Statistical analysis of short-term prediction for Safety State-of-Function

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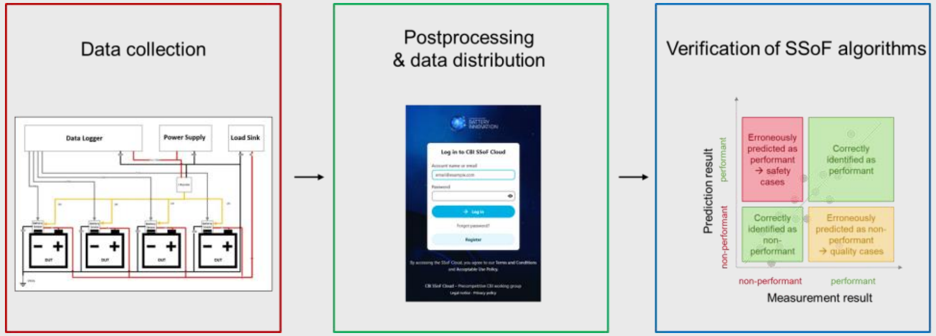
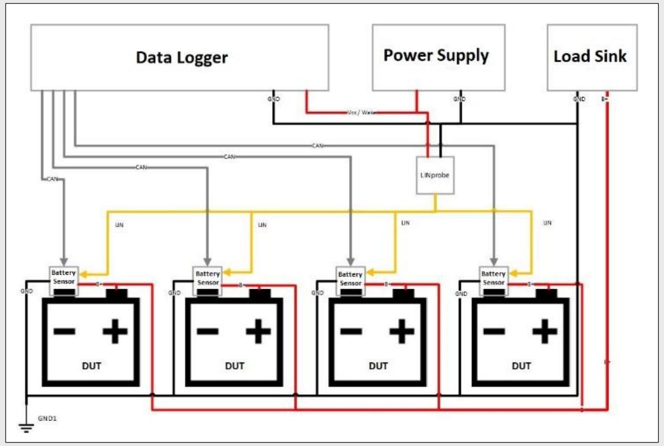


Outline

- CBI SSoF database
  - Simulated real-world driving cycles and charging cycle
- „Self-prediction" of dch_step1 end voltage
  - Model 1: Based on internal ohmic resistance
  - Model 2: Based on DC resistance and pseudo capacitance
- Prediction of low-throughput SSoF
  - SSoF0 prediction based on model 2 (DC resistance, pseudo capacitance)
- Conclusion & Outlook

Steps for SSoF validation

Data collection



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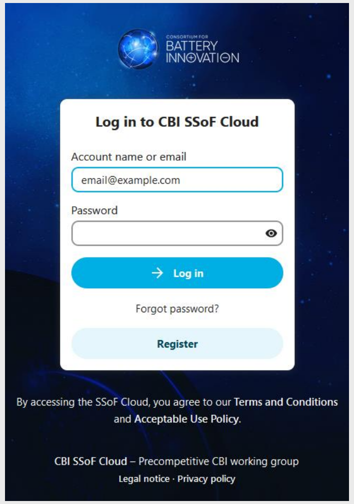
Postprocessing & data distribution



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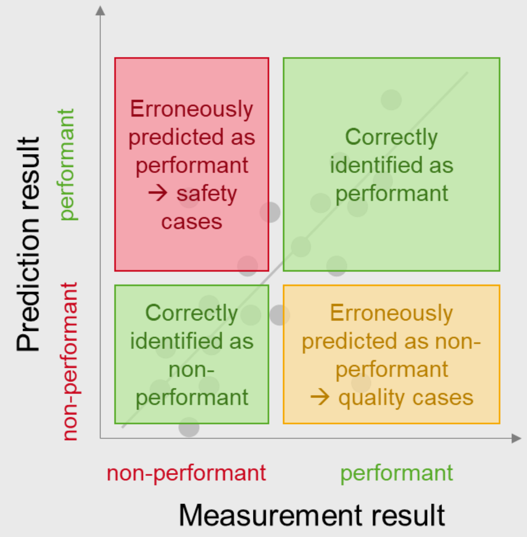
Verification of SSoF algorithms

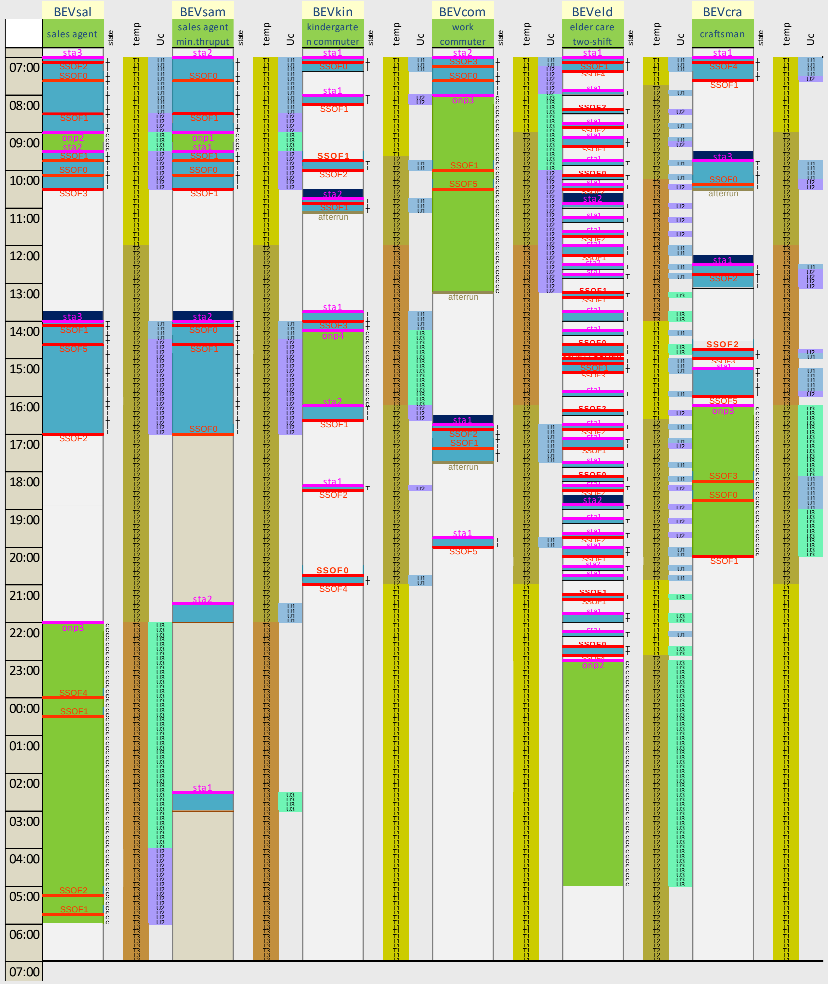


- 320 test days with > 3.000 SSoF, > 50.000 large signal stimuli, > 80.000 small signal stimuli as of now
- Dataset used in this study: 9 test days of one 70 Ah battery

