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Reducing Cell to Cell Variation of Lithium-Ion Battery Packs During Operation

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AQ:2 **ABSTRACT** In this work, an experimental approach to reduce the variation from cell to cell during battery operation is evaluated to reach a better battery utilization. Numerous theoretical considerations of intelligent battery management systems without long-term experimental validation of their capabilities lead to a gap in the literature, which this work aims to address. For this purpose, the ageing behaviour of two batteries is investigated for almost 1.5 years. One battery is connected to an active balancing battery management system (BMS) and the other to a conventional passive balancing BMS. Important battery parameters, such as capacity and internal resistance, are recorded in each cycle. The battery behaviour is evaluated in detail by observing the voltage difference of the individual cells at the end of discharge and by calculating the amount of charge balanced by the BMS. Significant differences between the BMS systems used are elucidated, which illustrate the advantages of active balancing. In contrast to passive balancing, active balancing can reduce the ageing rate of the battery and achieve better utilization with a more than five times lower voltage spread at end of discharge, a up to 3.1% higher discharge capacity and a 7.7% longer service life.

INDEX TERMS Ageing, active balancing, passive balancing, cell variation, battery management, lithium-ion.

I. INTRODUCTION

Due to the rising CO_2 concentration in the atmosphere and the associated climate change, the emission of climate-active gases must be significantly reduced in the future in order to keep global warming below the targeted 2 °C limit [1]. Besides the industrial sector, the transport sector is mainly responsible for the majority of emissions. Especially in the transport sector, a rapidly developing electrification of vehicles is taking place, which results in equally rapid growth for the production of lithium-ion batteries [2].

Today, lithium-ion batteries are the best compromise in terms of their energy and power density. They have been continuously improved and further developed over the past decades [3]. Hence, they are most suitable for electrifying the transport sector. Sales figures are therefore rising worldwide. Especially China and the USA have seen an enormous increase in battery electric vehicles. In the USA, sales of battery-powered vehicles tripled from 2015 to 2019, in China even quadrupled [4]. The amount of energy of the inbuilt batteries ranges from a few Wh for e-bikes to storage systems bigger than 100 kWh for electric cars like the Tesla Model X.

In order to meet the ever-growing demand for lithium-ion technology, an increasing number of resources, some of which are difficult to access, are needed [5]. It is therefore even more important to optimally utilize both aged batteries, for example in second life applications, and new batteries.

In the literature, various research teams are working on the better utilisation of batteries. In [6], for example, the energy efficiency and service life of energy storage systems in micro-grid applications are improved by special energy management. This management contains an intelligent local forecasting and planning algorithm, which predicts the energy required in the grid. At the same time, defined State Of Charge (SOC) limits of all available storage systems are ensured by the management. By complying with the predefined SOC limits, the service life is extended. A different approach is described in [7]. Here, comprehensive ageing of batteries in certain SOC ranges allowed the identification of states of charge at which ageing is as low as possible. If the determined ranges are kept in real operation, the service life can be extended. Hoke *et al.* [8] use partial charging to

