Akku4Future

Report for Workpackage 3/4

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# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1OTC</td>
<td>one Time Constant</td>
</tr>
<tr>
<td>2TC</td>
<td>two Time Constant</td>
</tr>
<tr>
<td>3TC</td>
<td>three Time Constant</td>
</tr>
<tr>
<td>AC</td>
<td>accelerated current</td>
</tr>
<tr>
<td>CT</td>
<td>charge transfer</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>EIS</td>
<td>electric impedance spectroscopy</td>
</tr>
<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>IR</td>
<td>internal resistance</td>
</tr>
<tr>
<td>Li - Ion</td>
<td>Lithium Ion</td>
</tr>
<tr>
<td>OCV</td>
<td>open circuit voltage</td>
</tr>
<tr>
<td>RDC</td>
<td>direct current resistance</td>
</tr>
<tr>
<td>SEI</td>
<td>solid electrolyte interphase</td>
</tr>
<tr>
<td>SOC</td>
<td>state of health</td>
</tr>
<tr>
<td>SOF</td>
<td>state of function</td>
</tr>
<tr>
<td>SOH</td>
<td>state of charge</td>
</tr>
<tr>
<td>ST</td>
<td>short time</td>
</tr>
<tr>
<td>WP</td>
<td>work package</td>
</tr>
<tr>
<td>Zarc</td>
<td>zarc element</td>
</tr>
<tr>
<td>ZWAR</td>
<td>warburg element</td>
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</table>
1.1 Motivation of using time domain models

The electrical impedance spectroscopy (EIS) and the measurement of the impulse response in the time domain are both suitable methods for the parameterization of an electrochemical cell.

The characterization of a cell in the time domain however, has some advantages when compared to the electric impedance spectroscopy (EIS). The measurement setup is much simpler. The continuous measurement of the direct current and the voltage is sufficient. This has no big impact on laboratory measurement setups, rather than the miniaturized measurement and signal processing on a future device. This kind of measurements allows the monitoring of the diffusion for an arbitrary long time with a high precision. Moreover the analysis of pronounced current pulses is possible, because they are part of the inherent usage of the cells. The EIS, respectively its accelerated current (AC) pulses alter the state of charge (SOC) remarkably. This means that the measurement impacts the overall state of the cell.

Coulomb counting is also a rather simple method and especially useful to determine the SOC. For a precise measurement it is necessary to calibrate the system with defined boundary conditions (e.g. full charge, empty charge). Otherwise an increasing offset would compromise the outcome over time.

Based on these facts it was decided to focus on impulse measurements. The following sections describe the theoretical background behind the method, the used models, their overall behavior and performance and implementation in Matlab®. Finally a short outlook on the planned activities is added to the report.

The description of the implemented measurement setup and the performed measurements are will be documented in an additional report.

1.2 Equivalent- circuit model

Various equivalent circuit [1] [2] [3] [4] [5] [6] [7] [8] models are used to derive the dynamic behavior of electrochemical cells, especially Lithium Ion (Li-Ion) cells. The parameters of the models can be derived either with electrical impedance spectroscopy and/or via pulse responses.

A suitable model should be able to describe the physical and chemical characteristics of a cell (see the previous report for their detailed description). These effects include the internal resistance, the solid electrolyte interface film (SEI), the charge transfer (CT), the short time behavior, summarizing the previous effects (ST) and the diffusion. The idea is to parameterize the model with the conducted measurements. Further investigations should reveal if the change of one or more circuit components can be put in relation to the overall behavior of the cell. So the ultimate goal would be to derive measures such as the SOC, state of health (SOH) and others from the parameters of the model respectively their variation (Figure 1 illustrates this process).
A broad range of models can be used for the characterization of an electrochemical cell. Not all of the models are able to fully characterize the cell, moreover is the needed computation time and by that the energy consumption of the simulation process quite different for the models.

The simplest model is composed of only one ohmic resistance $R$ accounting for the internal resistance (IR) and an ideal voltage source. This model is known as $R_{\text{INT}}$ [8] or IR [6] model in the literature (see Figure 2). The discrete element is obviously not suitable to reproduce the dynamical behavior of a cell.

