EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Inhomogeneities in Battery Packs

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Abstract

The market of accumulator based technologies is changing very fast, especially the electromobility market due to different decisions made to prevent the climate change. In most markets battery packs are used, which means accumulators are connected to form a battery system consisting of a few accumulators up to thousands. Research of battery technologies often focuses on single cells, however considering the applications it is important to also know the behaviour of cells in a system. This paper deals with the inhomogeneities which influence the electrical behaviour of the system in simulation and measurement with a special focus on parallel connected cells.
Keywords: lithium battery, modeling, battery management, battery model, BMS (Battery Management System)

1 Motivation and State of Research

Many applications are using battery systems. For a better unterstanding of interactions between cells in a system, measurements and dynamic battery pack simulations have to be carried out. Consequently, inhomogeneities caused by production differences or current/temperature distribution lead to different behaviour of the battery system. Ways to sort cells to configure a battery systems are needed, whether by the inner resistance or the capacity [1]. Current distributions in parallel connections needs to be considered [2] and how it effects ageing compared to the ageing of a single cell [3]. The inhomogeneities which lead to these current distributions are the mechanic connections (welding, soldering, pressing) of the cells with the conductor, the positions of the measurements, the influence of different capacities and resistances in connections and also the position of the plus and minus pole of the battery has an influence on the system. To understand the battery system behaviour it is necessary to conduct battery pack simulations and measurements.

2 Battery Pack Modelling and Simulation

The state of the art in electrical battery pack modeling reaches from single cell models extrapolated for packs to single cell models for each cell of the pack like it is proposed by Bruen [4]. Modeling a battery pack in the state space leads to fast simulations without losing too much information. Every single cell is modelled by an equivalent circuit model with an inner resistance and up to n RC-Elements. The cell model is shown in Fig. 1.

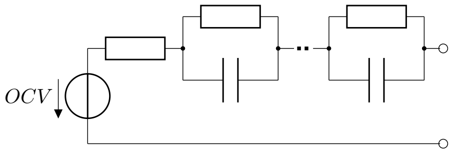

Figure 1: cell model

Its state space representation is shown in formula 1 to 2, which is given by [4].

$$\begin{bmatrix} \dot{SOC} \\ \dot{v_p} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{R_p C_p} \end{bmatrix} \begin{bmatrix} SOC \\ v_p \end{bmatrix} + \begin{bmatrix} \frac{1}{3600Q} \\ \frac{1}{C_p} \end{bmatrix} i_{cell} \tag{1}$$

$$\begin{bmatrix} v_t \end{bmatrix} = \begin{bmatrix} \frac{f(SOC)}{SOC} & 1 \end{bmatrix} \begin{bmatrix} SOC \\ v_p \end{bmatrix} + \begin{bmatrix} R_D \end{bmatrix} i_{cell} \tag{2}$$

These cells can be connected in different arrangements and are leading to different behaviour of the battery pack. They could be arranged in a 4 series with 2 parallel strings (i.e. Fig. 2a) or the other way around with 2 parallel cells connected 4 times in series (i.e. Fig. 2b).

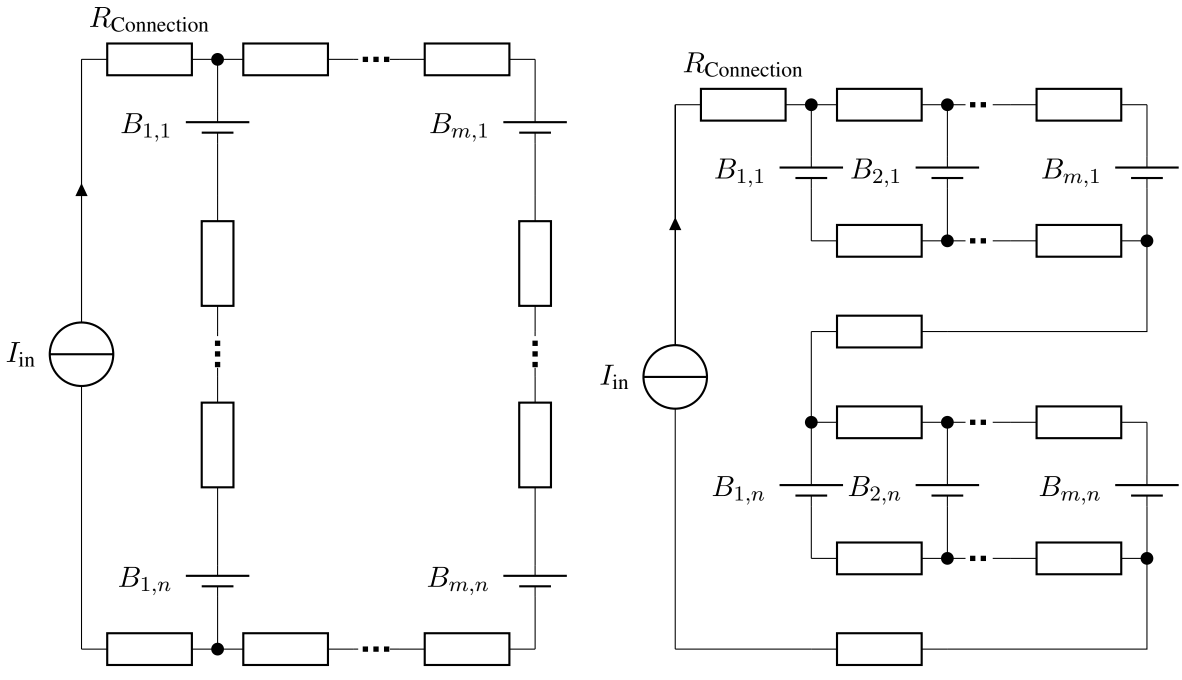

Figure 2: The figures show a a) system of parallel connected series strings and a b) system of series connected parallel strings

