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Adaptive frequency-separation-based energy management system for electric vehicles

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HIGHLIGHTS

- This paper deals with EMS design on board of electric vehicles (EV).
- A battery and an ultracapacitor are used as primary and secondary source, respectively.
- An adaptive-frequency splitter is used for power sharing between the two sources.
- The proposed EMS is validated by real-time experiments on a dedicated test rig.
- This power source coordination method can be generalized to microgrids.

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ABSTRACT

This paper deals with an adaptive frequency-based power sharing method between batteries and ultracapacitors (UC) as power sources within an electric vehicle. An adaptive frequency splitter is used for routing the low-frequency content of power demand into the battery and its high-frequency content into the UC system, taking profit from the UC as a peak power unit. Autonomy may thus be increased while preserving battery state of health and ensuring that UC voltage variations remain confined within certain desired range. Results obtained by real-time experiments on a dedicated test rig validate the proposed energy management approach and recommend it to be applied as power source coordination method to microgrids in general.

1. Introduction

Technologies employed for all-electric vehicle embedded grids are various, but they are almost invariantly based on batteries [1,2]. Battery management systems depend on their manufacturing technology and applications, being oriented towards improving battery reliability and extending its life duration [3]. A known solution to battery ageing problem consists in its association with ultracapacitor (UC) banks [1]. Indeed, such hybridization provides an additional degree of freedom to reduce battery current variations. Being able to support sudden, high-frequency variations of power demand, UCs are nowadays effective for managing power flows within various electrical system applications such as uninterruptible and portable power supplies, renewable energy conversion systems, *etc.* [4]. Their high charging/discharging efficiency, fast charging, long life cycle, relatively high specific power, wide operating temperature range, *etc.*, allow to use UCs as high-power-density supplies, mostly recommended to supplement main high-energy-density sources such as fuel cells or lead-acid batteries, which are specialized to cover low-frequency variations of power demand [5–8]. In this way, hybridization of power sources together with suitable power sharing strategy improves exploitation conditions of main source (*e.g.*, battery), thus contributing at reducing ageing effect and capacity loss [9,10].

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Nomenclature

EV	electric vehicle
UC	ultracapacitor
PMSM	permanent-magnet synchronous motor
EMS	energy management system
PSS	electric vehicle's power supply system
DE	driver environment
T, T_{ref}	separation filter time constant and its reference, respectively
Ω_M, T_M	motor rotational speed and torque
v_{DC}, i_{DC}	DC-link voltage and current
i_L	load current
v_{bat}, i_{bat}, v_{UC}, i_{UC}	battery and UC voltages and currents
i_1, i_2	currents supplied into DC-link by battery and UC, respectively
α_{bat}, α_{UC}	battery and UC converter duty ratios

Such hybrid power supply structure, consisting of an accumulator battery as main source and a UC pack as secondary source, both coupled on a common DC link, is considered in this paper in the context of an electric vehicle (EV) application. Road electric vehicles typically require a significantly variable and random load current in response to unsteady traffic conditions, especially in urban areas (frequent sequences of acceleration and deceleration, up-hill followed by down-hill runs, *etc.*). In this context, the EV power supply system must ensure a certain power sharing strategy between battery and UC packs, depending on application and battery type. Thus, in some applications UCs are designed to optimize batteries power ratings; therefore, they are used to regulate peaks and valleys of the power required. In this paper it is required that battery current variations to be reduced according to some *a priori* established proper operation conditions – which depend on manufacturing technology of battery and exploitation conditions – irrespective of the driving conditions. In this way, battery reliability parameters are preserved through a more regular exploitation, whereas sudden peaks of power demand are provided by the UCs. This corresponds to a strategy that ensures low-frequency variations of load power demand being ensured by the battery and high-frequency variations by the UC. An energy management system based on using a *fixed-frequency* separation filter has been previously proposed and validated by real-time simulation [11,12]. A recent experimental validation of this type of power sharing strategy on a battery/ultracapacitor hybrid supply system is reported in Ref. [13]. The *adaptive* frequency-separation-based power sharing method proposed here employs a splitting filter whose folding frequency is rendered variable in real time depending on UC state of charge and load current sign. In this way, reasonable UC exploitation – by confining its voltage within some admissible limits – can also be ensured.

