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Capacity Dispersion and Impact of Outliers in a Second Life Battery

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Abstract—Reducing heterogeneities between battery elements is paramount to ensure good performance and lifetime of this type of storage system. Since second life batteries may be more heterogeneous than fresh batteries, quantifying and limiting cell spread is an important task. This paper proposes an experimental and modelling study of cell spread in a second life battery module. The capacity spread in a battery module that has been used in an electric vehicle for several years is presented. The battery modelling study also highlights the detrimental effect of an outlier cell on the overall performance of the battery. This study is a first step towards considering this dispersion in the modelling and diagnosis of reused batteries.

Index Terms—second life battery; capacity dispersion; voltage spread; cells balancing; battery management system

I. INTRODUCTION

Reducing greenhouse gas emissions is a major challenge to ensure a sustainable future for the next generations. As transportation and energy production account for more than half of this pollution [1], reducing their associated environmental impact is paramount. Lithium-ion batteries play an important role in this task by enabling the transition to electrified mobility and renewable energy production. For a large number of applications, the energy and power requirements for a storage system involves the assembly of several battery elementary units, called “cells”. The capacity dispersion of seemingly identical cells can be observed even during the manufacturing and assembly processes [2], which can lead to inhomogeneities in the different elements of an assembly, commonly called a “module”.

During use, different cells may also not experience the same current or temperature, which would exacerbate cell variations [3]. Since the performance of a storage system is directly dependent on the performance of its weakest element. Reducing cell-to-cell heterogeneity is crucial for ensuring excellent battery performance and longevity, particularly as the effects of this capacity dispersion increase with cell aging [4], [5]. Therefore, proper modelling and diagnosis can be particularly important for the development of battery reuse applications. Despite being in its early stages, battery reuse has become

increasingly popular due to the growth of electromobility. Reuse can be defined as the complete or partial reuse of the battery for the original purpose for which the battery was designed [6]. Scientific literature commonly refers to reused batteries as “second life batteries”.

Although reuse is recognised as beneficial in terms of reducing environmental impact, there are still technical and economic uncertainties associated with this new use. The performance evolution of batteries that have undergone a change of use during their lifetime is not yet well understood. Some works have focused on the experimental evaluation of the dispersion of batteries removed from electric vehicles [7]–[9]. Currently, there are only a few modelling studies concerning this topic.

This paper introduces an experimental and modelling study that focuses on cell capacity dispersion in a second life battery module. This study makes two significant contributions to the existing literature. Firstly, the experimental results presented in this study contribute to the limited number of existing studies on parameter dispersion in second life batteries. It helps to improve the understanding of the primary issue of dispersion in the battery pack. In addition, the simulation study appears to be one of the earliest to introduce and apply a module model of a battery obtained from the second life market.

The article is organised into the following sections: The first section assesses cell spreading through an experimental study. The next section models the cells individually and assembles them into a module. Subsequently, a simulation is performed to assess the voltage imbalances resulting from cell heterogeneity. The final section presents the conclusions drawn and possible extensions of this study.

II. EXPERIMENTAL STUDY

In this study, a second life battery module extracted from a BMW i3 vehicle is studied. The battery tested had previously been used in an automotive application for just under four years and was purchased from the second life battery market. This module is an assembly of 12 prismatic cells connected in series.

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Fig. 1. Second life battery module (left) and disassembled cells (right)

Characteristics of the tested cells are summarized in table I.

TABLE I
CELL CHARACTERISTICS

Characteristics	Value
Format	Prismatic
Nominal capacity Q_{BOL} [Ah]	95.2
Positive electrode material	NMC111
Negative electrode material	Graphite
Voltage range [V]	4.15-2.7
Size L \times W \times H [mm]	173 \times 125 \times 45
Weight [kg]	2.06

This module was disassembled and each lithium-ion cell was tested using a Bitrode battery cycler. The characterization test provided various information about the cells, such as their capacity, internal resistance, and low-current behavior. Data processing was done with the open software DATTES [10].

In this work, the focus is on the cell capacity, which was measured at 25°C with a constant current discharge rate of -1C and calculated thanks to the equation 1.

$$Q(t) = \frac{1}{3600} \int_{t_0}^t i(t) dt \quad (1)$$

with

- $Q(t)$: the discharge capacity measured (Ah)
- $t - t_0$: the duration of a full discharge cycle (s)
- i : the discharge current applied to the cell (A)

The state of health (SoH) was calculated thanks to the equation 2 and taking into account the nominal capacity given in the data sheet.

$$SoH = 100 \times \frac{Q(t)}{Q_{BOL}} \quad (2)$$

with

- SoH : the state of health (%)
- $Q(t)$: the capacity measured at a given time (Ah)
- Q_{BOL} : the capacity measured at the beginning of life (BOL) (Ah)

The figure 2 shows the capacities of the 12 cells in the second life module, with μ showing the mean capacity and σ highlighting the standard deviation.

