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Modelling and experimental evaluation of parallel connected lithium ion cells for an electric vehicle battery system

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HIGHLIGHTS

- Experimental evaluation of energy imbalance within parallel connected cells.
- A validated new method of combining equivalent circuit models in parallel.
- Interdependence of capacity, voltage and impedance for calculating cell currents.
- A 30% difference in impedance can result in a 60% difference in peak cell current.
- A difference of over 6% in charge throughput was observed during cycling.

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ABSTRACT

Variations in cell properties are unavoidable and can be caused by manufacturing tolerances and usage conditions. As a result of this, cells connected in series may have different voltages and states of charge that limit the energy and power capability of the complete battery pack. Methods of removing this energy imbalance have been extensively reported within literature. However, there has been little discussion around the effect that such variation has when cells are connected electrically in parallel. This work aims to explore the impact of connecting cells, with varied properties, in parallel and the issues regarding energy imbalance and battery management that may arise. This has been achieved through analysing experimental data and a validated model. The main results from this study highlight that significant differences in current flow can occur between cells within a parallel stack that will affect how the cells age and the temperature distribution within the battery assembly.

1. Introduction

Cells in a battery pack may be electrically connected in parallel in order to increase the pack capacity and meet requirements for power and energy [1,2]. For example, the Tesla Model S 85 kWh battery pack uses 74 3.1 Ah cylindrical cells to create a parallel unit, and 96 of these units in series. Conversely, the Nissan Leaf 24 kWh battery pack consists of 33 Ah cells, with 2 in parallel and 96 in series [3]. The nature of a parallel connection means that the voltage over each cell is the same and the applied current is equal to the sum of the individual cell currents. It is commonly assumed that energy balancing is only required for cells in series [4,5] since the cells in a parallel unit are inherently balanced due to the common voltage [6,7]. However, there has been little experimental data to explore this further. Variations in internal resistance mean that the cells within a parallel unit will undergo different currents. However, individual cell currents are typically not measured, and so any variation in current is not detected by the battery management system (BMS). Differences in current can change the state of charge (SOC), temperature and degradation rate of each cell [8,9], meaning cells in parallel may not be at the same SOC despite being at the same terminal voltage [10], and could degrade at different rates. State of health (SOH) is often used to quantify cell degradation, with common definitions using the increase in resistance or decrease in capacity relative to when the cell is new [11]. Accurate SOH estimation is a key challenge for battery management systems (BMSs) [12].

The objective of this paper is to introduce a model that allows for thorough analysis of parallel-connected cells in a battery pack, while integrating with existing frameworks. This can be used to aid

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battery pack design, for example evaluating different series-parallel configurations of cells, and analysis of the temperature distribution within the battery pack. The robustness of BMS functions such as SOC estimation and fault detection can also be tested.

Gogoana et al. [13] cycle-aged two cylindrical lithium iron phosphate (LFP) cells connected in parallel. They found that a 20% difference in internal resistance resulted in a 40% reduction in the useful life of the pair of cells compared to if the cells had approximately equal internal resistances. The authors attribute this to the uneven current distribution between the cells. Their results highlight that each cell will go through periods where it experiences high currents that will in turn age the cells more quickly. Gong et al. [1] drew similar conclusions from their experimental work with 32 Ah cells. When two cells with a 20% impedance difference were connected in parallel, the peak current experienced was 40% higher than if the cells were identical. The authors also performed simulation studies, using the Mathwork's Simscape extension to Simulink to connect two equivalent circuit models (ECMs) in parallel. This is one of the few examples of parallel cell modelling within the literature. Wang et al. also used Simscape for modelling cells in parallel [14], although the current distribution was not analysed in detail. Offer at al. used a simple cell model in Simscape for analysing the effect of poor connection resistance between parallel cells [15]. This effect was explored further in Ref. [10], where an electrochemical model was used to simulate the impact interconnection resistance between cells in parallel has on battery system performance. Often, a parallel unit ‘lumped’ model is created, where the parameters of a single cell model are scaled to create an effective parallel unit, such as in Ref. [16], in which the authors screen a large batch of cells to ensure that only similar cells are connected in parallel. While this may be valid for new cells, there is no guarantee that the cells will degrade in the same way, as demonstrated in Ref. [17]. Similar assumptions are made in Ref. [6], where the SOC of cells in a parallel is assumed to always be equal. While assumptions such as these allow for the high-level simulation of a battery pack, it assumes the cells within a parallel unit are identical and as such all experience the same electrical and thermal loading. This limits the accuracy of the model and means that some potential physical phenomena, such as temperature gradients and current variations, are not analysed and accounted for as part of a model-based design process. While an acausal approach such as Simscape can account for variations in parameters, it is less well suited to analysis and manipulation than solving a system of ordinary differential equations (ODEs), as is the case for a single cell model.

