

Model-Based Analysis of Cell Balancing of Lithium-ion Batteries for Electric Vehicles

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ABSTRACT

Cell balancing is a key function of battery management system (BMS) that is implemented to maximize the battery's available capacity and service life. The increasing demand of larger and better performance pack has raised the need to investigate the various cell balancing techniques so that the energy of the battery can be fully realized. In this work we develop a phenomenological model in order to quantify the benefits of passive balancing and active balancing. The electrical response of a model pack consisting of serially connected lithium ion cells is simulated with Matlab. The effects of the variance of cell capacity, internal resistance, self-discharge rates, pack configuration and size are studied. The possible optimization rooms for implementing passive and active balancing are suggested.

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INTRODUCTION

Lithium-ion (Li-ion) cells for automotive applications are connected in series to achieve the required voltage and in parallel to achieve the required capacity. Due to the manufacturing inconsistency, Li-ion cells from production vary in characteristics such as capacity, internal resistance, and self-discharging rate. During service these characteristic variances become even larger not only because the cells intrinsically have different aging dynamics but also because they experience different local temperature and are monitored electronically for cell supervision and protection. The failure of a pack is often determined by the worst cell. For example, the usable capacity of a pack consisting of cells connected in series is determined by the cell with the smallest capacity. Therefore various cell balancing (or cell equalization) techniques are implemented in order to maximize the usable capacity of the pack. Cell balancing will also protect the cells from being overcharged or over-discharged.

Many cell balancing methods have been proposed [1]. Passive methods apply high Ω resistors to remove energy from the most charged cell and disperse the energy as wasted heat.

Active methods transfer energy between cells and therefore do not waste the energy as heat. The various active balancing methods can be classified into capacitor-based,

inductor/transformer-based, and converter based methods. For active methods the topology affects performance metrics such as efficiency, balancing speed, complexity, cost, etc. Comparisons between these balancing methods have been covered by several reviews [1, 2, 3, 4].

Every balancing method has its advantages and disadvantages. Active methods deliver more usable energy than passive methods but they cost more. Inductor or converter-based methods balance the cells faster than capacitor-based methods but are more expensive due to the magnetic parts included [2]. Using single-switched capacitor saves parts compared to the switched capacitors but involves more complicated control strategies which raise the problem of reliability [5, 6, 7]. Most previous research on cell balancing focused on specific balancing techniques and used a couple of imbalanced cells to investigate the performance of certain cell balancing technique or algorithms [2, 5, 6, 7, 8]. Considerations of the statistical nature of cell characteristics are very limited. For electrical vehicle (EV) the battery pack often consists of hundreds of cells and the pack size must grow larger and larger to extend the driving range. Increasing cell capacity and count will have significant impact on cell balancing. The driving profile studied also impacts the results of the system. Previous research focused a constant charging and discharging profile whose results may

not reflect the true scenario of a real-world driving profile [5]. Moreover there is a coupling between cell balancing and cell characteristics evolution which may also affect the accuracy of those evaluation results.

In this work we present a model for simulation of the electrical response of a Li-ion pack in EV in which the cell balancing strategy, cell characteristics, and real-world driving profile are all coupled together. In this work we use this model to investigate the effects of cell characteristics on balancing performance. Our purpose is to provide guidance for pack design and cell balancing strategy design in order to achieve the optimized performance for the pack. For example in choosing between passive and certain active method, the designer may want to know by this active method how much energy can be possibly saved and how much more capacity can be extended in regard to a particular pack design assuming the pack configuration and cell characteristics are known. This model will provide more accurate evaluations on choices of balancing strategies.

The paper is organized as follows. First, we will describe the model framework and explain details of the various model components. Next, the simulation results of effects of cell characteristics, pack configuration and size on balancing performance are presented. Comparisons between passive balancing and active balancing are shown and discussed. Finally major findings are summarized and optimization rooms are suggested.

MODEL DEVELOPMENT

Model Framework

The model framework we develop contains five major components illustrated in Figure 1. Inputs consist of driving profiles, balancing strategy, the cell characteristics, and pack configuration and size. The output is the performance component. The core component is the pack and cell model based on equivalent circuit model.

