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Comparison of energy management strategies of a battery/supercapacitors system for electric vehicle under real-time constraints

Ali Castaings [a,b,c], Walter Lhomme [a,c,*], Rochdi Trigui [b,c], Alain Bouscayrol [a,c]

[a] University of Lille1, L2EP, France
[b] IFSTTAR, Transport and Environment Laboratory, 69675 Bron, France
[c] MEGEVH, French Network on HEVs, France[1]

HIGHLIGHTS

- Effective energy management strategies for a battery–supercapacitor system.
- Optimisation-based and rule-based strategies.
- Supercapacitor voltage limitations taken into account.
- Experimental tests along unknown real driving cycles.

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ABSTRACT

The paper deals with real-time energy management strategies for a hybrid energy storage system including a battery and supercapacitor for an electric vehicle. Besides efficiency concerns, a key issue for real-time applications is ensuring safe operations for the considered system. In such a system it is mandatory to limit the supercapacitor voltage by the energy management strategy to comply with efficiency and safety constraints. An optimisation-based strategy (*λ-control*) and a rule-based strategy (*filtering*) are compared in this paper. The active limitation of the supercapacitor voltage is ensured in both strategies. Experimental results show that the two strategies have equivalent performances under real-driving cycles not known in advance. A difference of 2% between the strategies on the battery current root mean square value is shown. By varying the desired supercapacitor voltage range, the results show that the *λ-control* is better-suited for a high supercapacitor voltage range whereas the *filtering* gives the best performances for a low supercapacitor voltage range.

1. Introduction

The urban travel demand is significantly growing [1]. According to the International Energy Agency the 2012 concentration of CO_2 was about 40% higher than in the mid-1800s [2]. Battery-Electric Vehicles (B-EVs) have a significant potential to reduce transport sector energy and emissions [3]. However, the battery has to perform high current rates in some cases what is harmful for its lifetime [4]. It is important to find out a solution to extend the battery lifetime in EVs in order to make them viable.

Hybrid energy storage systems (H-ESSs) using a battery and supercapacitor (SCs) are a possible solution to enhance the lifetime of the battery in EVs [5]. Indeed, current battery technologies do not allow more than tens of thousands of charge–discharge cycles while the lifetime of SCs is over half a million cycles. Many kinds of associations (passive and active) have already been studied [6,7]. Passive association does not require any expensive power electronic converters but the SCs stored energy cannot be effectively used. Active association allows both the SC voltage to vary in a wide range and the battery voltage to be lower than the DC bus voltage. That results in a reduced number of battery cells in series and an effective use of the SC stored energy. However it requires two full-size bidirectional converters to interface the battery and

Abbreviations: EMR, Energetic Macroscopic Representation; EMS, energy management strategy; EV, electric vehicle; H-ESS, hybrid energy storage system; SC, supercapacitor; SoC, State of Charge; RMS, root mean square.

* Corresponding author at: University of Lille1, L2EP, France.
E-mail address: Walter.Lhomme@univ-lille1.fr (W. Lhomme).

[1] megevh.univ-lille1.fr.

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Nomenclature

f_0	filtering cut-off frequency (Hz)
H	Hamiltonian
i_{b_ref}	battery current reference (A)
$i_{b\_ref\text{-}filt}$	filtering low-pass filter output (Hz)
i_b	battery current (A)
i_{bm}	battery current minimum level (A)
i_{bM}	battery current maximum level (A)
i_{dc}	DC–DC converter modulated current (A)
i_L	inductor current (A)
i_t	traction current (A)
J	optimisation performance criterion (A)
OCV	battery open-circuit voltage (V)
P_b	power of the SCs bank (W)
P_{dc}	DC–DC converter output power (W)
P_{tract}	traction drive power (W)
R_b	battery series resistance (Ω)
r_L	inductor series resistance (Ω)
u_b	battery voltage (V)
u_{dc}	DC–DC converter modulated voltage (V)
u_M	SC voltage maximum level (V)
u_m	SC voltage minimum level (V)
u_{M1}	SC voltage intermediary maximum level (V)
u_{m1}	SC voltage intermediary minimum level (V)
u_{SC}	SC voltage (V)
Z_{CPE}	constant-phase-element impedance (Ω)
α	DC–DC converter duty cycle
η	DC–DC converter efficiency
η_g	global efficiency between the inductor and the DC–DC converter
λ_0	λ-control initial Lagrange multiplier value
λ_{ref}	λ-control Lagrange multiplier reference

SC and can be then bulky and expensive. Since it yields a balance between cost and performance, the use of a single DC–DC converter for SC interfacing is often studied [8]. For the studied architecture the battery is directly connected to the DC bus of the vehicle.

