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Single cell analysis of lithium-ion e-bike batteries aged under various conditions

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HIGHLIGHTS

- Parameters of 1000 cells from 20 batteries are collected and statistically evaluated.
- The growth of variation during ageing is confirmed.
- The variation of internal resistance depends on the type of use.
- Capacity limitation due to capacity variation is not expected.

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ABSTRACT

In most cases, batteries consist of multiple cells with different interconnections in which the weakest cells determine the usable capacity, performance and lifetime. Since data on initial production-related cell to cell parameter variance is well known, only little data on variance change over lifetime is available. This work investigates how variance spreads with age. Twenty differently aged electric bike (pedelec) batteries are disassembled and the state of health, as well as the internal resistance, are measured cell by cell for each of these batteries. The results show the development of cell to cell variation of aged batteries. Gathered data is also used to calculate capacity limitations through progressed variation. The methodology of the investigation can be used to analyse potential use cases for active balancing systems.

1. Introduction

Today carbon emission is one of our biggest global challenges. It is considered to be responsible for climate change and needs therefore be drastically reduced within the next decade, especially in the industrial and transport sectors, which are the main producers of greenhouse gases [1]. In order to slow down climate change, environmentally sustainable solutions are needed for these big sectors [2].

A key-technology for a cleaner future is the use of regenerative energy like solar and wind energy. However, the energy of regenerative sources is not permanently available. So suitable systems to buffer energy and appropriate power electronics with low power dissipation to connect these systems to grid are needed [3,4]. One possible storage technology is the lithium-ion battery [5].

Formerly lithium-ion batteries were used in small portable devices like cell phones. Today the use in bigger applications like storage systems or Electric Vehicles (EV) and even electric bikes is possible.

For those use cases, the battery has to meet demanding requirements [6] [7], such as durability and a typical lifetime of 10 years in case of EVs or even longer in case of storage systems.

Battery packs are built from single cells. In order to reduce energy loss, cells can be serially connected thus achieving high voltage values. If cells are connected in parallel the usable capacity increases. A parallel-serial combination of multiple cells enables any custom specific battery pack meeting both requirements. So, a battery pack can consist of a huge amount of cells [8]. However, with a high number of cells, it is very important that the parameters of all individual cells are as even as possible [9,10], since the usable capacity and performance of a battery pack depends on the weakest cell.

During lifetime the cells of battery packs are exposed to different load and environmental conditions that affect the ageing processes [11]. Additionally, cell production quality, as well as material variations, lead to different ageing processes and thus behaviour of each single cell [12,13]. Despite being important and of great interest, the effect and impact of these uneven cell ageing processes within a battery have not been in the focus of scientific investigations nor publications so far. From [14] the initial cell parameter variation from the production process is well known. But these initial cell parameters can't give a

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clue on how the parameters of the individual cells within a battery will change over their lifetime. Therefore it is necessary to investigate battery packs in detail, i.e. cell by cell, to better understand the ageing process and thereupon estimate upcoming consequences for the battery pack performance [15]. and [16] analyses the cell to cell variation of two electrified trolley buses by evaluation of the open circuit voltage. The main inconsistency factor of internal resistance values is found to be the battery temperature. An equal SOC level of all cells is also important to ensure consistency of the battery. In [17] temperature, self-discharge rate and coulombic efficiency affect parameters of cell variation most [18]. builds battery modules with pre-matched cells and investigates cell ageing behaviour compared to module ageing behaviour.

The motivation of this work is to determine cell variation in aged battery packs and to investigate thereby resulting limits on the battery usage. For these investigations, twenty various aged battery packs are used. These battery packs had been aged in field applications as well as in laboratory cycling tests. The main objective focuses on the determination of cell capacity variation within the battery. The variation of Direct Current Internal Resistance (DCIR) is of high interest as well. The results of these investigations may be also interesting for the use of second life batteries [19].

2. Laboratory and field ageing of battery packs

The investigated battery is a commercially available e-bike battery (format BL03) produced by TranzX. It has a nominal capacity of 13 Ah and a nominal voltage of 36 V.

The batteries used for these investigations had been aged in a prior experiment. The aim of the experiment was to analyse the ageing behaviour of e-bike batteries in field. Simultaneously the same type of battery packs had been aged in laboratory as well.

The cycle plans used for laboratory ageing have been created from real e-bike driving-cycle data. The used e-bikes had three different supporting modes with a DC current of 5 A, 10 A and 15 A. The laboratory cycle plan applies these currents proportionally to the times from real driving. Real driving periods for each mode have been captured with built-in data loggers. Overall, the mean discharge rate of the used cycle plan was 0.3C. Finally, ageing during real driving, i.e. in the field, was successfully verified in laboratory. Ageing development from both tests is matching. A detailed description of this prior comparative ageing experiment can be read in [20].

