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Cell-balancing currents in parallel strings of a battery system

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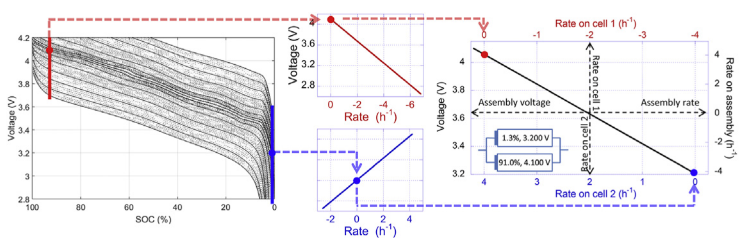
HIGHLIGHTS

- Li-ion cells balancing behavior in parallel is investigated.
- A simple model to estimate balancing currents is proposed.
- Model is applied to investigate battery packs failure modes.
- Model is applied to investigate impact of string swapping.

GRAPHICAL ABSTRACT



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ABSTRACT

Lithium-ion batteries are attractive for vehicle electrification or grid modernization applications. In these applications, battery packs are required to have multiple-cell configurations and battery management system to operate properly and safely. Here, a useful equivalent circuit model was developed to simulate the spontaneous transient balancing currents among parallel strings in a battery system. The simulation results were validated with experimental data to illustrate the accuracy and validity of the model predictions. Understanding the transient behavior of such cell and string balancing in a parallel circuit configuration is very important to assess the impacts of current fluctuation and cell variability on a battery system's performance, regarding durability, reliability, safety, abuse tolerance and failure prevention, including possible short circuit or open circuit conditions. Additional features and advantages, including the ability to assessing impacts on the performance of the string assemblies from string swapping or cell/module replacement in the strings, could be realized to aid battery management, maintenance and repair.

1. Introduction

Reliability and safety are important and timely issues for lithium-ion batteries [1] that shall be addressed by stakeholders in all sectors where large battery packs are required to meet high-energy and high-power demands. Particularly, if multiple-cell configurations have parallel strings, the transient current distributions and variations among the strings are of great concerns in battery management systems (BMS) to perform cell balancing and protection in the battery module or system levels. These transient current distributions and variations may introduce some long-lasting effects on battery performance, which are not easy to detect in a short time frame. To address these issues, a high-fidelity equivalent circuit model could be used as a powerful tool to simulate these transient current distributions and variations to help engineers deal with the reliability and safety issues.

Here, we tested a group of commercial 18,650 cells as a platform to develop useful techniques to understand and to model the transient behavior of cells in parallel configurations, and to perform validation. These lithium-ion cells are made of graphite negative electrode (NE) and a blend of {$Li_xMn_{1/3}Ni_{1/3}Co_{1/3}O_2$

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(NMC) + $Li_xMn_2O_4$ (LMO)} mixture as the active material in the composite positive electrodes (c-PE). These cells were made by a brand name manufacturer. The cell chemistry has been studied in our laboratory in a series of investigations on subjects from cell variability [2], cycle aging and degradation mechanism [3], capacity fading in temperature excursions [4], a peculiar capacity fade phenomenon in the c-PE associated with overdischarge [5], to the methodology in determining state-of-charge (SOC) and state-of-health (SOH) of the cells and multi-cell strings [6,7]. Here, we discussed the transient aspects of parallel string configurations and the string balancing issues.

Prior studies on parallel configurations and their impacts on performance with lithium-ion batteries are limited in numbers and scopes. Most of the studies focused on circuit topology and electrical balancing issues rather than on the electrochemical behavior of the system (e.g. Refs. [8–13]). To the best of our knowledge, only a few of the impacts of cell performance with parallel multi-cell configurations have been published with electrochemical characterizations [14–27]. In Ref. [14], the experiments were conducted to investigate a set of graphite (Gr) || $LiFePO_4$ cells with small temperature gradients introduced; however, the time for the cells to reach balance and transient fluctuations of the current in the circuit were not discussed. In Ref. [15], electrode plates stacked in parallel in a cell were studied to understand the static distribution of current among the plates. The transient balancing current distribution during the initial period of polarization was not discussed. Only a few studies provided electrochemical data for both voltage and current evolutions during constant current discharging of commercial cells [17,20,21,25]. These studies showed the results of current distributions among strings via modeling or experimentation but did not explain the mechanism that drives the initial balancing current distribution in the parallel configurations.

Understanding the transient behavior of the cells in parallel is of great interest for practical applications in vehicle or energy storage systems and some key issues need to be addressed with sufficient detail in understanding. The best introduction to these key issues can be found in Ref. [28]. Understanding these issues is crucial to assuring durability, reliability and safety of the battery systems. Such information is critical to the strategy of protecting cells from abuses by the users and malfunctions in the battery pack. Possible solutions may include building in redundancies to withstand negligence and abuse and to manage reliability issues beyond the cell level, handling failure modes (in either open or short circuit conditions) by proper detections, and accommodating string reconfigurations (e.g. changing defective strings with new ones) in system maintenance and repair; just to name a few.

