

Effects of compensating current in the parallel connection of battery cells

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Summary

The aim of this paper is to show the effects of the current distribution in parallel connected cells. With a simulation model and a test bench the dependencies of this effect are analyzed. The test bench is built up with a set-up of six current sensors to ensure high accuracy at all amperages. In the current paths of the two parallel connected cells hall and fluxgate sensors are used. This means that no additional resistance influences the current distribution. Measurements and simulations show the effects of battery cell parameter variations. Different ohmic resistances lead to short-term current effects and different capacities lead to long-term current differences.

Keywords: battery, battery model, efficiency, safety

1 Introduction

Automotive batteries consist of a high number of parallel and/or series connected cells. E.g. Tesla combines thousands of cells in their batteries. Series connection is used to increase the voltage and parallel connection is used to increase the capacity of the storage system. In both cases cell parameter variance leads to inhomogeneities in the battery while the battery is in use. The series circuits battery management systems equalize the cells in most cases. In the parallel connection, the compensation takes place automatically. Nevertheless, the inhomogeneities in the parallel circuit have influence on important storage characteristics like safety, efficiency or lifetime.

There are only a few publications focusing on current distribution in parallel connected cells. Plett et al. [1] did simulations on parallel and series connected cells. They compared the economic and technical advantages and disadvantages of parallel and series modules. In terms of parallel modules, it was determined that in transient behavior the cell parameters affect the cell currents. A detailed analysis of the influences was not their focus.

Miyatake et al. [2] did measurements and simulations on parallel connected cells. The current measurements were executed with one shunt resistor (Welwyn Components, OAR-3, 5 m Ω) per cell. This means that the resistance between two cells is 10 m Ω . According to Brand et al. [3] the transfer resistance of laser or spot welded cells is in the range of 0.15 m Ω . As the parallel connected cells have a very different characteristic the influence of the additional resistance is low. Therefore the paper of Miyatake et al. investigates discharge and charge characteristics, of a multi-cell battery with nonuniform cells. There were no explorations regarding the behavior on dynamic processes like steps or sine load.

Another paper by Gong et al. [4] investigates the current distribution of new and aged cells. In this paper simulations with a simple equivalent circuit model and measured data are presented. The scientists use hall sensors to measure the current. These sensors do not bring additional impedance in the current path. However,

they are not as accurate as shunt based sensing. The comparison between measured and simulated data show considerable differences. It is not clear whether they exist because of the current sensing or the use of a model that is too simple.

The newest publication on the topic comes from Bruen et al. [5]. They measured and simulated a parallel connection of four cells. Like Miyatake and his colleagues, they used shunt based current sensing and a simple equivalent circuit model like Gong's. As results the authors assert that there is a significant increase in charge throughput and a nonuniform heat generation.

All these publications show the effects of parallel connected cells with different parameters. Table 1 compare the approaches.

Table 1: Overview on publications investigating the current distribution within parallel battery cells

First author	Theme	Simulation	Measurement	Comment
Plett [1]	Simulation of parallel connected cells compared with series connected cells	Yes	No	The theoretical behaviour of parallel connected cells is illustrated properly. A comparison with measured data is missing
Miyatake [2]	Simulation and measurement of nonuniform parallel connected cells	Yes	Shunt	The measuring with a shunt is problematical because it influences the current distribution. Only long-term effects are analysed and not dynamic effects.
Gong [4]	Analysis of the effects of parallel connection of cells	Yes	Hall-Sensors	Only one hall effect sensor is too imprecise at low currents. The simulation result does not fit very well with the measured result.
Bruen [5]	Simulation and measuring of parallel connected cells	Yes	Shunt	The measuring with a shunt is problematical because it influences the current distribution.

2 Test bench

A test bench makes it possible to measure these compensation currents. With a composition consisting of connections for two cells and several current sensors the current distribution of two parallel connected cells can be measured. Measuring the current distribution between parallel connected cells is a challenge when it comes to good measurement accuracy and low distortion of the current distribution due to the sensor network and electrical impedances inside the test bench. A test bench was developed to measure the current distribution between two parallel connected 18650 battery cells.

