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Computationally efficient methods for state of charge approximation and performance measure calculation in series-connected battery equalization systems

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HIGHLIGHTS

- Simultaneous equalization and charging or discharging processes are considered.
- An algorithm is proposed to estimate real-time state of charge of individual cells.
- Formulas are derived to evaluate equalization, charging and discharging times.
- Formulas are derived to evaluate the real-time maximum and minimum cell SOCs.
- These tools are computationally efficient and accurate for large-scale systems.

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ABSTRACT

The battery system plays an important role in a number of modern power applications. In practice, cell charge imbalance is a very common issue in battery system operations, which may cause serious problems in power efficiency, equipment reliability and safety, etc. To analyze the performance of battery equalization systems, physical experiments with actual devices and computer simulations based on circuit models are typically used. These approaches, however, may be time-consuming and energy-inefficient for larger-scale systems. In this paper, based on the proposed mathematical model for series-connected battery equalization systems, we develop an analytical algorithm to approximate the state of charge (SOC) of battery cells at any time instant during the equalization process, and derive the formulas to calculate critical performance measures of the system. Extensive numerical experiments are carried out to justify the accuracy of the algorithm and formulas developed. In addition, the proposed methods use much less computational time as compared to computer simulations.

1. Introduction

The battery system is one of the key components in a number of modern power applications, such as electric vehicles (EVs), wind and solar electric systems. However, charge imbalance among different cells is very common in a battery system, which may lead to serious problems in power efficiency, equipment reliability and safety, etc. In general, the battery charge imbalance can be caused by internal or external factors [1–4], such as manufacturing variance in physical volume, internal impedance, and self-discharge rate, and uneven thermal distribution across the battery packs. Due to charge imbalance, the voltages of individual cells gradually differ over time and the capacity of the battery pack decreases quickly, which may even result in the failure of the entire battery system [5].

In order to reduce the charge imbalance in a battery system, a number of equalization circuit modules, referred to as *equalizers*, are developed and connected to the battery cells to form the battery equalization system. For the design of equalizers, two types of methods have been proposed: passive and active balancing. Based on these methods, various kinds of equalizers have been developed (see Refs. [5–9]). Of all the structures of battery equalization systems developed, the simplest but most widely-used one is the series-connected equalization structure. In this structure, every

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Nomenclature

SOC	State of charge
b_i	The ith cell of the battery system
e_i	The equalizer connecting cells b_i and b_{i+1}
τ	Duration of each time slot
r_e	Equalization rate
r_c	Charging rate if $r_c > 0$ or discharging rate if $r_c < 0$
l_e	Equalization loss rate
lim_u/lim_l	Upper/lower limit of cell SOCs
$x_i(t)$	SOC of cell b_i at time t
$\hat{x}_i(t)$	Approximated SOC of cell b_i at time t
$BG(g,i)$	The g-cell battery group from cell b_i to cell b_{g+i-1}
$x_{(g,i)}(t)$	Sum of cell SOCs of $BG(g,i)$ at time t
$\bar{x}_{(g,i)}(t)$	Average cell SOC of $BG(g,i)$ at time t
$\bar{x}^u_{(g,i)}(t)$	Upper bound of $\bar{x}_{(g,i)}(t)$ in the equalization process
$\bar{x}^l_{(g,i)}(t)$	Lower bound of $\bar{x}_{(g,i)}(t)$ in the equalization process
$\hat{\bar{x}}_{(g,i)}(t)$	Approximated average cell SOC of $BG(g,i)$ at time t
$t_{merge}(i)$	Merging point of cells b_i and b_{i+1}
$t_e^{int}(g,i)$	Time instant when all cells of $BG(g,i)$ merge together for the first time
$t_e^{ext}(g,i)$	Time instant when $BG(g,i)$ merges with any neighboring cell for the first time
MBG	Any battery group with $t_e^{int}(g,i) < t_e^{ext}(g,i)$
$t_{ideal}(g,i)$	Time for $\bar{x}_{(g,i)}(t)$ to reach $\bar{x}_{(B,1)}(t)$ in the fastest way
$T_e/T_c/T_d$	System equalization/charging/discharging time
$\hat{T}_e/\hat{T}_c/\hat{T}_d$	Approximated system equalization/charging/discharging time

two adjacent cells are connected with one equalizer, which monitors the status of the two adjacent cells and transfers charge from the one with higher state of charge (SOC) to the other one (see Refs. [10–12]). Here, the cell's SOC is usually defined as the ratio of the cell's remaining charge and its charge capacity.