A prerequisite to address these issues is sufficient knowledge of cell variability, i.e. cell-to-cell variations in various cell characteristics [2,24,29–31], and the ability to accommodate them [29,32]. In this work, this aspect is accomplished by using an equivalent circuit model (ECM) modified to simulate battery strings in parallel. This model was dubbed *kaulike*, the Hawaiian word of "evenly balanced," to emphasize its unique capability in the simulation of parallel strings in a battery pack.

2. Experimental

A batch of 1.9 Ah 18650 lithium-ion cells comprising graphite NE and {$Li_xMn_{1/3}Ni_{1/3}Co_{1/3}O_2$ + $Li_xMn_2O_4$} (NMC + LMO) c-PE was used as test samples for illustration. One of the cells was subjected to a reference performance test (RPT) consisting of C/25, C/5, C/2, 1C, 2C, and 2.5C cycles at 25 °C over an extended voltage range from 2.300 V to 4.250 V to characterize the cells' performance characteristics. The results were used to extract parameters for the ECM [32,33]. The same methodology was used to build an ECM from an aged cell for which the RPT data was taken from Ref. [3].

The 18650 cells were placed in cell holders [34] made by Arbin Instruments (College Station, TX) to handle high current testing. These cell holders offer low resistance (on the order of a few mΩ) to maintain reliable contact, provide ability to handle high power testing, and introduce minimum impact on test results from external resistive influences. These cell holders have a lever that can be used as a mechanical switch to close the circuit quickly and safely. In order to record precise current passing through each string without artifacts from the influences of additional resistance and voltage perturbation possibly induced by the introduction of DC shunt resistors, CTH Hall-effect DC transducers [35] were used in the measurements, which have 0.5% precision over a current range of ±25 A.

Three tests were performed with cells at different SOCs. Cells were pre-conditioned using an Arbin HVBT-5560 58-channel 5 V/5 A tester and cycled at C/2 rate to specified cutoff voltages at 3.050 V, 3.350 V, or 4.200 V, respectively; followed by a 24-h rest prior to commencing parallel-string tests. The parallel-string tests with 1S2P, 1S3P, and 2S2P configurations were conducted in a temperature-controlled environment. In the tests, a 6-h rest between consecutive test regimes was typically exercised to allow cells and strings recuperate from polarization. Each test was launched with only one string connected to the ARBIN tester first, while the other strings were hot connected 30 s after commencing the test on the first string in order to record the voltages of the cells in the strings before and after the hot connection to the test. Hot connections of the strings could be enabled safely by using the levers on the cell holders. Auxiliary voltage monitoring channels were used to record the voltage of every cell in the circuit and the current sensing output of the Hall-effect transducer in each string.

3. Results

3.1. Equivalent circuit model

Fig. 1 presents a series of cell voltage (V_{cell}) *vs.* SOC ($V_{cell} = f$(SOC)) curves determined from the nominal cell with rates from C/25 to 2C in the charge and discharge regimes. In addition, a pseudo open circuit voltage *vs.* SOC (*ps-OCV* = *f*(*SOC*)) curve was derived from the charge and discharge ($V_{cell} = f(Q)$) curves at C/25 with an SOC

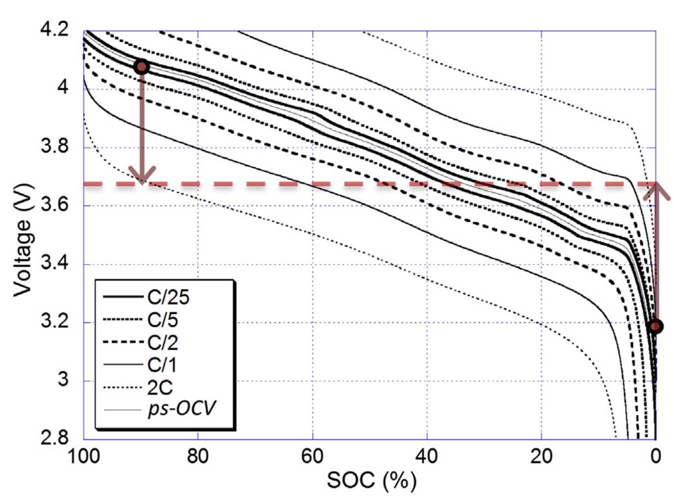

Fig. 1. Cell voltage *vs.* SOC curves determined by experiments for a nominal cell and a schematic illustration of a hypothetical 1S2P configuration in which how the rate of the balancing current and the final voltage of the assembly determined for the two cells at 91.0% and 1.3% SOC (4.100 V *vs.* 3.200 V), respectively, initially before being connected in parallel.