Often a connection of parallel strings in series is used, because the cells are balancing each other in parallel strings without an additional balancing system. Also the location of the plus and minus pole is important for the behaviour of the system. Using the networks of a parallel string, the meshes and knots are calculated and lead to the matrices A,B,C and D of the state space model. The scheme is given by [4] and leads to the following state space model, which is adjusted such that the terminal voltage of a parallel cell string could differ from the voltage of the first cell and all cell voltages are included in the output vector.

$$\begin{bmatrix} 0 \\ \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_N \end{bmatrix} = \begin{bmatrix} 0 & \cdots & & 0 \\ & A_1 & & \\ \vdots & & A_2 & \\ & & & \ddots & \\ 0 & & & & A_N \end{bmatrix} \begin{bmatrix} 0 \\ x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} 0 & \cdots & & 0 \\ B_1 & & & \\ & B_2 & & \\ & & \ddots & \\ & & & B_N \end{bmatrix} \begin{bmatrix} i_{\text{cell}_1} \\ i_{\text{cell}_2} \\ \vdots \\ i_{\text{cell}_N} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} v_{\text{tbp}} \\ v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} = \begin{bmatrix} 0 & C1 & 0 & & \cdots & 0 \\ 0 & C1 & 0 & & \cdots & \\ \vdots & \ddots & C2 & \ddots & \ddots & \vdots \\ & & \ddots & \ddots & \ddots & \\ 0 & & & \cdots & 0 & C_N \end{bmatrix} + \begin{bmatrix} 2R_{\text{Connection}} + D_1 & 2R_{\text{Connection}} & \cdots & 2R_{\text{Connection}} \\ D_1 & 0 & \cdots & 0 \\ 0 & D_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & D_N \end{bmatrix} \begin{bmatrix} i_{\text{cell}_1} \\ i_{\text{cell}_2} \\ \vdots \\ i_{\text{cell}_N} \end{bmatrix} \tag{4}$$

Every cell current has to be calculated for the i_{cell_x} vector. This calculation is the same as in [4]. The model was explained for a series connected parallel strings, where the terminals of the parallel strings are at the first cell. The connection of the terminals influences the overall behaviour as well. Different connections of the terminals could be implemented with the model, too, by modifying the D matrix and the calculation of the cell currents. Battery systems typically consist of parallel and series connected cells, often series connected parallel strings, therefore the matrices of the parallel connected cells are concatenated to form the matrices of the whole system. This leads to a model of a battery system with multiple layers consisting of the cell model, parallel string and the whole system. So the concatenation of the parallel strings results also in a diagonal matrix as shown in the following equations, where the index ps indicates one parallel string.

$$\begin{bmatrix} \dot{x}_{\text{ps}_1} \\ \dot{x}_{\text{ps}_2} \\ \vdots \\ \dot{x}_{\text{ps}_N} \end{bmatrix} = \begin{bmatrix} A_{\text{ps}_1} & & & \\ & A_{\text{ps}_2} & & \\ & & \ddots & \\ & & & A_{\text{ps}_N} \end{bmatrix} \begin{bmatrix} x_{\text{ps}_1} \\ x_{\text{ps}_2} \\ \vdots \\ x_{\text{ps}_N} \end{bmatrix} + \begin{bmatrix} B_{\text{ps}_1} & & & \\ & B_{\text{ps}_2} & & \\ & & \ddots & \\ & & & B_{\text{ps}_N} \end{bmatrix} \begin{bmatrix} i_{\text{ps}_1} \\ i_{\text{ps}_2} \\ \vdots \\ i_{\text{ps}_N} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} v_{\text{ps}_1} \\ v_{\text{ps}_2} \\ \vdots \\ v_{\text{ps}_N} \end{bmatrix} = \begin{bmatrix} C_{\text{ps}_1} & 0 & & \cdots & 0 \\ 0 & C_{\text{ps}_2} & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \\ & & & & 0 \\ 0 & & \cdots & 0 & C_{\text{ps}_N} \end{bmatrix} + \begin{bmatrix} D_{\text{ps}_1} & 0 & \cdots & 0 \\ 0 & D_{\text{ps}_2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & D_{\text{ps}_N} \end{bmatrix} \begin{bmatrix} i_{\text{ps}_1} \\ i_{\text{ps}_2} \\ \vdots \\ i_{\text{ps}_N} \end{bmatrix} \tag{6}$$

3 Measurement and Simulation

Battery systems used in applications often consist of parallel and series connected cells. Most research considering the connection of cells and battery systems concentrates on series connections and often the voltages of parallel connected cells are considered equal, what leads to less sensors in a battery system. This paper therefore concentrates much more on parallel connections and the influence of inhomogeneities on these. A few different measurements were conducted, where the cells have different capacities, inner resistances and different connections. Due to the concentration on parallel connected cells the measurement setup consists of four parallel connected cells where the current in each path and each temperature is measured. The setup is variable and the interconnections could easily be changed. For the measurements two different high power 18650 cells were used. One cell is the LGHE4 with a nominal capacity (C_n) of $2,5$ Ah and the other is the VTC5 with $C_\mathrm{n} = 2,6$ Ah. They have slightly different inner resistances as well, see table 1.

