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Cell sorting for parallel lithium-ion battery systems: Evaluation based on an electric circuit model

Fuqiang An[a,b,1], Jun Huang[b,c,1], Chengyu Wang[c], Zhe Li[c,d], Jianbo Zhang[c,d,*], Sean Wang[b], Ping Li[a,**]

[a] Institute for Advanced Materials and Technology, University of Science and Technology Beijing, Beijing 100083, China
[b] Boston-Power Battery, Inc., Westborough, USA
[c] State Key Laboratory of Automotive Safety and Energy, Department of Automotive Engineering, Tsinghua University, Beijing 100084, China
[d] Beijing Co-innovation Center for Electric Vehicles, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

This study dwells upon two key aspects of cell sorting including what descriptors should be concerned and how stringent the limits of these descriptors should be. Evaluation is made on a parallel multi-cell block using an electric circuit modelling (ECM) approach, which features a model validation based on separate current tracking of each cell in the parallel cell block via Hall sensors, and a detailed comparison of methods to determine model parameters. We find that: (1) the ECM can accurately capture the current balancing behavior in the parallel block; (2) the current interrupt method with a rest duration of 120 s is recommended for the determination of cell resistance; (3) the current distribution in the parallel block is insensitive to the hysteresis in open circuit voltage (OCV); (4) cell-to-cell variations decrease the capacity of the block (5) a descriptor accounting for aging variations among cells is suggested to be included in the cell sorting process and the OCV drop rate can be a potential candidate.

1. Introduction

In lithium-ion battery industry, cell sorting, referring to selection of qualified cells from raw ones according to quantitative criterions in terms of accessible descriptors such as capacity, resistance, open circuit voltage (OCV) etc., is an indispensable process to assure reliability and safety of cells that are further assembled into strings, blocks, modules and packs.[2] Making use of a multi-cell block in parallel configuration, this study evaluates the effect of sorting strategies, viz., different descriptors and varying constraint extents, on the assembling performance by using an electric circuit model (ECM). This ECM approach features a model validation based on separate current tracking of each cell in the parallel cell block via Hall sensors. Emphasis is also put on comparison of methods to determine parameters of the ECM, as it is usually a formidable task to select an appropriate method among a plethora of options.

We note that very few open publications on cell sorting can be found, and the searched two papers all focus on the sorting algorithm, including fuzzy C-means algorithm [1] and self-organizing map algorithm [2]. Nevertheless, the descriptors and their constraints adopted in the sorting process, which are of fundamental significance, are not investigated.

On the contrary, considerable attention has been paid to study of cell-to-cell variation which is closely pertaining to cell sorting. These efforts are summarized below in a sequence spanning from material constituents to manufactured raw cells and to assembled blocks and modules. Santhanagopalan and White presented a quantitative analysis on the impact of material uncertainties on the initial cell-to-cell variations using an impedance model. The relative importance of uncertainties in different component materials was compared [3]. Dubarry et al. conducted a statistical and electrochemical analysis of 100 unassembled cells at the room temperature, and then differentiated the origins of cell-to-cell

* Corresponding author at: Tsinghua University, State Key Laboratory of Automotive Safety and Energy, Department of Automotive Engineering, Beijing 100084, China. University of Science and Technology Beijing, Institute for Advanced Materials and Technology, Beijing 100083, China
** Corresponding author.
E-mail addresses: jbzhang@mail.tsinghua.edu.cn (J. Zhang), liping@ustb.edu.cn (P. Li).
[1] Equally contributing authors.

[2] Nomenclature: a string/block refers to a multi-cell system with series/parallel configuration; a module, as a system on a larger scale, usually consists of several strings and blocks with mixed configurations; a pack, assembled by connecting many modules together, is an integrated and independent battery system for an application such as electric vehicles.

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variations into thermodynamic and kinetic aspects [4]. Paul et al. [5] unraveled discrepancies in aging among cells assembled into a block as a consequence of cell-to-cell variations in loading. Thermal and degradation effects are incorporated into the electric circuit model. Gogoana et al. [6] demonstrated the significance of cell resistance matching for a parallel-connected block. Specifically, they reported that, as far as two cells cycled in parallel are considered, a 20% variation in cell resistance would lead to a 40% reduction in cycle life of the block compared to the case of two identical cells [6].

It can be epitomized by saying that those researches on assembled blocks and modules, with predetermined variations among cells, justify the importance of cell sorting to select uniform cells for building a block, while those studies spanning from material constituents to unassembled raw cells provide guidance on how to reduce the intrinsic cell-to-cell variations. A gap between these two clusters of studies is that how to engineer a block with predesignated performance targets from a batch of raw cells with predetermined cell-to-cell variations. This study, on cell sorting, aims at filling this non-trivial gap.