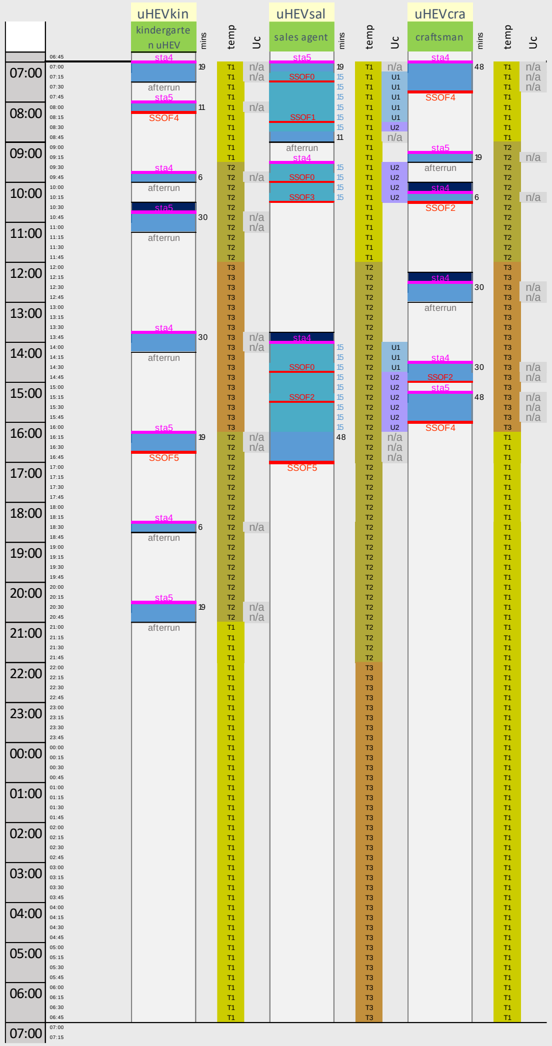
Simulated real-world driving – cycle definitions

- **BEV and µHEV**
  - Charging cycle for BEV
  - Urban and extra-urban trips of different duration for µHEV (incl. stop/start)
- **Usage patterns**: Sales agent, kindergarten or work commuter, eldercare, craftsperson, …
- **Climate conditions**: Temperature and generator/alternator setpoint adjustments for different scenarios

BEV scenarios



µHEV scenarios



BEV charging cycle

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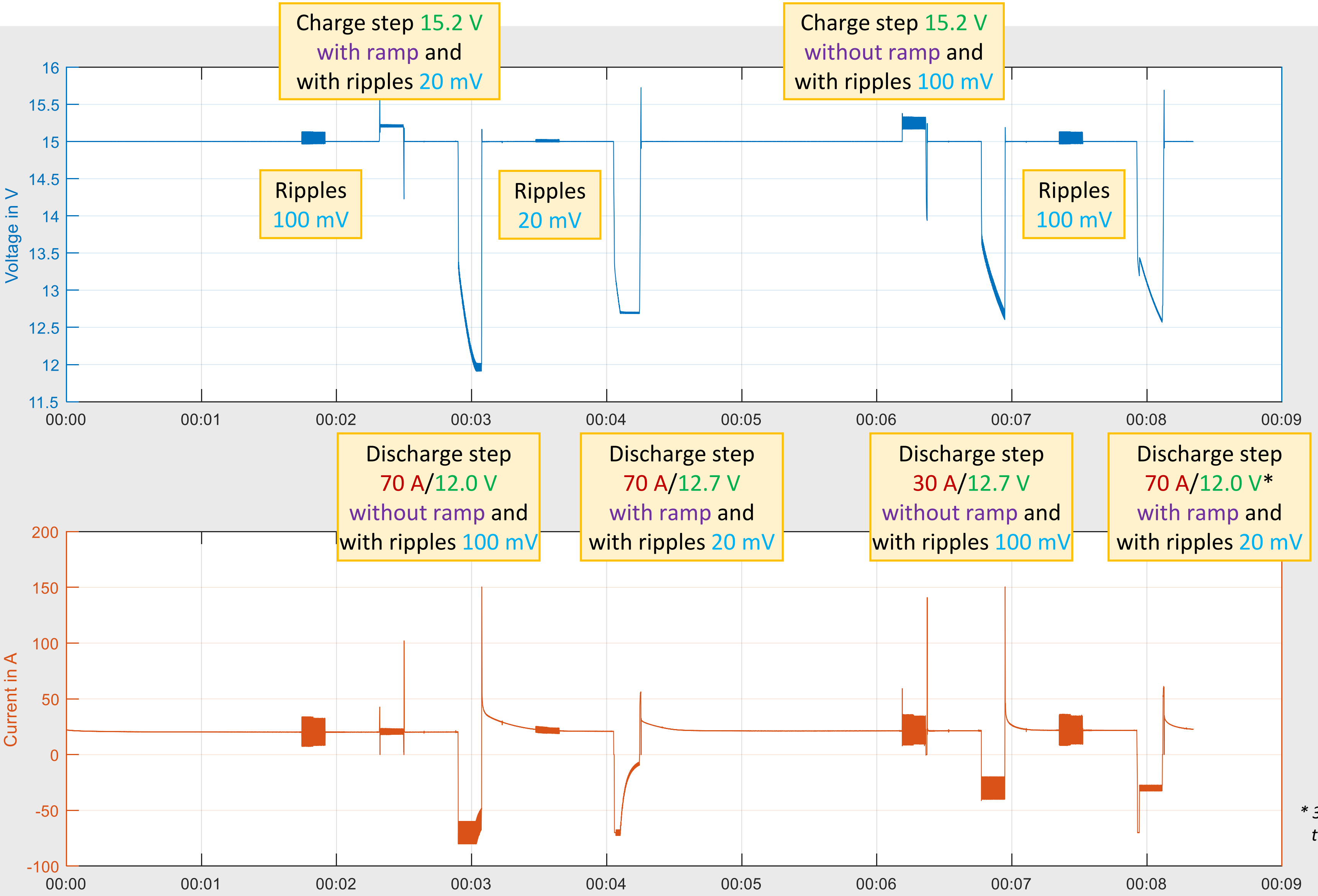


** 30 A for ripples in this measurement*

Ripples, charge steps and discharge steps (with and without ramps)

Voltage setpoints:

- 15.2 V for charging steps
- 12.7 V and 12.0 V for discharging steps

Ripple amplitudes:

- 20 mV and 100 mV

Current limits:

- 150 A for charging steps
- 70 A and 30 A for discharging steps

SSoF recovery out of charging condition

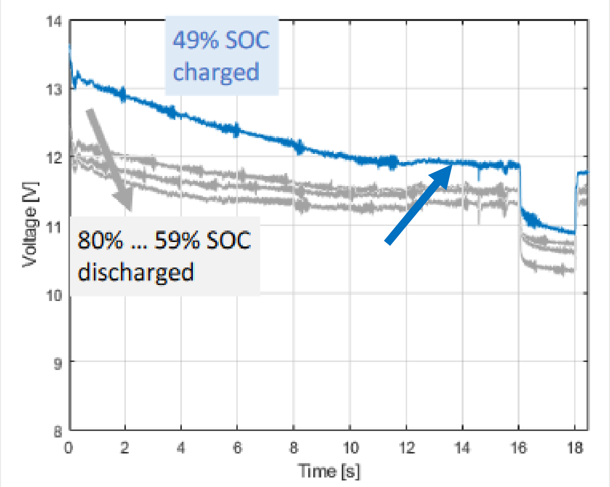
- Effects accelerating transient recovery of SSoF over SoC recovery

  - Pseudo-capacitance of positive electrode building up during charging
    (cf. Eberhard Meissner, ALBA 2024)

  - Discharge voltage stabilizes at elevated level compared to battery at equilibrium or freshly discharged
    (cf. Grzegorz Pilatowicz, Dissertation 2017)

  → During charging, SSoF recovers very fast already over a few percent of SoC change

- Passive equivalent circuit models without SoC parameterization will be used in this study



Source: Eckhard Karden, ALBA 2024

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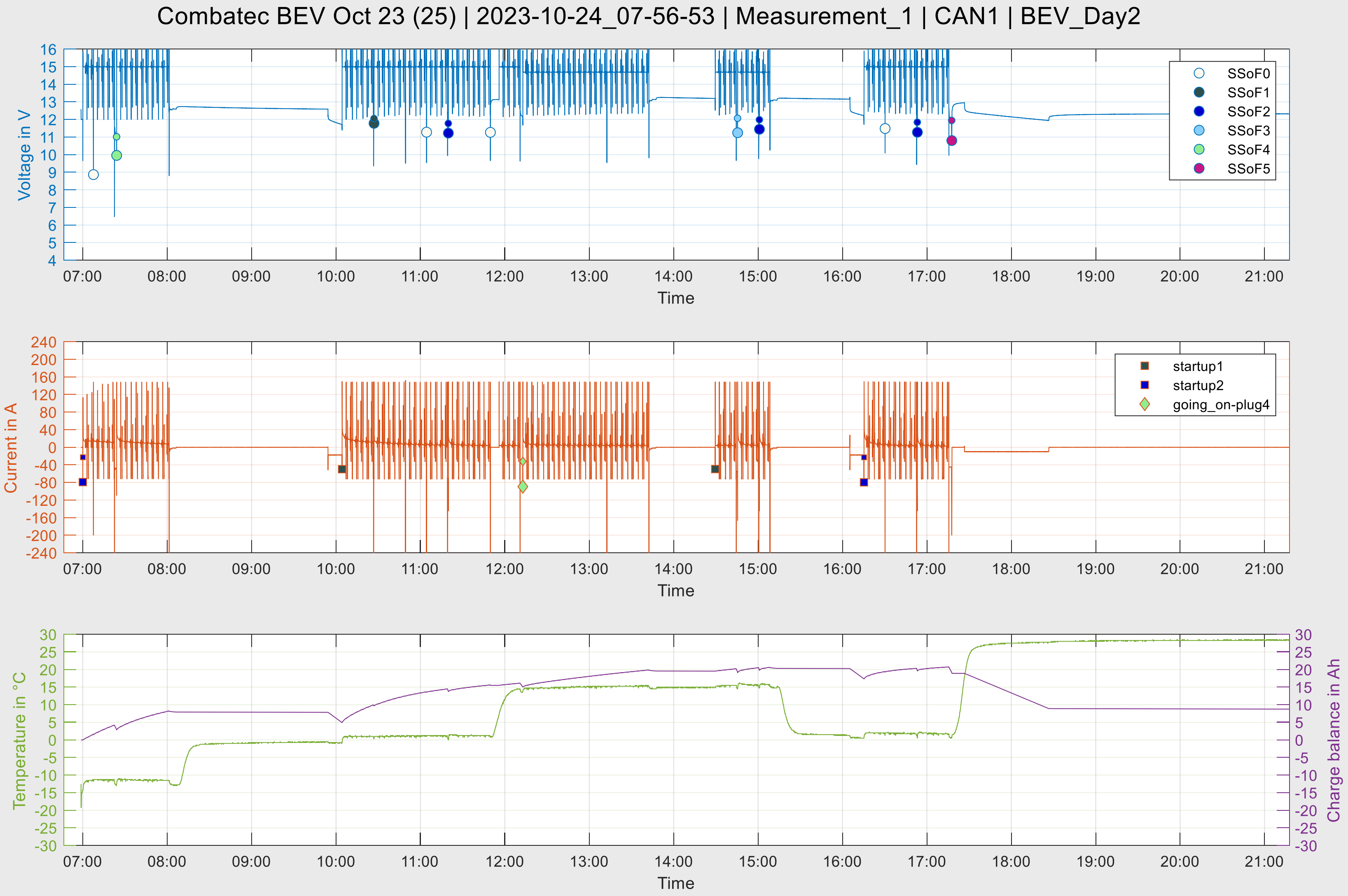
Example of BEVsal