This test bench is optimized in the measurement accuracy and impedances inside the battery strings. It is designed for pulse shape and sinusoidal current profiles with offset. The pulse width can be in the range of a few seconds or hours which relate to constant current (CC) discharge/charge conditions. The sinusoidal current can be measured up to frequencies of 25 kHz.

The total measurement set-up comprises two power supplies which generate the total current I_{tot} . The test system GSM form BaSyTec is used for CC profiles and the test system VMP3 with boost channels from Biologic for short pulse and sinusoidal profiles. The test bench enables a reversible parallel connection of the battery cells and includes five current transducers, one measurement resistance and four Pt100 temperature sensors. All sensor data are measured and saved by the data acquisition system PXIe 6259 form National Instruments. The test bench is placed in a temperature chamber at 25 °C for low thermal effects on the battery cells and sensors.

Figure 1 shows the schematic circuit and photography of the test bench in connection with the power supply which generates I_{tot} . I_{tot} is split into the cell currents I_{bat1} and I_{bat2} at clamp x1.1 which first pass the current transducer LTSR and CTSR for direct determination of the cell currents. Afterwards I_{bat1} and I_{bat2} flow through CTSR3 in reverse manner to extract the cell current difference I_{diff} . At clam x2.1 and x3.1 I_{bat1} and I_{bat2} pass the battery cells and merge to I_{tot} at x2.2 and x3.2. After passing a measuring resistance I_{tot} flows back to connected power source.

The measurement set-up comprises three different techniques to reduce errors in the current measurement during static signals, which appear, for example, in the case of constant current discharge profiles. The first technique reduces gain errors for all current sensors. The second technique applies just for the CTSR sensors and reduces offset error via an integrated degauss mode of the sensor which is triggered prior every measurement. The third way of generating higher accuracy lies in sensor data fusion values which are calculated sensor values from the raw data. By the fusion of sensor data, benefits of different sensor technologies can be combined.

One useful derived current value for the cell current is shown in formula (1). By the fusion of shunt resistor I_{shunt} and the CTSR flux sensor in differential configuration, small measurement errors are achievable in the case of small differences between the cell currents. Another derived current value is shown in formula (2) which is a weighted average value including three raw sensor values and the offset values of the LTSR sensors $I_{ltsr1,off}$ and $I_{ltsr2,off}$ at the beginning of the measurement. The weight factor g_1 is constantly set to 100 and g_2 is calculated in a manner to have no offset error in $I_{d1,l1l2s}$. By means of determining the cell current value in this way, offsets are reduced even if $I_{ltsr1,off}$ and $I_{ltsr2,off}$ change during the measurement.

$$\begin{aligned} I_{str1,CtsrShunt} &= 0.5 \cdot (I_{shunt} + I_{Ctsr3}) \\ I_{str2,CtsrShunt} &= 0.5 \cdot (I_{shunt} + I_{Ctsr3}) \end{aligned} \quad (1)$$

$$\begin{aligned} I_{d1,l1l2s} &= \frac{g_1 \cdot I_{ltsr1} + g_2 \cdot (I_{shunt} - I_{ltsr2})}{g_1 + g_2} \\ g_1 &= 100 \\ g_2 &= \begin{cases} \left| \frac{g_1 \cdot I_{ltsr1,off}}{I_{ltsr2,off}} \right| & \text{for } I_{ltsr1,off} \neq 0 \wedge I_{ltsr2,off} \neq 0 \\ 100 & \text{otherwise} \end{cases} \end{aligned} \quad (2)$$

With two raw sensor values and two derived values for each cell string an automatic value selection was necessary. For every second the measurement program decides which value is the best in regards of maximum measurement error. This is done by a sensor value database which contains the measurement error after calibration for every raw sensor value and derived values. The outcome of this process is depicted in Figure 1 for the first cell string. The automatic selection of the best sensor value is highlighted in bold grey circles. On the x-axis one can see the measured value and on the y-axis the deviation from the current of the test system GSM from BaSyTec. Figure 1 shows the performance of the derivate data which were correctly chosen for every current as the values with the lowest measurement error. In consideration of Figure 1 the highest measurement error for I_{str1} and I_{str2} is lower than 30 mA if cell current exceeds 1.0 A and lower than 10 mA if cell current is lower than 1.0 A.