It should be noted that, despite the important and valuable research efforts in the development of battery equalization systems (see, for instance, [2,13–17]), so far, most of the results reported have focused on the electrical hardware design and realization of the equalization systems. On the other hand, investigation of the battery equalization process from the system level has rarely been explored and a number of questions remain open. For example, given the initial SOC of each battery cell and all the system parameters, how long will it take to complete equalization, charging, and/or discharging? How to predict the SOC of each individual cell at any time instant during the equalization process (with or without charging or discharging)? To answer these questions, experiments with physical devices and computer simulations of the circuit models remain as the main tools at present. These tools, however, could be costly and time-consuming as the scale of the system becomes large. The low efficiency of these tools prohibits systematic investigation and understanding of the system behavior during the battery equalization process. Therefore, in order to carry out comprehensive analysis of the system performance, accurate and computationally efficient tools are necessary, especially for larger-scale systems. Some preliminary results have been obtained in Ref. [18], including the mathematical models and calculation formulas of equalization time for different equalization structures. However, paper [18] still relies on the simulation of the mathematical models to obtain the SOC of each cell during the equalization process. Also, it does not consider the energy loss during the equalization process. In addition, the interactions of charging and discharging with the equalization process are not studied.

In this paper, we focus on the analysis of battery equalization systems operating in various working states and consider the effects of energy loss on overall system behavior. Specifically, we consider the series-connected battery equalization system in the following parts of this paper and assume that the battery system may operate in one of the three operating states: charging, discharging, or idle state. In addition, the battery equalization may occur in any operating state. Moreover, the energy loss during system operation is considered, which, in practice, may be caused by internal circuit resistance, conversion between chemical and electrical energy, etc.

To analyze systems with the above features, the remainder of this paper is organized as follows: In Section 2, the mathematical model of series-connected battery equalization system with equalization energy loss is introduced. Then, in Section 3, two important basic concepts, merging point and merging battery group (MBG), are defined and their properties are discussed. Based on the mathematical model and the properties of merging point and MBG, computationally efficient algorithms are proposed in Section 4 to approximate each cell's SOC at any time instant of the equalization process and to calculate the system equalization time. In Section 5, analytical formulas to calculate the maximum and minimum cell SOCs, charging time, and discharging time, are derived and validated by numerical experiments. Finally, conclusions and future work are provided in Section 6. All proofs are given in the Appendices.

2. Mathematical modeling for series-connected battery equalization system

2.1. Model description and assumptions

Consider the battery equalization system with series-connected cells and equalizers shown in Fig. 1 based on the following assumptions:

(i) The battery system consists of B cells, $b_1,b_2,\ldots,b_B$, connected in series, and the equalization system consists of $B-1$ equalizers, $e_1,e_2,\ldots,e_{B-1}$, connected with every two adjacent cells.

(ii) All cells have the same capacity, then the cell SOC can be used to characterize each cell's charge state. All equalizers have the same working cycle, τ, then the time axis is slotted with slot duration τ.

(iii) Each equalizer e_i is characterized by its equalization rate, $r_{e,i}$ units of SOC per time slot, and energy loss rate $l_{e,i} \in (0,1)$, $i = 1,\ldots,B-1$. For simplicity, assume all the equalizers have identical and constant parameters, i.e., $r_{e,i} = r_e$ and $l_{e,i} = l_e$.

(iv) At the beginning of each time slot, if cell b_i's SOC is higher than cell b_{i+1}'s SOC, then during this time slot equalizer e_i takes r_e units of SOC away from b_i with constant rate and sends $(1 - l_e)r_e$ units of SOC to b_{i+1} also with constant rate. The remaining $l_e r_e$ units of SOC is consumed by the system as energy loss. Similarly, if cell b_i's SOC is smaller than cell b_{i+1}'s SOC, then equalizer e_i takes r_e units of SOC away from b_{i+1} and sends $(1 - l_e)r_e$ units of SOC to b_i with the rest $l_e r_e$ units of SOC consumed as energy loss. If b_i and b_{i+1} have equal SOC, then during the time slot no charge transfer takes place between them.

(v) The external charging/discharging of the battery system is characterized by a constant parameter r_c. During the system