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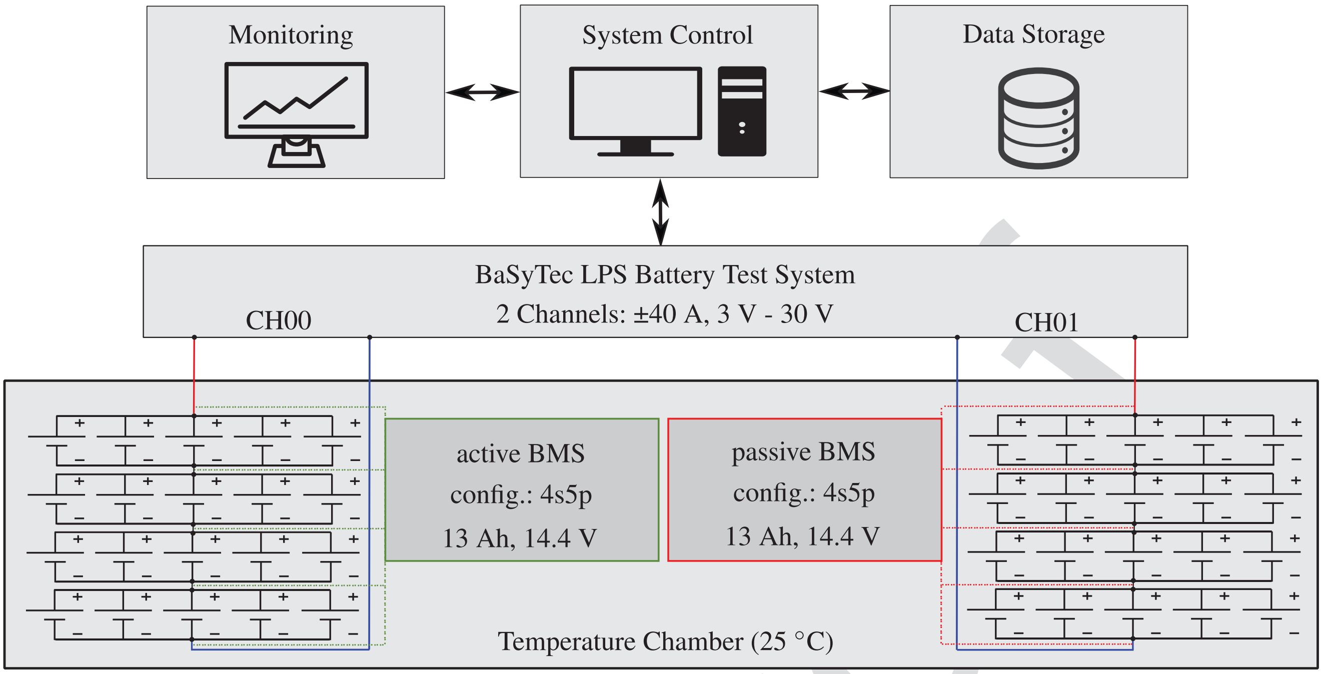


FIGURE 1. Schematic overview of the test-setup.

improve the service life. Here, an intelligent algorithm determines how much energy needs to be charged into the battery in order to supply enough energy for the next day or the next application planned. The main aim here is to avoid high SOC ranges.

All presented approaches for extending the service life and better utilisation of lithium-ion batteries limit the battery use to certain areas that extend the service life. However, complete utilisation of the available capacity is therefore not possible. The use of intelligent BMS with the possibility of balancing the individual cells is another attempt to extend service life and has already been discussed in the literature. [9]–[11]. In this article, a long term test is used to demonstrate a better utilization of batteries by such a BMS. For this purpose, two batteries are exposed to the same loads and equipped with different BMS for comparison. The experiment took place over 1.5 years.

Thus, the article is structured as follows. Section II introduces the used battery modules, their respective BMS and the conditions used for the ageing experiment including the used test equipment. In section III the generated data from the ageing experiment out of section II is presented. Here the results are discussed parameter by parameter. In addition to the usual parameters such as discharge capacity and internal resistance, the data required for the utilization evaluation such as capacity spread and voltage spread are analysed. After a discussion of the presented data in section IV, section V leads to the conclusion of the article.

II. EXPERIMENTAL SETUP

Two battery packs consisting of 20 Samsung ICR18650-26F cells in a 4s5p setup are used for the experiment. That means the batteries consist of four cell levels (CLs) consisting of five parallel cells each. Each cell has a nominal capacity of 2.6 Ah. The resulting nominal capacity of the two batteries is therefore 13 Ah with a nominal voltage of 14.4 V. One battery pack is equipped with an active BMS, the remaining pack with a conventional passive BMS.

Thus, in the experiment, one battery with active balancing and one battery with passive balancing are aged simultaneously. The experiment stops when both batteries have reached a State Of Health (SOH) of 60%.

Advantages and disadvantages between the different BMS systems are also investigated in order to reach an improved battery utilization. While disassembling the battery after the test, the authors identified the production code and noticed that the purchased cells had an calendar age of 2.5 years at the beginning of the test. With help of the battery manufacturer, the authors were able to discover that the batteries were delivered with an age of 6 months and a SOC of 96% (4.13 V). Afterwards, they were stored at room temperature. During storage, the voltage, which was 4.13 V on arrival, dropped to about 4.07 V in ca. 740 days. To determine the charge difference between the two voltages, an Open Circuit Voltage (OCV) vs. SOC curve was generated using a new identical cell. From this curve, it can be derived that a SOC loss of 6% took place. This value is comparable with data from the literature [12]. Fig. 2 shows the overview of the test procedure and the duration.

