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BATTERY CONFERENCE
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Modelica-based Modeling of the Electro-Thermal Behavior Deviations within a Lithium-Ion Battery Module

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Motivation

- Increasing market relevance of large-scale stationary battery systems in recent years [1]
- Rising demand for battery models as tools for:
  - System dimensioning and design
  - Economic/ecological assessment
  - Model-based operation optimization
  - Model-based predictive maintenance
- Electro-thermal battery cell models already widely available in literature
- **Battery system models representing the distribution of the individual cells around the average electro-thermal behavior far less common**

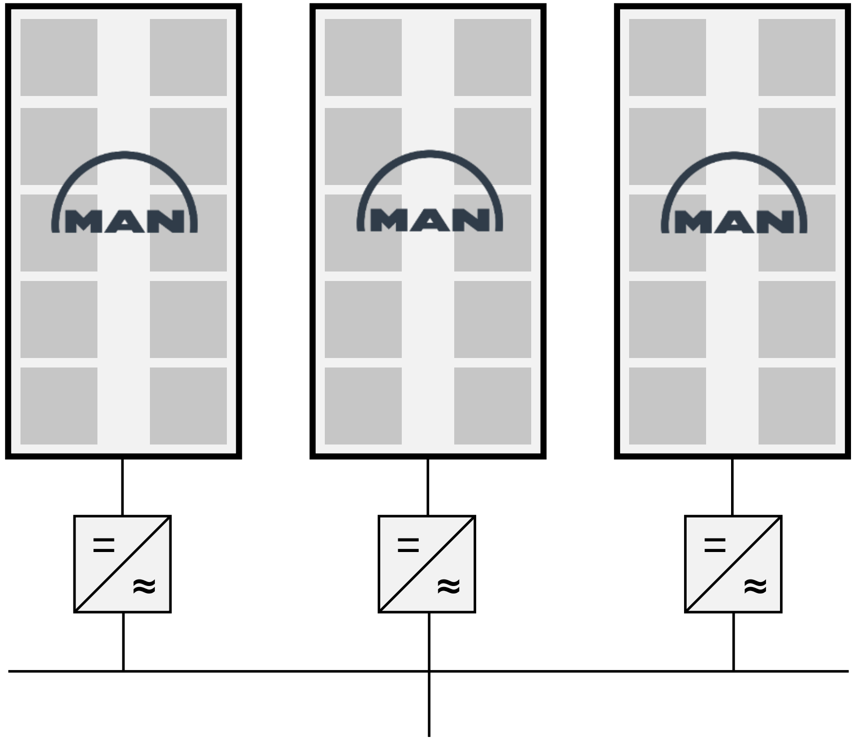


Figure 1: Large-scale stationary battery system, schematic depiction

[1] J. Figgener et al.: “The development of stationary battery storage systems in Germany – A market review”, *Journal of Energy Storage,* 2020

Motivation

Causes for behavior deviations within multi-cell structures [2,3]

- Cell capacity and resistance deviations
- Resistive parallel cell connectors and contact resistance deviations
- Uneven heat generation and dissipation
- Deviations of the aging progress

Resulting behavior deviations [2,4,5]

- Current and voltage distributions
- Uneven cell SoCs
- Temperature gradients in the system
- Deviating and often generally increased aging

Weaknesses of existing system models

- Consideration of cross-domain interactions/combined models
- Difficult adaptation to different systems
- High computational effort
- Time-consuming and demanding parameterization processes

