Journal of Power Sources 267 (2014) 566–575

Contents lists available at ScienceDirect

Journal of Power Sources

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

Control design for robust tracking and smooth transition in power systems with battery/supercapacitor hybrid energy storage devices[☆]

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HIGHLIGHTS

- Control design problems addressed for battery/supercapacitor hybrid energy systems.
- Active current control implemented via two bi-directional buck–boost converters.
- Controller designed via efficient numerical optimization.
- Robust tracking achieved for regulating battery current and dc-bus voltage.
- Smooth transition achieved during load switch.

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form
27 March 2014
Accepted 7 May 2014
Available online 2 June 2014

Keywords:
Battery
Supercapacitor
Hybrid energy storage
dc–dc Converter
Robust tracking
Smooth transition

ABSTRACT

This paper considers some control design problems in a power system driven by battery/supercapacitor hybrid energy storage devices. The currents in the battery and the supercapacitor are actively controlled by two bidirectional buck–boost converters. Two control objectives are addressed in this paper: one is to achieve robust tracking of two reference variables, the battery current and the load voltage, the other is to achieve smooth transition of these variables during load switch. Based on the state-space averaged model we newly developed, the control design problems are converted into numerically efficient optimization problems with linear matrix inequality (LMI) constraints. An experimental system is constructed to validate the control design methods.

1. Introduction

Batteries and supercapacitors have been combined into hybrid energy storage devices which have both the high energy density of the batteries and the high power density of the supercapacitors. The main function of supercapacitors in a hybrid energy storage system is to provide high currents during hard transience such as motor start, which is essential to protecting the batteries from fatal damages caused by over-discharge. Supercapacitors are also used to absorb excess current when wind/solar power is abundant, and to store energy from regenerative braking. The battery/supercapacitor hybrid energy storage systems have been widely used in electric, hybrid and plug-in hybrid electric vehicles, e.g., see Refs. [1–4]. They have also found applications in wind systems [5–7], communication systems [8], photovoltaic systems [9], and micro-grids [10]. In some hybrid electric vehicle applications, the hybrid energy storage system also include fuel cells as one power source [11–13].

There are various configurations to combine batteries and supercapacitors. The advantage and disadvantage of each configuration are discussed in Refs. [3,14–16]. In Ref. [17], the performance of different configurations were compared via simulation on a stand along power system. The simplest configuration is to connect the battery and the supercapacitor in parallel. This will reduce the current stress of the battery but the two power sources need the same voltage and the power flow cannot be controlled. To achieve active control of currents, especially the current from the battery,

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[☆] Research supported by the National Science Foundation under grants ECCS-0925269, 1200152.

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http://dx.doi.org/10.1016/j.jpowsour.2014.05.061
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dc–dc converters are needed to connect the power sources and the load or dc bus. In some configurations [18–21], one dc–dc converter is used to connect the battery and the supercapacitor.

The most commonly used configuration contains two bidirectional buck–boost converter connected in parallel at the load side, and fed by a battery and a supercapacitor respectively, see Fig. 1. The advantage of this configuration is that both the current from the battery and the current from the supercapacitor can be actively controlled. Such a configuration has been considered, for example, in Refs. [8,14,16,22]. Similar configurations have been used to combine fuel cells and supercapacitors, e.g., in Ref. [11], where the fuel cell is connected to the dc bus via a one-directional boost converter. In Ref. [23], three buck–boost converters were connected in parallel to combine three power sources. For the configuration in Fig. 1, different strategies have been proposed to actively control the current flow from the battery and the supercapacitor.

A common strategy is to use a certain power management algorithm to determine a reference current that is needed from the battery or the supercapacitor, then use decentralized reference tracking control, typically PI control, on each dc–dc converter to track the respective reference current. In Ref. [24], one algorithm was proposed for maximum efficiency and the other algorithm for minimal battery current to prolong the life span of batteries. In Ref. [16], a power management algorithm was proposed for minimization of the magnitude/fluctuation of the battery current and energy loss. In Ref. [25], three piecewise linear functions were proposed for allocating the battery current and supercapacitor current. Simulation results were generated to demonstrate the effectiveness of the allocation function under different operating conditions. In Ref. [10], several current allocation strategies were proposed by considering the power demand, the state of charge of the battery and the supercapacitor. In Ref. [22], three classical control loops were constructed to regulate the battery current, the output voltage and the supercapacitor voltage.

