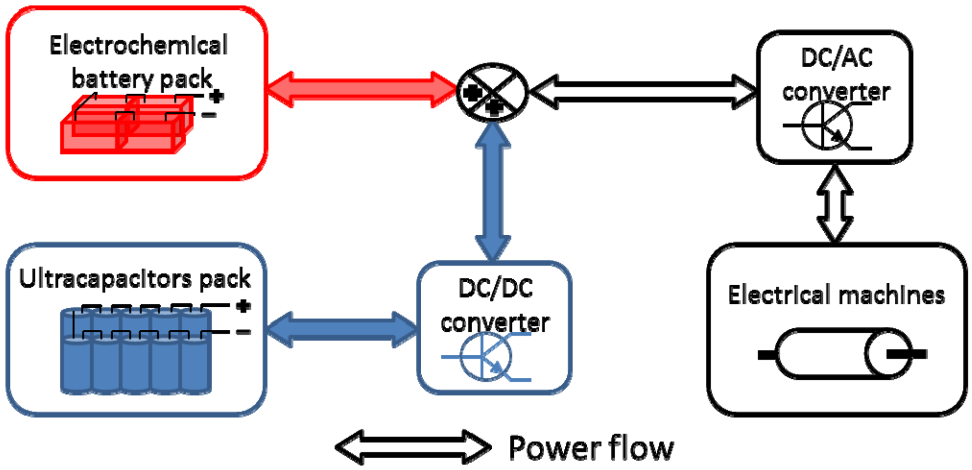

Fig. 1. Schematic of the BEV power system.

Currently, the majority of EB suppliers are proposing batteries that use Lithium (Li). The positive features of Li-based battery technology are its high energy-to-weight ratio, no memory effect, and low self-discharge, as compared to other solutions like Ni/Cd or Ni/MH [2]. Li-ion battery technology has arrived to maturity and is expected that the prices will decrease substantially in the following years [9]. Other EB technologies are under research and promise greater Wh/kg factor: Li-Air, Aluminum-Air, Iron-Air, Silicon-Air etc.

UCs work in much the same way as conventional capacitors, in that there is no ionic or electronic transfer resulting in a chemical reaction, i.e. energy is stored in the electrochemical capacitor by simple charge separation. The main advantage of the UCs is the high power capability that makes them highly suitable to be used in conjunction with the electrochemical batteries. While the batteries are defined as high-energy, low-power devices, the UCs have opposite characteristics: high power and low energy. The energy stored (E) in UCs varies linearly with the equivalent capacity (C) and with the square of the voltage (U):

. (1)

3. Fuzzy-Logic Supervision Strategy

This supervision strategy was developed considering two objectives: EB life increase and UC minimum capacity. These objectives are interdependent;

UCs capacity and their mode of use are affecting the EB energy capacity degradation. The reasoning behind the supervision strategy is based on the knowledge of the power demand during BEV operation. Thus, it has been considered that when the BEV is at stop, the UC should have a high State of Charge (SoC), to be able to provide power when BEV starts moving. During speed increase, the UCs should reduce their energy storage and when arriving at high speeds should be discharged to be able to recover most or all of the energy generated when braking (Table 1).

Table 1

UC SoC reference for different speeds of the BEV

BEV Speed	Zero	Low	Medium	High
UC SoC	High	High-Medium	Low-Medium	Low

Considering these logic assumptions, the fuzzy-logic supervision was considered to be implemented. Fuzzy logic has three steps of development: fuzzyfication, inference and defuzzyfication. In the fuzzyfication and defuzzyfication phases each input and output variables receive several (usually three to five) membership functions (MFs) on the whole variable variation range. The inference consists of selecting the rules between the input and output variables. Fuzzy systems with many inputs and outputs are difficult to develop due to high number of rules to be established. A methodology to asses this problem is presented in [10].

The proposed fuzzy-logic supervision strategy is developed on two levels. Each level of supervision has two inputs and one input. The input variables of the first supervision level are the BEV speed and acceleration. The output is a power coefficient of the UC (Fig. 2). All variables are expressed in p.u. values. These are representing the ratio of each considered parameter to its nominal value.