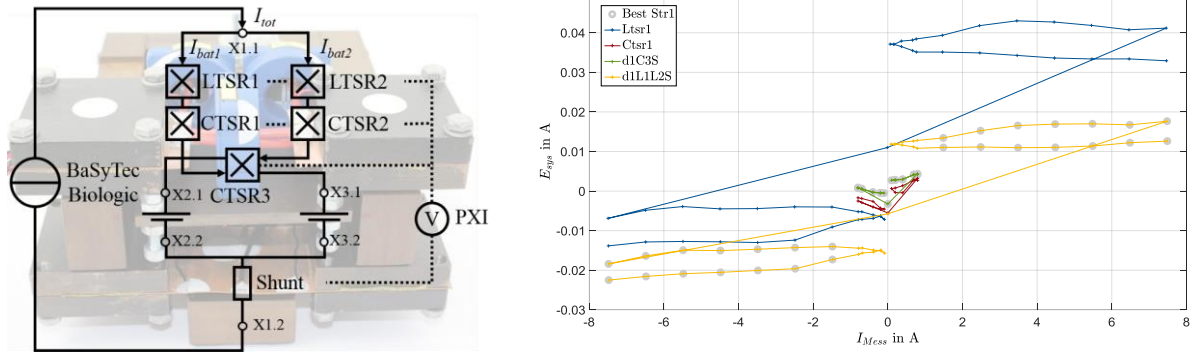


Figure 1: Photography and schematic circuit of measurement set-up (left) and a diagram of the measuring error of the different sensors (right)

No measuring resistance was placed in the cell strings due to high influence on current distribution in the case of high resistance values and high measurement error in the case of low resistance value. Outside the cell strings low offset and dynamic errors of the measuring resistance are used to measure I_{tot} . Inside the cell strings three sensors with flux technology and two sensors with hall technology were implemented. The LTSR hall sensors are used for the cell currents which are higher than 0.85 A. In case of lower current values, the CTSR flux sensors are used to determine the current with lower error.

The impedance of the test bench has an ohmic part of 1.4 mΩ per string. Till a frequency of 100 Hz, there is hardly any imaginary part. At higher frequencies, the real and imaginary impedances grow. The following values are measured by an electrical impedance spectroscopy. Thereby the clamps x2.1 and x2.2 plus the clamps x3.1 and x3.2 were short-circuited.

$$\begin{aligned}
100 \text{ Hz: } \underline{Z}_{str} &= (0.0014 + j0.0012)\Omega \\
10 \text{ kHz: } \underline{Z}_{str} &= (0.0115 + j0.0187)\Omega
\end{aligned} \tag{3}$$

3 Simulation

Load profiles for battery application are very different. They include frequencies in the range of microhertz e. g. the charging of a photovoltaic stationary storage. A driver of an electric car causes dynamic processes in the hertz region and fast switching power electronic charge or discharge with kilohertz and above. To cover this spectrum a model is needed which can calculate the performance of the cells in a wide area of frequencies. For this purpose, an equivalent circuit model was built up and fitted in high frequency and low frequency domain. Figure 2 shows the structure of the model.

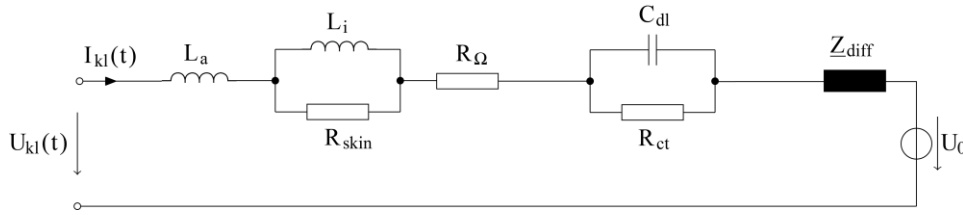


Figure 2: Equivalent circuit model for high frequency simulation of compensation currents

A parallel connection of two cells can be built up out of this model. In Figure 3 the results of measured and simulated results are compared. From a charge of 200 cells of the same type (E-One Molicel IHR18650A), the cells with the highest and lowest ohmic resistance are chosen. The cells are connected parallel and charged with a pulse load. Also the cells with the highest and lowest capacity were connected parallel and charged this way. The results show good accordance between measurement and simulation.