A. BATTERY MANAGEMENT SYSTEMS

The DC1653A Evaluation Board from Linear Technology is chosen as passive balancer. The maximum balancing current per cell is 130 mA. Balancing is enabled from a cell voltage of 4 V and is performed when the voltage difference between the CLs is more than 15 mV. The CL with the highest voltage

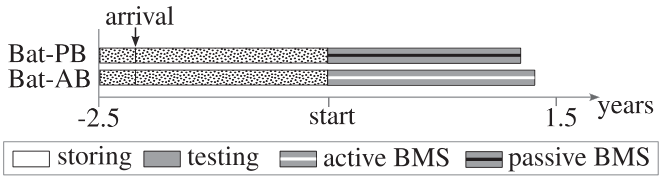


FIGURE 2. Test duration overview.

is discharged by a parallel resistor until the voltage difference falls below 15 mV again. As a result, balancing is mainly performed during the constant voltage (CV) phase to ensure a complete charge of all CLs and to protect them against over-voltage during the charging process.

As active balancer, a self-developed balancer board is used. This board is able to balance the charge of four CLs connected in series, with a 2 A charge current and 1.3 A discharge current. Functionality and hardware layout are based on a Linear Technology demo system [13], [14]. The active balancer board is controlled by an ATmega2560 running a self-developed algorithm. The development of the installed active BMS is further explained in several publications of the authors [9], [10], [15]. Based on [15], the operation of the algorithm can be briefly described as follows: The algorithm consists of two different strategies. First, a conventional voltage-dependent equalisation is performed at the end of the charging process. This equalisation strategy is activated when a CL voltage is higher than 4.1 V and a charge current can be measured. The voltage-dependent equalisation compensates different initial charges that may occur due to different self-discharge rates and prevents individual CLs from overcharging due to different internal resistances. The CLs with a voltage difference of more than 15 mV to the average cell voltage must be equalised. This procedure is comparable to that of passive balancing, with the crucial difference that an active balancing system can selectively charge CLs in this phase. The second balancing strategy is capacity-based balancing, in which each CL reaches its final discharge voltage simultaneously. Capacity-based balancing compensates different CL capacities and the influence of different internal resistances when reaching the final discharge voltage. This allows the maximum capacity of the battery to be used. The functioning of this strategy is based on an iterative calculation of the different charges to be balanced (individually per CL). These balancing charges indicate how much a CL should be additionally charged or discharged in the following discharge cycle. The equalisation charges are calculated by measuring the voltage of the individual CLs at the end of discharge and then comparing it with the characteristic open circuit voltage curve of the cells. The remaining capacity and therefore the capacity difference of the individual CLs can be iteratively determined from the open-circuit voltage curve.

B. TEST CONDITIONS

A BaSyTec Low Power System (LPS) is used to age the batteries. This battery test device is able to stress batteries with ±40 A in a range of 3–30 V. The accuracy of the voltage measurement is ±1.1 mV and the current accuracy in the selected range is ±2 mA. To maintain a constant ambient temperature of 25 °C during the test, the batteries with their BMS are placed in a Memmert IPP55 temperature chamber.

The batteries are charged with a constant current (CC) of 10 A until either a battery voltage of 16.7 V or a single CL voltage of 4.21 V is achieved. In the following CV phase, the battery voltage is kept constant at 16.7 V until the current drops below 650 mA. After that, a balancing phase begins during which the battery is charged for 1 hour at 200 mA. In this balancing phase, the BMS have additional time to execute their balancing actions. While the passive balancer is only able to balance cells in this phase or the CV phase, the active balancer can work independently from the actual battery state at any time. After a short pause of 10 minutes, the battery is discharged with 10 A until the entire package or a single CL reaches the discharge voltage limit of 12 V or 3.0 V for 5 s, respectively. For a schematic overview of the full test-setup see Fig. 1.

III. MEASUREMENTS AND RESULTS

In this section, the measurement results from the experiment described above are presented. First, the effects of calendar ageing in this test are determined. Furthermore, in addition to the common parameters of capacity and internal resistance, the voltage and capacity spread of the individual CLs are examined in detail. In a combination of all parameters estimations about the degree of utilization can be made. Based on this, the performance of both BMS can be evaluated.