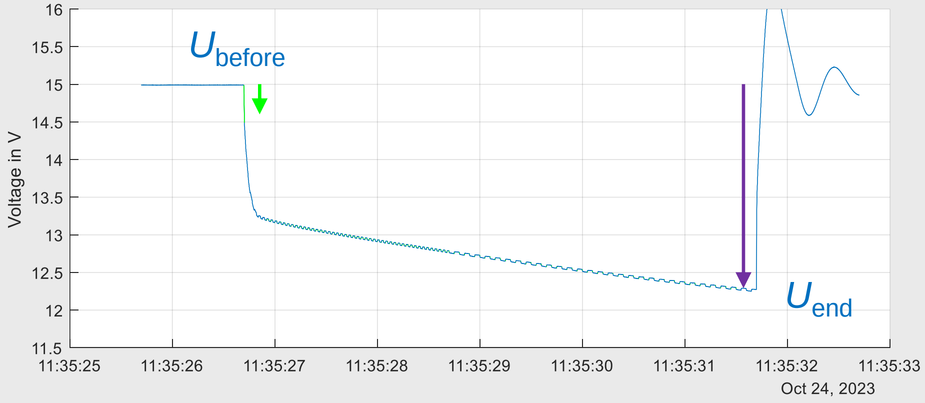


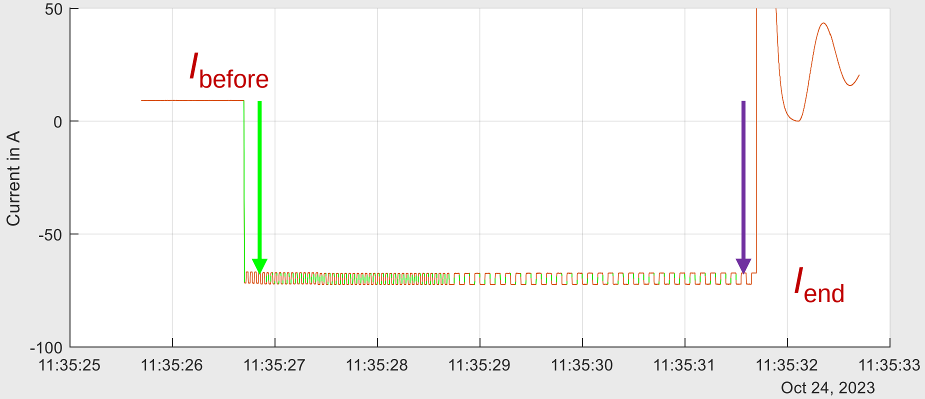
Battery voltage with end voltages of SSoF

Battery current with end currents of startups, going on-plugs

Temperature and charge balance (fixed scales for comparison)

Model 1: Ohmic resistance model





Specification dch_step1:
- 70 A for 5+ s*
- 12.0 V voltage limit
- superimposed ripples ± 10 A/ ± 0.1 V

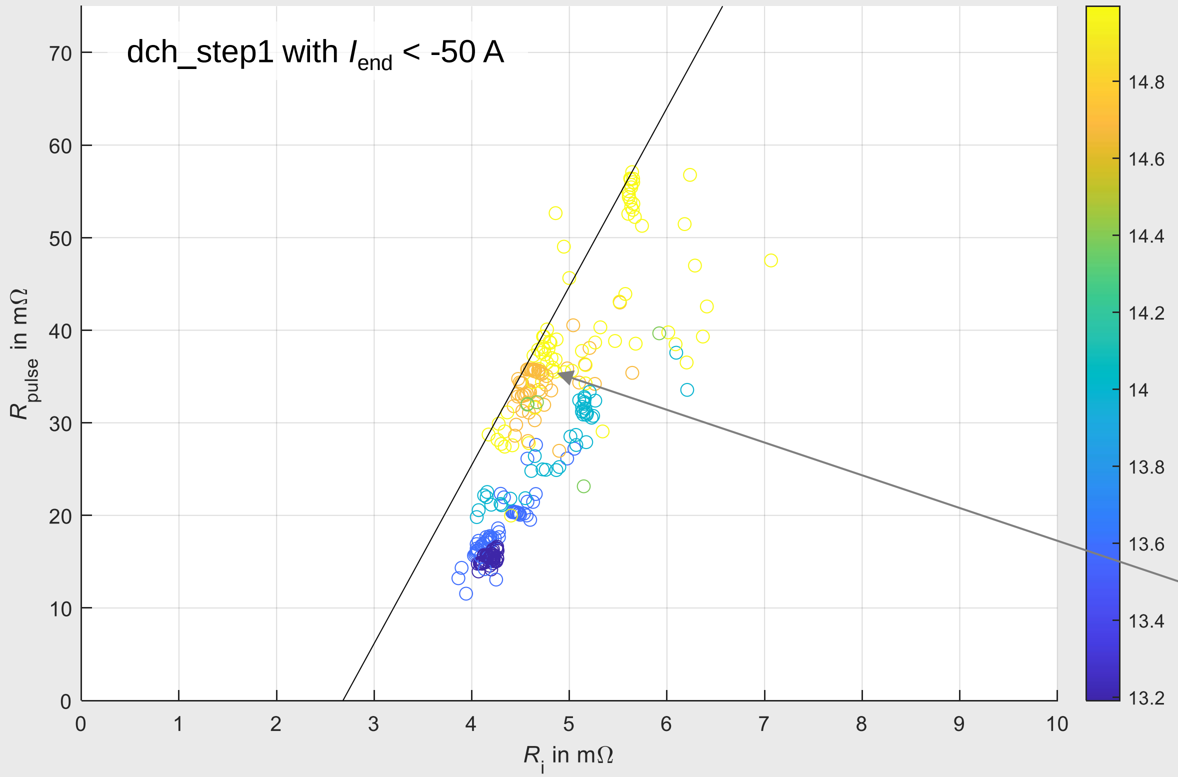
* duration depending on test bench control

Ohmic drop based on ohmic resistance R_i from fast changes in ripples

Prediction of U_{end} needs further knowledge about ratio between pulse resistance R_{pulse} and R_i

$$R_{pulse} = \frac{U_{end} - U_{before}}{I_{end} - I_{before}} = \underbrace{f(U, I, T, \Delta t, \dots)}_{\substack{= \text{const.} \\ \text{(for this model)}}} \cdot (R_i - k)$$

Model 1: Parameter extraction



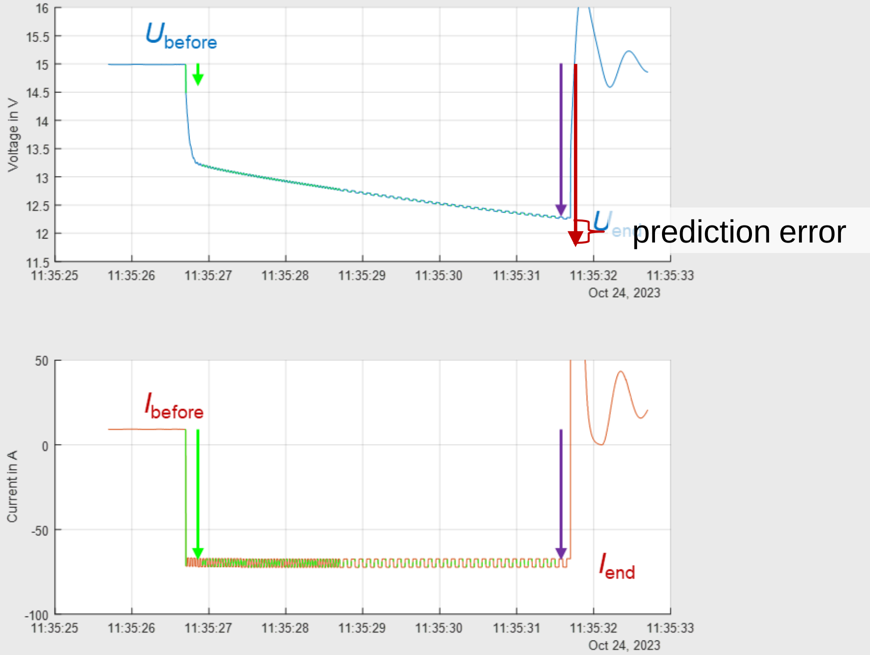
Conservative fit: $R_{\text{pulse}} = (R_{\text{i}} - 2.68\ \text{m}\Omega) \cdot 19.3$