![Figure 2 R_{\text{INT}} or IR model](image)

The one time constant (1TC) [6] model features an additional RC network when compared to the previous model. This model also known as Thevenin model [8] is able to describe the dynamic behavior of the cell by means of the diffusion (see Figure 3). The other physical effects are not accounted for by this model. The internal resistance sums up for the ohmic resistance and the polarization resistance, the capacitance however describes the dynamic behavior during charging and discharging.

![Figure 3 1TC / Thevenin model](image)

A more complex model should be able to describe the short-time effects (charge transfer and the SEI) in addition to the diffusion. The presented model does not differentiate between both effects but summarizes them in one parameter.
The straightforward improvement to the previous model is a two time constant (2TC) model (Figure 4) which adds an additional RC network. The deviation between measured data and modeled data is still expected to be rather pronounced.

Additional RC elements can be added to improve the simulation accuracy of the diffusion. It will be shown later that the addition of such elements leads to a remarkable improvement (see Table 1 for the additional models).

![Figure 4 2TC model](image)

The simple RC elements can be replaced by the more sophisticated elements like the well-known Warburg element ($Z_{\text{WAR}}$) and $Z_{\text{ARC}}$ elements [9] [10]. The $Z_{\text{ARC}}$ element is basically a parallel circuit of a constant-phase element and a resistor. The element is expected to describe the behavior of the SEI passivation film and the charge transfer in more detail. The $Z_{\text{ARC}}$ element is approximated in the time domain via a RC network, made of 5 elements [11]. A more detailed description of the elements can be found in the previous report. The equations describing all the elements of the circuit were included alongside with the optimization factors for the time domain in the previous report. The easiest way to realize these elements in Matlab is via anonymous function handles.

![Figure 5 Z_{ARC} element and its equivalent circuit](image)

A likewise approach has been implemented for the simulation of the diffusion. It is expected to reproduce the diffusion behavior in more detail with the $Z_{\text{WAR}}$ element. Similar to the $Z_{\text{ARC}}$ element it is possible to approximate the element with a RC network in the time domain. In this case 7 RC elements are used.

These elements increase the flexibility and therefore the sheer number of models. Additional models can be created, starting from the 2TC model. First the RC network describing the diffusion is replaced with a $Z_{\text{WAR}}$ element. Next a ZARC element replaces the RC element describing the short term behavior (Table 1).
The obvious next step is the separate examination of the three main physical effects: the charge transfer, the SEI passivation film and the diffusion.

In consistency to the previous models, these models will be referred to as three time constant (3TC) models. The simplest model for this typology is made of 5 RC elements. One RC element each describes the SEI film respectively the charge transfer. The remaining 3 elements are used for the simulation of the diffusion. Staring from there, a punch of different models can be implemented, by substituting each part. First the diffusion can be modeled with a Z\textsubscript{WAR} element. Next the charge transfer is modeled with a Z\textsubscript{ARC} element, instead of a simple RC element. The remaining RC element is finally replaced by a Z\textsubscript{ARC} element. Two additional models have been implemented. The starting point is again the 5 RC model. First the RC element modeling the SEI is replaced with a Z\textsubscript{ARC} element. Finally the diffusion is simulated with a Z\textsubscript{WAR}.

The following table lists the used models, specifies its components and links them to the used name in the implemented software.
Previous studies have shown that it might not be possible to differentiate between all the effects with the mentioned models. Preliminary results (see later in the report) support these findings. They highlight a pronounced deviation in the deviated parameters when compared to each other. The assumption however, is that even if the parameters are not exactly matched to the physical effect, it should still be possible to draw meaningful conclusions from their variation, as a function of ambient conditions like temperature, the drawn current and other factors.