A. CALENDAR AGEING

The active BMS battery (Bat-AB) has reached a capacity of 12.05 Ah in the first cycle. The passive BMS battery (Bat-PB) has a capacity of 12.29 Ah in the first cycle. So the difference between the two batteries at the beginning of the experiments is 0.24 Ah.

Only a very small difference can be measured in internal resistances of the batteries. Internal resistances are calculated by using a current pulse method, in which the voltage difference between the switch-on point $U(t_0)$ and a preset time interval Δt of 10 s after switch on $U(t_1)$, divided by the battery current I_{bat} equals to the battery resistance R_i:

$$R_{\mathrm{i}}(\Delta t) = \frac{U(t_0) - U(t_1)}{I_{bat}} \tag{1}$$

Bat-AB shows a starting value of 72.4 mΩ and Bat-PB 71.7 mΩ. This difference is therefore 0.7 mΩ what is in the range of the measurement uncertainty. The internal resistance value at the beginning of the experiment is quite high. If the measured values are homogeneously converted from the 4s5p module to a single cell regardless of the contact resistance of the welded metal plates one cell has an average value of 90.5 mΩ and 88.8 mΩ respectively. Own experiences have shown that this cell type has about 60 mΩ in its new state at 100% SOC at 10 seconds. An evaluation of the internal resistance in the seconds' range allows a better

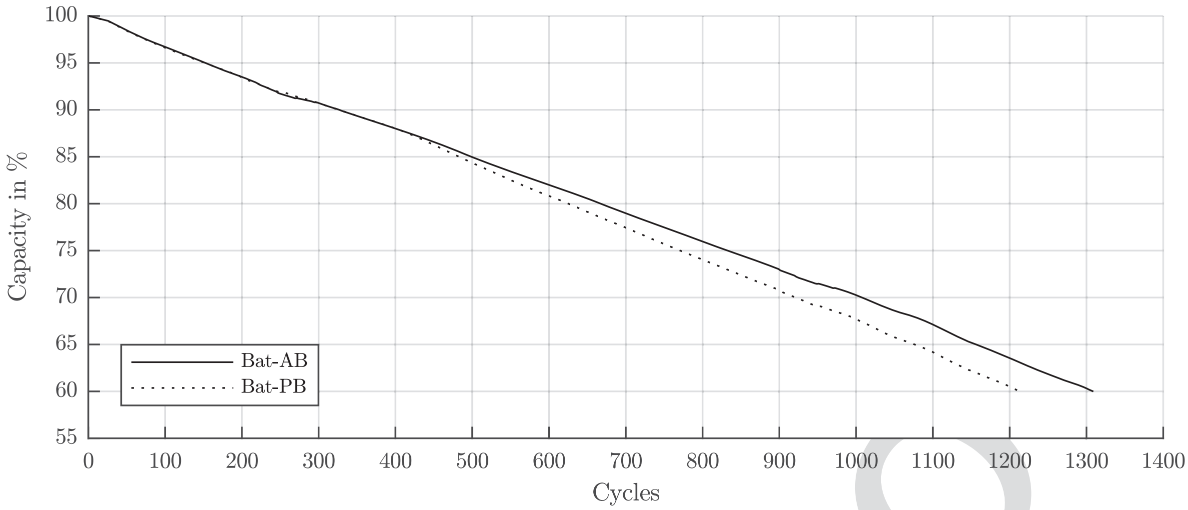


FIGURE 3. **Relative values - ageing trend of all batteries.**

comparison of the battery's performance with reality based on measured values. A consideration of the internal resistance at 0 s does not fully reflect the dynamic voltage response of the battery to a sudden change in current. In corresponding literature, Waag *et al.* [16] also evaluate a 10 s current pulse. In [17]–[19] extensive investigations on calendar ageing were carried out. The results show that calendar ageing is fastest at low anode potentials and high temperatures. Conversely, low anode potentials mean a high full-cell SOC, as was the case in this experiment. Schmitt *et al.* [20] found a time dependence in calendar ageing. The investigations showed that the capacity loss is linear with time. The increased values of the two batteries can thus be explained by the long period of 2.5 years and the high SOC during storage.