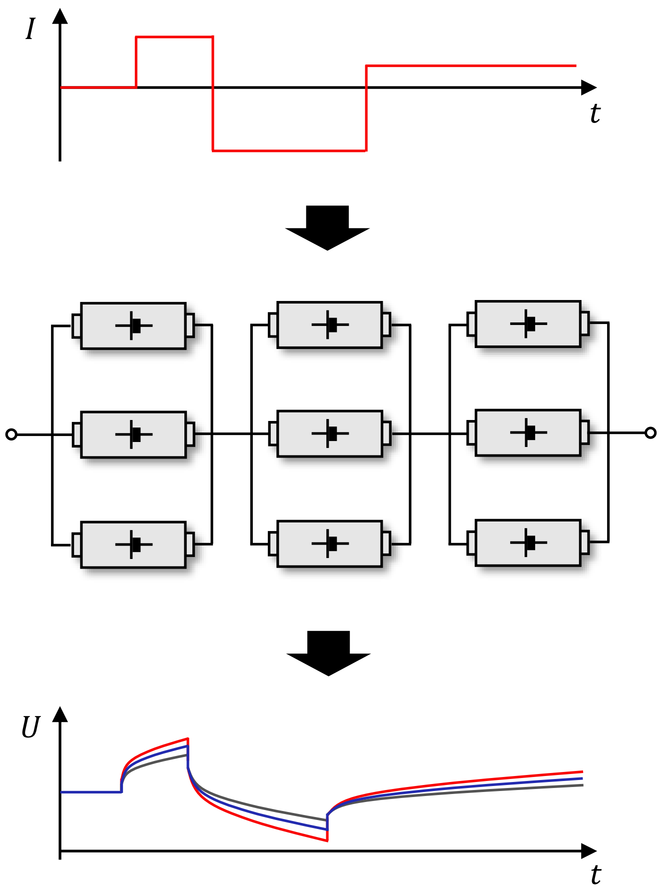


Figure 2: Behavior deviations within multi-cell structures, schematic depiction

[2] M. Baumann et al.: "Parameter variations within Li-Ion battery packs – Theoretical investigations and experimental quantification", *Journal of Energy Storage,* 2018
[3] S. Lehner et al.: "Disparity in initial lifetime parameters of lithium-ion cells", *IET Electrical Systems in Transportation*, 2014
[4] M. Brand et al.: "Current distribution within parallel-connected battery cells", *Journal of Power Sources*, 2016
[5] R. Gogoana et al.: "Internal resistance matching for parallel-connected lithium-ion cells and impacts on battery pack cycle life", *Journal of Power Sources,* 2014

Battery System Model

→ Based on the Open-Source *Modelica* standard

→ Exemplarily implemented for commercial 14s2p battery module for stationary applications (Figure 3)

→ Can be adapted to arbitrary configurations with low effort

Cell level: 0D-lumped parameter model

- Electrical equivalent circuit (R_S + 2·RC)
- Thermal lumped parameter model with uniform cell heat capacity
- Internal heat generation calculated from electrical losses

Module level: Electro-thermal equivalent circuit interconnecting multiple cell objects

- Adaptive electrical interconnection of multiple cell objects according to original structure with cell-specific capacity and resistance deviation
- Thermal equivalent circuit with additional static thermal resistances and capacities representing the mechanical structure (Figure 4)

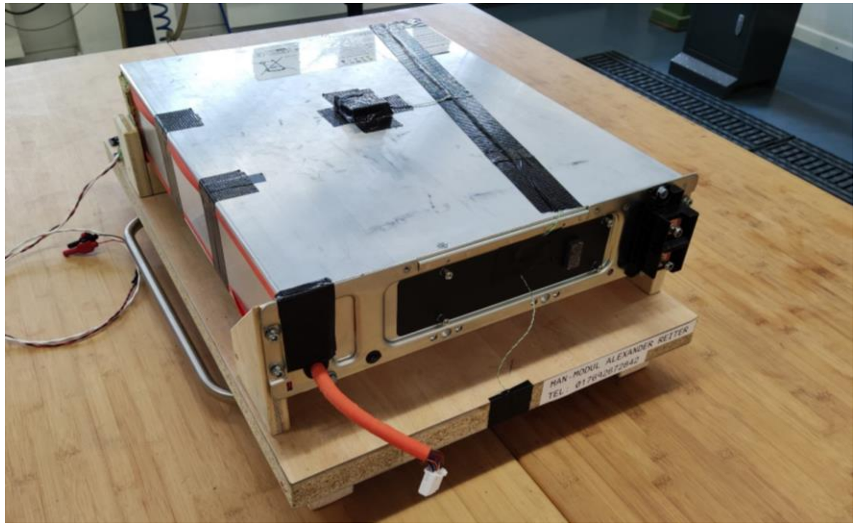


Figure 3: Battery module for stationary applications used for exemplary implementation