3.1 Characterization and Parameterization

The described model had to be parametrized and therefore the cells have to be characterized and tested to generate the profiles to parametrize the battery model. By conducting a quasi open circuit voltage (QOCV) measurement the capacity could be calculated and the measurement result could be used as characteristic map for the cell models. The cells were charged and discharged with a current of $C/20$. Fig. 3 depicts some example results of the QOCV measurement.

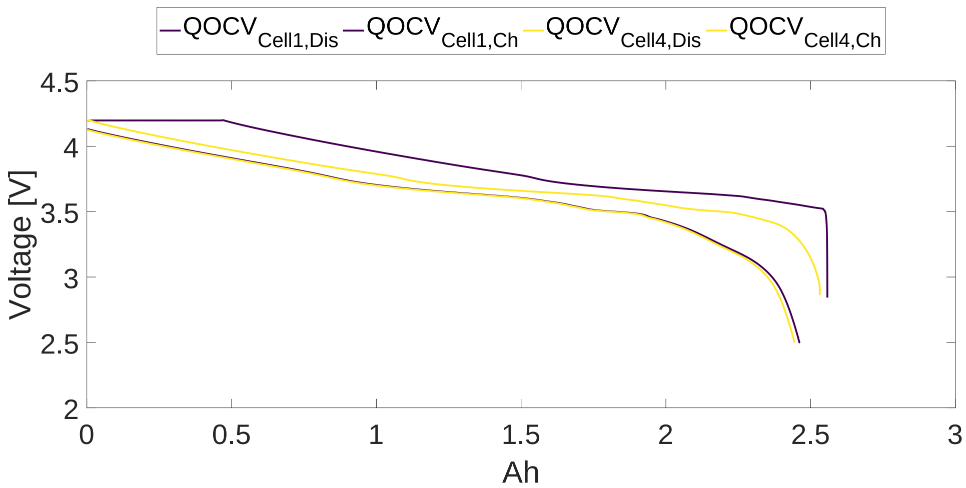

Figure 3: QOCV results both charging and discharging of two of the LGHE4 cells

It can be seen that one of each type has a higher inner resistance than the other cells, while they have similar capacities. That leads to an extended constant voltage phase during the charging procedure. At this point it has to be mentioned that the cells are all new and seem to suffer from different productions or even flaws. That is a perfect example for the tolerances of production. Each battery system can suffer under the production tolerances of the single cells, which lead to slightly different capacities and inner resistances. To parametrize the cell models additional tests were carried out. The cells were charged and discharged in 10% steps of the state of charge (SOC). After the charge or discharge steps there were two hours of relaxation. These relaxations of the voltage were used to identify the parameters for a cell model consisting of an inner resistance and two RC parallel elements. An example pulsed discharge profile is depicted in Fig. 4. The relaxation parts were extracted and fitted using a Nelder-Mead algorithm to identify the models parameters.
To accomplish a successful fitting, the start-parameters of the fittings were calculated for each relaxation by identifying the different areas for the inner resistance and the RC parallel elements. By subtracting the voltage drop across the inner resistance and the OCV the remaining voltage is the voltage across the RC parallel elements. Thus the voltage was divided into different parts which should be represented by the RCs. Therefore the resistances can be calculated and the time constant can be determined. Table 1 sums up the inner resistances and capacities of the 8 cells.

3.2 Measurement cases

The measurements belonging to the parallel connections consider different capacities, inner resistances and different interconnections of the cells, which means that the terminals of the pack are at different locations of the pack. These cases lead to four different measurements. Each measurement is conducted using the same current profile. The cells start at 4 V and are discharged with a constant current of 4 A with intermitting charge and discharge pulses of 8 A till the terminal voltage of the pack reaches 3.4 V. Afterwards the pack is charged with the constant current constant voltage scheme to 4 V. The operation window is on purpose between 3.4 V and 4 V, because the terminal voltage isn't always the

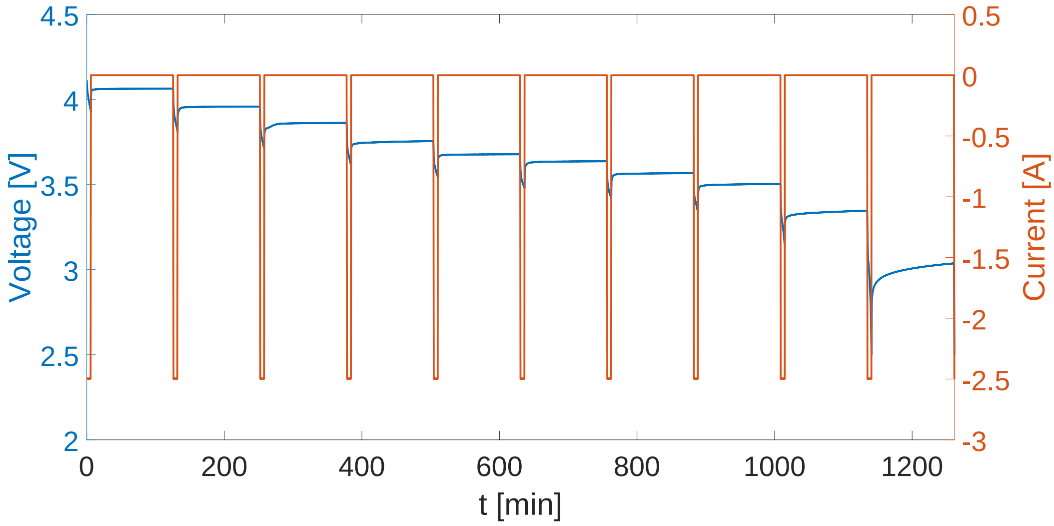

Figure 4: current and voltage measured during the pulsed discharge for the parametrization of the model