B. CAPACITY FADE

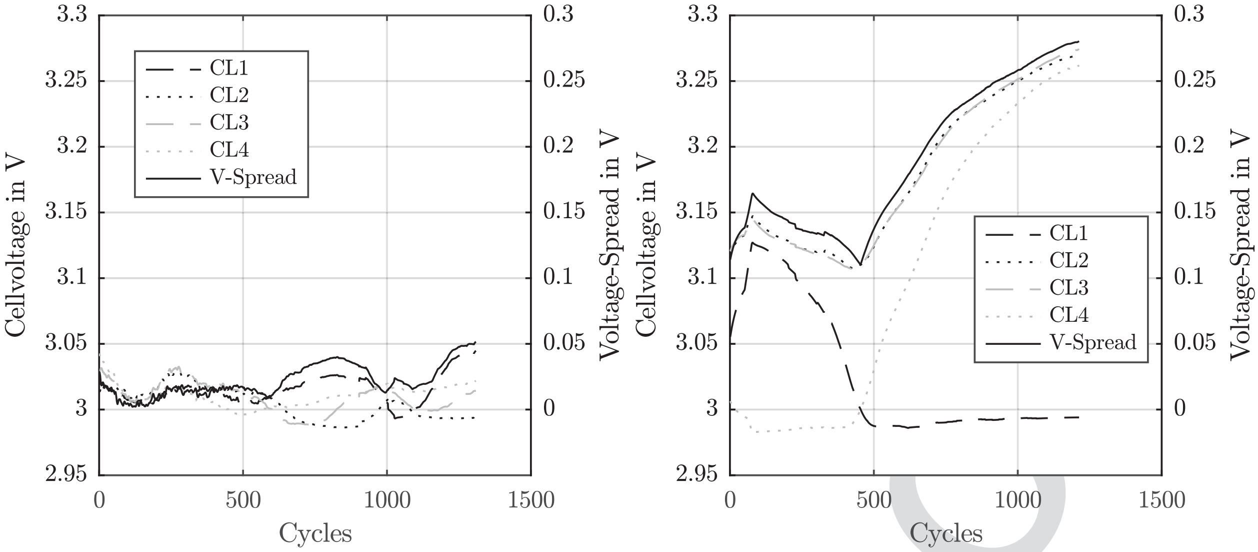
In order to show influences and differences, the decrease of the battery capacity during cyclic ageing is observed. The battery pack capacity C_{bat} refers to the maximum amount of charge Q that can be released by a pre-charged battery. More precisely, this quantity of charge is the integral of the discharge current i (whether constant or variable) over the duration of the discharge t_{d}, calculated as follows:

$$C_{\text{bat}} = \int_0^{t_{\text{d}}} i(t)dt \tag{2}$$

In other words, the integrated battery current during the discharge process defines the amount of charge taken from the battery. This amount of charge is used as the actual battery capacity in the corresponding cycle. The capacity development is shown in Fig. 3 in relative values. The capacity decrease is displayed until the end of the lifetime of each battery (SOH: 60%). After approximately 400 cycles, the capacity of the battery Bat-PB decreases significantly faster. Since the different ageing behaviour of the batteries only seems to start at about 400 cycles, it is possible to attribute this effect to different ageing mechanisms within the battery cells. In the first phase of battery ageing from cycle 1 to cycle 400, the main reason for the reduction in capacity is the loss of cyclisable lithium. Another ageing mechanism, the loss of active material within the cells, occurs after 400 cycles until the end of the test. Yang *et al.* described the ageing mechanisms with Solid Electrolyte Interphase (SEI) growth at the beginning of ageing and a starting nonlinear ageing in the further process, which is attributed to exponential increase of a lithium plating rate [21]. These two different ageing effects for a capacity decrease in lithium-ion cells, also described by Matthieu Dubarry *et al.* [22], often cause the characteristic bend in the ageing curve of single cells [23], [24]. Regarding the ageing process, there is a significant difference between Bat-AB and Bat-PB. In Bat-AB the above-described ageing behaviour of the single cells with a characteristic bend is superimposed by the balancing system. The battery ageing process is therefore more linear. This behaviour is described in more detail in the following sections. The behaviour of the Bat-PB instead follows that of a single cell, because, in a battery pack with passive balancing, the worst cell always determines the behaviour of the battery as the passive balancer is not able to support weak cells during discharge. The ageing of Bat-PB seems to be quite linear as well, which can be caused by the overlapping effects of different ageing behaviour of the single cells inside the battery pack, also described in the following sections. Bat-AB with active balancing reaches 60% SOH after 1309 cycles and the second battery with passive balancing after 1213 cycles. This clearly shows the advantages of active balancing in terms of 3.1% more usable capacity and a 7.7% longer service life.

