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Mathematical analysis and coordinated current allocation control in battery power module systems

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HIGHLIGHTS

- A new current allocation method is proposed for battery power module systems.
- Both desired charge equalization level and time can be achieved using this method.
- An algorithm is proposed to control both charge balance and total power efficiency.
- The algorithm is very computationally efficient for having analytical solutions.
- The results obtained can be implemented by adjusting the duty ratios of converters.

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ABSTRACT

As the major energy storage device and power supply source in numerous energy applications, such as solar panels, wind plants, and electric vehicles, battery systems often face the issue of charge imbalance among battery cells/modules, which can accelerate battery degradation, cause more energy loss, and even incur fire hazard. To tackle this issue, various circuit designs have been developed to enable charge equalization among battery cells/modules. Recently, the battery power module (BPM) design has emerged to be one of the promising solutions for its capability of independent control of individual battery cells/modules. In this paper, we propose a new current allocation method based on charging/discharging space (CDS) for performance control in BPM systems. Based on the proposed method, the properties of CDS-based current allocation with constant parameters are analyzed. Then, real-time external total power requirement is taken into account and an algorithm is developed for coordinated system performance control. By choosing appropriate control parameters, the desired system performance can be achieved by coordinating the module charge balance and total power efficiency. Besides, the proposed algorithm has complete analytical solutions, and thus is very computationally efficient. Finally, the efficacy of the proposed algorithm is demonstrated using simulations.

1. Introduction

Battery systems have been used for over one hundred years and their applications can be found almost everywhere in daily life, from portable devices, such as cellphones and laptops, to large equipments, such as electric vehicles and energy storage devices in power systems. It is thus of great importance to ensure the safe, reliable, and efficient operation of these battery systems. In multi-cell battery systems, it is noted that one common issue in system operation is *charge imbalance* among battery cells or modules, i.e., cells/modules in a battery system have different amount of remaining charge. Battery charge imbalance may be caused by manufacturing variance, different aging effects, uneven thermal distribution, etc. [1–4], and may result in premature cell degradation, early termination of charging process and discharging process, and even safety hazard such as fire and explosion [5–7].

In order to maintain the charge balance or equalization among battery cells/modules, two important issues have to be considered, i.e., how to determine the battery state of charge (SOC) and how to balance battery SOCs. For the former, various estimation methods have been proposed and they are generally categorized into four classes in Refs. [8–10]: direct measurement, book-keeping estimation, adaptive systems, and hybrid methods. For the latter, a great number of circuit designs and control strategies have been developed for various battery system structures [6,7,11–20]. In recent years, the technologies of battery power module (BPM) [21–23] and integrated battery building block [24,25] have emerged to be promising solutions to battery charge

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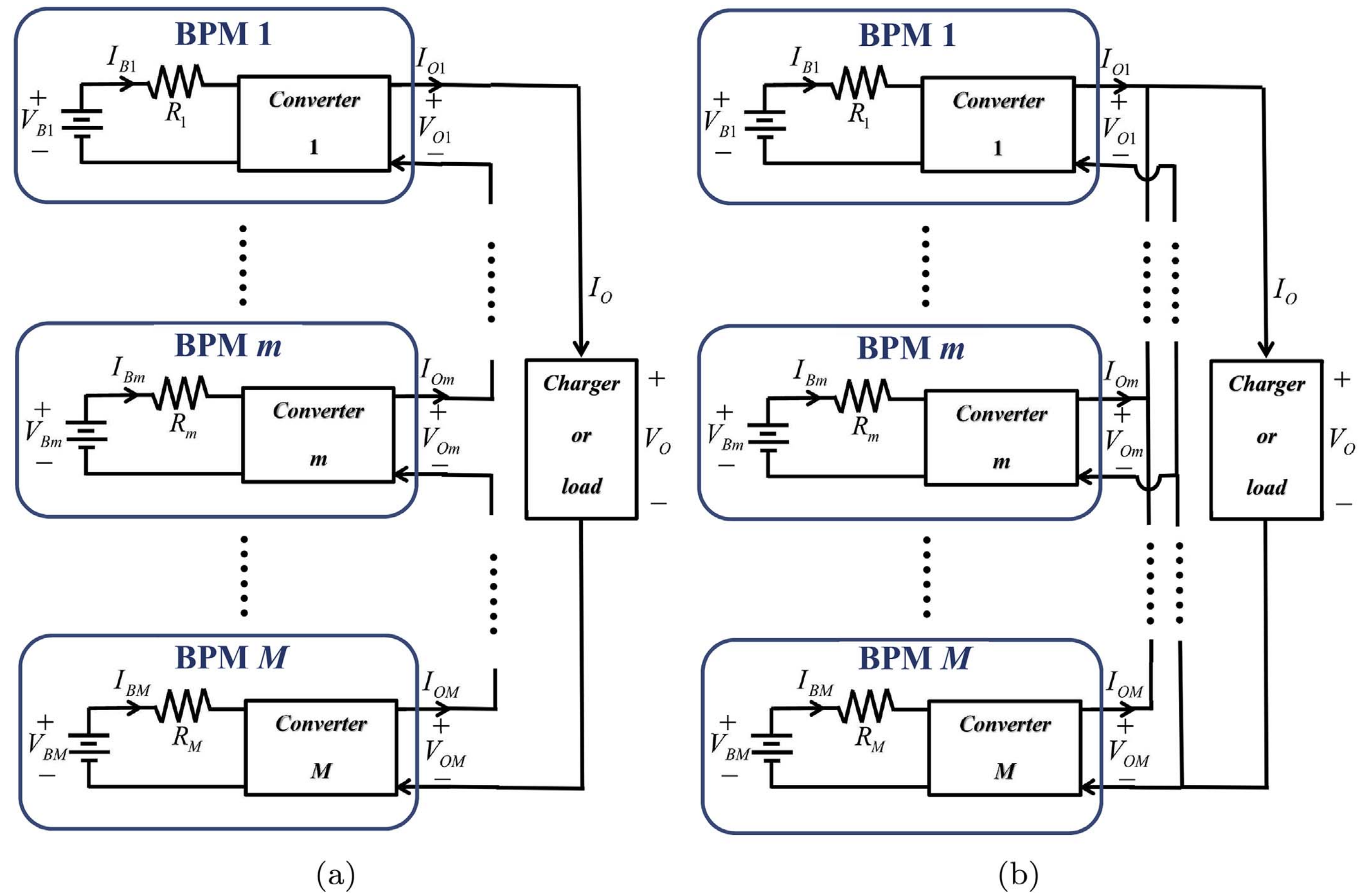