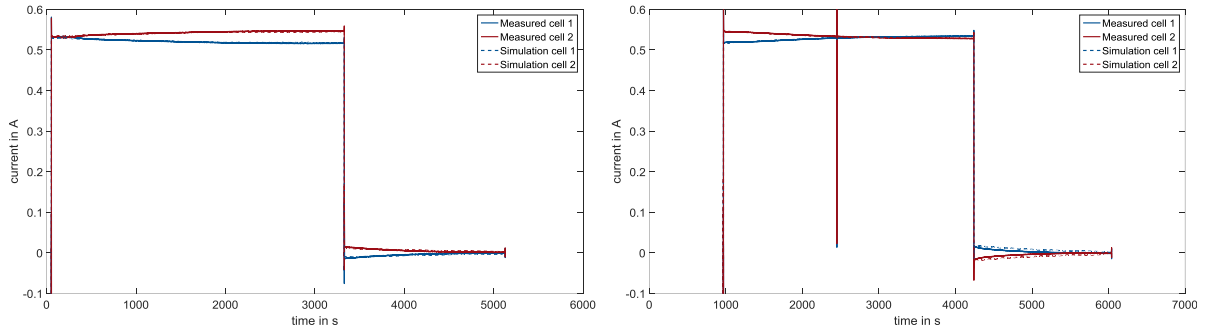


Figure 3: Measurement and simulation of a parallel connection of two cells. The cells of the same type have different ohmic resistance (left) or different capacity (right)

With this validation of the simulation an advanced simulation experiment is possible. A variation of the cell parameter leads to an inhomogeneous current distribution. Hence cell parameters of parallel connected cells are varied. The following simulation results show the current distribution, the losses and the state of charge (SOC) difference. Two load profiles are applied to the parallel connection and four parameters are varied. The parameters of the simulation are shown in Table 2.

Table 2: Simulation parameters

Resistance ohmic	$R_\Omega = 10 \text{ m}\Omega$
Capacity	$C_n = 1.0 \text{ Ah}$
Starting SOC	$SOC_0 = 50 \%$
Slope of the OCV	$dOCV/dSOC = 9.0 \text{ mV}/\%$

3.1 Different ohmic resistance

In the first step the ohmic resistance is varied, Figure 4. When the current rises, the distribution depends on the resistance. The parallel connection behaves like a current divider:

$$I_x = \frac{R_{total}}{R_x + R_{total}} \cdot I_{total} \quad (4)$$

The higher current lead to a SOC difference. This is calculated using the two cell currents and the charge at the beginning. With the SOC difference, the open circuit voltage (OCV) grows too. This leads to an assimilation of the cell currents. After the pulse, the total current drops to zero. Caused by the SOC difference, compensating current flows from the cell with higher resistance to the cell with lower resistance till there is no SOC difference anymore. Ohmic differences in parallel connected cells lead to short-term current differences. The losses of the parallel connection with a greater difference in the ohmic resistance are higher than the losses at lower difference.