A key issue in battery–supercapacitors systems is the energy management. It means defining the best power flows sharing to enhance the battery lifetime. A relevant way to achieve this objective is to control the battery current to limit the battery stress [9]. The energy management strategy (EMS) aims to determine the best-suited battery current reference value. Two approaches have been depicted in the literature [10], EMSs using rule-based approach [11,12] and EMSs using optimisation-based approach [13–15].

Off-line optimisation-based strategies lead to the best performances. However, due to high computation and memory resources requirements they are not viable for real-time applications. Moreover the driving cycle has to be known in advance to use these strategies. Rule-based strategies are viable for real-time implementation but do not ensure the best performances. Some simplified optimisation-based EMSs allow real-time implementation [16]. Moreover, a combination of both approaches is used in some works. For instance Zhang et al. used and optimisation-based EMS, dynamic programming, in order to design a rule-based strategy [17]. Santucci et al. have proposed to organise the energy management of a three sources Hybrid Electric Vehicle (HEV) in two level. The first level was managed by an optimisation-based EMS while the second level can be managed by a rule-based or an optimisation-based EMS [18]. Whatever the approach for the EMS, the variations of the driving cycle affect the EMSs performances. Indeed, the EMSs parameters are usually determined for a specific driving cycle that represents an ideal case (known in advance). Furthermore, since it concerns safety, it is mandatory to limit the SC voltage in such a system (overcharges). For off-line applications these limitations are managed in a passive way. In this case the EMS parameters choice allows keeping the SC voltage within its limitations. It is only suitable for the driving cycle known in advance. The variations of the driving cycle require an active SC voltage limitation to comply with this requirement for all possible driving cycles. That means forcing the SC voltage to stay within its range by implementing a limitation method.

A variety of real-time EMSs for battery–SCs systems have been depicted in the literature. Wang et al. have proposed a real-time optimisation-based EMS for a battery–SCs H-ESS using a single DC–DC converter. A validation on a standard urban driving cycle ECE-15 considered known in advance has been performed [19]. The study was performed without using an active SC voltage limitation. This strategy was then not viable for real-time conditions since the safety of the system was not ensured. Song et al. have proposed a comparative study between three rule-based EMSs and a Model Predictive Controller (MPC) for this kind of battery–SCs H-ESS [20]. The study was performed by taking into account the SC voltage limitations with a hysteresis controller for all the EMSs. Simulation tests have been made using two driving cycles, a real driving cycle known in advance and the European driving cycle NEDC considered as not known in advance. In this study the SC voltage limitations practically never occurred, what represents an ideal case where the SCs are large enough to fulfil all power demands from all possible driving cycles. Armenta et al. have proposed a rule-based EMS for the same architecture of battery–SCs HESS [21]. The impact of the SC voltage limitations has been highlighted in terms of energy recovery form regenerative braking. However, the proposed EMS has been tested by simulations over three normalised driving cycles what does not totally reflect real driving conditions. Nguyen et al. have proposed a comparative study of two real-time EMSs using both approaches by simulation for a battery–SCs architecture using a unidirectional DC–DC converter [22]. The study was performed on a standard driving cycle (Artemis Extra-urban) considered known in advance. As a consequence the EMSs were tested in an ideal case since they were defined for the driving cycle. Also the SC voltage limitations occurred for a very short time what is not realistic for real-time conditions Furthermore, Allègre et al. have proposed a comparative study of two rule-based EMSs applied on a two converters battery–SCs system. Experimental tests have been performed using the ECE-15 driving cycle [23]. Since the driving cycle was particularly soft, the SC voltage limitations did not often occur. Trovão et al. have proposed an energy management strategy using optimisation and rule-based approach for a two converters battery–SCs system [24]. The EMS has been validated using experimental tests over a normalised driving cycles Artemis. Since the SCs bank size was well-suited for the driving cycle the SCs voltage limitations practically never occurred. Florescu et al. have proposed a rule-based energy management strategy for the same topology of battery–SCs HESS [25]. The SC voltage limitations have been taken into account by using a feedback control on the SC voltage. The EMS has been validated in real time over a "soft" normalised driving cycle (ECE 15) and a real driving cycle. The impact of the SCs voltage limitations on the proposed rule-based EMS was not studied in this work.

The objective of this paper is to compare two EMSs of a battery–supercapacitors system for electric vehicle by assessing the impact of the real-time limitations of the supercapacitor