Various applications that illustrate the sustainable development – such as renewable energy conversion systems [14–17] or off-grid applications, more electric aircrafts [18,19], smart house [20] or hybrid and electric vehicular applications [21–27,56] – make wide use of multisource – or otherwise hybrid – supply systems. This is the reason why rich research investigation is focused on such systems and design of their power flow management strategies that rely on use of advanced control design methods.

Design of well-performing strategies of power sharing inside multisource supply systems explored in this paper has already been approached in the literature, among which one can cite rule-based or fuzzy logic approach [22,28–30,57], frequency-separation approach by polynomial control design [31,32], model-predictive control [33], nonlinear approaches based on Lyapunov design techniques [34] and control with reference filtering [11–13,35,36]. The latter approach has offered a departure point for developing our adaptive strategy; this relies on considering the power sources as current-controlled sources whose references result by filtering a global reference provided by an upper control level according to frequency-domain specialization of sources. In this paper a new degree of freedom is added – the filter folding frequency – which is adjusted in real time to allow more flexible operation. No assumption about load power demand is needed – only that this is frequency-bounded, which is perfectly realistic – neither it is necessary to be measurable; instead, it is sufficient to have information about the current exchanged through DC link, as it is an image of load power, provided that DC-link voltage is maintained at some constant reference level.

This paper is organized as follows. Section 2 presents the electric vehicle power configuration under study. Section 3 presents the main modelling results of subsystems within the global power supply system. The structure and basic idea of the proposed adaptive frequency-separation-based energy management system (EMS) are given in Section 4. Details on basic control design are presented in Section 5, whereas Section 6 presents design guidelines for the proposed EMS. The dedicated hardware-in-the-loop-simulation test bench that served for validation is presented in Section 7; the real-time physical simulation results obtained on it are discussed in Section 8. Section 9 concludes this paper and mentions some issues for further investigation.

2. Electric vehicle power configuration

Fig. 1 presents the configuration of the considered electric vehicle power architecture, with emphasis on the main interactions between the various subsystems of the vehicle.

Vehicle power supply system (PSS) is hybrid, composed of an electrochemical battery pack as main source and an auxiliary source employing ultracapacitors [37]. Both sources use synchronous rectifiers in order to supply the common DC-link. This dual DC-DC-converter configuration [38,39] offers flexibility in terms of management by allowing that both sources' currents to be directly controlled. The two DC–DC converters, based upon PWM-controlled IGBTs, allow bidirectional power flow: from the sources to the load (discharging mode) and from the load into the sources (charging mode) [40].

Notations in Fig. 1 are as follows: R_{bat} is battery internal resistance, v_{bat} is battery open-circuit voltage, L is the converter inductance (the same for both battery and UC DC–DC converters), C_{DC} and R_{DC} are the DC-link capacity and resistance, respectively, C_{UC} and R_{UC} are the UC capacity and internal resistance, respectively, α_{bat} and α_{UC} are converter duty ratios for battery and UC, respectively.

Vehicle dynamics and its electromechanical drive compose the so-called driver environment (DE), which is submitted to external perturbations due to the driving conditions and vehicle speed reference variations (driver behaviour). The driver environment also interacts with the PSS by draining power from its DC-link.

Electric traction is performed by permanent-magnet synchronous motor (PMSM) which can be controlled either as a motor (when accelerating) or as a generator (when braking). In the latter regime electric power is recovered and used for charging sources. The driver itself acts as a speed controller to track the vehicle speed setpoint. The PMSM is torque controlled by means of a three-phase voltage source inverter coupled to the DC-link. A classical vector control structure [41] makes effective the current/torque imposed