C. INTERNAL RESISTANCE INCREASE

The internal resistances were measured, as mentioned before, at the beginning of each cycle with a DC-Current pulse of 10 A at 100% SOC, evaluated after 10 seconds. At the beginning of the test, they show almost identical values of ≈72.4 mΩ (Bat-AB) and ≈71.7 mΩ (Bat-PB). As the test progresses, the values show a homogeneous and almost linear increase. The deviation between the batteries becomes



(a) Voltage spread of Bat-AB

(b) Voltage spread of Bat-PB

FIGURE 4. **Cell level voltage differences at end of discharge.**

somewhat greater, but never with any significance worth mentioning. At the last comparable data point (1213 cycles) the batteries reach values of ≈138.5 mΩ (Bat-AB) and ≈135.1 mΩ (Bat-PB), which corresponds to a relative difference of 2.5%. Bat-AB reaches its highest value of ≈143.7 mΩ at 1309 cycles.

D. VOLTAGE SPREAD

To get an insight into how the individual CLs vary in the battery, the CL voltage is recorded at the end of each discharge. The voltage difference between the individual CL voltages provides information about variations in capacities and internal resistances of the single CLs. Thus a small voltage spread indicates efficient utilization of the battery. An ideally used battery with perfectly balanced CLs would have a voltage spread of 0 V at the end of the discharge, as all CLs reach their final discharge voltage at the same time. As the voltage spread increases, the CL variation increases and the utilization of the battery decreases. Fig. 4 shows the development of the voltage spread at the switch-off point over the number of cycles. Due to the delayed switch-off at 5 seconds after discharge cut-off, the voltage of the CLs can also be below 3 V.

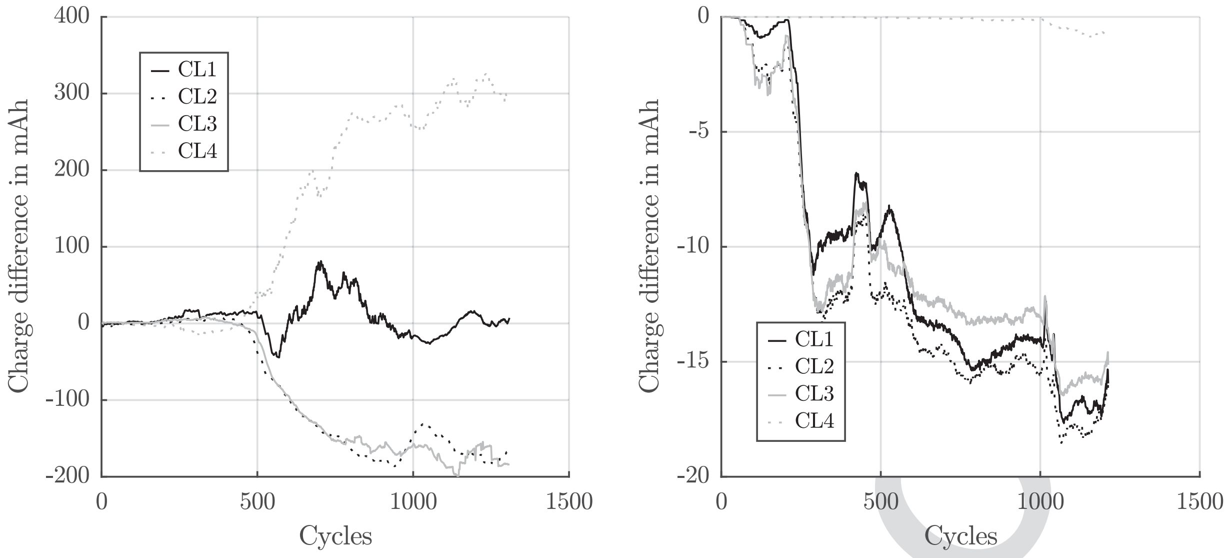
The advantage of active balancing is very clear from the beginning. Bat-AB is able to keep the voltage difference significantly lower compared to Bat-PB with help of intelligent charge exchange between the battery CLs even during the discharge process. From cycle 1 almost until the end of life, the voltage difference of the active balanced battery is statically in the range below 50 mV at the switch-off point. It should be mentioned here that the active balancer used also has a previously defined accuracy voltage spread and in this case, cannot achieve a lower voltage deviation. As the CLs to be balanced diverge further and further in the process of ageing, it is essential that the balancer has a correspondingly high balancing current available. If the balancing current would not be sufficient, the balancing process cannot be completed till the end of the discharge process. The necessary balancing charges calculated by the system would not be fully achieved and the voltage spread would increase too. The measured data show how the battery can be operated ideally over a long period of time with well balanced single CLs. The visible oscillations are due to the control behaviour of the algorithm, which adapts to new conditions in a similar way as a control loop and thereby shows a low-frequency settling behaviour.