Example of ratio between pulse resistance R_{pulse} and R_{i} fitted for one battery, independent of temperature, charging voltage, SoC, …

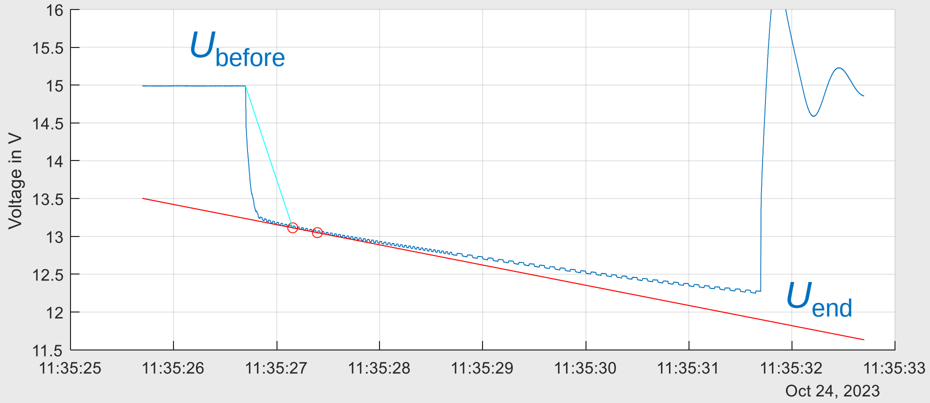
$$R_{\text{pulse},pred} = (4.85\ \text{m}\Omega - 2.68\ \text{m}\Omega) \cdot 19.3 = 41.9\ \text{m}\Omega$$

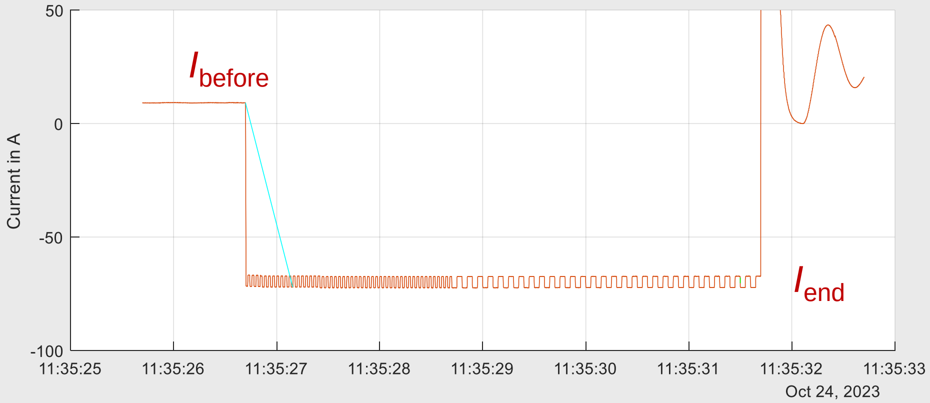
$$U_{end,pred} = U_{\text{before}} + R_{\text{pulse}} \cdot (I_{\text{end}} - I_{\text{before}}) = 11{,}78\ \text{V}$$

$$=$$



Model 2: Pseudo-capacitance model





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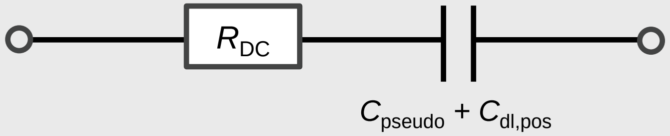
* duration depending on test bench control

R_{DC} after discharge of 0.0125% × C_n to include fast transients of neg. electrode

Slope ΔU/ΔQ is dominated by pseudo-capacitive behavior of positive electrode
(cf. Eberhard Meissner, ALBA 2024)