Table 1: table of the inner resistance (R_0) and the actual capacity of the cells

LGHE4			VTC5		
CellID	C_{act}[Ah]	$R_0[\Omega]$	CellID	C_{act}[Ah]	$R_0[\Omega]$
LGHE4-1	2.51	0.036	VTC5-1	2.68	0.029
LGHE4-2	2.55	0.038	VTC5-2	2.68	0.029
LGHE4-3	2.49	0.03	VTC5-3	2,74	0.029
LGHE4-4	2.49	0.05	VTC5-4	2.69	0.039

highest or lowest voltage during the measurements, which means that a cell in the parallel string could be overcharged or exhausted. To prevent the measurement leaving the safe operation area of the cells the window is smaller than the possible operation area.

Measurement case 1 - all one cell type with one cell having a higher inner resistance The first test uses every cell of one single type, in this case all cells were LGHE4s, and the current profile described above. The terminals are both connected to the first cell in the string. Fig. 5 displays the resulting voltages and the current of the pack.

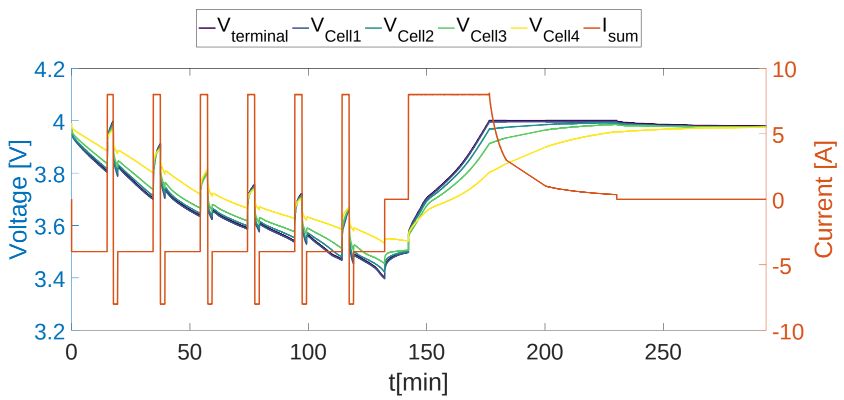

Figure 5: voltages of the cells and the pack current during case 1

Table 2: pack configuration

CellNr	CellID
1	LGHE4-1
2	LGHE4-2
3	LGHE4-3
4	LGHE4-4

The terminal voltage is in this case always the lowest or the highest voltage depending whether the cells are discharged or charged. This voltage is used to control the pack, such that the pack switches to charge at 3.4 V of the terminal voltage and to the constant voltage phase when it hits 4 V. Because of the connection of the cells the voltages differ from the first to the last cell in the row, where in addition the fourth cell is the cell with the highest inner resistance, which results in lower load for the last cell. The result is that the other cells don't reach the 4 V when the constant voltage phase starts. They meet in the resting phase below at about 3.9 V, because the cells with the higher voltages charge the other cells and are therefore discharged. That leads to a loss of the charged capacity due to the efficiencies of balancing between the cells. Another aspect is that the battery pack wouldn't be fully charged. These mentionend aspects are substantiated by the calculated charge displayed in Fig. 6.

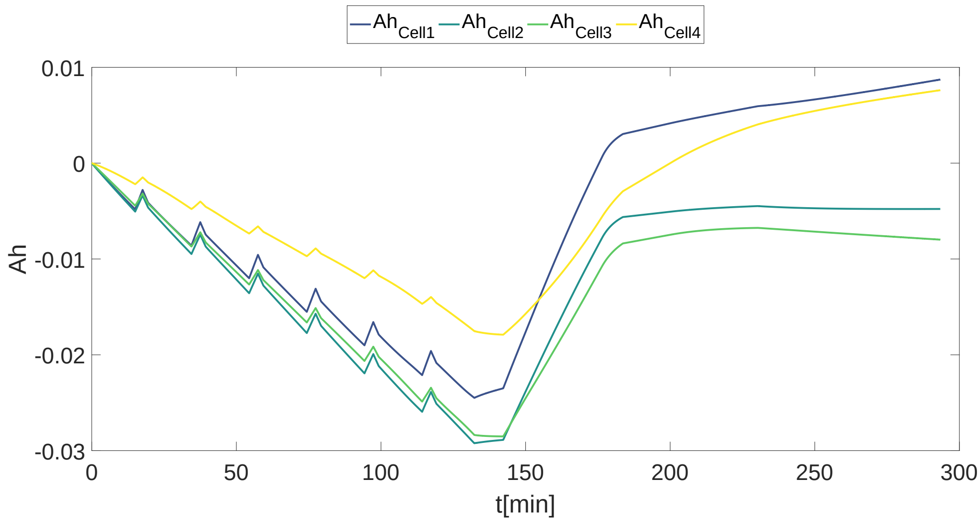

Figure 6: discharged and charged Ah calculated from case 1

The shown charge balance over the whole measurement shows that the last cell, which is the cell with the lowest workload and cell two, which is the one with the highest, were charged the most. And the first cell, as it was expected, is not the cell with the highest discharged Ah, it is in fact the second one, which has highest capacity and second highest inner resistance. Cell two was also charged the least at the end. The third cell is the cell with one of the smallest capacities and the smallest inner resistance. Instead is the first cell the cell with the highest peak current, but with lesser current at the lower current phases as depicted in Fig. 7.