<table>
<thead>
<tr>
<th>R_i</th>
<th>SEI</th>
<th>CT</th>
<th>Short</th>
<th>Diffusion</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>3RC</td>
<td>3TC_1</td>
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<tr>
<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>Z_{WAR}</td>
<td>3TC_2</td>
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<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>Z_{WAR}</td>
<td>3TC_3</td>
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<tr>
<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>Z_{WAR}</td>
<td>3TC_4</td>
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<tr>
<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>Z_{WAR}</td>
<td>3TC_5</td>
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<tr>
<td>R</td>
<td>RC</td>
<td>RC</td>
<td></td>
<td>Z_{WAR}</td>
<td>3TC_6</td>
</tr>
</tbody>
</table>

Table 1 Equivalent circuit, physical components and model name
1.3 Signal Processing and Simulation

The data processing and analysis has been fully realized in Matlab®. Various functions have been implemented in the course of WP3 and WP4. They are used for the adaption of data, the parameterization of the used models and the presentation of the results. They are kept as flexible as possible. This simplifies their integration or adaption for future applications (e.g. by a company). Moreover should it be possible to adapt the functions easily, for the characterization of other electrochemical cells.

A clear nomenclature for the file names and the arrangement of the data has been defined and used throughout the measurements and the implemented software. Again the idea behind this approach is to keep the functions as flexible as possible, for future applications. The source code is fully documented and freely available.

The following chapter illustrates the process from the raw data to the fully processed data. The description of the functions covers only the absolutely necessary information. The source code files contain a more detailed description.

1.3.1 File conversion from TDMS to Mat files

The data is measured with National Instruments equipment (Labview and DAQ- cards) and stored in TDMS files. These files can’t be processed in Matlab directly. This makes it necessary to convert them to Mat (*.m) files. Figure 6 illustrates this process.

![Figure 6 Conversion of TDMS files to Mat files](image-url)
Implemented Matlab functions:

**TDMS_lesen:** Matlab functions provided directly by Matworks. They are used for the actual transformation of the TDMS file.

**dateiname_MESSFILE:** analyses the information contained in the file name and processing of the information in a cell array.

**INPUT:**
The function gets the TDMS file. The file name is composed of the following parts: aaa_bbb_cccc_dddd_eeeee_ffff_gggg_hhhh_iiii.*

- **aaa)** description which type of measurement has been performed
  - soc100 100% State of Charge
  - ocv relation of the open circuit voltage and the SOC
  - pulse pulsed charging and discharging of the cell
  - dp charging and discharging of the cell, to quantify the degradation of the cell

- **bbb)** TA_Name (name of the section)
  - dch discharge
  - chg charge
  - wch waitCH
  - wdc waitDCH
  - ddc deepDischarge
  - pch pushcharge

- **ccc)** number of the performed cycle (three digit number)
  - ZZZ

- **ddd)** charging current (in milli C)

- **eee)** discharging current (in milli C)

- **fff)** ambient temperature (in milli Kelvin)

- **ggg)** Date
  - YYMMDD

- **hhh)** Time
  - HHMM

- **iii)** ZellID (three digit number)
  - ZZZ

**OUTPUT:**
The information regarding the file are stored in a structure for the further usage in the following functions.

**matFile_gen:** the actual transformation of the TDMS file to a Mat files is done in this part. The name of the newly created file is generated from the output of the function "dateiname_MESSFILE".

**TDMS_MAT_umwandlung:** determination of all TDMS files in a folder and conversion to Mat files with the previously described functions. The Mat files are stored in a new subfolder.
1.3.2 Import of the data

The function “messdaten_einlesen.m” is used to import all the measurement files in a specific folder. It is possible to choose a subsection of files by constraining the relevant parameters, like charging current etc. The amount of data is compressed by interpolating them logarithmically. A side effect of that is the improvement of the simulation results, because it puts more attention to the very beginning of the measurement data. The function “impulse_data.m” cuts the impulse to the essential data, by deleting the initialization phase.

Implemented Matlab functions:

**messdaten_einlesen:**  
*Input:*  
Pathname : location of the folder containing the files.  
auswahl : specifies the subsection of files that should be used in terms of the charging current, pulse type and others.  

*Output:*  
messdaten = Structure containing the information regarding the subsection and the measurement results.  
daten_info = contains the information of the subsection and has the same format as the output of “dateiname_messfile”.  
messwerte = contains the actual measurement data  
1. collum = number of the section  
2. collum = time  
3. collum = current  
4. collum = voltage  
5. collum = temperature

**impulse_data:**  
the subsection does not begin with the actual impulse. This is because it takes some time for the current to stop and/or start. The function finds the rising or decreasing edge of the current and skips the initial data. This is important for the correct computation of the direct current (DC) resistance.
1.3.3 Correlation SOC and the open circuit voltage

The function “SOC_Uklemm” computes the relation between the SOC and the open circuit voltage (OCV). The used measurement protocol can be found report covering the performed measurements. The charge of each impulse is computed and directly linked to the voltage at the very end of the waiting impulse. Finally, the step size between the values is increased to 0.5% by interpolating the values.