The contribution of this paper is to extend the existing literature in terms of both simulation method and experimental data. In Section 2 a generic parallel cell model is derived, which allows for the calculation of cell currents and states within a parallel stack while maintaining the same model structure as a single cell model. This means that cells in parallel can be modelled and evaluated within conventional frameworks without having to make assumptions about cell uniformity. The experimental work is introduced in Section 3, in which four commercially available 3 Ah 18650 cells are aged by different amounts to create differences in their respective capacity and impedance. The cells are then connected in parallel and cycle-tested to analyse and quantify the variations in performance, such as current and temperature, which arise from these differences. The model is validated against experimental data in Section 4. Results from the experimental and simulation studies are analysed in Section 5, in which various vehicle usage cases are considered and the impact of using cells in parallel for these applications is evaluated. Conclusions and further work are presented in Section 6.

2. Model development

The ECM is commonly used to simulate the voltage response of individual cells, due to its relative simplicity, ease of parameterisation and real-time feasibility [18,19]. The primary aim of the ECM is to match the voltage response of a physical cell based on a current input, rather than to model the cell using fundamental electrochemical theory. Despite the lack of a physical basis to the model, elements of the circuit can be related to aspects of the cell's physical response, such as charge transfer and diffusion [20].

2.1. Equivalent circuit model

The single cell ECM consists of several elements, as shown in Fig. 1a: the open circuit voltage v_{OC}, internal resistance R_D and a resistor-capacitor (RC) pair, which is a resistor R_p and capacitor C_p in parallel. Multiple RC pairs in series can be used depending on the bandwidth and fidelity of the response required. Eq. (1) shows that for a given current i_{cell}, the terminal voltage v_t is comprised of the v_{OC}, the voltage over the internal resistance and the sum of the RC pair voltages v_p. v_p and SOC are governed by ODEs, given by (2) and (3) respectively. Typically, v_{OC} is not calculated directly; instead SOC is calculated using (3), where Q is the cell capacity in Ah, and v_{OC} found from (4). Unlike (3), the v_{OC}-SOC function in (4) is typically nonlinear. By treating SOC, not v_{OC}, as a model state variable, the state equations are kept linear. Commonly, systems such as this are written in state-space form as in (5). The system for one RC pair is shown in linear state-space form in (6). Throughout this paper, a one-to-one relationship between SOC and v_{OC} has been assumed, which can often be considered sufficiently accurate [21]. In reality the cell response may exhibit hysteresis, in which the v_{OC} at a given SOC may be different depending on whether the cell is being charged or discharged. As discussed in Ref. [22], this can be accounted for by adding additional states (ODEs) to the model.

$$v_t = v_{OC} + R_D i_{cell} + \sum_{n=1}^{N} v_{p,n} \tag{1}$$

$$\dot{v_p} = -\frac{v_p}{R_p C_p} + \frac{i_{cell}}{C_p} \tag{2}$$

$$S\dot{O}C = \frac{i_{cell}}{36Q} \tag{3}$$

$$v_{oc} = f(SOC) \tag{4}$$

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{5}$$

$$\begin{aligned} \begin{bmatrix} S\dot{O}C \\ \dot{v_p} \end{bmatrix} &= \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{R_p C_p} \end{bmatrix} \begin{bmatrix} SOC \\ v_p \end{bmatrix} + \begin{bmatrix} \frac{1}{36Q} \\ \frac{1}{C_p} \end{bmatrix} i_{cell} \\ \begin{bmatrix} v_t \end{bmatrix} &= \begin{bmatrix} \frac{f(SOC)}{SOC} & 1 \end{bmatrix} \begin{bmatrix} SOC \\ v_p \end{bmatrix} + \begin{bmatrix} R_D \end{bmatrix} i_{cell} \end{aligned} \tag{6}$$