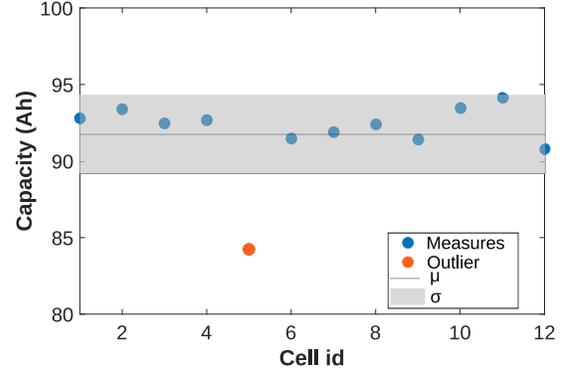


Fig. 2. Capacity dispersion of cells in a second life module

All cells belonged to the same module and consequently had the same first life automotive conditions. Therefore, the different capacities observed in the characterisation test are explained by the fact that identical cells can age differently even under similar conditions, as shown in [2]. These experimental results show that even four years after its production a battery can still perform excellently as the average value for state of health is 96.8%. These results highlight the relevance of defining the second life battery based on a change of application rather than a performance level. Cells in a second life battery pack can reach the end of their automotive life with a performance level well above the commonly accepted threshold of 20% capacity loss [11], [12].

The table II presents some statistical indicators of the cell spread in the tested second life battery module.

TABLE II
SPREAD OF MEASUREMENTS RESULTS

	Mean value	Median value	Standard deviation	Worst cell
$Q(t)$ [Ah]	91.8	92.4	2.6	84.2
SoH [%]	96.4	97.1	2.7	88.5

The above figure and table highlight the presence of an outlier cell, which presents a significant difference in capacity compared to the others. To date, there is no widely accepted definition of an outlier cell in the battery field. Schuster et al. chose a qualitative definition, defining outliers as elements that are more distant from the mean than the majority of cells [4]. Vitols et al. defined them as elements outside a range of three standard deviations from the mean [13]. Ramirez-Meyers added the concept of interquartile range to the former definition. According to these authors, a cell outlier has parameter values far outside the interquartile range [9]. The worst performing cell is 3 standard deviations and 6.8 interquartiles from the mean in the tested module.

As all cells in the module were connected in series, this means that the actual module capacity was limited by this outlier cell at a state of health of 88.5%. Therefore, 11 out of the 12 cells in the pack were hindered by the presence of this limiting cell. The ability to diagnose this outlier and replace

it with another cell that would perform closer to the average may therefore be an interesting prospect for increasing battery life, especially in second life applications.

III. SIMULATION STUDY

A simple electrical model consisting of an open circuit voltage, an internal resistance and two RC branches was used to model the cell and is shown in Figure 3. This model was chosen for its simplicity and ability to be easily implemented [14].

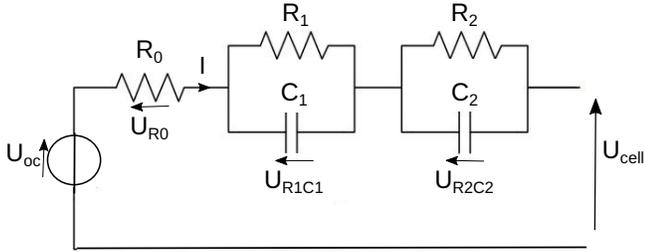


Fig. 3. Electric model used for the simulation study

The calibration methodology of the model consisted of using experimental data to fit the different parameters of the models, it has been described in detail in [11]. Once all cell models were defined, a model of the 12 cells assembly was made in Simulink using the Simscape toolbox. Figure 4 shows the module model used to simulate the behaviour of the cells. During the simulation, the state of charge of each cell is determined thanks to equation 3.

$$SoC = SoC_{t_0} + 100 \times \frac{1}{3600 \times Q_{BOL}} \int_{t_0}^t i(t) dt \quad (3)$$

with

- SoC : the state of charge of the cell (%)
- SoC_{t_0} : the initial cell state of charge (%)
- Q_{BOL} : the capacity measured at the beginning of life (BOL) (Ah)
- $t - t_0$: the time variation (s)
- $i(t)$: the current at a given time (A) (Current is negative in discharge)

In this study, the influence of capacity dispersion on voltage spread is evaluated. To perform the simulation study, all cell models were defined with the same impedance parameters taken from a previous work [11]. Only the capacity was defined specifically for each individual cell to match the experimental results shown in Figure 2.