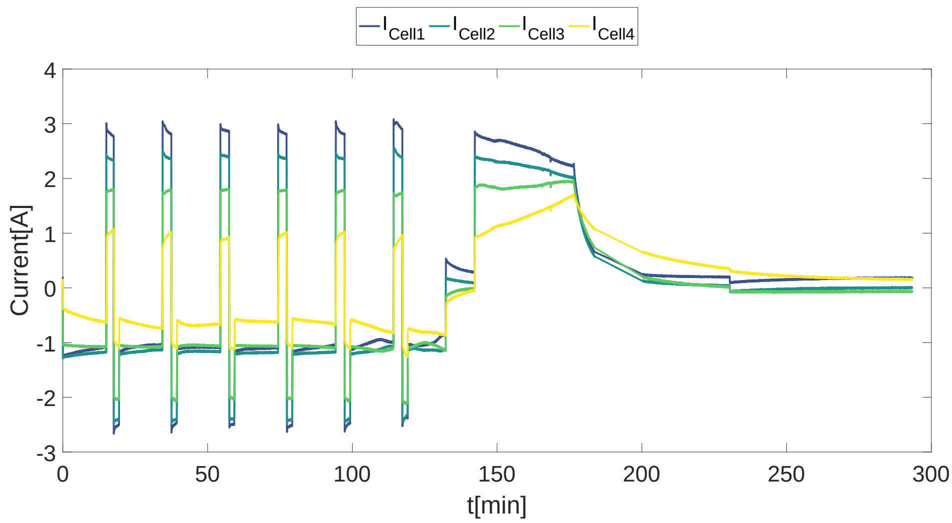

Figure 7: cell currents during case 1

Measurement case 2 - similar to case 1 but with a changed order During this test the cells were sorted in another way. The second cell was exchanged with the last cell. That means that the cell LGHE4-4 with the highest inner resistance is positioned second in the string expecting that the voltage of second cell could be higher than the first, but that is not the case. The considerable change is that cell 4 is the cell which is charged to the highest amount. Fig. 8 displays the charge calculated from the measurements.

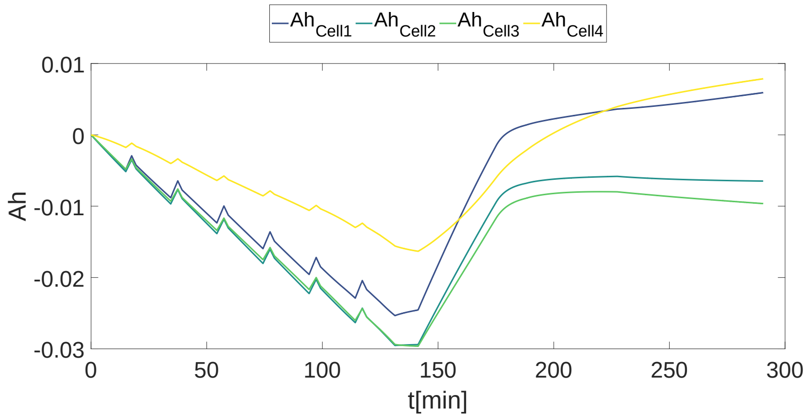

Figure 8: discharged and charged Ah calculated from case 2

Table 3: pack configuration

CellNr	CellID
1	LGHE4-1
2	LGHE4-4
3	LGHE4-2
4	LGHE4-3

Measurement case 3 - similar cells but one with a lower capacity This measurement case has three similar cells, VTC5 cells, which are at the positions given by table 4. Then there is one LGHE4 cell which is placed at the second position of the string, which means that in the second position is one cell with a lower capacity and inner resistance comparable to the highest inner resistance of the VTC5 cells. The voltages did not change that much, the cell voltages still are descending with ascending cell numbers. By analyzing the calculated charge in Fig. 9 it can be seen that the deepest discharged cell is cell 2, which is the LGHE4-2 with the lowest capacity and second highest inner resistance in this pack configuration, but it is cell 3 (VTC5-2) with average characteristics, which is the cell that has the smallest charge window. And it is cell 4 that ends with the lowest state of charge. Cell 4 (VTC5-4) is the cell with the highest inner resistance in this configuration. But still cell 1 is the cell with the highest peak currents, that can be seen due to the steepest ascends and descends of the charge at higher current phases.

