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Experimental investigation of parametric cell-to-cell variation and correlation based on 1100 commercial lithium-ion cells

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ABSTRACT

In order to prevent battery modules from inhomogeneity during operation, the integrated battery cells should be matched. Therefore, the cell-to-cell variations of relevant cell parameters due to manufacturing tolerances need to be quantified. Regarding cell matching, three points are lacking in current literature: first, reported parameter analyses have either based their statistic analysis on a too small number of cells. Or, second, few different cell parameters have been considered – hence, it was not possible to discuss which parameter would be beneficial to be used for classification. Third, potentially sensible correlations between different cell parameters have not been determined and discussed adequately. This paper provides a unique combination of analysing multiple different cell parameters and discussing their correlation – both based on a large number of examined cells: we investigate the parametric cell-to-cell variation and correlation of 1100 commercial production fresh $LiFePO_4$-graphite cells which originate from two batches. The cell parameters are experimentally determined by conducting DC check-up (CU)- and AC EIS-measurements under monitored temperature and relaxation conditions for all 1100 cells. The data is statistically analysed for 15 different parameters: different discharge capacities, different DC and AC impedances, the mass and mean temperature of the cells. The determined relative variation of capacity and impedance is small: 0.28% and 0.72% respectively, which corresponds to a variation ratio of 1:2.2. The variation of the cell impedance allows no conclusion about the variation of the cell capacity. From the results, we derive four major implications concerning recommended characterisation parameters for the development and modelling of battery modules as well as for the quality control during cell production. Our experimentally determined parametric variation values and drawn conclusions are valuable for model fittings and battery pack analyses which have up to now been based on assumptions about cell-to-cell variations. The data set for all 1100 cells and 15 parameters is provided as supplementary material [1].

1. Introduction

Manufacturers of storage systems for electric cars and stationary storage applications aim to produce reliable and long-lasting battery modules. In order to ensure these high quality standards, inhomogeneity within a module should be avoided [2]. Inhomogeneity in a battery module in this context denotes a gradient of a certain parameter across connected battery cells. There are different reasons which can lead to inhomogeneity within battery modules: the integration of unmatched cells showing cell-to-cell variations in capacity and impedance [2–7], uneven [8] or defective cell contacts [9,10], an ineffective cooling strategy [11] or an external heat source next to the battery module [12,13].

This work will investigate cell-to-cell variations of new cells. These can, in spite of high quality standards for commercial lithium-ion cells, result from manufacturing tolerances [3,14] and varying shipping or storage conditions. When integrating unmatched cells into battery modules, these variations can lead to

Abbreviations: AC, alternating current; CC, constant-current; CCCV, constant-current-constant-voltage; COC, coefficient of correlation; COD, coefficient of determination; COV, coefficient of variation; CTS, cell test system; CU, check-up; CV, constant-voltage; DC, direct current; DCH, discharge; ECM, equivalent circuit model; EIS, electrochemical impedance spectroscopy; fpd, frequencies per decade; LFP, lithium iron phosphate; mpf, measures per frequency; MU, measurement uncertainty; NCA, lithium nickel cobalt aluminium oxide; NMC, lithium cobalt nickel manganese oxide; OC, open circuit; SOC, state of charge; SOH, state of health.

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local temperature peaks and may result in inhomogeneous [3] and accelerated ageing [4,5]. Hence, parametric variations are crucial to consider when designing and assembling battery modules.

When aiming to determine the parametric variation of lithium-ion cells due to manufacturing tolerances, it must be ensured that possible cell-to-cell variations do not result from external reasons. Such reasons could be that the cells originate from different production batches, that the cells have been shipped under different conditions, thus experiencing a different calendaric ageing, or that the cells have already experienced an operational history, i.e. have been cycled prior to the cell characterisation measurements, maybe even under different measurement conditions. Concluding, in order to being able to rely on experimentally determined parametric variations due to manufacturing tolerances, the cells to be used for investigation should be production fresh.

1.1. State of the art

The experimental determination of commercial cell-to-cell parametric variations has been addressed by a handful of research groups. However, measurements to determine cell-to-cell variations are time consuming: in order to allow for a thorough statistic analysis a large amount of cells has to be investigated. In terms of cell characterisation, this requires excessive measurement capacities.

Most publications, which base their work on a statistic analysis of battery cells, aim to investigate ageing behaviour [4,5,14–17] or the assembly and performance of battery modules [4–6,16–20]. In these cases the statistic analysis is mostly addressed marginally alongside the main focus of the respective work.