Model 2: Example for parameter evolution during one trip

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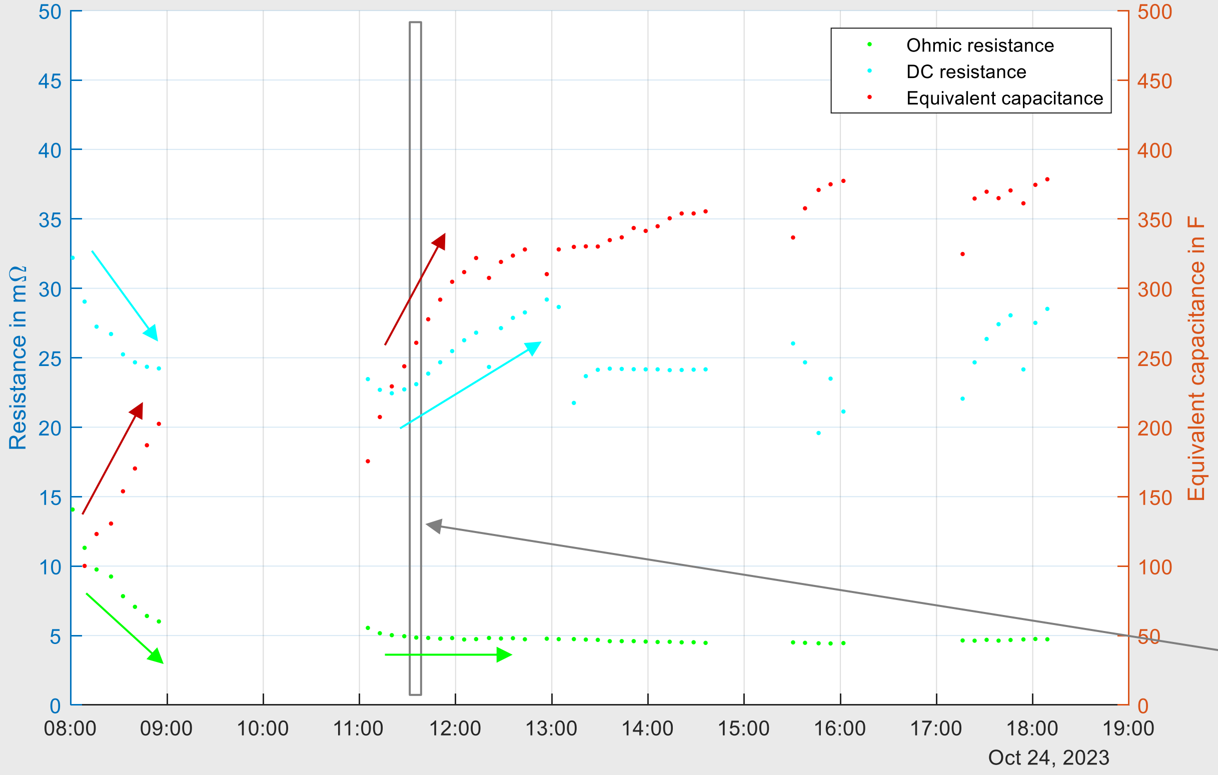
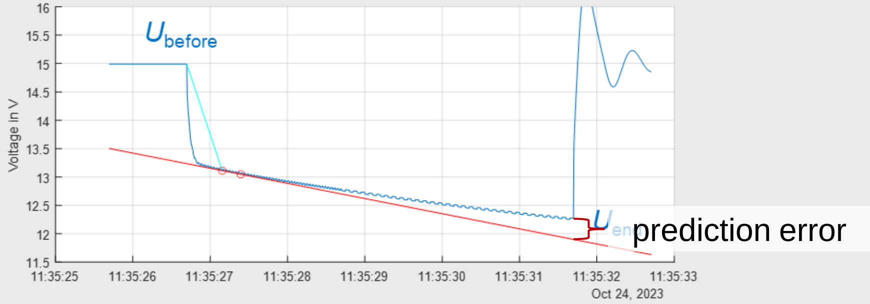
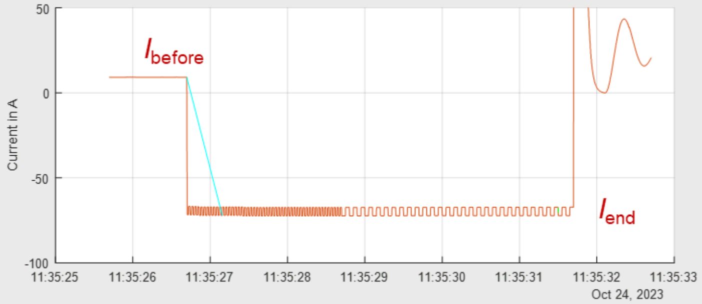
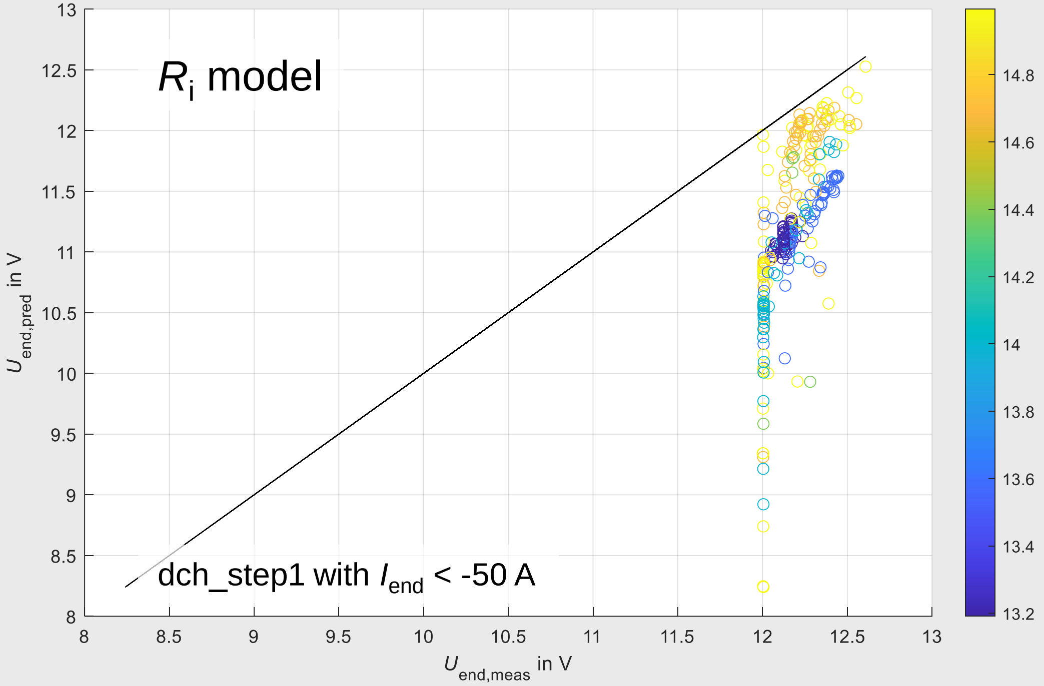


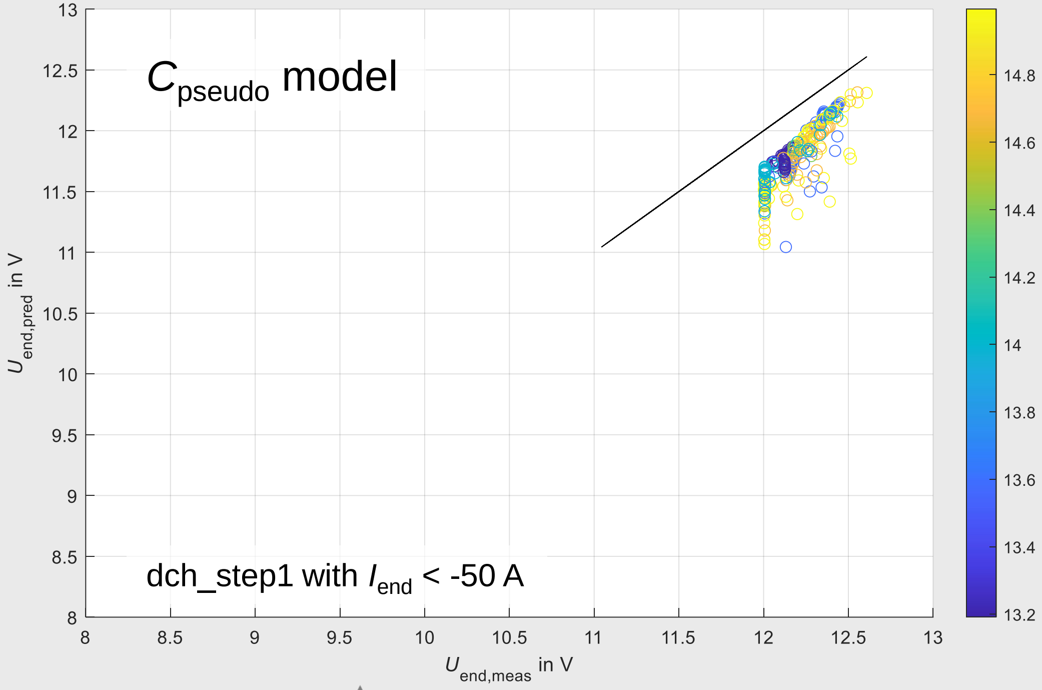
- Example for transient recovery
  - R_{DC} first decreases almost parallel to R_i, but then diverges significantly over time
  - Pseudo capacitance C_{pseudo} builds up in course of the day and contributes significantly to recovery of battery performance