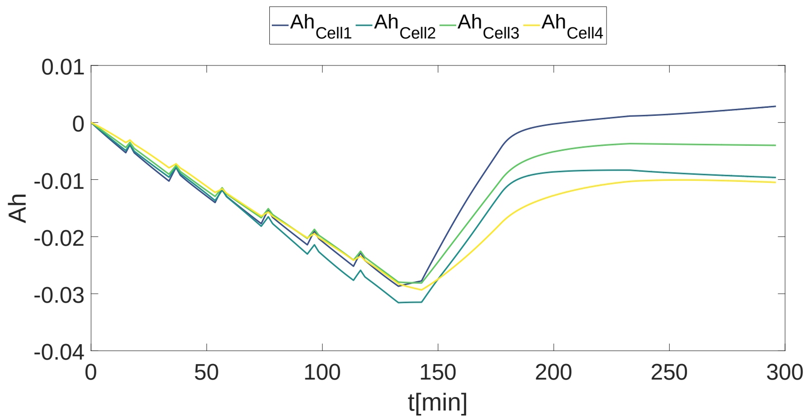

Figure 9: discharged and charged Ah calculated from case 3

Table 4: pack configuration

CellNr	CellID
1	VTC5-1
2	LGHE4-2
3	VTC5-2
4	VTC5-4

Measurement case 4 - similar cells but one with a higher capacity and lower inner resistance Also in this case the voltages have not changed significant. But the charges differ. This time the currents of the the second and the third cell are very similar,where the second cell is the cell with the higher capacity and the lower inner resistance, which leads to similar progression of the charge of these cells. A higher current in cell two leads in this case to an even smaller current through cell four, which results in an even smaller discharge charge, but it during the cv phase, it is the cell with the highest current and is therefore charged to the highest state. And it is, as in case one and two, again the third cell which is charged the least. The described progession are displayed in Fig. 10.

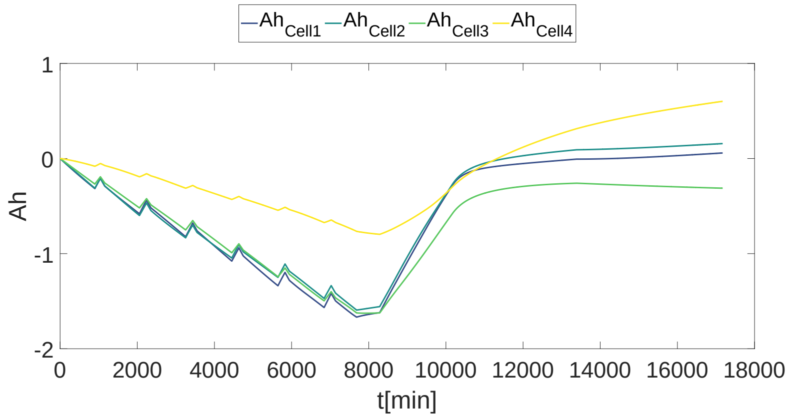

Figure 10: discharged and charged Ah calculated from case 4

Table 5: pack configuration

CellNr	CellID
1	LGHE4-1
2	VTC5-3
3	LGHE4-2
4	LGHE4-3

Measurement case 5 -another terminal location This case is in terms of the used cells as the first case but the plus terminal is at the first cell and the minus terminal of the pack at the last cell in the parallel string. Expected is that the outer cells are the cells with the highest workload due to fewer connections and therefore smaller resistances to these cells. Also the current should be distributed more equally than before. That is the case, the currents through the first three cells were much more equally distributed than in the other cases, see Fig. 11. Only the fourth, which is one of the cells which should have the highest workload, was charged clearly less than the other cells. But that is the cell with the highest inner resistance as well.

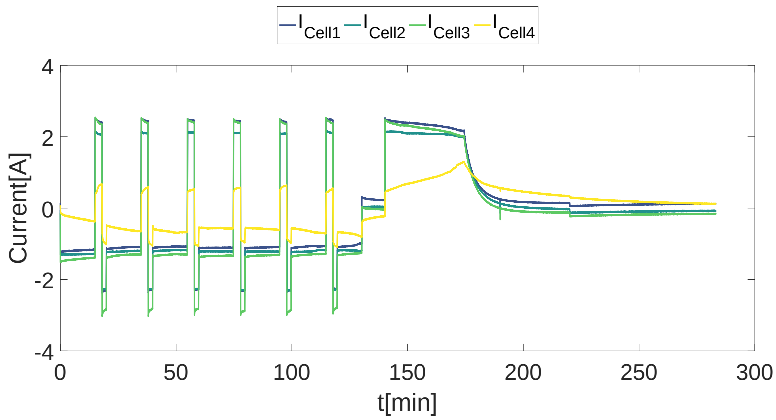

Figure 11: currents of the cells during case 5

Table 6: pack configuration

CellNr	CellID
1	LGHE4-1
2	LGHE4-2
3	LGHE4-3
4	LGHE4-4

Cell three was the cell which experience the highest current during the lower current phases followed by cell two, both the middle ones, which leads to the suspection that cell three and two were the cells with the deepest discharge. In this measurement case the first cell is one of the cells with the highest peak loads. All that is depicted in Fig. 12.
The different cases have shown that different inner resistances and capacities have different influences on the behaviour in a parallel connected string of cells. Also the location of the terminals influence the distribution of the currents. Due to the circumstance that the fabrication of the cells could not result in absolutely equal cells each measurement case was perturbed by the production tolerances of the cells leading to different inner resistances and capacities. So each case covers different influences. To differentiate the influences substantiating simulation have been conducted.