1.1.1. Number of investigated cells

Many publications base their statistic analysis on no more than 250 cells [2,5,14–16,18–21].

Dubarry et al. [2] have investigated 100 cells and measured their respective distribution of weight, initial (SOC) (as delivered), and discharge capacity. By simulation they identified cell internal attributes which resulted in the experimentally determined cell-to-cell variations: the amount of active material, polarisation resistance, and localised kinetic factors. Following this, they further investigated 10 cells towards their cell-to-cell variations [21] and chose a nominal sample cell in order to examine ageing phenomena in the cells [15].

Zheng et al. [19] have examined 96 cells regarding the variation of impedances in order to distinguish between the internal and contact resistance increase faults when the cells are connected in series. After having measured the variation of capacity of 16 cells, they connected 8 of them in series to a small battery module and parameterized a model which describes both, the battery module's state and the single cells' inconsistencies [20].

Miyatake et al. [18] have experimentally examined the influence of cell-to-cell variations in capacity on the discharge capacity of differently connected battery module topologies assembled from up to 12 cells: when cells are connected in series, the module capacity is affected by the cell with the smallest capacity. When cells are connected in parallel, the capacities of the single cells add up to the module capacity. When cells are connected in series and parallel, the module capacity depends on the module configuration.

Gogoana et al. [5] have measured the impedance variation of 72 cells in order to show that when two cells, which have a 20% different impedance, are connected in parallel, they experience an up to 40% higher ageing than two parallel-connected cells which have a similar internal resistance.

Campestrini et al. [16] compared battery module ageing to that of single cell ageing. For this they examined two battery modules consisting of 112 cells each which had been matched from a lot of 250 cells. Disassembling the battery modules allowed for an ageing analysis of capacity fade and impedance rise regarding local temperature distribution and cell-to-cell variation within the modules.

Baumhöfer et al. [14] have analysed the variation of capacity (constant-current-constant-voltage (CCCV)) of 48 commercial cells at two states of ageing. Moreover, they determined different pulse and alternating current (AC) impedances in order to identify parameters to be measured at the begin-of-life in order to predict ageing behaviour. They found that the deviations between the capacities of the aged cells increase compared to the capacity distribution of the new cells. They point out that using more cells for the statistic investigation, would be beneficial [14].

Some research groups do examine larger lots of cells [4,6,17,22,23].

Paul et al. [4] have investigated 20,000 lithium-ion cells. They measured the initial cell capacity and the direct current resistance. Using 96 of these cells they furthermore examined ageing inhomogeneity in battery systems due to both, cell-to-cell variations and temperature gradients and validated a battery module simulation approach based on the Monte Carlo method.

An et al. [22] have measured the rate dependency of cell-to-cell variations of lithium-ion cells. Therefore they analysed the distribution of cell capacity and mass based on 5473 cells. From these they used 198 cells to additionally examine the direct current (DC) impedance and correlate both parameters to the current rate. From the capacity distribution of 7739 cells they moreover matched cells to build parallel-connected battery modules. Using these, they validated their ECM and studied the effect of cell sorting methods on the battery modules performance [6].

Schuster et al. [17] have analysed 484 new and 1908 aged lithium-ion cells from two identical battery electric vehicles towards their capacity and impedance distribution: the distribution shapes change during ageing from normal towards Weibull distribution. Following this, having complemented the data set by additional 83 partly aged cells, they furthermore examined the correlation between capacity and impedance of lithium-ion cells during calendar and cycle life in order to conclude upon whether testing the cell impedance can be used to deduce the cell capacity [23]: the correlation behaviour is strongly dependent on operational and storage conditions.

1.1.2. Number of investigated parameters

What becomes clear: most papers do only examine the variation of one DC or AC impedance and one discharge capacity – sometimes even without clearly specifying whether the discharge capacity has been determined during the constant-current (CC) phase or the CCCV phase. Only a small number of publications determine the cell-to-cell variations of different impedances [14,17]; none of them reports on a comparison of different capacities. However, such a comparison for both, capacities and impedances, seems crucial to us in order to make sure that the determined parameter during cell characterisation is the most promising to be used in order to reveal the desired information. What is more, discussing the dependency between different external cell parameters, i.e. a certain cell capacity and impedance, can help to reveal dependent parameters of which one could in consequence be omitted during cell characterisation and which would thus save measurement time.

1.1.3. Correlation between parameters

The dependency between different external cell parameters can be depicted by investigating the correlation between these