The result is stored to a file, alongside with the used ambient temperature and the information if the measurement has been performed during a charging or discharging cycle.

**Implemented Matlab functions:**

\[ \text{SOC}_\text{Uklemm} : \text{Output} \]

- structure containing the SOC (in 0.5% steps) and the related OCV

Figure 7 Relation of the open circuit voltage and the state of charge.
1.3.4 Adaption of the imported data

The actual parameterization of an impulse can only be done after some additional steps. First the SOC at each measurement point has to be computed. Next the SOC – OCV relation for the specified ambient temperature is loaded differentiating between charging and discharging pulses. Finally the direct current resistance $R_{DC}$ for each point is computed. A graphical user interface (GUI) has been implemented to display the results. Figure 8 illustrates this process.

![Diagram](image.png)

**Figure 8** Implemented process for the adaption of the measurement data and their display.

Figure 9 illustrates the output of this function. In the first row the type of impulse (charging, discharging, waiting ...) is illustrated. The following rows illustrate the clamp voltage, the drawn current and finally the computed $R_{DC}$. This function manly serves for the visual inspection of the measurement data.
Figure 9 Implemented GUI, illustrating the performed impulses, current, voltage and finally the $R_{OC}$

Implemented Matlab functions:

- **mess_SOC**: the SOC for each measurement point is computed. The information is added to an additional column of the “messdaten” matrix.
- **U0_SOC**: loads the structure containing the SOC and OCV relation. Depending on the ambient temperature and the investigated impulse (charge, discharge) the associated data is loaded.
- **Rdc**: the direct circuit is computed based on the measurement data. The relation between SOC and open circuit voltage is used to eliminate its influence from the measured voltage.
- **plot_messwert**: presentation of the measurement data. The first section displays the color coded subsection. Next the current and voltage are displayed. Finally the direct current resistance is displayed.
1.3.5 Parameterization of an impulse

The parameterization of the impulse response is based on the computed direct current resistance. A curve-fitting algorithm based on the least squares is used to find the optimal solution.

The challenge is to find the coefficients that solve the following problem:

\[
\min_x \| F(x, xdata) - ydata \|^2 = \min_x \sum_i (F(x, xdata_i) - ydata_i)^2
\]

The vectors xdata and ydata contain the time vector respectively the computed $R_{DC}$. $F(x, xdata)$ is a vector of the same size as ydata. The Matlab function “lsqcurvefit” solves this equation. Some additional parameters have to be defined to get the best performance of the algorithm.

\[
x = \text{lsqcurvefit}(\text{fun}, x0, xdata, ydata, lb, ub, options)
\]

fun... contains the analytical equation describing the used equivalent circuit, respectively the underlying function that has to be fitted. The function takes two input vectors (x, xdata) and returns the object function evaluated at the points x and xdata. The following equation describes the 2TC_1 model analytically:

\[
R_{DC\_model} = R_{INT} + R_{SH} \left( 1 - e^{-\frac{t}{\tau_{SH}}} \right) + R_{DIFF} \left( 1 - e^{-\frac{t}{\tau_{DIFF}}} \right)
\]

An anonymous function handle is used to define the model within Matlab:

\[
F\_Handle = @(x,xdata) x(1)+x(2).*(1-exp(-xdata/x(3)))+x(4).*(1-exp(-xdata/x(5)));
\]

x0... initial values for the algorithm. The algorithm works best if the starting values are close to the real values.

xdata... time vector of the measurements serves as input for the objective function

ydata... computed direct current resistance to be matched by the objective function

lb,ub... lower and upper bounds of the parameters

options... additional settings (used algorithm, max iterations....)

x... Vector that contains the results for used model. The elements of the vector are directly linked to their analytical counterpart: $x[1] = R_{INT}$; $x[2]=R_{SH}$; $x[3]=\tau_{SH}$; $x[4]=R_{DIFF}$; $x[5]=\tau_{DIFF}$. The capacitance of the RC network can easily be computed based on the relation $\tau = R \times C$.