As aforementioned, the evaluation of sorting strategies on assembled performance of the parallel block relies on an ECM. A multitude of publications on modelling battery blocks and modules using an ECM approach can be found [5–9]. These previous studies usually utilizes an overall voltage-current curve [8,10], or the overall capacity [6,9], of the parallel-connected block for model validation. However, we deem that a good consistency between model prediction and experimental data in terms of overall indicators cannot sufficiently guarantee a reliable description of each constituent cell. Consequently, distributed current data by separate current tracking of each constituent cell are preferred for a more reliable model validation. To reach this goal, in this study, we design a special setup which uses Hall sensors to record the current of each cell in a parallel block during charge/discharge. In addition to the model validation, model parameterization is also a formidable task as there are many methods to estimate one property. For example, the cell resistance can be measured using both DC method and AC impedance technique. A natural question is which method is more appropriate? Suggestions on selecting method for parameterization are also provided by this study.

The rest of this paper is organized as follows: the development of the ECM is introduced in details in Section 2, followed by experimental specifications to measure distributed current data of a parallel block and to determine the model parameters in Section 3. Succeedingly we present the model validation and compare different parametrizing methods in Section 4. Finally, using the validated ECM model and mass production data from a battery manufacturer, we look into how the sorting strategies can affect the assembled performance of a parallel block, resulting in several practical suggestions to perform an effective cell sorting in Section 5. Section 6 concludes major findings.

2. Electric circuit model (ECM) development

This section describes the ECM for the study of charge/discharge characteristics of a parallel-connected block, so as to serve the evaluation of sorting methods on the block performance, as shown in Fig. 1.

Main assumptions and the corresponding considerations in this model are:

(1) Thermal effects are not considered. This assumption is reasonable because we charge/discharge the cells at relatively small currents (the maximum current is less than 0.5 C) in a temperature chamber with strong convection to provide a constant temperature.

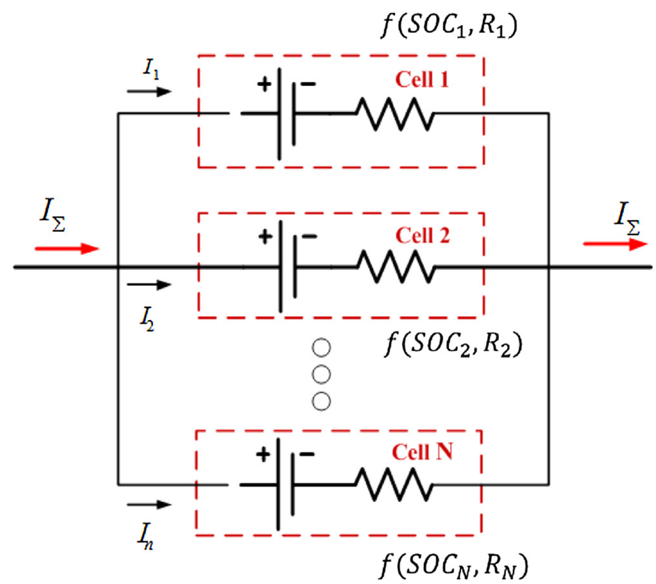

Fig. 1. Schematic of a parallel-connected block.

(2) Single cell is represented by a resistance in series with a voltage source. This assumption is substantiated by a good agreement, as described below, between simulated and experimental current distribution in a two-cell block under constant current discharge.
(3) The discharge of the block is terminated as long as one of the following conditions is fulfilled: (a) the terminal voltage of block is smaller than a presetted lower limit; (b) the state-of-charge (SOC) of any cell is smaller than 0.
(4) Cell parameters, including the capacity, cell resistance and OCV curves, are measured separately and would not be changed after assembling these cells into a parallel block.
(5) The contact resistance is well controlled and proven to have negligible interference on the current allocation among constituent cells. To confirm this assumption, we construct a parallel block with two new cells with nearly identical properties and obtain a uniform current distribution (scientifically speaking, the current variation is submerged by the noise of the measurement system, as shown in Fig. 4(a) and (b)) between these two cells.
(6) In the statistical simulation in Section 5, a negative linear correlation is assumed between the cell capacity and its resistance. Such an expedient strategy is used because it is practically impossible to measure the resistance-SOC curves for 7739 cells.

Based on these assumptions, the controlling equation for each cell in the block during discharge at a certain current is expressed as:

$$OCV_i(SOC_i) - I_iR_i(SOC_i) - V_b = 0 \quad (i = 1 \ldots N) \tag{1}$$

where OCV_i,SOC_i, R_i refer to the OCV, SOC, and resistance of cell i, respectively. V_b is the terminal voltage of the block. OCV_i, and, R_i are functions of SOC_i.

According to the definition of SOC, the cell current I_i is equivalent to:

$$I_i = C_i \frac{dSOC_i}{dt} \tag{2}$$

where C_i is the cell capacity, t is the discharge duration.