Journal of Power Sources 374 (2018) 237–248

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review article

Hybrid battery/supercapacitor energy storage system for the electric vehicles

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HIGHLIGHTS

- The impact of the HESS system on overall efficiency of the EVs is discussed.
- The importance of the design and configuration of the HESS is reviewed in detail.
- The effect of ambient temperature on system performance is discussed.
- The significance of the EMS on system performance is discussed.

ARTICLE INFO

Keywords:
Hybrid energy storage system
Battery
Supercapacitor
Electric vehicles
Regenerative braking

ABSTRACT

Electric vehicles (EVs) have recently attracted considerable attention and so did the development of the battery technologies. Although the battery technology has been significantly advanced, the available batteries do not entirely meet the energy demands of the EV power consumption. One of the key issues is non-monotonic consumption of energy accompanied by frequent changes during the battery discharging process. This is very harmful to the electrochemical process of the battery. A practical solution is to couple the battery with a supercapacitor, which is basically an electrochemical cell with a similar architecture, but with a higher rate capability and better cyclability. In this design, the supercapacitor can provide the excess energy required while the battery fails to do so. In addition to the battery and supercapacitor as the individual units, designing the architecture of the corresponding hybrid system from an electrical engineering point of view is of utmost importance. The present manuscript reviews the recent works devoted to the application of various battery/supercapacitor hybrid systems in EVs.

1. Introduction

The use of electric vehicles (EVs) was first prompted by the California Air Resources Board (CARB), as a strong signal was sent out to reduce pollution from automobile users. The preliminary works suggested that the obstacles against the wide adaption of the EVs can be overcome and the fuel economy requirements can be met if the battery designers are directly worked with the development team of the vehicle electrical system to improve the power and energy density, as well as cycle life of the batteries [1,2]. The batteries lose their performances over time for several reasons associated with the properties of the electroactive materials, conductivity and chemical stability of the current collectors, selection of the electrolytes compatible with the morphology of the electrodes, redox activities of the additives in electrodes or in electrolytes, as well as overcharging, internal and external environment and the application specifications.

Although significant advancements have been made during the past decades to improve the battery performance, the main problem comes from the peak usage. Even in small electronic devices such as mobile phones and laptops, the battery damage occurs upon sudden usage of the battery's energy. This situation is constant in EVs, as different factors such as driving style, road, etc., cause rapid changes in the power consumption. A battery performs well when it is discharged monotonically because the corresponding electrochemical reaction can proceed monotonically. However, when EV requires the sudden power consumption during its acceleration, the battery pack cannot be discharged quickly enough to satisfy this requirement. The same applies to a high current storage into the batteries that generated during the braking of the EV. These fluctuating flows of a high electric current into and from the battery could have a detrimental effect on the electrolytes. When this acceleration/braking is repetitive (city driving for example), this can shorten the life of the batteries.

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https://doi.org/10.1016/j.jpowsour.2017.11.040
Received 22 June 2017; Received in revised form 20 October 2017; Accepted 10 November 2017

Nomenclature

ADVISOR	Advanced Vehicle Simulator
BMS	Battery Management System
BE	Braking Energy
BPR	Buffer-Power Ratio
BD-DC/DC-C	Bidirectional DC/DC converter
CBDC	China Bus Driving Cycle
CP	Constant Power
DC	Duty Cycle
DP	Dynamic Programming
DM	Dynamic model
ECE-15	Economic Commission for Europe-urban driving cycle
EDLC	Electric (or Electrochemical) Double-Layer Capacitor
EIS	Electrochemical Impedance Spectroscopy
EMS	Energy Management System
EP	Each Pulse
ESS	Energy Storage Systems
EUDC	Extra-Urban Driving Cycle
EV	Electric Vehicle
Ch/Dch	Charge/discharge
GPS	Global Positioning System
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HV	High Voltage
LEV	Law Emission Vehicle CARB - California Air Resources Board
Li-ion	Lithium-Ion
$LiFePO_4$	Lithium Iron Phosphate (LFP)
LV	Low Voltage
MCS	Mobile Charging Stations
NEDC	New European Driving Cycle
Ni-MH	Nickel-Metal Hydride
OCV	Open Circuit Voltage
OPM	Optimal Power Management
PbA	Lead Acid
PSAT	Powertrain System Analysis Toolkit
PU	Power Unit
RB	Regenerative Breaking
RBE	Regenerative Breaking Energy
RE	Regenerative Energy
SC	Supercapacitor
SOC	State of Charge
SOD	State of Discharge
SOH	State of Health
UDC	Urban Driving Cycle or ECE-15
UDDS	Urban Dynamometer Driving Schedule
VRLA	Valve-Regulated Lead-Acid
VTB	Virtual Test Bed
V2G	Vehicle-to-grid
ZEBRA	Zero Emission Battery Research Activity
ZVS	Zero-Voltage Switching
ZVT	Zero-Voltage Transition