In contrast, the voltage difference of the CLs in the passively balanced Bat-PB varies from cycle 0 to approximately cycle 500 in the range between 120 mV and 170 mV, then it rises to approximately 280 mV. The passive balancing is therefore not able to keep the CLs permanently balanced and ensure optimum battery utilization. Due to the topology consisting of resistors that can be connected in parallel, the passive balancer manages to reach the set voltage band of 15 mV between the CLs at the end of the charging process in each cycle, but it cannot intervene when discharging begins. If the battery is being discharged, the CLs always diverge due to their different capacities, regardless of how precisely the passive balancer has adjusted the voltages before. This disadvantage becomes more and more obvious as the number of cycles and therefore the difference in single CL capacities increases [25].

Finally, there is a difference of 228 mV between Bat-AB and Bat-PB in cycle 1213, which means that active balancing reaches up to five times lower voltage spread in this test.

E. CAPACITY SPREAD

To investigate the impact of the parameter variation on battery ageing, the amounts of charge balanced by the BMS are calculated. For this purpose, the voltage pulses caused by the operation of active and passive balancing in the voltage



(a) dQ-Chart of Bat-AB (b) dQ-Chart of Bat-PB

FIGURE 5. **Cell level charge differences (dQ) of tested batteries.**

measurements are evaluated. A software routine examines the voltage curves of the individual CLs during operation and evaluates the number and duration of the voltage changes caused by the BMS. From this, taking into account the known, almost constant balancing current of the two BMS systems, the charge differences that are balanced between the individual CLs can be calculated. The active BMS can carry out both positive and negative charge changes, whereas passive balancing can only carry out negative charge changes. The negative charge change represents an additional discharge, the positive charge change represents an additional charge of the single CLs. A battery which does not need to be balanced contains a charge difference of 0 mAh. The more charge difference of one CL has to be balanced, the higher is the difference between the single CLs. However, the calculated differences in CL charge are only an illustration of the actual work done by the BMS and do not necessarily reflect the real capacity deviation. This is particularly clear in the case of the passively balanced battery, where the balanced charge is approx. 10 times smaller due to the smaller balancing current, although it has already been shown that the CLs are significantly further apart in the voltage band.

Looking at Fig. 5, it becomes clear that the tested batteries behave in the same way. The CLs of Bat-AB and Bat-PB drift further and further apart in the test progress. At the end of the test, the combined balanced charge amounts of Bat-AB are $\approx$648 mAh and $\approx$45 mAh for Bat-PB. Up to 15 times more charge is redistributed by the active balancer to ensure optimised battery operation.

IV. DISCUSSION

Taking into account the development of capacity (Fig. 3) in connection with the voltage spread (Fig. 4), it becomes clear, that in the first 400 cycles the higher spread of Bat-PB has no effect on its discharge capacity. First after 400 cycles the capacity of Bat-PB decreases faster and the voltage spread starts to increase compared to Bat-AB. Considering the information gained from the capacity spread (Fig. 5) Bat-AB balances significantly more charge than Bat-PB in order to keep the voltage spread low and thus keep the discharge capacity above the level of Bat-PB. Assuming that a passive balancing system has an efficiency of 0% due to its controlled resistors and in return, an active control system redistributes energy with an efficiency of approx. 90% [15], there is an interesting aspect regarding energy efficiency. As the amount of charge to be balanced increases, a battery with a passive balancing system could have higher energy efficiency as a battery equipped with an active balancing system. In this case, the active balancing system will redistribute a huge amount of charge and lose more energy due to its converter efficiency than the passive balancing system due to its switched on resistors. Since no more precise measurements are available in this article, this issue should be further investigated. At this point, it must also be mentioned that the active balancing has a fixed balancing current and can therefore also reach its limits if the battery cells are too far out of balance, so the balancing process is not completed in time. An adjustment of the balancing current must always be taken into account.

