Verbesserte Mess- und Modellierungsverfahren für Li-Ionen Batterien

Projekt Nr. 1105

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Introduction
On taking shortcuts

Model Targets:

- **Good Real-time Capabilities**
  - model structure deployable on microcontroller

- **Scalability**
  - accuracy and computational effort easy adaptable

- **Automization of Parameterization**
  - model quality does not depend on human expertise
Introduction
Battery Modeling Today

EIS Measurement

- electrochemical impedance measurements
- non parametric representation of linear dynamics
- variation of operating points (SOC, T)
Introduction
Battery Modeling Today

EIS Measurement

Model selection and fit

- a priori knowledge necessary
- stabilization of fit procedure critical
- subtraction of differential capacity

Fractional impedance elements

Differential capacity
Introduction
Battery Modeling Today

EIS Measurement

Model selection and fit

Approximation of fractional impedance elements

- Fractional impedance elements cannot be simulated directly in time domain
- Approximation with sum of RC-Elements:
  - empirical relation [1]
  - analytical expansion to sum
  - discretization of the distribution of relaxation times

Analytical expression for the measured impedance has to be known!

Introduction
Battery Modeling Today

EIS Measurement

Model selection and fit

Approximation of fractional impedance elements

Time Domain Model and Simulation

Approximation of fractional impedance elements

Loss of accuracy

time effort

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The Distribution of Relaxation Times

The Continuous Distribution of Relaxation Times

\[ Z_{pol}(j\omega) = R_{pol} \int_0^\infty \frac{g(\tau)}{1 + j\omega \tau} d\tau \]

\( g(\tau) \): distribution function of relaxation times (DRT)


**ideal process: RC-Elements**

\[ g(\tau): \text{Dirac pulses} \]

**real process: RQ-Elements**

\[ g \]

Calculation of the Discrete Distribution of Relaxation Times

\[ Z_{pol}(j\omega) = \sum_{n=1}^{N} \frac{g(\tau_n)}{1 + j\omega \tau_n} \delta_\tau \]

- \( N \) is the Number of RC-Elements
- discrete distribution: \( \tau \) is logarithmical equally spaced
- \( g(\tau_n) = 0 \) at highest and lowest \( \tau_n \)
Introduction
Battery Modeling Today

- EIS Measurement
- Model selection and fit
- Approximation of fractional impedance elements
- Time Domain Model and Simulation

Approximation of fractional impedance elements

EIS Measurement
Model selection and fit
Approximation of fractional impedance elements
Time Domain Model and Simulation

Loss of accuracy
time effort

I

OCV
SOC

U

I

t

U

t

PLECS

Loss of accuracy
time effort

I

OCV
SOC

U

I

t

U

t

PLECS
Introduction
Battery Modeling based on DRT

EIS Measurement

Method of the Distribution of Relaxation Times

\[ Z_{pol}(j\omega) = R_{pol} \sum_{n=1}^{N} \frac{g(\tau_n)}{1 + j\omega\tau_n} \]

distribution of relaxation times

decovolution of EIS

Time Domain Model and Simulation

\[ U_{OCV} + \text{PLECS} \rightarrow U(t) \]
Verification of the DRT Model
Experimental

2 Ah Li-ion cell from KOKAM

- Pouch-cell
- Anode: Graphite
- Cathode: NCA/LCO-Blend

Anode: Graphite

Cathode: LiNi$_{0.8}$Co$_{0.15}$Al$_{0.05}$O$_2$/LiCoO$_2$ Blend
Verification of the DRT Model
Experimental

Electrochemical Measurements

- quasi stationary OCV
- discharge/charge at C/40

EIS

- $f = [100\text{kHz} \ldots 5\text{mHz}]$
- $U_{\text{ampl}} = 10\text{mV} / 5\text{mV}$
- merger of high and low frequency range
- impedance spectra $f = [100\text{kHz} \ldots 10\mu\text{Hz}]$
- completely automized process

Pulse

- pulse height 1C
- pulse length = 10s
- transformation to frequency domain\(^1\)
- merger of high and low frequency range

Validation Profile

- Variation of $I_{\text{max}} = \text{C/4} \ldots 2\text{C} \rightarrow 0.5\text{A} \ldots 4\text{A}$
- average discharge with $I_{\text{max}}/2$