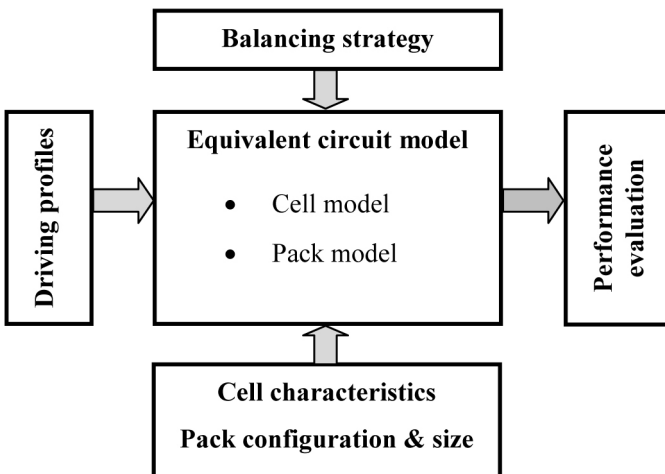


Figure 1. Model framework

Equivalent Circuit Model

The model we build presents three features: 1) it allows dynamic coupling between driving profile, balancing strategy, and cell characteristics; 2) it must handle a reasonably large pack size that may contains hundreds of cells; 3) The computation speed must be fast enough to allow simulating the pack response over years because cell balancing events should be rare and sufficient data must be collected for statistical interpretation. Additionally long time simulation is required to evaluate the cell balancing performance with respect to cell aging dynamics. Based on the above considerations we choose to use the equivalent circuit model instead of electrochemical model and mathematical model [9, 10, 11]. The equivalent circuit model allows physics-based coupling between various processes and have reasonable computational speed.

Cell model

The equivalent circuit model for a single cell is illustrated in Figure 2 which contains a voltage source (E_0), an internal resistance (R_0), two parallel RC circuits. [9]

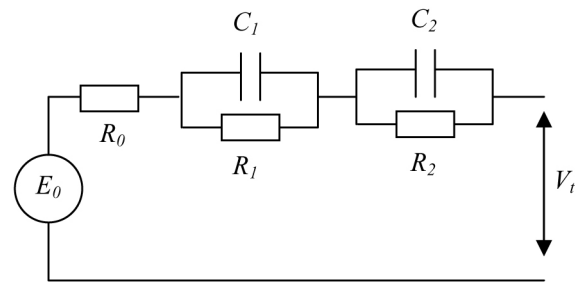


Figure 2. Equivalent circuit model for a single cell

The terminal voltage of the cell, V_t , is written as: [9]

$$V_t(t) = E_0(t) - R_0 I(t) - V_{c1}(t) - V_{c2}(t) \quad (1)$$

Here, the current $I(t)$ is positive for discharging and negative for charging. E_0 is the open circuit voltage of the cell. To specify $V_t(t)$, the voltage across the capacitor needs to be solved first. Assuming at t_0 the voltage of the capacitor is $V_c(t_0)$, if $t-t_0$ is small enough the voltage of the capacitor at t can be written as:

$$V_c(t) = e^{-\beta(t-t_0)} V_c(t_0) + \frac{\gamma(t)}{\beta} (1 - e^{-\beta(t-t_0)}) \quad (2)$$

Where $\beta = 1/RC$, and $\gamma = 1/C$. Combining eq.1 and eq.2 we get

$$V_i(t) = E_0(t_0) - e^{-\beta_1(t-t_0)}V_{c1}(t_0) - e^{-\beta_2(t-t_0)}V_{c2}(t_0) + I(t) \left[-R_0 - \frac{\gamma_1}{\beta_1}(1 - e^{-\beta_1(t-t_0)}) - \frac{\gamma_2}{\beta_2}(1 - e^{-\beta_2(t-t_0)}) \right] \quad (3)$$

In principle, the E_0 , R_0 , R_1 , C_1 , R_2 , C_2 can be all set as functions of state of charge (SOC) to model the cell behavior in an accurate manner. In this work we are considering large capacity cells (36Ah) and use the SOC difference instead of terminal voltage as the signal to start a balancing event (the threshold SOC difference is 3%). For Li-ion cells the time constants of RC are normally in range of a few seconds which will not contribute to SOC imbalance of interest. Therefore the RC components are not included and we only consider E_0 as a function of SOC and treat R_0 as constants. As we will show in next section the DC resistance has little effects on balancing performance.

Pack model

Based on the cell model the pack model can be derived. A general pack with $mPnSpM$ configuration is illustrated in Figure 3. It contains p modules in series, each module has m parallel strings and each string has n cells connected in series.

