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Parameter variations within Li-Ion battery packs – Theoretical investigations and experimental quantification

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ABSTRACT

Single lithium-ion cells within electric vehicles' battery packs generally show variations in capacity and impedance due to the manufacturing process as well as operational conditions. Therefore, cells connected in parallel experience different dynamic loads during vehicle operation, which may potentially result in uneven and accelerated aging behavior. However, in literature only little is mentioned about the different reasons for parameter variations within single cells of parallel connections as well as their magnitude in real-life conditions. In this work, capacity and impedance variations within parallel-connected cells are investigated theoretically and are quantified exemplary by a batch of new cylindrical 18650 cells as well as an retired BEV battery pack with a 2p96s configuration of prismatic cells. Furthermore, the development of existing parameter variations along cycling are analyzed for two modules of the battery pack. It is demonstrated, that the aged cells show a strong increased parameter spread compared to the new cells. During further aging, the existing capacities spread of the block and especially the state of inhomogeneity of parallel couples increases. Hence, the widespread theory of a self-balancing effect inside a parallel connection, which leads to a convergence of the cells' SOH, is disproved.

1. Introduction

Nowadays hybrid and electric vehicles batteries are composed of a multitude of single Lithium-ion cells. Thereby, parallel connections are utilized to increase the total battery pack capacity and serial connections to fulfill vehicles' power requirements without excessive current rates [1]. If cells with a small individual capacity are chosen many cells need to be connected in parallel, which enhances the system's reliability in case of an open wire failure at the expense of increased complexity and higher contacting efforts [2]. This approach has been practiced e.g. in the Tesla Model S, where several thousand cylindrical 18650 cells are used within the battery pack [3]. In contrast to that, there are also examples where only two cells in parallel are sufficient to reach the desired capacity and power level or where manufacturers totally forgo a parallel connection, as is done e.g. in the BMW i3 [2]. The battery in this study was built out of prismatic cells with a capacity of 50 Ah in a 2p96s configuration, resulting in a nominal voltage of 374 V and 100 Ah capacity of the entire pack.

Many publications exist on the aging behavior of single Li-Ion cells [4–6], as few deal with whole battery packs and especially with the influence of parallel connections on the pack performance and aging behavior. Cells connected in parallel experience different dynamic loads during vehicle operation caused by parameter variations. Load imbalances result in different magnitudes of stress factors for cell aging and will therefore force individual cells within parallel connections to degrade at different rates. This in turn is going to make a contribution to parameter variations themselves. The aim of this paper is to extend the state of knowledge in this field of research. Thereby the main goals are:

- **Theoretical and experimental investigation of the origins and effects of parameter variations within parallel-connected cells:** Variation of all critical parameters as well as their influence on load imbalances are analyzed in detail. Furthermore, literature on the effect of those variations on aging behavior is reviewed. (Section 2)
- **Quantification of parameter variations in real-world conditions:** A new cell batch (NCB) as well as a retired BEV battery pack (RBP) are characterized by means of capacity and internal resistance variations. This is done for single cells as well as for parallel couples and their respective state of inhomogeneity of the RBP (Section 4).
- **Examination of parameter spreads during aging:** Further cycle aging tests with two modules and characterization measurements after every 100 cycles have been performed. Thereby, the development of initial parameter variations within parallel couples as well as effects on the aging rates are studied (Section 5).

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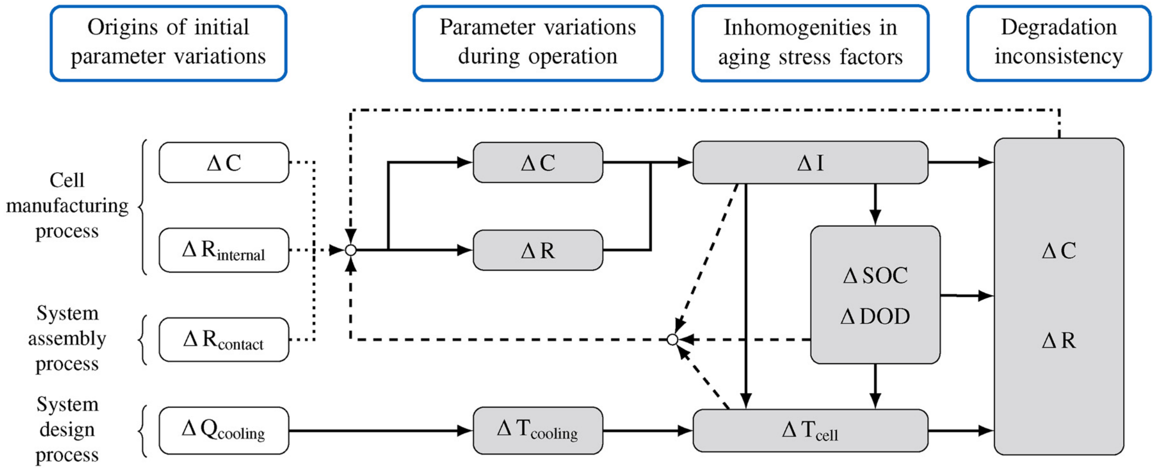

Fig. 1. Overview of parameter variations, their origins and mutual influences with load imbalances and inconsistent degradation.