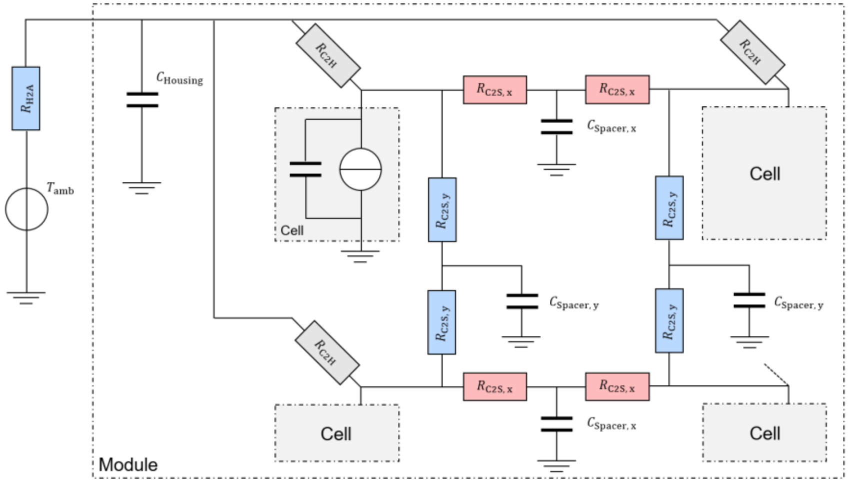


Figure 4: Thermal equivalent circuit for the calculation of the temperature distribution

Parameterization

Average electrical parameters

- Determined via common literature methods
- CCCV capacity test, qOCV determination, pulse tests

Cell-specific capacity/resistance deviation

- Capacity deviations calculated from relaxed cell voltages after extended relaxation capacity test (Figure 5)
- Resistance distribution determined from cell-specific pulse fits converted into scalar DC resistance

→ **Reduced effort compared to individual cell measurements**

Thermal equivalent circuit parameters

- Heat capacities calculated via stationary state/cooling curve experiments on the unisolated module and additional analytical calculations (Figure 6)
- Thermal resistances calculated from stationary temperature gradients caused by internal pulse heating on partially isolated module

→ **Non-destructive measurement process not requiring costly thermal testing equipment (e.g. calorimeter)**

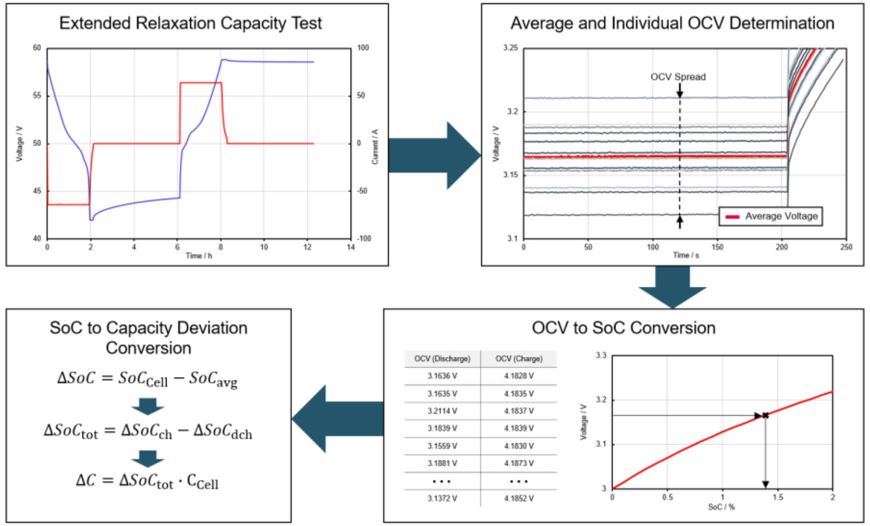


Figure 5: Process for the determination of the capacity deviation via extended relaxation capacity tests