The second level of supervision has also two inputs, i.e. the output of the level one and the SoC of the UC, and one output, the UC power, all expressed in p.u. Using two levels of supervision simplifies the inference development. Considering that for each input and output only three MFs are used, one needs to define only 18 rules instead of 27 rules for the case of a single supervisor with three inputs and one output. The gain multiplier makes the passing from p.u. to real power systems values. This multiplier can also be used to increase or decrease the dynamics of the supervision strategy.

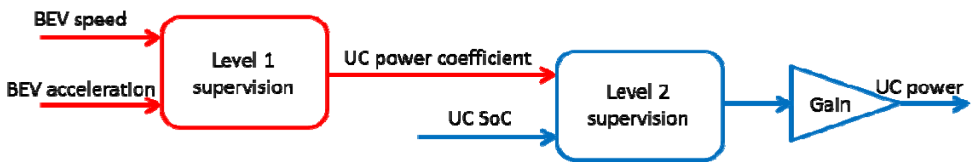

Fig. 2. Supervision strategy methodology.

The fuzzy-logic supervision strategy was developed using Fuzzy Logic Toolbox from Mathworks. In Fig. 3, the first-level fuzzy-logic supervision surface is shown. It can be observed that, due to centroid defuzzyfication method, the output varies from about -0.55 p.u. to 0.85 p.u. Hence, the UC power coefficient input of second-level supervision was developed with a variation between -0.5 p.u. and 0.8 p.u. to increase the supervisor dynamic response at the limits of variation.

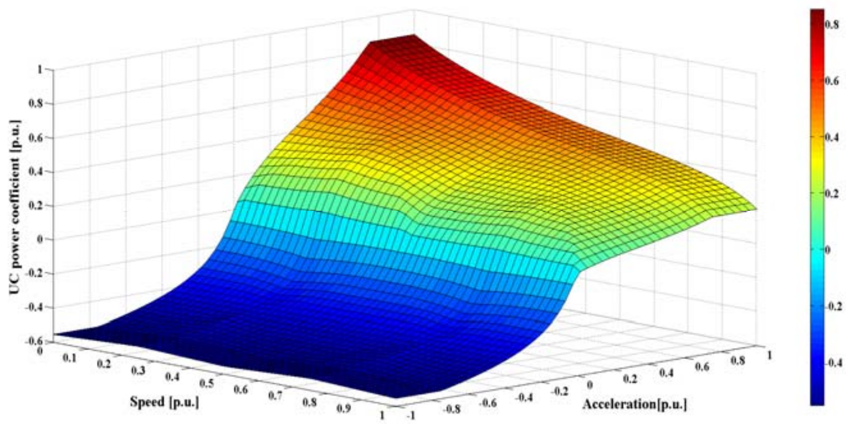

Fig. 3. Level 1 fuzzy-logic supervision surface.

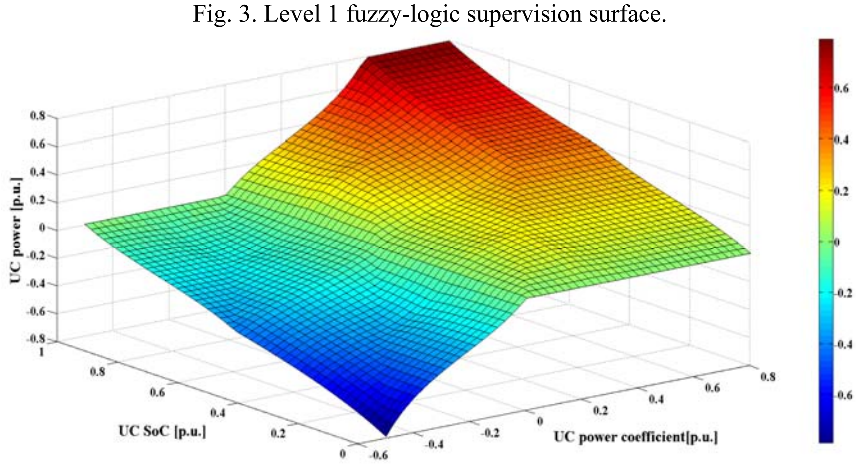

Fig. 4. Level 2 fuzzy-logic supervision surface.

In Fig. 4, the second-level fuzzy-logic supervision surface is shown. As it can be observed, the variation range in p.u. of the output, i.e. UC power, is between -0.8 and 0.8, by using also centroid defuzzyfication. Thus, if the power variation range of the UCs is between -20kW and 20kW, the gain value should be 25000.