Various types of batteries have been utilised in EVs [3–6], but the most promising one is the lithium-ion (Li-ion) battery, which is now the most common type of energy storage in portable electronic devices such as mobile phones and laptops. Scaling up the Li-ion batteries for EVs is not straightforward due to the different pathway of energy consumption in the EVs as compared with the small electronic devices. Therefore, novel Li-ion batteries should be designed for the EV applications. In modern Li-ion batteries, there is a demand for sacrificing the classically high cell voltage in favour of improving other factors such as rate capability or cyclability [7], and the electrode materials should be chosen for specific applications. For example, as will be reviewed later, most of the Li-ion batteries employed for the EV applications are designed for a sudden power consumption based on $LiFePO_4$, which is not the dominant cathode material in the small Li-ion batteries, but has huge potentials for high rate capabilities and excellent cyclability in the EV performance [8].

Supercapacitors (SCs) are similar electrochemical systems for the energy storage, but the main difference is that they have high rate capability for fast charging/discharging. They cannot be used as the power source of EVs since they have low energy density as compared with the batteries. Nevertheless, they are good options to compensate the high peak of usage during short periods of time when the battery power is not sufficient. In this scenario, the responsibility of the coupled SC is similar to that on the classic capacitors in electronic devices to supply electricity instantaneously.

The electrical response of SCs is an analogous to that of the classic capacitors, but as the prefix suggests, the specific capacitance is much higher. The term "supercapacitor" was commercially utilised to describe the first generation of double-layer capacitors, but in the scientific context, it was referred to the electrochemical systems working based on capacitive or pseudo capacitive behaviours. The performance of the so-called pseudo capacitors is based on the electrochemical redox system rather than double layer charging. This provides an opportunity for delivering a significantly higher specific capacitance, though, the cyclability is much worse. However, many of the available SCs utilize both mechanisms. It has been highlighted in many published literature [9–14] that SC's can effectively operate longer than any other energy storage systems (ESS).

The combination of the battery-SC is known as a hybrid energy storage system (HESS), which complements advantageous properties of each modules. In this arrangement, the detrimental effect of the current fluctuation on the battery is reduced and its operational time is prolonged. This is an essential aspect for the HESS use. Fig. 1 illustrates new opportunities provided by the HESS.

The use of the HESS has not limited only for the shielding the distractive current spikes to the batteries but in addition, the HESS is an efficient storage system in the EVs. The HESS could increase the efficiency of the EVs by storing the energy from brakes during the

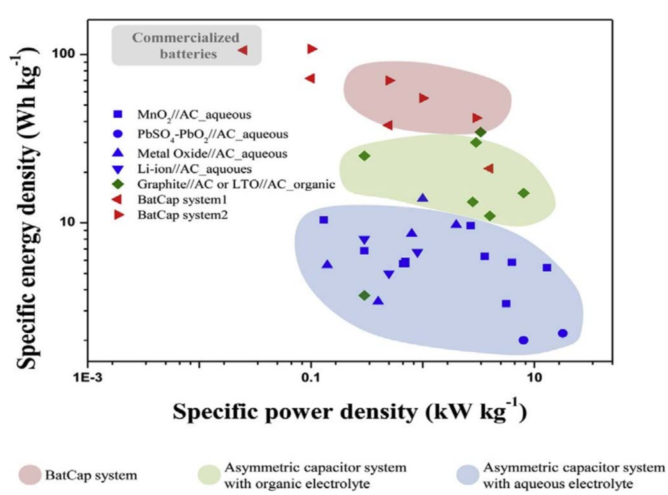

Fig. 1. Specific power density-specific energy density plot of typical commercialized batteries (grey region), an asymmetric capacitor system with an aqueous electrolyte (blue region), an asymmetric capacitor system with an organic electrolyte (green region), and the BatCap system (red region) using various electrode materials. Reproduced with permission from Ref. [15]. Copyright 2014, Elsevier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)