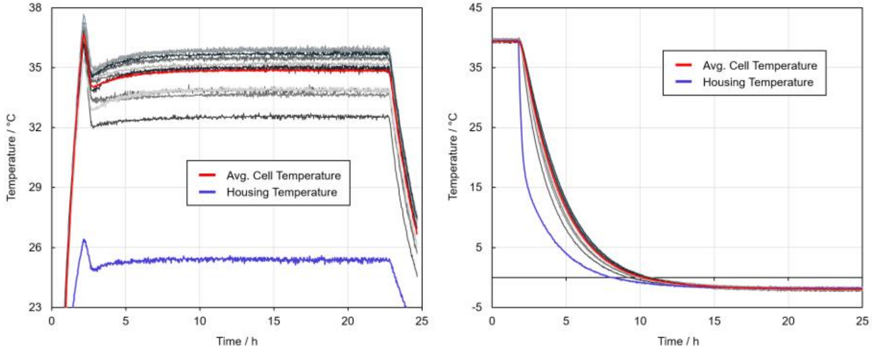


Figure 6: Stationary state and cooling curve measurements for cell heat capacity determination

Electro-Thermal Validation Results

Electrical System Behavior

- Validated with 24h grid service load profile [6]
- Model represents voltage spread ($U_{Cell,max} - U_{Cell,min}$) accurately for large parts of the profile
- Exceptions: Regions with SoCs < 10% and SoCs between 55-65%
  → qOCV determination identified as primary cause

Average Thermal Behavior

- Validated with 5.5h synthetic pulse load profile
- Model reproduces general behavior over the whole profile
- General overestimation likely caused by overestimation of cell-to-housing thermal resistances
- Reduced dynamics likely caused by negligence of reversible heat via entropy changes

Thermal System Behavior

- Model reproduces general behavior over whole profile
- Overestimation and reduced dynamics resemble average behavior

→ **General capability of the modeling approach proved**

→ **Computational effort significantly reduced compared to common approaches (avg. 225s/h computation time on Office PC)**

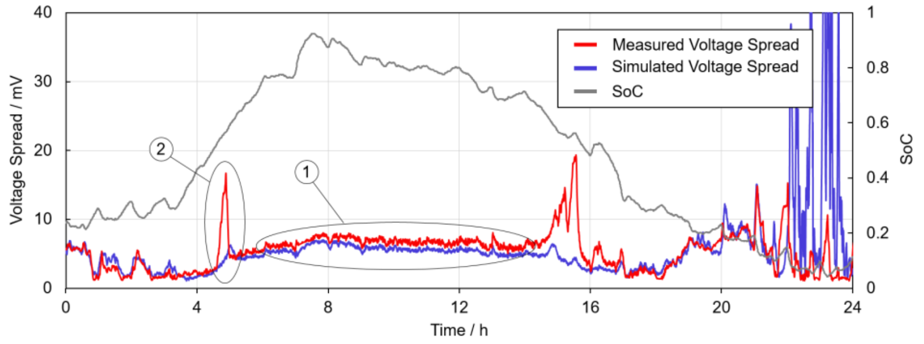


Figure 7: Comparison of the measured and simulated voltage spread for a PRL validation profile

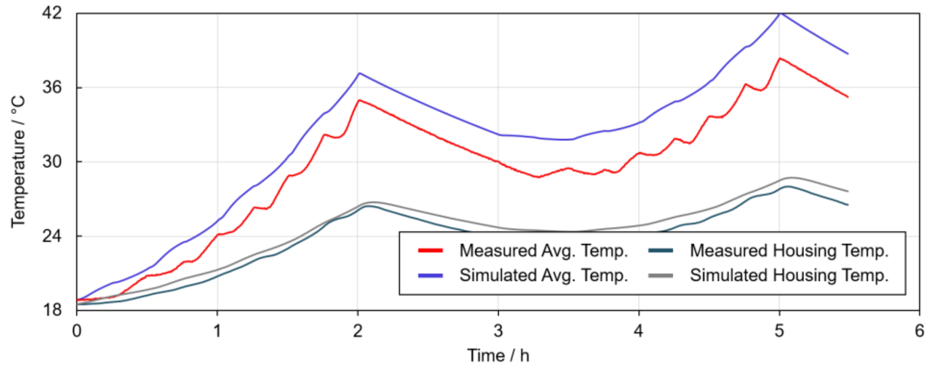


Figure 8: Comparison of the measured and simulated average temperature for a synthetic pulse profile