As the BEV has different loads, and has to negotiate negative and positive road gradients, the power needed at some instant can vary dramatically. In order to accommodate the actual power consumed or recovered (PBEV) with the reference UC power PUCref, the following algorithm was used:

(2)

(3)

From Eqs. 2 and 3 results that the UCs power, P_{UC}, is the power referenced by the supervision system when this power does not exceed P_{BEV} neither on negative or positive values.

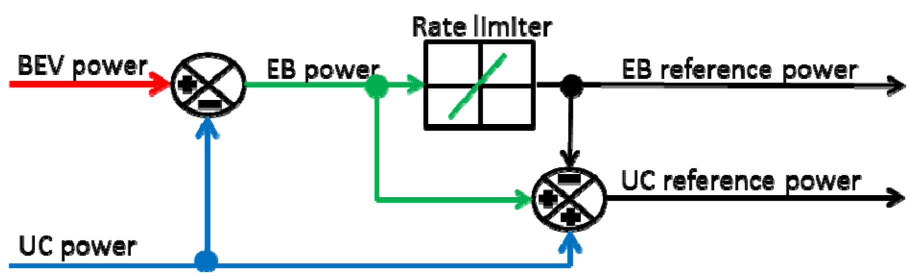

Fig. 5. Reference EB and UC powers.

Finally, in order to protect the EB from rapid power pulses, a rate limiter for the EB power was imposed, having the slew rate ± 10 kW/s (Fig. 5). The difference between BEV power and UC power is fed into the rate limiter. The output of the rate limiter gives the EB reference power. Obviously, the difference between the input and the output of the rate limiter should be taken by the UC, resulting the UC reference power.

4. Simulations Results

The simulations are made using Matlab/Simulink environment. The BEV simulated has a total mass of 1400 kg, the equivalent frontal area is 2.2 m2 , and the aerodynamic drag coefficient is 0.25. The air density was considered 1.2 kg/m^3 and the air mass speed, zero. Two driving cycles were used in simulations

[11]: the first one, the New European Driving Cycle (NEDC) that consists of four ECE-15 cycles followed by one EUDC cycle (Fig. 6), and the second one, the Urban Dynamometer Driving Schedule (UDDS), as presented in Fig. 13.

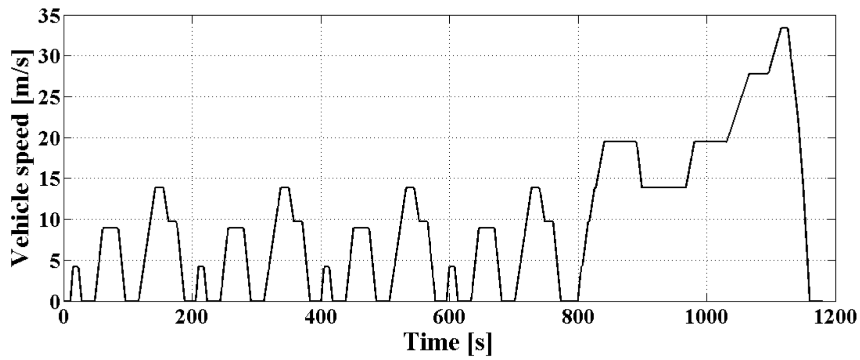

Fig. 6. BEV speed (NEDC cycle).

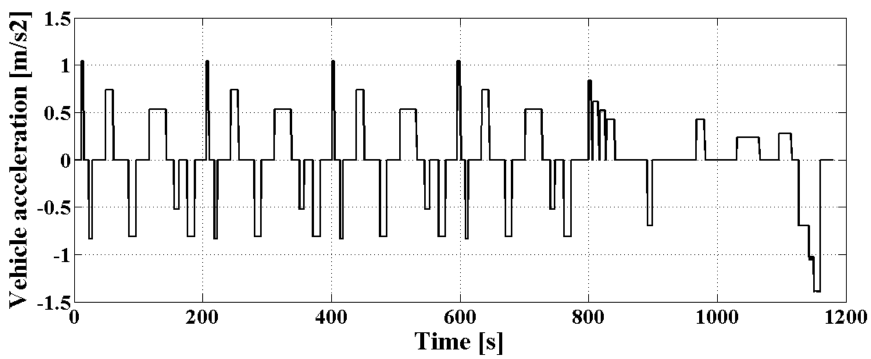

Fig.7. BEV acceleration (NEDC cycle).