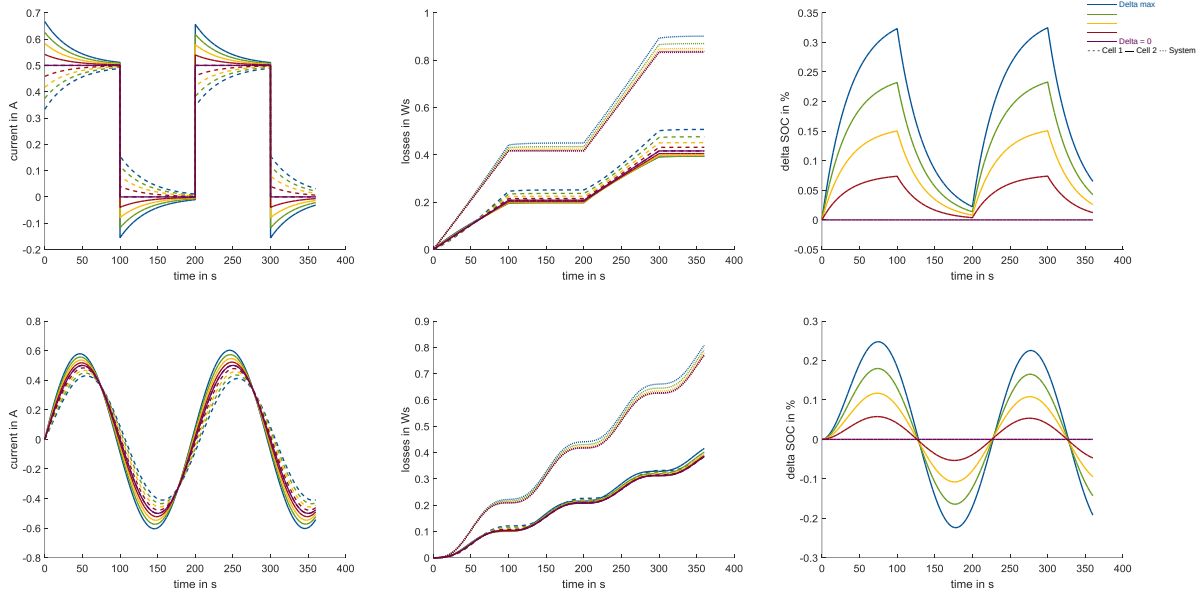


Figure 4: Variation of the ohmic resistance by a factor of 2.3 to 1

3.2 Different capacity

The parallel connection of the cells causes a similar voltage at the terminals. Hence, a fully charged process means that all cells are charged for minimal voltage to maximal voltage at the same time. As the cells have different capacity, the currents cannot be the same.

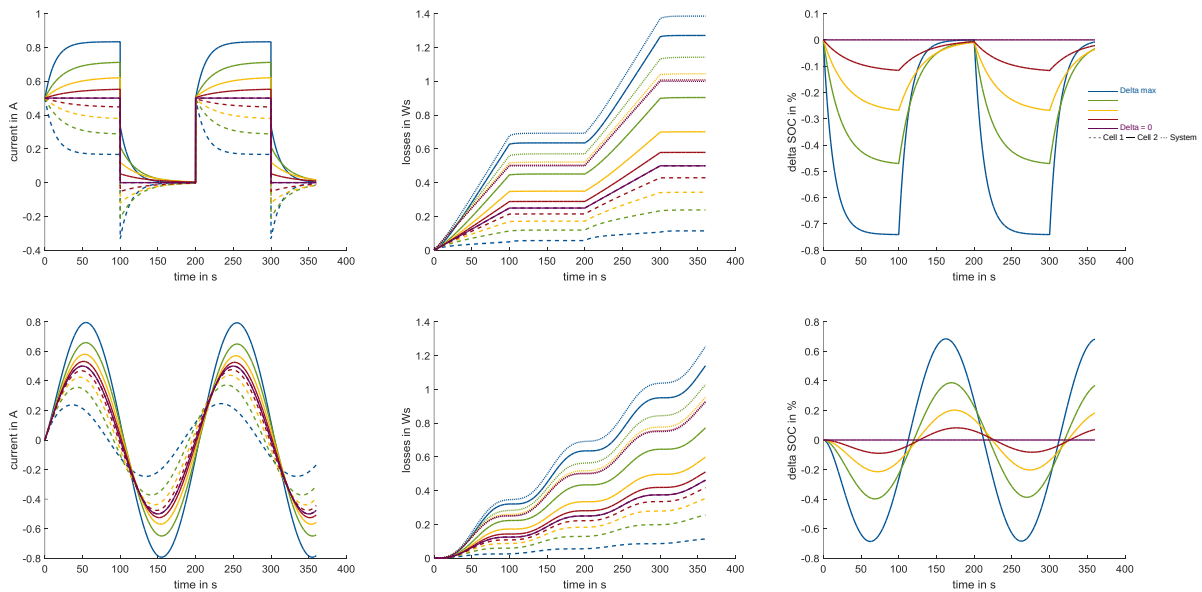


Figure 5: Variation of the cell capacity by a factor of 5 to 1

At the beginning of a current charge pulse, the distribution is driven by the cell resistances. In Figure 5 the impedance of the cells is similar. As the capacity of the cells is different, the current causes different SOC to rise. The SOC spread brings an OCV spread, which causes the long-term current difference. After the pulse a current between the cells eliminates the SOC difference. The long-term current distribution can be calculated with this equation:

$$I_x = \frac{C_{n\ cell\ x}}{C_{n\ cell\ 1} + C_{n\ cell\ 2}} \cdot I_{total} \quad (5)$$

3.3 Different SOC at the beginning

Also the SOC at the beginning can differ. In this case a current equals the SOC from the first second. The difference of OCV leads to a compensation current that brings the SOC difference to zero. The height of the current depend on the difference in voltage and the impedance in the loop. It can be calculated with Kirchhoff's loop rule.