3. Experimental setup

The experiment was divided into two parts. At first, the complete battery was investigated. Afterwards, all single cells were considered. In total twenty batteries were used for the investigations. Twelve had been cycled in laboratory at 5 °C (1), 25 °C (9) and at 45 °C (2) and eight batteries had been aged in field (real driving).

3.1. Battery pack measurement

At first general battery data is gathered. To get information about cycle count, the built-in battery monitor is readout over I2C communication bus. Furthermore manufacturing date of the cells of each battery pack is identified in order to determine the exact calendar age.

Before the Reference Parameter Test (RPT) begins, the batteries rest for about 2 h for acclimatisation.

The first step in the following RPT is capacity determination. The discharged battery is charged with a constant value of 0.2C until the desired voltage of 42 V is reached. Afterwards, voltage is held constant until the current is lower than 650 mA (0.05C). Discharge is also conducted with a constant current of 0.2C. Once the battery reaches 30 V or one single cell 3.0 V capacity determination stops and is then followed by recharging phase and pulse resistance measurement for DCIR determination. The duration of the pulses is 30 s with an intensity of 1C. The pulse measurements are conducted at seven different voltage levels. The DCIR can then be determined by monitoring the voltage response of the battery during the pulse.

Table 1
Overview of battery data.

Name	Age years	Cycles	Capacity Ah	DCIR 50% mΩ	Cycle temperature °C
1	2.5	40	12.39	175	–
2	3.5	68	12.09	216	–
3	4.3	95	12.03	199	–
4	3.5	122	12.15	216	–
5	3.5	273	12.25	210	–
6	3.5	284	11.85	226	–
7	4.3	286	12.15	197	–
8	3.5	287	11.98	218	–
9	3.2	303	11.50	209	25
10	2.5	321	10.81	204	5
11	3.2	347	11.88	192	25
12	3.2	357	11.28	208	25
13	3.2	425	11.89	193	25
14	3.2	428	11.49	196	25
15	3.6	483	11.24	240	45
16	3.2	497	11.21	233	45
17	3.2	577	11.42	233	25
18	3.2	640	11.30	193	25
19	3.2	1464	10.12	234	25
20	3.2	1480	10.37	223	25

Table 1 is divided into two sections. The first section contains eight batteries, named 1 to 8, that had been aged in field. The second section contains 12 batteries, named 9 to 20, that had been aged in laboratory.

To determine capacity and DCIR values of the complete batteries a High Power System (HPS) by BaSyTec GmbH was used. The accuracy of the used HPS in the chosen current range is ± 20 mA, leading to a tolerance of measured capacities of ± 0.1 Ah. During measurements, all batteries were stored within a Memmert IPP55 temperature chamber. The operating temperature for all RPT-tests was 25 °C. All gathered data can be seen in Table 1. The batteries are sorted by cycle number.

Even though most of the batteries have different calendar age and cycle temperature [21] the correlation between cycles and capacity can be seen. Correlation between DCIR and cycles is less obvious but also given (see Fig. 1).

The measurements of complete batteries were carried out to find potential abnormalities, that could indicate cell to cell variation. However, the investigation of the batteries was inconspicuous. All values follow the trend line. So far no clues for a limiting variation in cell parameters can be seen. For more information, single cell

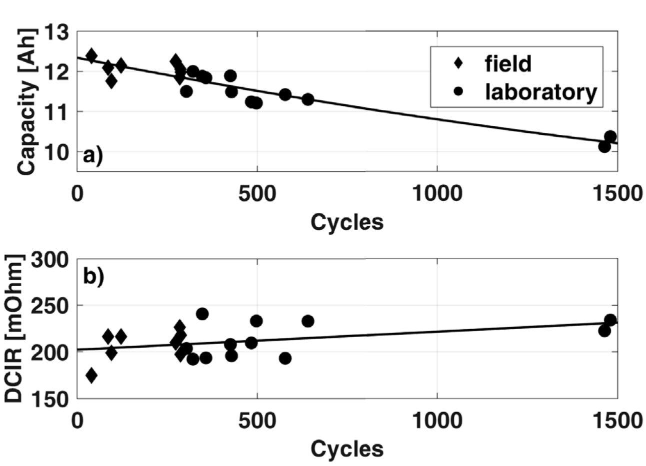

Fig. 1. Capacity and DCIR vs. cycles of all involved battery packs.