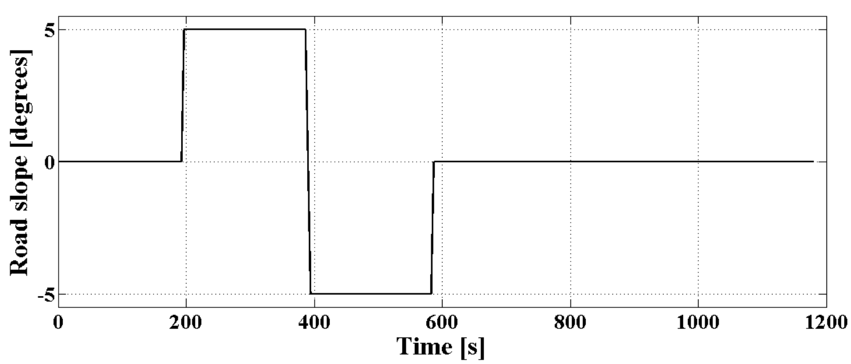

Fig.8. Road gradients (NEDC cycle).

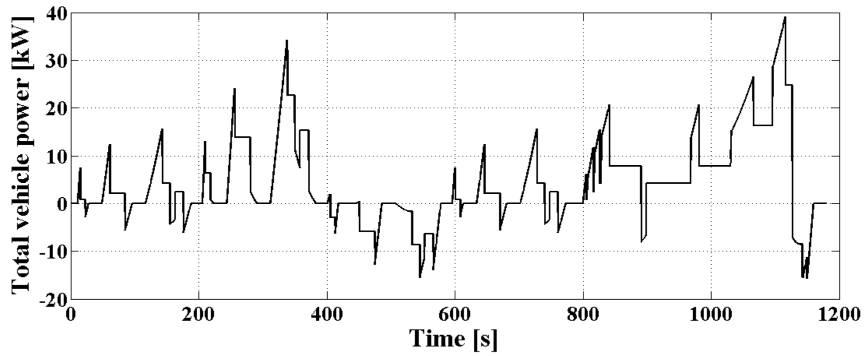

Fig. 9. Total BEV power (NEDC cycle).

In Fig. 6, the BEV speed is presented. It was considered that above 50 km/h (13.8 m/s), the vehicle has a high speed. This is important for the fuzzy-logic supervision system. The BEV acceleration (Fig. 7) has values well below 1.5 m/s2. Two road gradients have been introduced for the second and third ECE-15 cycles (Fig. 8). The BEV climbs a hill with a constant slope of 5 degrees during the second ECE-15 cycle, and then descends a hill with a constant slope of 5 degrees during the third ECE-15 cycle. In Fig. 9, the total BEV power submitted to the power system is shown. It was computed using the methodology presented in [12]. It should be noted that an efficiency of 90% was considered for the drive train from wheels to storage system. Also, only 75% of the recovered energy during braking was considered to be stored into the storage system. The rest is considered lost during classical braking, especially at low speeds. Thus, only 67.5% of the energy available during braking is retrieved to the EB and UC.

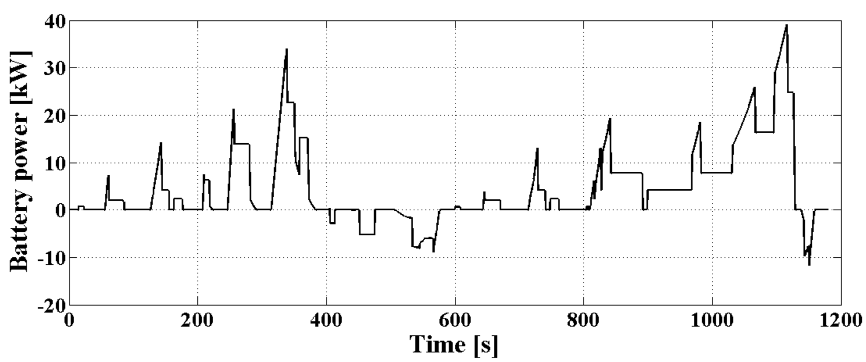

Fig. 10. EB power (NEDC cycle).