Test procedures and statistical methods used to experimentally investigate parameter variations are described in Section 3. A conclusion is given in Section 6.

2. Parameter variations within lithium-ion cells

2.1. Origins of parameter variations

Due to the system's complexity, multiple origins can be identified to cause initial parameter variations within a battery pack (Fig. 1). On the one hand, cell-specific parameters, namely capacity and impedance can differ from cell to cell due to imperfections in the manufacturing process as well as impurities in cells' raw materials like e.g. the active material [7–11]. On the other hand, parameters on the battery system level, such as contact resistances, underlay manufacturing and/or human operating tolerances, depending on the joining technique [12,13]. Also, the design of the battery pack's package and its cooling system can be an origin of initial parameter variations [14,15]. These initial parameter variations partly affect each other during vehicle operation and can thereby even be amplified. The presence of capacity and impedance variations within parallel-connected cells causes inhomogeneous current loads that result in different power losses and thereby inhomogeneous heating of the cells. Also, the varying current loading forces the individual cells to operate at different state of charge (SOC) levels and thereby different depth of discharge (DOD) windows. This results not only again in parameter variations due to the SOC dependency of impedance parameters but also means varying aging stress factors and therefore inconsistencies in the individual cells' aging behavior, which are superimposed to the present aging spreads due to production tolerances [11,16,17]. Within the next chapter, this complex mutual interaction of initial and operational parameter variations will be explained in detail. Relevant publications are summarized in Table 2.

2.2. Mutual influences of critical parameter variations and load imbalances

The electrochemical behavior of a cell depends on many parameters such as temperature, SOC, current rate (C-Rate) and previous history. Due to this fact, there are many intrinsic parameters that affect the current distribution within parallel cells, beside extrinsic ones arising from the battery pack system design. In the following, these parameters shall be explained in detail.

2.2.1. Internal resistance

An electric circuit that connects two resistances R_1 and R_2 in parallel is called a current divider. Thereby, the current through one branch of the circuit is calculated by $I_1 = (R_2/R_1)\cdot I_2$. This means, when resistances differ, the current distribution will be uneven [7]. This fundamental principle can also be applied for parallel-connected cells, but instead of pure ohmic behavior, each cell's impedance with various time constants has to be taken into account [18]. Consequently, a higher internal resistance mismatch leads to higher imbalanced currents. This in turn increases the risk for operating the less resistive cell in an improper high current range [19]. The same results can be observed not only for two, but for any number of parallel-connected cells. Bruen et al. [3], for example, connected four cells with different internal resistances in parallel, where $R_1 < R_2 < R_3 < R_4$. The resistance mismatch results in unequally distributed branch currents, whereby $I_1 > I_2 > I_3 > I_4$.

2.2.2. Contact resistance

The same considerations as for the internal resistance lead to the conclusion that also unequal inter-cell connections on the pack level can cause imbalanced currents. When multiple cells are connected in parallel, the current flow through each cell may vary due to differences in the sum of electrical contact resistances and different amounts of bulk material (as a consequence of the pack configuration). Brand et al. [12,20,21] did different work on the electrical contact resistance of press contacts, different welding techniques and, most recently, on soldering cell connections. The resistances were measured via four-point probe method on two metal specimens overlapping by 15 mm × 15 mm. Table 1 lists the range of pure electrical contact resistance R_c and the corresponding variation $R_{c,\Delta}$ (90% confidence interval) of the five examined techniques for brass test samples. Thereby, existing dependencies for each technique such as contact pressure, contact area and surface roughness (press contacts), number of weld

Table 1
Typical range of contact resistance R_c and variation $R_{c,\Delta}$ (90% confidence interval) of contact resistances for different joining techniques. Listed values determined by experiments according to [12,20,21].

	Press contact	Resistance spot welding	Ultrasonic welding	Laser beam welding	Soldering
R_c/mΩ	0.154–0.195	0.167–0.196	0.169–0.318	0.130–0.162	0.080–0.111
$R_{c,\Delta}$ / mΩ	0.01	0.02	0.06	0.02	0.02

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