Although the voltage spread provides information about the CL voltages at the switch-off point of the discharge, it does not necessarily reflect the pure usability of the battery. In any case, as it is shown in Fig. 4, it must be taken into account that the voltage spread only shows the difference between the best and worst CL at the cut-off point. The other two CLs in the battery have no influence on this and their voltage value lies between the best and worst CLs. Hence, it can occur that two batteries with almost the same voltage spread have different levels of utilisation. For example, as in Fig. 4b, only one CL can limit the discharge process. In this case, residual energy is left in the remaining CLs indicated by their higher voltage. On contrary to the behaviour of Bat-PB, also 3 CLs can end the discharge process and just one CL has residual energy. In the latter example, the utilisation is improved. The best possible utilisation is achieved when all 4 CLs reach the end of discharge voltage simultaneously. In order to assess battery utilisation, other indicators such as the capacity spread must be considered in addition to the voltage spread. When these investigations are combined, it becomes clearer that the faster-decreasing capacity of Bat-PB is indeed also due to poorer utilisation and not only to different chemical ageing.

The used cells in the experiment showed that proper storage and keeping alow SOC ($\lesssim$50%) during non-use periods are essential. Keil *et al.* [17] showed that a graphite anode lithiated more than 50% accelerates the loss of cyclable lithium. Additionally, low anode potentials aggravate electrolyte reduction and therefore promote SEI growth. Due to the violation of this requirement, a measurable calendar ageing of the cells was already visible at the beginning of the experiment. This article presents a method to extend the lifetime of batteries in order to achieve the best possible utilization of resources. However, it also reveals that the correct storage and the correct delivery condition can already contribute to the extension of the lifetime. Therefore, in order to achieve the maximum possible life span, many factors have to be taken into account at cell production and module assembly.

This experiment revealed that active balancing for the application shown at 25 °C and a constant battery load has almost no effect on a new battery and can only show its potential with increasing numbers of cycles. If the test had been completed at 80% SOH, it could be concluded that active balancing has little effect for this first live use of the batteries. However, if a second life application is set up starting at 80% SOH, the benefits of active balancing become more noticeable. The authors therefore suggest that the use of active balancing would be more appropriate for second life battery use in the tested scenario. The authors are also aware that a different scenario with different ambient temperature and battery load can massively influence the ageing behaviour of the battery and thus also the test result of active balancing. It becomes clear that active balancing can only be evaluated in relation to passive balancing, which is operated under the same test conditions.

A critical look at the active balancing used also reveals that such a system is significantly more complex and thus inherently more susceptible to errors than conventional passive balancing. In addition, systems available on the market are often larger and more expensive than passive systems. It seems logical that active balancing should be used in areas where the battery is exposed to extreme conditions (load, temperature) and the battery cells therefore age more quickly and, above all, with a higher cell to cell variation.

Finally, the proposed application of an active balancing system in this experiment would contribute to better and more efficient use of the important battery resources already mentioned in the introduction of this article by significantly increasing the usable capacity and the service life of the battery using intelligent balancing.

V. CONCLUSION

This work shows that reducing the cell to cell variation by active cell balancing improves battery utilization. By considering the voltage differences of the individual cells in each cycle, it becomes clear that the active balancing system in this specific test can achieve a voltage difference up to 5 times smaller compared to the passive balancing system. The calculation of the balanced charge quantities shows that approximately 15 times more charge is redistributed in the active balancing battery than in the passive balancing battery. In this test active balancing stabilizes the ageing behaviour, achieves a five times lower voltage spread at end of discharge, increases the capacity by 3.1% and the lifetime by 7.7% compared to passive balancing. Finally, the results demonstrate that an active BMS can have a higher influence on aged batteries due to their suspected higher cell to cell variation and seems to suit best for second-life applications. Further tests with different batteries, other chemistries and at different ambient temperatures seem to be useful to make the results more transferable.

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