Journal of Power Sources 241 (2013) 112–120

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

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

Modeling and experimental validation of a Hybridized Energy Storage System for automotive applications

Simone Fiorenti [a,1], Jacopo Guanetti [a,1], Yann Guezennec [a,b], Simona Onori [a,*]

[a] *Center for Automotive Research, The Ohio State University, Columbus, OH 43212, USA*
[b] *Mechanical and Aerospace Engineering Department, The Ohio State University, Columbus, OH 43212, USA*

HIGHLIGHTS

- Experimental identification of equivalent electric circuit lead-acid battery model.
- Experimental identification of equivalent electric circuit supercapacitor model.
- Development of lead-acid battery + supercapacitor system for Start&Stop applications.
- Comparative analysis between battery vs. hybrid system for Start&Stop applications.

ARTICLE INFO

Article history:
Received 28 December 2012
Received in revised form
2 April 2013
Accepted 5 April 2013
Available online 22 April 2013

Keywords:
Circuit models
Dynamic models
Energy storage
Identification
Validation

ABSTRACT

This paper presents the development and experimental validation of a dynamic model of a Hybridized Energy Storage System (HESS) consisting of a parallel connection of a lead acid (PbA) battery and double layer capacitors (DLCs), for automotive applications. The dynamic modeling of both the PbA battery and the DLC has been tackled via the equivalent electric circuit based approach. Experimental tests are designed for identification purposes. Parameters of the PbA battery model are identified as a function of state of charge and current direction, whereas parameters of the DLC model are identified for different temperatures. A physical HESS has been assembled at the Center for Automotive Research The Ohio State University and used as a test-bench to validate the model against a typical current profile generated for Start&Stop applications. The HESS model is then integrated into a vehicle simulator to assess the effects of the battery hybridization on the vehicle fuel economy and mitigation of the battery stress.

1. Introduction

The trend in automotive market is nowadays toward the design of vehicles achieving better fuel economy and lower pollutant emissions. Several Hybrid and Plug-in Hybrid Electric Vehicles (HEVs and PHEVs) are now available on the market and are experiencing a fair commercial success, albeit they come with a significant increase in their powertrain complexity and cost, if compared to conventional vehicles [1]. On the other hand, Mild Hybrid Vehicles (MHVs) and the vehicles equipped with Start&Stop technology can still improve the fuel economy and reduce pollutant emissions, and are regarded as short and medium term solution.

In MHVs and Start&Stop applications PbA batteries play a dominant role for their lower cost and their simplicity of use. Nonetheless, more frequent engine starting and in some cases high charging currents due to regenerative braking can result in accelerated aging of the battery. Using a bigger battery or coupling the battery with another energy storage device could, in principle, mitigate those side effects. In this paper we look at the feasibility of a Hybridized Energy Storage System (HESS) involving PbA batteries and DLCs. Compared to PbA batteries, a typical DLC has higher power density but can store a lower amount of energy, as it is shown in Fig. 1. The underlying idea in the HESS is that the DLC delivers the high current peaks, while the battery processes only the average current.

In this paper, we propose a methodology for developing and experimentally identifying the models of the PbA battery and of the DLC. By connecting these two models in parallel, a model of the HESS is obtained, which is experimentally validated through tests designed with the purpose of reproducing the power requirements

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* Corresponding author. Tel.: +1 614 247 1855; fax: +1 614 6884111.
E-mail addresses: simone.fiorenti@gmail.com (S. Fiorenti), jacopoguanetti@gmail.com (J. Guanetti), onori.1@osu.edu (S. Onori).

[1] These authors contributed equally to this work.

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http://dx.doi.org/10.1016/j.jpowsour.2013.04.017

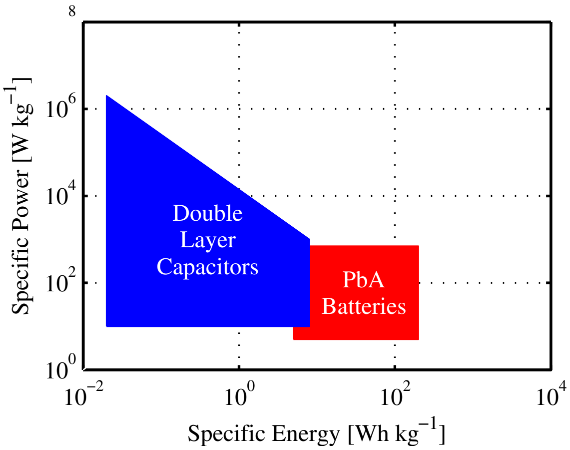

Fig. 1. Ragone plot for PbA batteries and DLCs [2].

of a vehicle equipped with the Start&Stop technology. The HESS model and the PbA battery model are integrated into a vehicle simulator; the operation of the vehicle is simulated both with the standalone PbA battery and with the HESS, and with and without the Start&Stop technology. The vehicle fuel economy and the battery stress are evaluated in these four different scenarios.