In most of the existing literature which considered similar configuration as in Fig. 1, the control design algorithms were focused on generating reference currents for the battery and the supercapacitor. It was generally assumed that a classical reference tracking loop would yield a required current from the battery or the supercapacitor. These control strategies do not consider the interaction among the control loops and the power loss in the circuit elements. In fact, the parallel dc–dc converters are coupled via the same dc-bus or load and have complex interactions. If the interactions among the different control loops are ignored, the transient behavior may not be desirable, such as with large overshoot or undershoot, which may damage the circuit parts. If the power loss is not carefully considered in the current allocation algorithm, the output power may be different than the desired power.

For better analysis and control of the coupled dc–dc converters, we need effective and faithful models for the whole power electronic system. Recently, we derived two state-space averaged models for the system in Ref. [26]. One for simulation and analysis of the open-loop system and the closed-loop system, and the other for control design. The advantage of the averaged models is the simplicity and that they have clear structure in terms of the two duty cycles. Furthermore, they are much faster for simulation than the SimPower models.

In this paper, we would like to address some control design problems for the typical configuration with two bidirectional dc–dc converters as in Fig. 1. A standard control problem in such power systems is to achieve reference tracking for some variables such as battery current, supercapacitor current, load voltage and load current. Since the hybrid energy storage system has two control inputs, the duty cycles of the two dc–dc converters, it should be able to track references for two circuit variables. One may still choose the battery current and the supercapacitor current as in some earlier works. In this paper, we will choose the battery current and the load voltage since the supercapacitor is playing a supporting role and it can supply or absorb almost any current as needed. After all, the state-of-health of the battery (which depends on its charging/discharging profiles) and the performance of the load are of high priority.

We will also address the problem of control design for smooth transition of some key variables during load switch. This will also help to protect the battery and to enhance the performance of the whole system.

It should be noted that this paper's control design methods can be combined with the existing current allocation strategies. With the reference currents generated by any of the existing method, the tracking control can be implemented by the controllers designed by our optimization algorithm.

This paper is organized as follows. In Section 2, we describe the circuit system and briefly summarize the two state-space averaged models developed in Ref. [26]. In Section 3, two design objectives

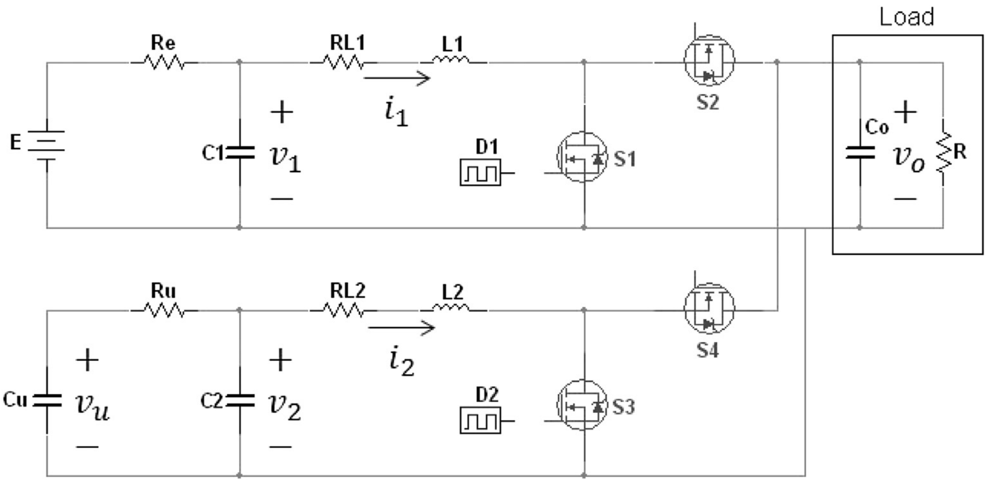

Fig. 1. Parallel topology of the buck–boost converters.