The same approach is used for the parameterization of all models. Next the parameters have to be linked to the physical effects. All these informations are stored in a struct-variable, carried out with the function (Rdc_g_STRUCT.m). The results can be displayed with a customized GUI function (see Figure 11).
Figure 10 illustrates the used process to derive the parameters for each of the model, step by step.

![Flowchart](image)

**Figure 10 Process for the parameterization of an impulse response**

The GUI compares the simulation results graphically. Figure 11 illustrates the computed results, based on a 10 minutes long waiting cycle after a charging impulse. The models are grouped according to their complexity (1TC, 2TC and 3TC). A second row highlights the absolute difference between optimized and measured data.
Even more information can be gathered from the parameters the diagrams are based on. The parameters in the upper half of are directly linked to the equivalent components of the models illustrated in Table 1. Based on these parameters, the value describing the actual physical quantity can be derived. The table gives an overview of the computation time (RZ in seconds) and the relative difference between the measured and simulated data. The error estimation was further split in two parts, \( F_{rel,SHORT} \) for the first 50 ms and \( F_{rel,DIFF} \) for the long time behavior. This is important because the rather precise simulation of the long time behavior might completely overshadow the inaccurate reproduction of the short time behavior, due to the much longer investigation time (factor 12000 in this example).

From these results it is evident that the modeling of the cell is not suitable with a single resistor. The average difference between measured and simulated value is far too high. The 1TC model adds a basic dynamic behavior to the model and increases the accuracy of the model by more than one order. When compared to the other models, it is obvious that it is not able to differentiate between the internal resistance (too high) and the diffusion parameters (too small). The pronounced error estimations confirm this finding.

All two time constant models estimate the internal resistance at basically the same value. The values for the short time behavior however, vary quite remarkably. This is interesting because all models expect the 2TC_5 model use a single RC element to reproduce the short time behavior. This can be explained by the fact that not all these models are able to separate the short time behavior and the diffusion. Meaning that the modeling of the diffusion strongly affects the short time behavior. The short time performance improves steadily by adding RC elements to the diffusion chain. The replacement of the RC element by a \( Z_{ARC} \) (2TC_5) elevates the accuracy even more.
<table>
<thead>
<tr>
<th>model - parameter</th>
<th>Ri (mΩ)</th>
<th>1TC</th>
<th>2TC_1</th>
<th>2TC_2</th>
<th>2TC_3</th>
<th>2TC_4</th>
<th>2TC_5</th>
<th>3TC_1</th>
<th>3TC_2</th>
<th>3TC_3</th>
<th>3TC_4</th>
<th>3TC_5</th>
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<td>2,57</td>
<td>0,16</td>
<td>2,55</td>
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<td>t (ms)</td>
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<td>11,73</td>
<td>8,32</td>
<td>3,57</td>
<td>1,71</td>
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<td>2,18</td>
<td>1,06</td>
<td>2,08</td>
<td>2,24</td>
<td>2,23</td>
<td>1,71</td>
<td>2,08</td>
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<td>F1 (%)</td>
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<td>22,71</td>
<td>14,09</td>
<td>8,82</td>
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<td>F2 (%)</td>
<td>188,23</td>
<td>8,97</td>
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<td>1,94</td>
<td>1,94</td>
<td>0,97</td>
<td>1,79</td>
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Table 2 Overview of the computed model – parameters, the derived physical parameters and the deviation between computed and simulated values.

Pretty much the same is valid for the diffusion. The long time accuracy increases by adding RC elements. It is interesting that the performance of the models featuring a Warburg element, which consists of 7 RC elements, is worse than the 2TC_3 model performance. This is because of the higher number of degrees of freedom. The overall behavior of the Z_{WAR} is described with only one resistor and capacitor while the while the 2TC_3 model features three independent RC networks.
In case that multiple RC elements are used, the diffusion resistance is obtained by simply adding all values. The resulting time constant is the slowest of the simulated elements. The relation $\tau = R \cdot C$ leads to the correlated time constant.