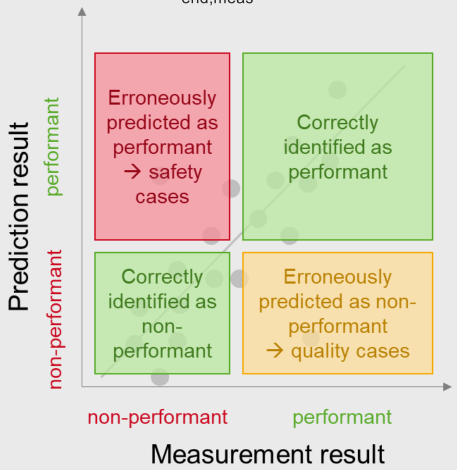


Comparison of model predictions





- Both models systematically do not show safety cases
- C_{pseudo} model reduces prediction error vs. R_i model
- Quality cases can be reduced further by model enhancements



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SSoF0 prediction – low error example

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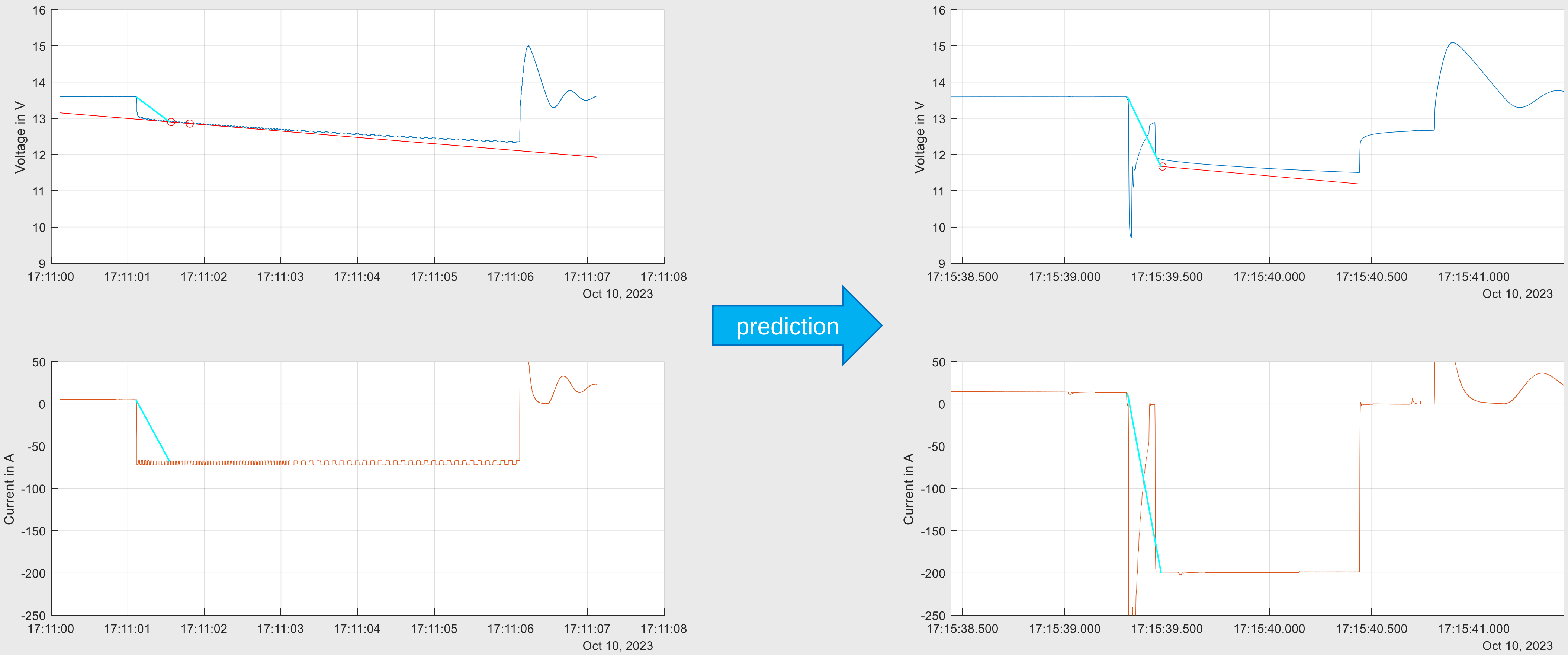

- Good accuracy for initial voltage drop despite extrapolation 70 A to 200 A
- Good accuracy for pseudo-capacitive behavior