At time zero of the simulation, all cells were set to the same state of charge. As the same current flows through all individual cells and the impedance parameters are strictly identical between cells, the voltage variation is solely related to the capacity dispersion. It is expected that the cell with the lowest capacity will reach voltage thresholds before all others, and that each cell will behave slightly differently as

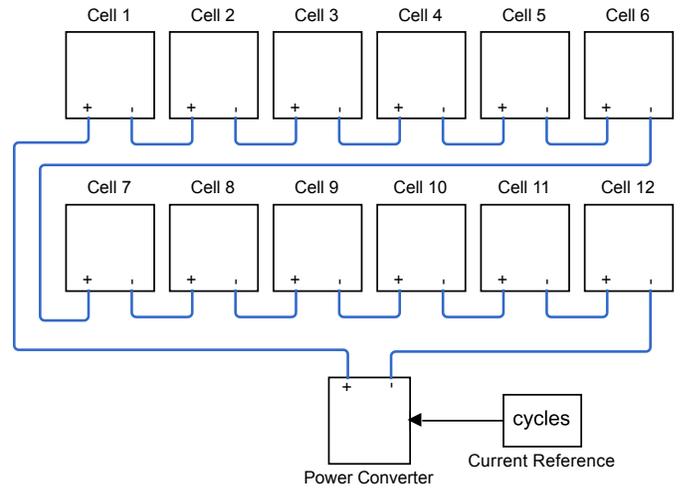


Fig. 4. Representation of the 12 cell models forming a module in a Simulink environment.

the model parameters depend on the state of charge, which in turn depends on the capacity.

To demonstrate this, a simulation was run with a Worldwide harmonized Light-duty vehicles Test Cycles (WLTC) profile and the voltage response of the cells was measured. The open-source software VEHLIB [15] was used to generate these battery profiles from a vehicular test procedure. The voltage response of the 12 cells during a WLTC profile is shown in figure 5. In this figure, the cell identified as an outlier is highlighted in orange.

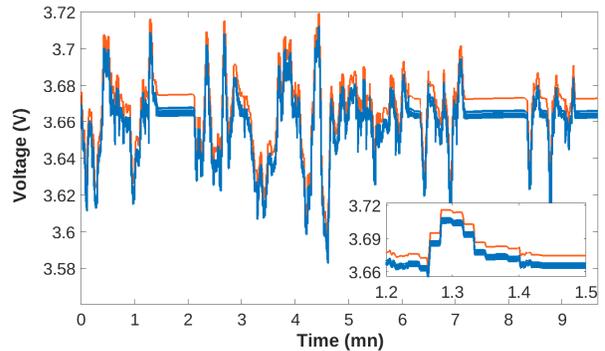


Fig. 5. Voltage responses of the 12 cells during a WLTC profile

In the module, 11 cells behave very closely, while the least performing cell is clearly outperforming. The voltage imbalance between cells is highlighted in Figure 6.

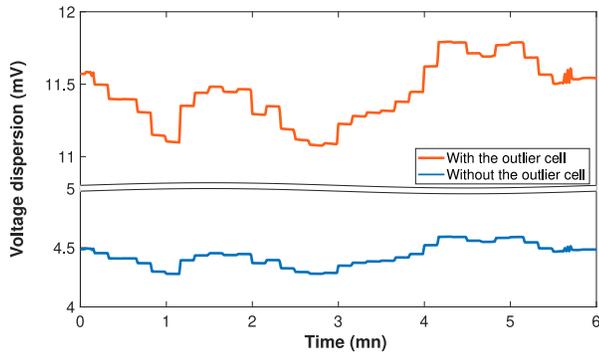


Fig. 6. Maximal voltage spread among second life cells during a WLTC profile

This figure shows the maximum voltage spread between cells over time. The dispersion of capacity between cells results in an average voltage spread of 11.3 mV, reaching a maximum of 11.8 mV during dynamic phases. This spread is mainly due to the outlying cell, as eliminating this element results in a division of the voltage spread by 2.5. This result shows the importance of measures such as thermal management or balancing strategies to reduce cell heterogeneity in order to guarantee battery pack performance.

IV. CONCLUSION

The experimental study has shown that a second life battery could have an excellent level of performance even four years after its production. The definition of a second life battery can then be discussed, as the performance threshold of 20% capacity loss usually accepted in the literature is not necessarily relevant, as a battery may have ended its first automotive life prematurely for various reasons. In addition, the module tested revealed the presence of an outlier cell, which can drastically reduce the performance of the whole module, as all cells are connected in series. This article then shows that even batteries removed from an electric vehicle with an apparently low capacity may in fact be limited by an outlier cell. Diagnostic procedures and techniques to evaluate the performance of all cells in a battery are then required to identify outlier cells and consider their replacement.

In the simulation study, the second life battery module was modelled using an assembly of twelve equivalent electrical circuits, each representing a cell of different capacity. This model was then used to simulate the effect of capacity variation on voltage variation. This simulation work is a first step towards more advanced and specific studies such as the sizing of the balancing resistor of the battery management system [16].

This work provides an opportunity to discuss an important issue associated with the reuse of batteries after their automotive life: the dispersion of battery cells. Future work will extend the model and simulation capabilities to include impedance dispersion.

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