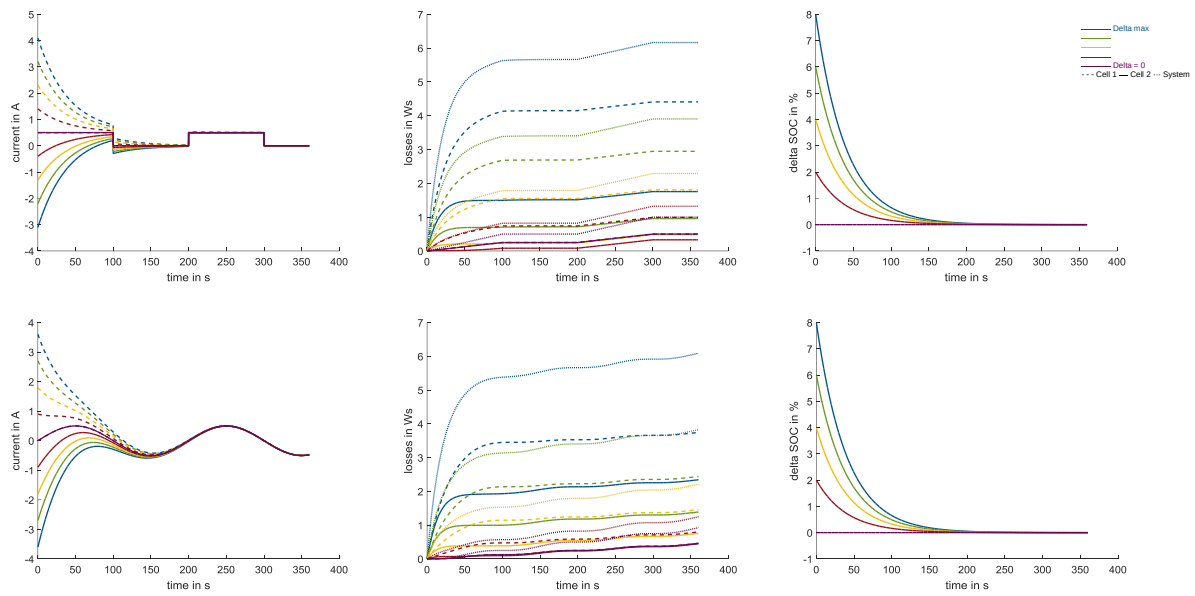


Figure 6: Variation of the start SOC of cell 2 from 42 to 50 %

3.4 Different slope of the open circuit voltage

Different slopes of the OCV can appear when the electrode materials of the parallel connected cells are not the same. The effects at different slopes of the OCV graphs are related to the effects at different capacity. In both cases, the OCV of one cell drops or rises faster than the OCV of the other cell. This leads to a long-term current spread.