3.3 Simulations

Owing to the fact that each cell differs from another even if they are produced on the same production line with the same standards and the same end of line tests it is useful to run simulations where it is possible to have exactly the same cells and specifically different parameters if necessary. Also the resistances of the connections can be neglected. To differentiate the influences on the behaviour of a parallel connection of

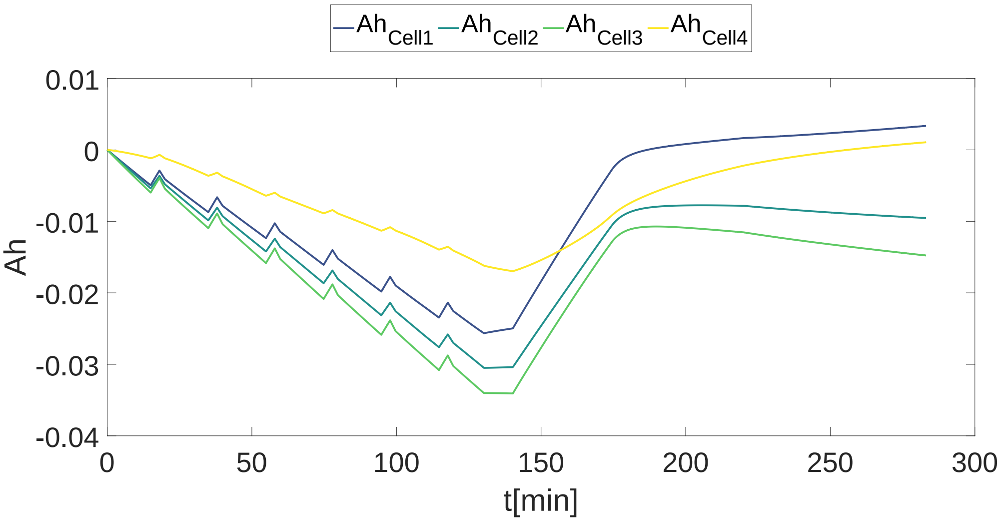

Figure 12: cell currents during case 5

cells, simulations with a single cell with higher resistance, lower resistance, higher and lower capacities were conducted.

Simulation case 1 - one cell with a higher inner resistance During this simulation the cells were exactly the same except one cell which had higher inner resistance. So the equal cells used the parameters of the LGHE4-1 cell and the fourth cell used the same open circuit voltage as the others but the model parameters of the LGHE4-4, which was the one with the higher inner resistance. The cells in this simulation are connected with the terminals of the battery pack at the first cell. Additionally the connection resistances were zero. The result in Fig. 13 shows that the inner resistance leads to a lesser workload for the fourth cell in the string. Due to the settings of the simulation the current between the other cells was evenly distributed. The difference of the current results in a differing voltage and charge.

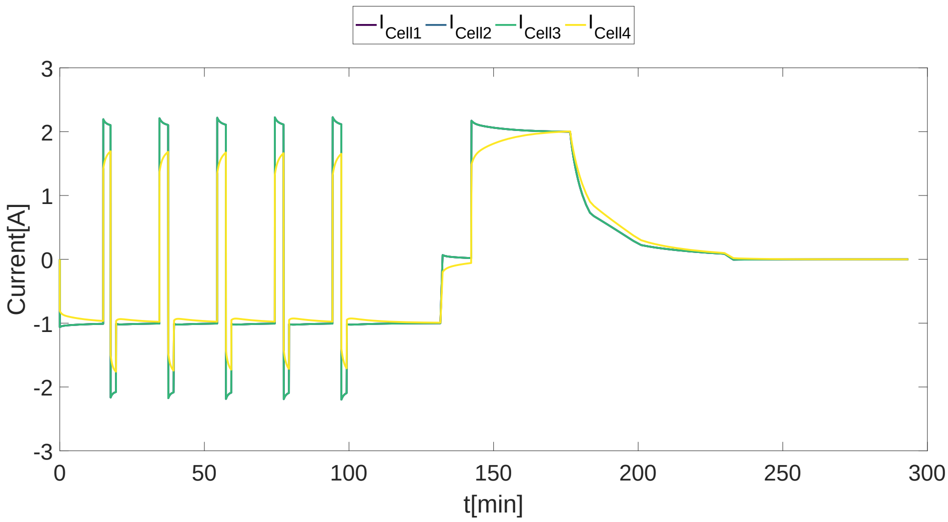

Figure 13: cell currents during simulation case 1

Simulation case 2 - one cell with a higher capacity The basic settings in this simulation are the same as in the simulation case 1. This time the fourth has a higher capacity, but the other parameters are exactly the same. By analysing the resulting Ah it can be seen that the difference rise with time, which has nearly no effect on the voltage. The equal voltages of the cells, which have different capacities means that the cells reach different state of charges and therefore are at different open circuit voltages, which leads on the other hand to higher discharge currents through the cell with the higher capacity. In the charging phase the charge of the cells hit each other again. Fig. 14 displays the calculated charge. The reason that the charge, the voltages and the currents are equal in the end is that there are no resistances of the connections which could lead to differing voltages of the cells. The cells are balancing each other.