In this group the 2TC_3 model seems to be the most accurate followed by the 2TC_5 model. It is however noteworthy that the needed computation time, is cut in half for the latter model. The 2TC_4 model with is even more inaccurate improves the computation time by an additional factor of two. It needs to be seen in a systematic review of all simulations, if the advantage of fast simulations does not weaken the results too much.

The three time constant models reproduce the internal resistance with basically no variation. The error estimation for the SEI effect and the charge transfer are not analyzed separately, to better compare the results to the 2TC models. Again the resistance is composed of the sum of the individual elements and the time-constant is the greater one of both values.

The absolute values of the elements vary to some extent, while the error estimation for the short time behavior reveals more or less the same value for all models, expect model 3TC_5. It is evident that its $Z_{ARC}$ element is not able to model the SEI of the cell. This means that the model theoretically simplifies to the 2TC_3 model. The numbers for the derived physical parameters confirm this prediction. Therefore and due to the extremely long computation time, the model will not be used for further investigations.

Replacing the RC chain of the 3TC_1 model with a $Z_{WAR}$ worsens the accuracy of the long time behavior. But again a remarkable change in the needed computation time can be observed. The same as for the 2TC models is true. A systematic review must reveal, if the use of a faster model does not compromise the results too much.

**Implemented Matlab functions:**

- **lsq_fit_puls**: Function executing the actual optimization process by calling the functions below and using the Matlab optimization toolbox. The parameters for each model are saved as additional information in the “messdaten” structure.
- **Startwerte**: Start values for the optimization algorithm.
- **warburg_element**: Function to approximate the Warburg element with 7 RC elements in the time domain.
- **zarc_element**: Function to approximate the Zarc element in the time domain with five RC elements.

  **Function handle for the models**

  - **FH_1RC**:
  - **FH_1RcW**:
  - **FH_1RcW**:
  - **FH_2RcW**:
  - **FH_3RC**:
  - **FH_4RC**:
  - **FH_5RC**:
  - **FH_R**:
  - **FH_RcZW**:
FH_ZRc3Rc:
FH_ZRcW:
FH_ZW:
FH_ZZW:

Rdc_g_STRUCT: Generates a consistent result structure for each of the used models, containing the following information (all the information is added as a struct-variable to the specific impulse):

Rdc_g.Daten: contains simulated and measured data
  .geschaezt = estimated Data based on the computed cell parameters
  .Messdaten = measured data
  .Zeitvektor = time vector
  .fehler_absolut = absolute difference between measured and computed data
  .fehler_avg_absolut = mean absolute error (average & median)
  .fehler_prozent = relative difference between measured and computed data
  fehler_avg_prozent = mean relative error (average & median)

Rdc_g.Opt_INFO: contains the Information for the optimization
  .resnorm = see Matlab-help
  .exitflag = see Matlab-help
  .iterations = see Matlab-help

Rdc_g.BatPar: parameters describing the cell. Their number changes based on the complexity of the model.

Rdc_g.PhEff: the computed parameter are assigned to the correlated physical effect.
  .IR internal resistance
  .SEI solid electrolyte interface
  .CT Charge Transfer
  .SHORT Short time behavior
  .DIFF Diffusion

Rdc_g.Name: Name of the model in the used nomenclature
Rdc_g.Rechenzeit: The needed simulation time.

plot_modelres Displays the results of the optimization process and the absolute difference between simulated and measured data.
Puls_series Performs the described optimization for a series of pulses. The length of the investigated pulse response can be chosen by the user.
find_puls Finds all the impulses of one type (charge, discharge, ...) in the “messdaten” structure.
2 Outlook

It is intended to perform multiple impulse measurements at different temperatures and with different charging and discharging currents. These measurements, described in more detail in the next report, lay the basis for the systematic investigation via the here presented models. The idea is to identify the models, respectively model parameters suitable to estimate the SOC as a function of the ambient temperature and the drawn current. The measurements are repeated for a number of times to provoke an artificial aging of the cell, to see if the models can also give some valuable hint with regard to the SOH and state of function (SOF).
3 Bibliography


