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Small-signal modeling and controller design of energy sharing controlled distributed battery system

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ABSTRACT

This paper presents small-signal modeling, analysis and closed-loop controller design guidelines for a distributed battery energy storage system with energy sharing controller which has recently been presented in the literature in order to achieve cell balancing with high cell balancing speed and energy efficiency. The derived small signal models provide deeper insight into the dynamics of the energy sharing controlled battery system under different operating modes, including discharge mode, constant current charging mode and constant voltage charging mode. Based on the derived small signal models, closed-loop controller design guidelines are provided based on rule-of-thumb frequency-domain design criteria. The small signal models and designed controllers are validated by MATLAB®/SIMULINK simulation and experimental prototype results.

1. Introduction

Batteries and battery systems are widely used in many applications including portable electronics, EVs/HEVs, and distributed smart power grids [1–6]. In addition to battery technologies, the battery management system (BMS) plays a critical role in enabling the widespread adoption of battery-powered applications [7–12].

A conventional battery system architecture is shown below in Fig. 1(a). A battery pack, which consists of a number of cells that are connected in series, is connected to the load through a single high-power converter. In this centralized architecture, additional cell balancing circuitries and controllers are needed in order to achieve the cell balancing between the battery cells in the battery pack. In other words, while the bus voltage regulation is achieved by using a single power converter with its own independent controller, the cell balancing functionality is independently achieved by using another controller that control several balancing circuits across the individual battery cells.

On the other hand, an energy sharing controller has been presented in [1] which achieves cell balancing for a distributed battery system with high cell balancing speed and energy efficiency during both discharging and charging operation. As shown in Fig. 1(b), unlike the conventional system of Fig. 1(a), the distributed battery system consists of a number of battery power modules (BPMs) connected in series in order to supply higher power to the load. Each BPM is made up of a battery cell and a small low-power DC-DC power converter. The selection of the BPM converter topology is a function of several factors including power density, efficiency, cost and size, among others [13–19]. In this work, a bidirectional boost/buck topology is used for BPM converter. The converter operates in boost mode during discharging operation while operating in

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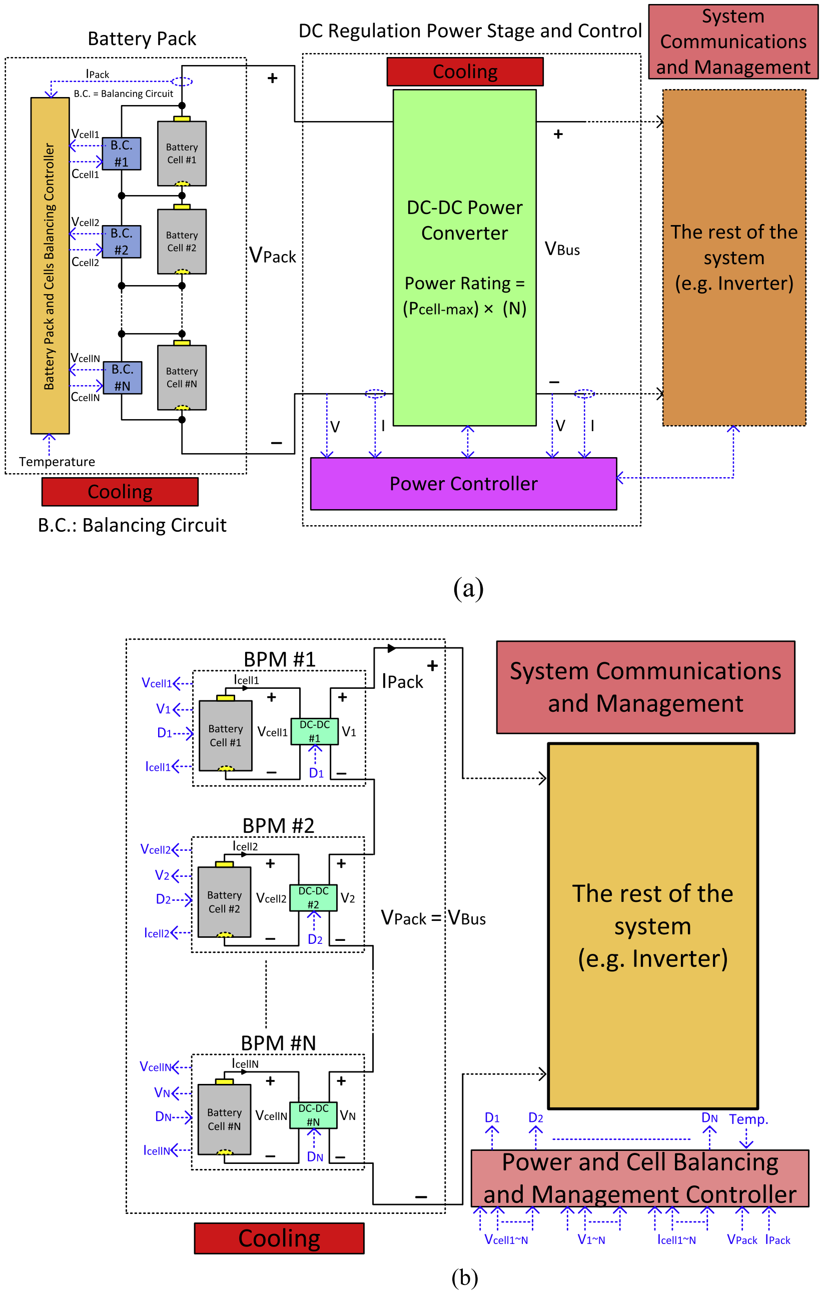

Fig. 1. A simplified block diagram of (a) a conventional centralized battery system architecture and (b) distributed battery system architecture with energy sharing control [1].

buck mode during charging operation. The steady-state operation and analysis of the energy sharing controller has been presented in [1].

The energy-sharing based distributed battery architecture addresses the cell balancing and the bus voltage and cell voltage/current regulation of the battery system simultaneously with the same converter system. Therefore, the cell balancing, bus voltage and cell voltage/current control loops are coupled with each other. In addition, the control loops of each battery power module also interact with one each other. This coupling and interaction nature and the use of the energy sharing control presented in [1] make it important to develop the small-signal modeling analysis in order to understand the dynamics and stability of the entire distributed battery system as well as provide insights into the design and optimization of the multiple control loops involved. This is the main objective of this paper.

Detailed small-signal modeling and analysis is performed in this paper for each operating mode, i.e., discharge mode, constant current charging mode and constant voltage charging mode. In each mode, the corresponding small signal model