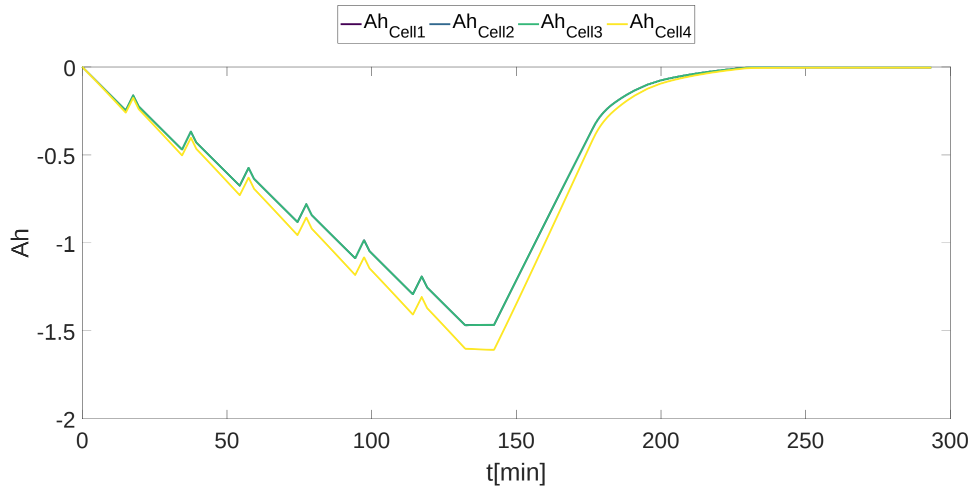

Figure 14: discharged and charged Ah calculated during simulation case 2

Simulation case 3 - optimal configuration for LGHE4 cells In this simulation the optimal connection of the cells was reviewed. At first the pack terminals were connected with plus to the first and minus to the last cell in the string. That leads to a symmetric distribution of the between the first and the last cell and between the cells in the middle, also if there are identical connection resistances. If the connection resistances were not identical the sorting would have been harder. This configuration leads to higher workloads for the outer cells. The workloads can also be influenced by the inner resistance of the cell. So the cells with the highest inner resistances are the outer most cells. The inner resistances descend to the middle of the pack. That reverses the effect of the location of the pack terminals. Using these placement and configuration the currents are distributed more equally than in the measurement case one as shown. Fig. 15 displays the result. That leads to a smaller unequality in the charged and discharge Ah.

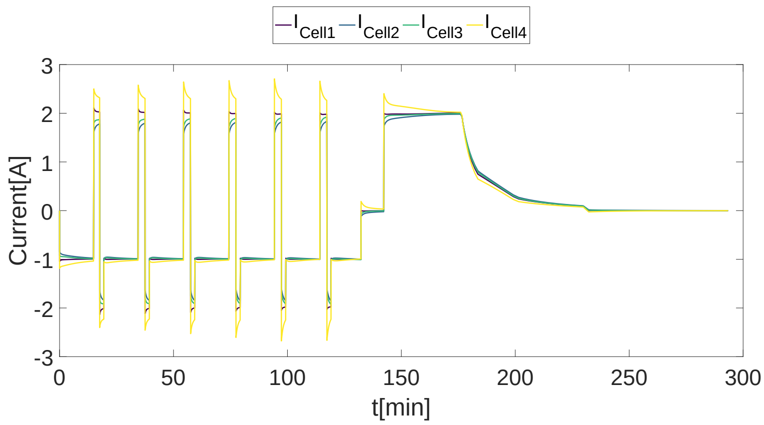

Figure 15: current during simulation case 3

Table 7: pack configuration

CellNr	CellID
1	LGHE4-4
2	LGHE4-1
3	LGHE4-3
4	LGHE4-2

4 Conclusion

The simulation and the measurement of the electrical behaviour of cells in a battery systems is inevitable to design adequate battery management systems. The model proposed is capable to simulate each cell

in a pack with different degrees of dynamics, varying cell behaviour, different interconnections, variable connection resistances and different measuring points. In future work it will be extended with a modular thermal model of a battery pack and an ageing model for the given pack, also taking the ageing of connections due to corrosion into account.
The measurements and simulations dealing with the different possible influences of different inner resistances, capacities and connections were conducted on parallel connections, because the influences in series connections are monitored by most battery management systems and are handle by balancing systems. But in parallel connections it is not monitored due to the assumption that the voltages of the cells are equal. That is the fact in a simulation environment as it was shown in the simulation part of this paper. Having no connection resistances between the cells leads to this assumption and ensures that the cells are balancing themselves, without additional hardware. It is also the case when there are connection resistances which are leading to differing voltages between the cells, but there remains a small offset corresponding to the resistances of the connections. As shown in the measurements and explicitly in the simulations higher inner resistances lead to less current through the cell, where it is the other way around for lower inner resistances. Unequal capacities lead to differing charge windows, if there are connection resistances the charged charges will differ and there will be a balancing in resting phases, but there will also be a offset in the state of charge of the single cells. One way to compensate the offset in the state of charge and the unbalanced distribution of the current is to adapt the wiring of the pack terminals as it is shown in the measurement case 5. But still there are imbalances due to the other influences like the inner resistances and capacities. So the best case would be sorting the cells such that the connection resistances and the other influences lead to a distribution as equal as possible.

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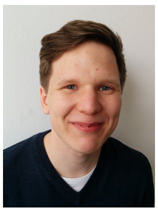

Steven Neupert received his M.Sc. degree in computer engineering from the Technische Universitaet Berlin in 2015 in the field of state estimation of cells using impedance data. Since 2015 he is a research assistant at the chair of Electrical Energy Storage Technology. His topic of research is the state estimation and prediction of cells in battery systems.

Prof. Dr.-Ing. Julia Kowal has been the head of the chair of Electrical Energy Storage Technology since 2014. She received her PhD from RWTH Aachen University, ISEA, in 2010 on impedance based battery modeling. Her research focus is simulation and lifetime prediction of different battery technologies.