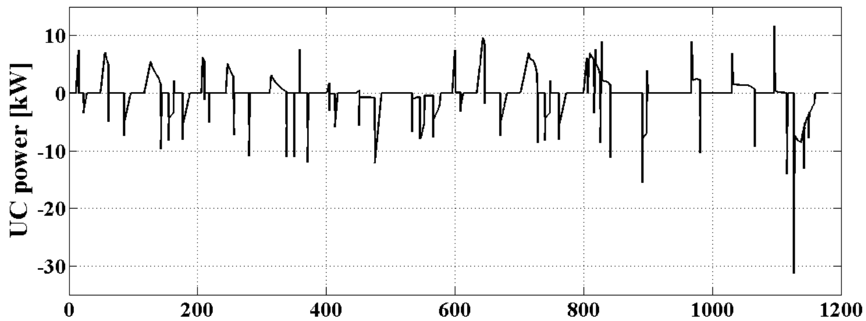

Fig. 11. UC power (NEDC cycle).

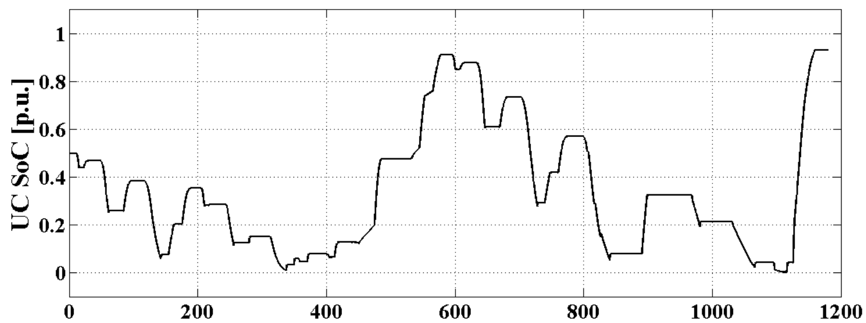

Fig. 12. UC State of Charge (NEDC cycle).

In Fig. 10, the EB power is presented. The number of EB CDCs is reduced, charging being limited only to high speed braking or downhill driving. Fig.s 11 and 12 show the UC power and SoC, respectively. It should be noted that the UC capacity is 250 kJ (from half to nominal voltage). If the power that the UC has to absorb exceeds a certain limit, a dissipative device could be used in order to limit the UC power. The UC SoC varies between 0 and about 0.92 p.u. SoC zero level means that the UCs have discharged to half of their nominal voltage.

A more realistic driving pattern could be considered, the UDDS cycle (Fig. 13). Two simulation tests were performed using this cycle, one with slopes (Fig. 14), and the other one, on flat road. The accelerations or decelerations are more abrupt for this driving cycle (Fig. 15). In order to keep this article within an acceptable number of pages, the results for these two tests are not presented in Figs. but in a table (Table 2).

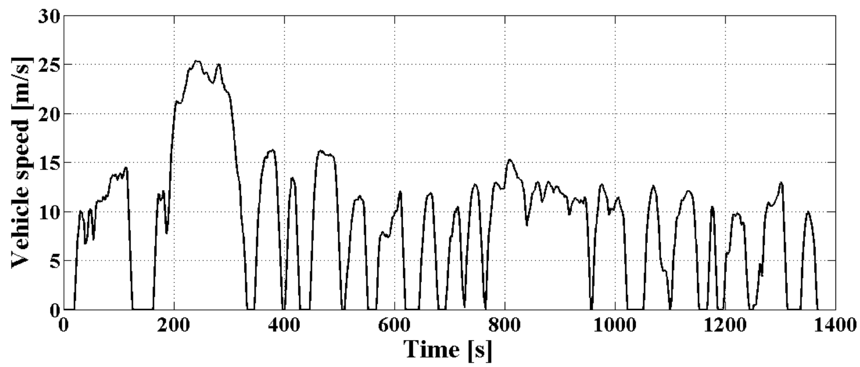

Fig. 13. BEV speed (UDDS cycle).