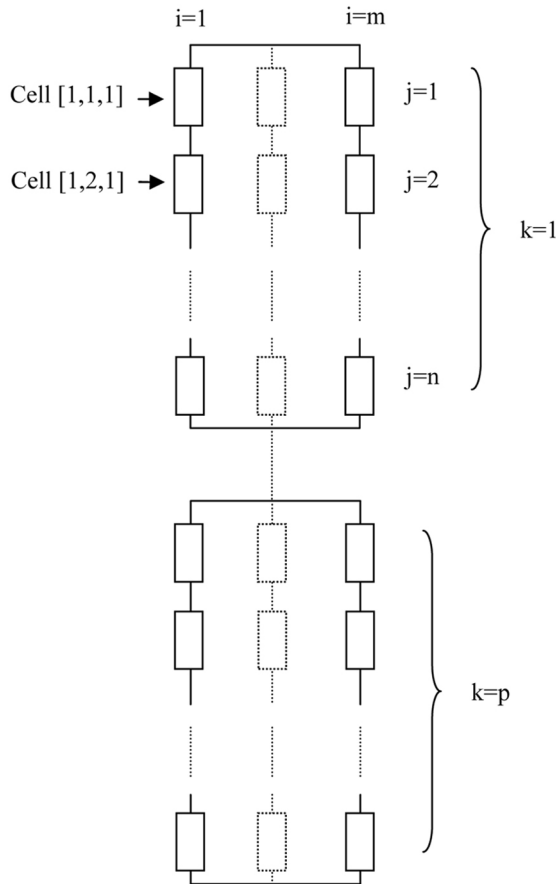


Figure 3. Illustration of a general pack with $mPnSpM$ configuration.

To specify the voltage response of a general pack the current splits among strings need to be calculated. For the k th module the currents of the m strings can be calculated by: [9]

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \vdots \\ \alpha_{m-1} \\ \alpha_m \end{bmatrix} = \begin{bmatrix} \Phi_1 & -\Phi_2 & 0 & \cdots & \cdots & 0 \\ 0 & \Phi_2 & -\Phi_3 & 0 & \cdots & 0 \\ 0 & 0 & \Phi_3 & -\Phi_4 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & \Phi_{m-1} & -\Phi_m \\ 1 & 1 & \cdots & \cdots & 1 & 1 \end{bmatrix} \begin{bmatrix} \Gamma_2 - \Gamma_1 \\ \Gamma_3 - \Gamma_2 \\ \Gamma_4 - \Gamma_3 \\ \vdots \\ \Gamma_m - \Gamma_{m-1} \\ I \end{bmatrix} \quad (4)$$

Where α_i is the current of the i th string, I is the current through the pack, and Φ_i and Γ_i are written as:

$$\Phi_i = \sum_{j=1}^n \left(-R_{0[jk]} - R_{1[jk]}(1 - e^{-\beta_1[jk]\Delta t}) - R_{2[jk]}(1 - e^{-\beta_2[jk]\Delta t}) \right) \quad (5)$$

$$\Gamma_i = \sum_{j=1}^n \left(-E_{0[jk]} - V_{c1[jk]}e^{-\beta_1[jk]\Delta t} - V_{c2[jk]}e^{-\beta_2[jk]\Delta t} \right) \quad (6)$$

where $[ijk]$ is the cell index.

Cell Characteristics and Pack Configuration & Size

One primary focus of this work is to investigate the effects of cell characteristics on cell balancing. Cells from production exhibit variability in characteristics such as capacity, internal resistance, self-discharge rate, capacitance, etc. Different cell characteristics have different effects on cell balancing. It is desirable to match the cells characteristics with the cell balancing techniques. In principle, all these characteristics depend on SOC, temperature, and aging time [12]. In this work we only considered capacity variance, internal resistance variance, and self-discharge rate variance and they are all independent of SOC and temperature. The aging effects are also not included. We should mention that there are two other possible sources that contribute to cell imbalance: different load currents from cell monitoring electronics and different cell coulomb efficiency. For Li-ion cells the coulomb efficiency is close to 100% and therefore not considered. No reliable data is available for load currents of cell monitoring electronics and thus not studied either.

Pack configuration is another important design variable to match the pack with the cell balancing. In this paper we simulated different pack configurations to elucidate the effects of pack configuration on balancing need and performance. The effects of pack size are also studied.

Balancing Algorithm

Terminal voltage, open circuit potential (i.e., SOC), or SOC history can be used to start a balancing [13]. Using terminal voltage is simple but may not reflect the true state of charge due to influence of internal resistance. Using open