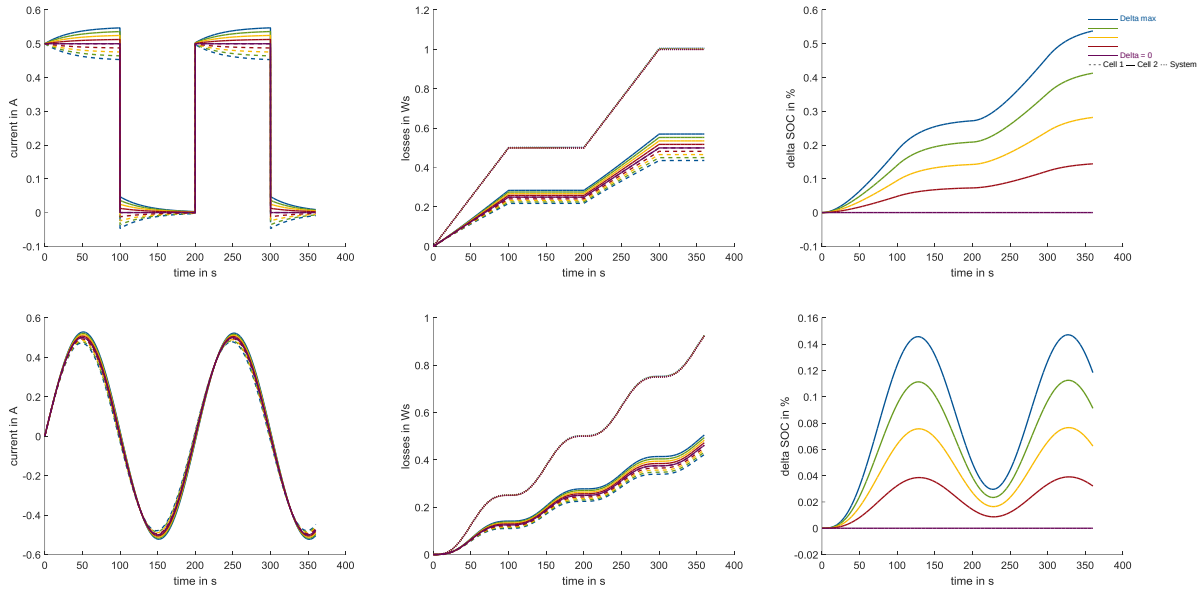


Figure 7: Variation of the slope of the OCV of cell 2 from 11 to 9 mV/%

In Figure 4, Figure 5, Figure 6 and Figure 7, the graphs show the sensitivity of four parameter studies calculated with a simple parameter set. The load profile of this simulation corresponds to square pulses and a sine wave.

4 Effects

As the current distribution is not homogeneous, it is expected that this affects safety, lifetime and efficiency issues. The graphs in chapter 3 show that differences in the ohmic resistance lead to short-term current spread and differences in the cell capacity lead to a long-term spread. The statistic distribution of cell parameters was investigated by Schuster et al. [6] or Baumhöfer et al. [7]. With the results of Schuster et al. [6] a worst case calculation of the current distribution is possible. The results are listed in Table 3. New cells and cells aged in two battery electric cars (BEV 1 and BEV 2) were analyzed regarding their statistic distribution of capacity and resistance. All cells were from the same type (E-One Molicel IHR18650A).

Table 3: Worst case analysis of current inhomogenities with the variation results of [6]. For the calculation, a 2p connection of the cells with a 2.0 A long-term pulse is assumed.

	New	BEV 1	BEV 2
Maximum capacity difference	0.09 Ah	0.26 Ah	0.27 Ah
Maximum ohmic resistance difference	8 mΩ	12 mΩ	12 mΩ
Long-term current distribution			
Cell with high capacity	1.023 A	1.068 A	1.073 A
Cell with low capacity	0.977 A	0.932 A	0.927 A
Short-term current distribution			
Cell with high ohmic resistance	0.943 A	0.920 A	0.917 A
Cell with low ohmic resistance	1.057 A	1.080 A	1.083 A

This may lead to exceeding the maximum permitted cell current. If the load profile is very dynamic with steep gains, the spread of current distribution is bigger. Additionally, the charge displacement is higher due to the circulating current. This affects the ageing and efficiency of the parallel connected cells. With these calculations and measurements of the test bench, statements on the effect of parameter variations can be made.

5 Conclusion

For safety reasons it is essential to keep the current limits of the cells. Due to parameter variance, the current distribution is not equal. A simulation model and a test bench for a parallel connection of two cells show this effect. The test bench does not influence the current distribution. There are no shunt sensors in the current path of the cells. The measurement set-up of a combination of hall and fluxgate sensors with different measuring ranges keeps the accuracy high at all currents. With this toolset, predictions for even more parallel

connected cells are possible. This allows statements on the current distribution caused by parameter inhomogenities, the effects on the efficiency and the need of cell matching.

Simulation results show the current distribution of two parallel connected cells with parameter variations. Different ohmic resistances lead to short-term current effects and different capacities lead to long-term current differences.

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