SSoF0 prediction – higher error example

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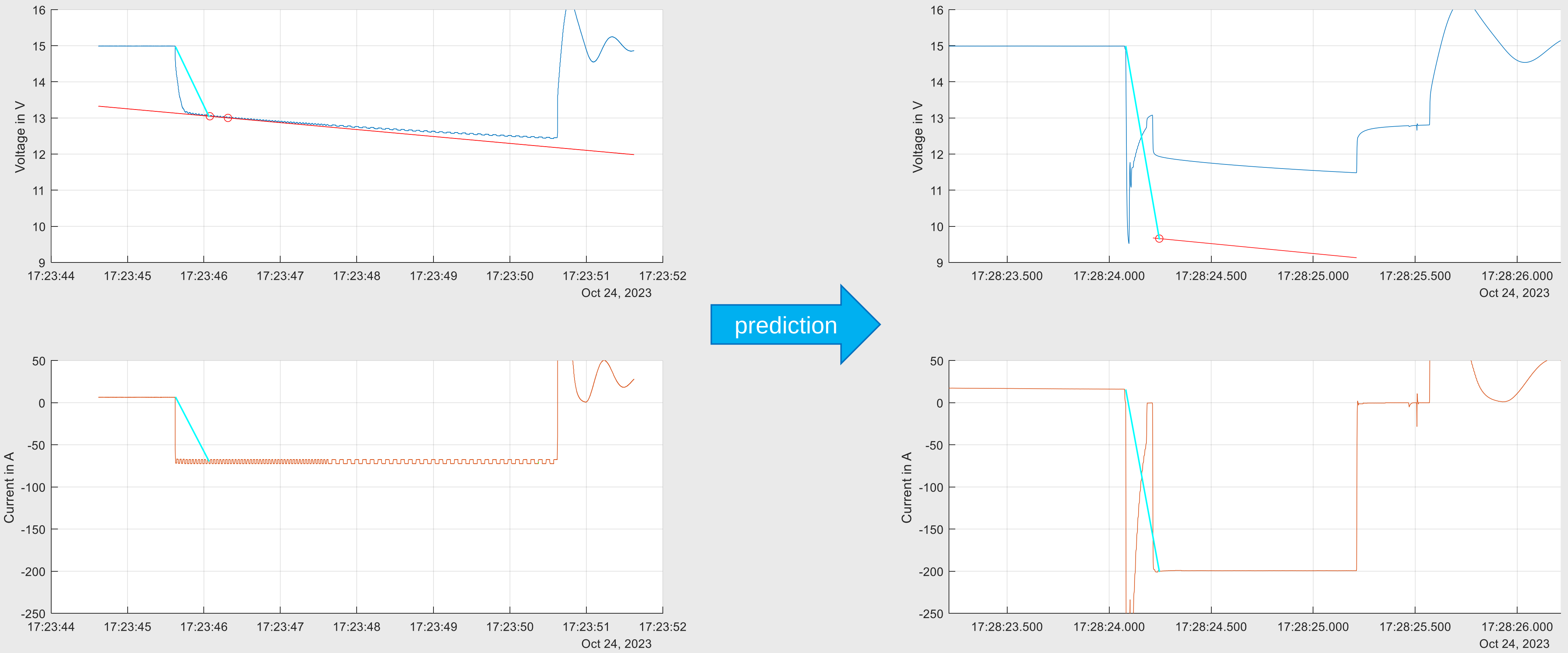
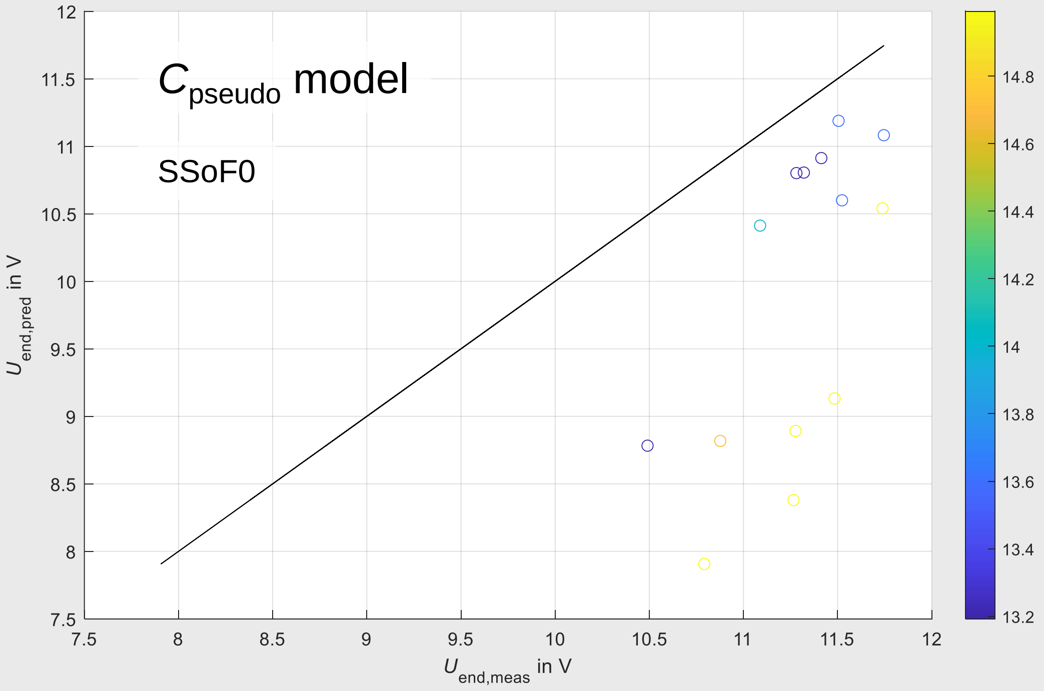
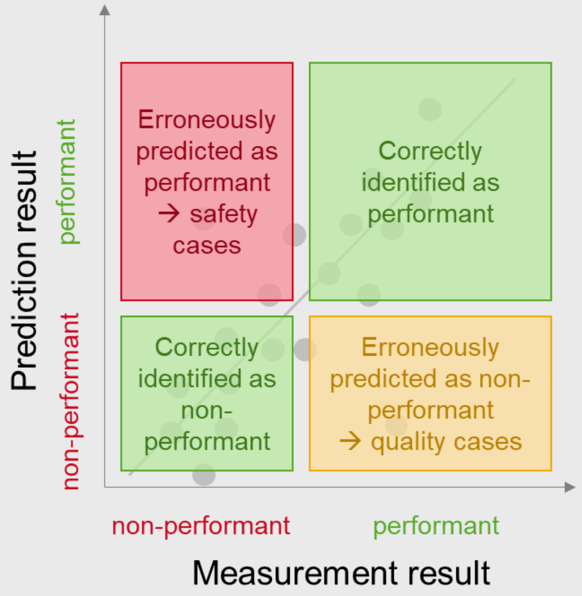


- Higher error due to charging/discharging linearization: High charging voltage with low charging current
  - 1.5…2.0 V for 6.4 A charging vs. 0.5…1.0 V for 70 A discharging

Model prediction results





- C_{pseudo} model systematically does not show safety cases
  - Good and safe extrapolation from 70 A to 200 A (Butler-Volmer behavior)
- Quality cases can be reduced further by model enhancements
  - Step-wise linear R_{DC} for charging/discharging, elevated discharge voltage plateau

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Conclusion and Outlook

- CBI SSoF database can be used to analyze transient behavior of starter and auxiliary batteries under realistic operating conditions
  - Only a small fraction of available data used in this study

- This study employs passive equivalent circuits …
  - … that do not require parameterization for SoC and temperature
  - … but adaptation to observed battery behavior in vehicle

- Short-term prediction of discharge peak voltages demonstrated with two primitive models
  - Primary functional safety requirement fulfilled → No false negative prediction
  - Vehicle availability may be compromised by large false positive errors

- Further model improvements could be achieved by
  - Step-wise linear R_{DC} for charging/discharging
  - Modeling elevated discharge voltage plateau (Pilatowicz)

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