Fig. 1. Equivalent circuits of BPM systems. (a) Series connection. (b) Parallel connection.

balancing for possessing the capability of independent control of each individual battery cell/module. Although these two technologies are different on the circuit level, both of them offer some similar functions on the system level. Therefore, in this paper, with a slight abuse of notation, both will be referred to as *BPM* for simplicity. The diagrams of typical BPM systems are shown in Fig. 1. As one can see, each BPM consists of a battery module and a DC/DC converter, and the BPMs can be connected either in series or parallel to be charged (discharged) by the charger (load). The BPM design has several advantages such as flexible individual module power or current control, better power protection, and easy installation and reconfiguration. On the other hand, as compared to conventional battery modules, BPMs usually cost more since they need extra converters [24]. This problem, however, is being offset thanks to the rapid advance in power electronics technology in recent years.

In a BPM system, by controlling the operation of each converter, each battery module's current can be individually adjusted. As a result, battery module charge imbalance in BPM systems can be alleviated by allocating different currents to each battery module. To reduce the battery charge imbalance in BPM systems during charging (discharging) process, it is intuitive that battery modules with higher SOC should be charged (discharged) with smaller (larger) current. In recent studies, some heuristic methods for current or power allocation among battery cells or modules have been discussed. One class of current allocation method is to assign the discharging current of each module in proportion to its open circuit voltage (OCV) or SOC [23,26,27]. In the current paper, we refer to this method as *SOC-proportional* current allocation. Obviously, this method can help to improve the battery charge balance during the discharging process. On the other hand, it should be pointed out that this method lacks flexibility. Indeed, the allocated module currents will be fixed as soon as the total power requirement on the load side is specified. To overcome this issue, we propose a new current allocation method, referred to as *charging/discharging space-based* (*CDS-based*) current allocation.

The major contributions of the proposed CDS-based current allocation and coordinated control algorithm are given as follows. First, different from the fixed system performance in SOC-proportional allocation, in the proposed CDS-based allocation we can flexibly tune the control parameters to achieve the desired time instant and SOC level at which all module SOCs will get equalized. Secondly, given the total power requirement in the CDS-based current allocation, a system performance control algorithm is developed to coordinate the module charge balance and total power efficiency. It should be noted that, since all the subproblems in the proposed control algorithm have analytical solutions, the algorithm is very computationally efficient. This is of great importance for its application to large-scale battery systems. Lastly, it will be shown that the SOC-proportional method is simply a special case of the proposed CDS-based method. This also explains the superior performance of the proposed method in terms of higher control flexibility and coordinated system performance.

The remainder of the paper is organized as follows. In Section 2, The effect of current allocation on charge balance in BPM systems is analyzed. Following the analysis, the CDS-based current allocation is proposed in Section 3. Then, the BPM system behavior under CDS-based current allocation with constant parameters is discussed in Section 4. Furthermore, in Section 5, an algorithm for system performance control is developed by considering the total power requirement, power loss constraint, and module charge balance. Next, simulation results are presented in Section 6 to illustrate the efficacy of the proposed current allocation. Finally, conclusions and future work are given in Section 7. All proofs are provided in the Appendices.