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Measurement Results

EIS

extended frequency range via pulse measurements
Measurement Results
DRT
Measurement Results
DRT

beneficial use of the DRT for identification and separation of Processes \(^1,2\)

interpretation not necessary for parameterization of time domain model

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Measurement Results Comparison: EIS / DRT-Model

Very good accordance of measurement and DRT-model
Analysis of the DRT-Model
Required Model Complexity

EIS Measurement / DRT-Model

\[ Z_{pol}(j \omega) = \sum_{n=1}^{N} \frac{g(\tau_n)}{1 + j \omega \tau_n} \]

<table>
<thead>
<tr>
<th>Variation of N</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N = 100 \rightarrow 11.6 \text{ RC / decade} )</td>
</tr>
<tr>
<td>( N = 20 \rightarrow 2.3 \text{ RC / decade} )</td>
</tr>
<tr>
<td>( N = 10 \rightarrow 1.1 \text{ RC / decade} )</td>
</tr>
<tr>
<td>( N = 4 \rightarrow 0.5 \text{ RC / decade} )</td>
</tr>
</tbody>
</table>

Results

- 20 RC-elements show no significant difference to 100 RC-elements
- 10 RC-elements show slight deviations
- 4 RC-elements result in a bad fit of the impedance data
Analysis of the DRT-Model
Required Model Complexity

Comparison of dynamic behavior

- seconds-timescale shows significant differences for 4 RC-model
- slight increase of accuracy between 10 and 20 RC-model
- no visible difference for 20 and 100 RC-model

10 RC-Model shows good accordance and modest calculation effort
Model Validation
Measured Profile and Time Domain Simulation (II)

\[ I_{\text{max}} = 2C \]
\[ I_{\text{max}} = 1C \]
\[ I_{\text{max}} = C/2 \]
\[ I_{\text{max}} = C/4 \]

Measurement

Significant increase of surface temperature
Model Validation
Measured Profile and Time Domain Simulation (II)

\[ I_{\text{max}} = 2C \quad I_{\text{max}} = 1C \quad I_{\text{max}} = C/2 \quad I_{\text{max}} = C/4 \]

- Measurement
Model Validation
Measured Profile and Time Domain Simulation (II)

\[ I_{\text{max}} = 2C \]
\[ I_{\text{max}} = 1C \]
\[ I_{\text{max}} = C/2 \]
\[ I_{\text{max}} = C/4 \]

Measurement
Model Validation
Measured Profile and Time Domain Simulation (II)

$$I_{\text{max}} = 2C$$

$$I_{\text{max}} = 1C$$

$$I_{\text{max}} = \frac{C}{2}$$

$$I_{\text{max}} = \frac{C}{4}$$

Measurement

Significant increase of surface temperature
Model Validation
Measured Profile and Time Domain Simulation (II)

- $I_{\text{max}} = 2C$
- $I_{\text{max}} = 1C$
- $I_{\text{max}} = C/2$
- $I_{\text{max}} = C/4$

**Graph 1:**
- Voltage ($U$) over time ($t$) with different current levels ($I_{\text{max}}$).
- Measurement indicated by a dotted line.

**Graph 2:**
- Significant increase of surface temperature.
- Temperature profiles for different current levels.

*Images and data from IWE Weber, Folie 22, 21.02.2013*
Summary

Measurement

OCV

EIS

Pulse

Validation Profile

Parameterization

Merger of Impedance Spectra

DRT Calculation

Model

Scalability
Publications

**Journal Papers**


**Conference Contributions**

- J.P. Schmidt, A. Weber, E. Ivers-Tiffée, *Fast and Scalable Models for Li-Ion Batteries Based on the Distribution of Relaxation Times*, 13th Ulm Electrochemical Talks (Ulm, Germany), 03.07. - 05.07.2012
- J.P. Schmidt, P. Berg, A. Weber, E. Ivers-Tiffée, *The Distribution of Relaxation Times as Basis for Time-Domain Models of Li-Ion Batteries*, Kraftwerk Batterie (Münster, Germany), 06.03. - 07.03.2012

**Student Thesis**

- Philipp Berg, Bachelor Thesis, “Modellierung einer Lithium-Ionen-Batterie hinsichtlich ihres Lade- und Entladeverhaltens mittels eines linearen, zeitvarianten Systemansatzes“
Thank you for your kind attention!