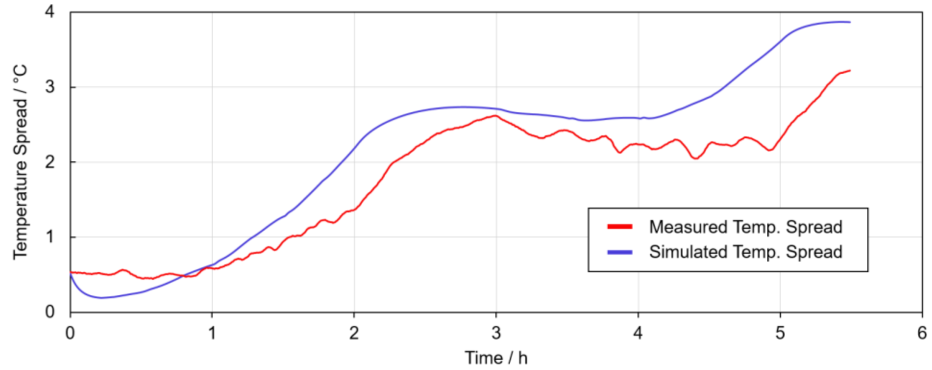


Figure 9: Comparison of the measured and simulated temperature spread for a synthetic pulse profile

[6] M. Mühlbauer et al.: "Analysis of power flow control strategies in heterogeneous battery energy storage systems", *Journal of Energy Storage,* 2020

Outlook and Statistical Model Reduction

Improvement of current model features

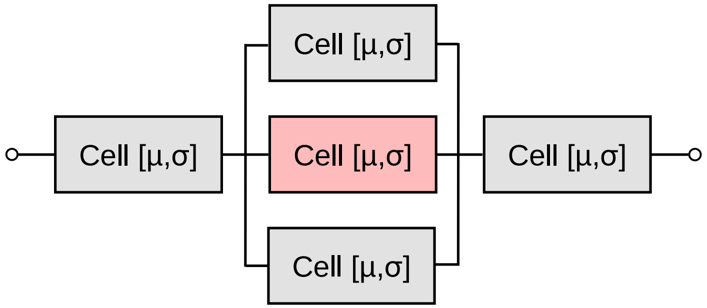
- Improvement of the OCV determination for better representation of regions between 55-65% SoC
- Integration of reversible heat due to entropy changes

Implementation of new features

- Resistive cell connectors/contacts
- Active cooling systems
- Scaling from module to rack and system level

Application of statistical model reduction methods

- Representing arbitrary electro-thermal structures by substitute arrangements
- Objective: Further reduction of computational and parameterization effort allowing implementation for full-size systems
- General method already introduced in [7]



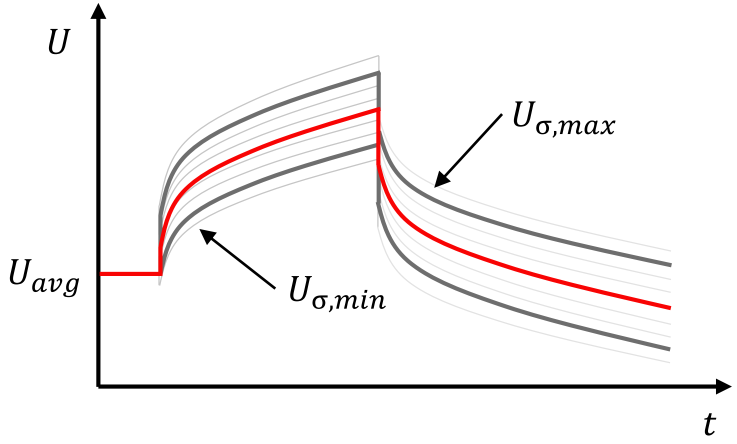


Figure 10: Statistical substitute arrangement and resulting voltage distribution prediction, schematic depiction

[7] A. Reiter et al.: "A Modelica-based Simulation Model for Large-Scale Stationary Lithium-Ion Battery Systems", *Advanced Battery Power Conference,* 2020

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Thank you for your attention!

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