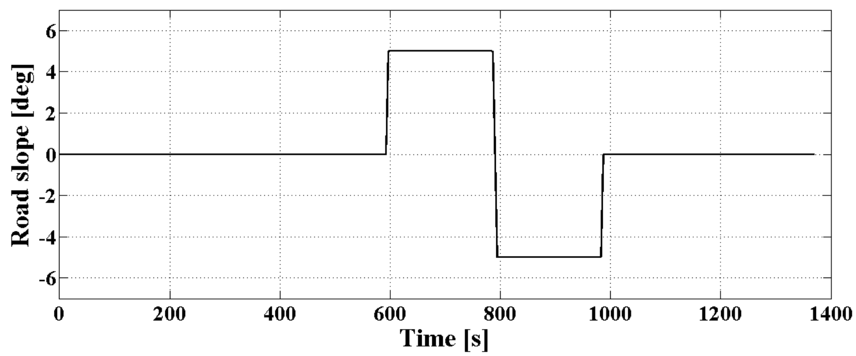

Fig. 14. Road gradients (UDDS cycle).

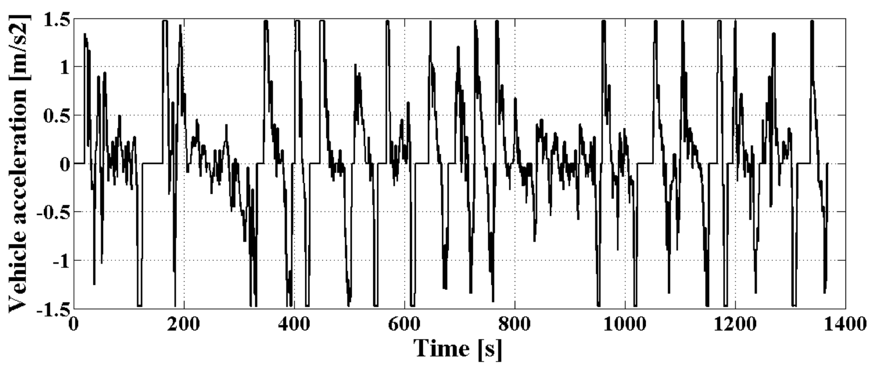

Fig. 15. BEV acceleration (UDDS cycle).

Following the simulation results, Table 2 emphasizes the level of fulfillment for the two main objectives regarding the EB: reduction of the number of CDCs and reduction of the energy processed. It can easily be observed, that CDCs are greatly reduced on any driving cycle (with or without road gradients). This could lead to a significant increase in EB life over a longer period of time, considering that most of the energy recovered during braking is relatively small. This could be the case for Lead-Acid, Ni/Cd, Ni/MH and some Li-based batteries. The EB energy processed is also reduced. It can reach even more than one third of the total energy supplied to the power system. Thus, considering the conclusions stated in [8], the battery life can be increased with a range from 15 to 40 %, much higher for urban vehicles. The capacity of the UCs could be increased over the considered value of 250 kJ in order to accommodate them with the DC/DC converter. This is necessary due to inferior voltage limit of the UCs that the DC/DC converter could accept. For example, if the UCs voltage varies from half the nominal voltage to nominal voltage, 75% of the total energy stored can be exploited. The UCs capacity of 250 kJ was chosen in order to have an important reduction of CDCs and energy processed for the EB (Table 2). An increase or decrease of this capacity will certainly impact on these two parameters.

Table 2

Electrochemical battery facts

EB facts / Driving cycle	Number of CDC without UC	Number of CDC with UC	CDC reduction [%]	Energy processed without UC [kJ]	Energy processed with UC [kJ]	Energy processed reduction [%]
NEDC	12	3	75	7480	6232	16.68
UDDC (with slopes)	37	6	83.7	8894	6332	28.8
UDDC (without slopes)	45	4	91.1	7172	4504	37.2

This supervision strategy could also allow a reduction of the EB capacity when endowing BEV for a presumed longevity. In order to reduce the aging of the EB, PHEV or EV, manufacturers are limiting their depth of discharge. If CDCs are reduced, and the energy processed is also limited, the depth of discharge could be increased, and, thus, the EB capacity could be reduced for the same life expectancy.

6. Conclusion

In this paper, a novel fuzzy-logic supervision strategy, aiming at the increase of the electrochemical battery life for electric vehicle applications, has been presented. Two levels of supervision have been used in order to simplify their development, and to ease their implementation. The results are offering good prospects in terms of battery life improvement by limiting the number of charge/discharge cycles and also the energy processed.

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