The paper is structured as follows: in Section 2 a brief introduction to the modeling problem of electrochemical devices such as batteries and DLCs is given; moreover, a review of some previous literature on HESSs consisting of PbA batteries and DLCs is discussed. Section 3 describes the experimental set-up used to test the PbA battery, the DLCs and the HESS. In Sections 4 and 5 the dynamic model of the PbA battery and the DLC are developed and experimentally identified. Section 6 describes the experimental validation of the HESS model. In Section 7 the model of the HESS is integrated in a vehicle simulator and the energetics of the energy storage systems are investigated through a simulation study. In Section 8 final remarks are discussed.

2. PbA battery, DLC and HESS modeling approaches

The PbA battery is the oldest type of rechargeable battery [3]. It is characterized by low energy density and relatively high power density. These features, the low cost and the simplicity of usage (no Battery Management System is needed) make PbA batteries well suited for automotive applications which do not involve a high degree of hybridization. Moreover, being the natural choice for conventional vehicles, in which the main requirement is to provide the cranking power to start the engine, PbA batteries are a good candidate for the lower levels of hybridization like Start&Stop and MHVs.

On the other hand, the DLC technology has come out over the last few decades. A DLC, also called supercapacitor or ultracapacitor, is an electrochemical device with extremely higher energy density compared to a conventional capacitor [4]. Its power density, although generally lower than the conventional one, is still significantly higher compared to batteries, as shown in Fig. 1. This feature makes it well suited for all those applications which require high levels of power without demanding a high level of energy and it can conveniently be used together with other devices, such as batteries, to increase their power capability.

Modeling PbA batteries [5–7] and DLCs [8–14] has been the subject of extensive research over the past decades.

Approaches to both PbA batteries and DLC modeling can be divided in three groups: electro-chemical models, data-driven models and equivalent circuit based models.

Manufacturers may use sophisticated, high order electrochemical models in order to improve the design of new devices [15,16]; although the device's behavior is well represented over a wide operating range, the complexity of the model itself makes this type of modeling approach unsuitable for the purpose of the present work.

Data driven models have been proposed (for instance, [14]) that do not have an *a priori* model structure or a direct physical meaning. The structure and the values of the parameters are tuned in order to get the best fitting of the experimental data. The data-driven approach generally leads to high order models and requires a large amount of data and computational resources.

Finally, the modeling approach which best meets the needs of this work is the one based on equivalent electric circuit representation of the devices. The order of the model is usually selected so as to have a good trade-off between accuracy and complexity [17–22].

The main objective of this work is the modeling of an HESS intended for Start&Stop applications, capable on one side to capture the most significant electrical dynamics of the systems and be reasonably accurate over the operating range of relevance, and on the other side to be simple enough to keep the parameter identification effort low.

In this work the choice is to use a 1st order equivalent circuit model for the battery (discussed in Section 4) and a 2nd order model for the DLC (discussed in Section 5) thus turns out to be a good compromise between complexity (from both the identification and the simulation standpoint) and accuracy over a reasonable time scale.

HESSs for automotive applications have been fairly studied in the last decade. They may be categorized into passive HESSs and actively controlled HESSs; the former are simply the parallel connection of a battery module and a DLC module, whereas the latter also involve a power electronic interface which actively controls the power flow between battery, DLC and load.

Passive HESSs consisting of a PbA battery and a DLC are investigated in Refs. [23,24], where simple models are used to size the components and analyze the interactions between battery and DLCs.

Actively controlled HESSs have been studied in more detail in the literature. HESSs consisting in PbA batteries and DLCs are investigated in Refs. [19,25–28]. In these works, the applications range from simple on-vehicle energy storage to solutions for battery life extension.

Not only PbA batteries, but also Li-ion batteries have been proposed for the usage in HESSs. In Refs. [29–32] an actively controlled Li-ion battery – DLC hybrid system for portable applications was investigated. Ref. [33] investigates the energy-power performance of an active HESS involving Li-ion batteries, intended for pulsed applications. On the other hand, [11] presents an identification method for both the Li-ion battery and the DLC, based on Electrochemical Impedance Spectroscopy.

Although a fair amount of work has been done on HESSs, with particular regard to actively controlled HESSs, a straightforward methodology for the modeling and experimental validation of a passive PbA battery-DLC HESS is still lacking.

3. Experimental set-up

The experimental set-up used to test a PbA battery, a DLC and a HESS is shown in Fig. 2. It consists of a programmable power supply, an electronic load, an environmental chamber, a data acquisition board, a computer and current, voltage, temperature sensors. The power supply and the electronic load are connected in parallel and remotely controlled through a PC; the current profile is submitted to the equipment through a LabView interface and actuated by either the supply or the load, depending on the current charge/discharge event.