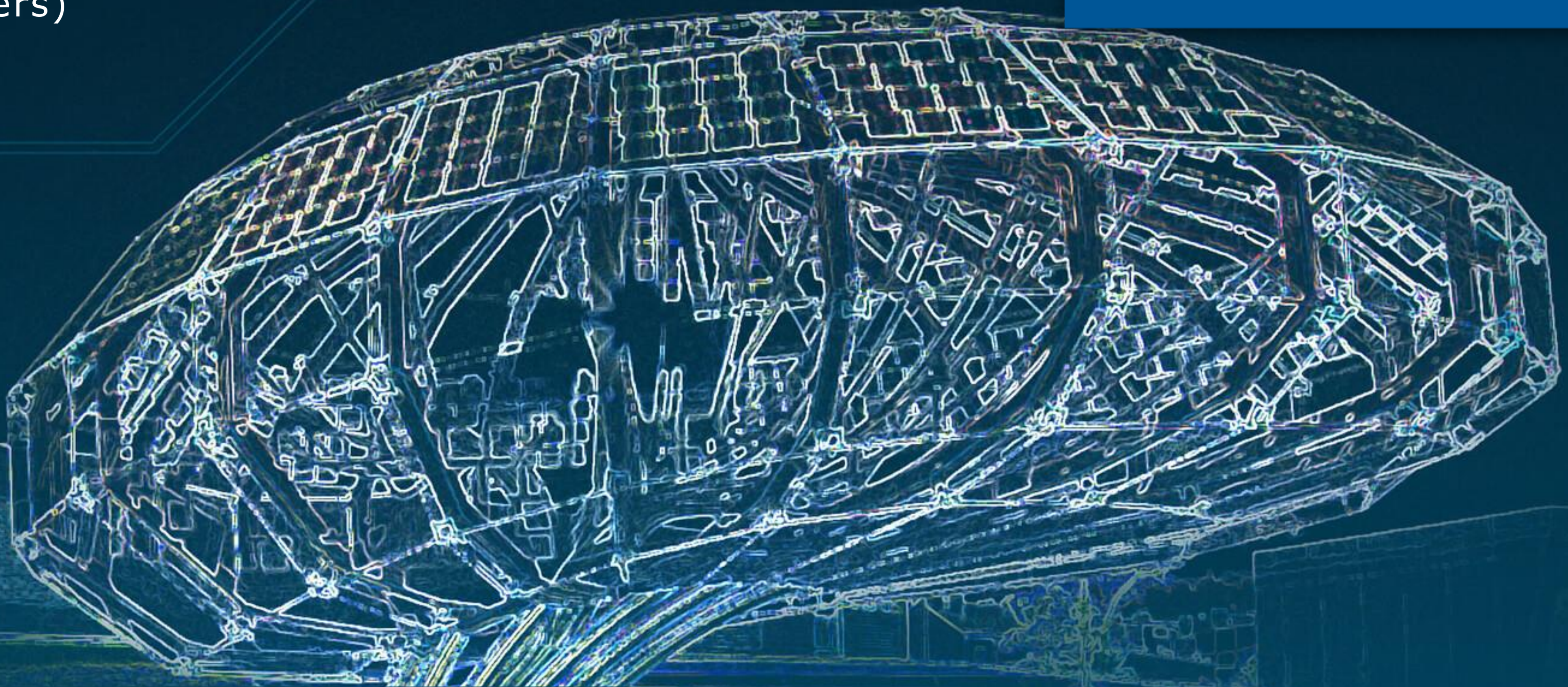
AVL List GmbH (Headquarters)

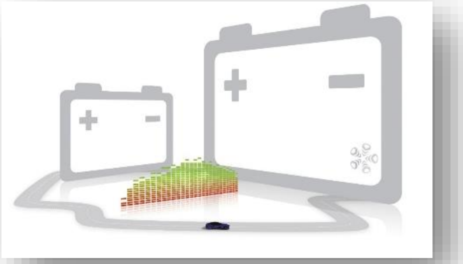


State of Health Estimation

R&D Activities AVL

Dohr, Markus

ADVANCED SOX ALGORITHMS

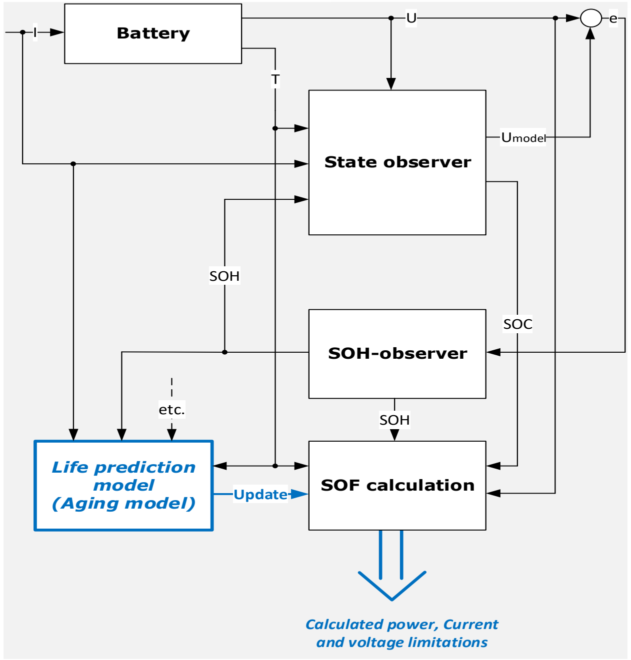


STATE OF CHARGE ESTIMATION

- nonlinear dynamic models based on local model network (data driven); to be used for any type of cell & chemistry
- optimum design of experiment to reduce testing and calibration efforts without reducing model accuracy
- automated parameterization of models for online state estimation

STATE OF HEALTH AND LIFETIME PREDICTION

- SOH including resistance, capacity and other parameters based on nonlinear observers
- Implementation of aging/lifetime prediction model
- Combination of SOH observer and lifetime prediction model



STATE OF FUNCTION CALCULATION

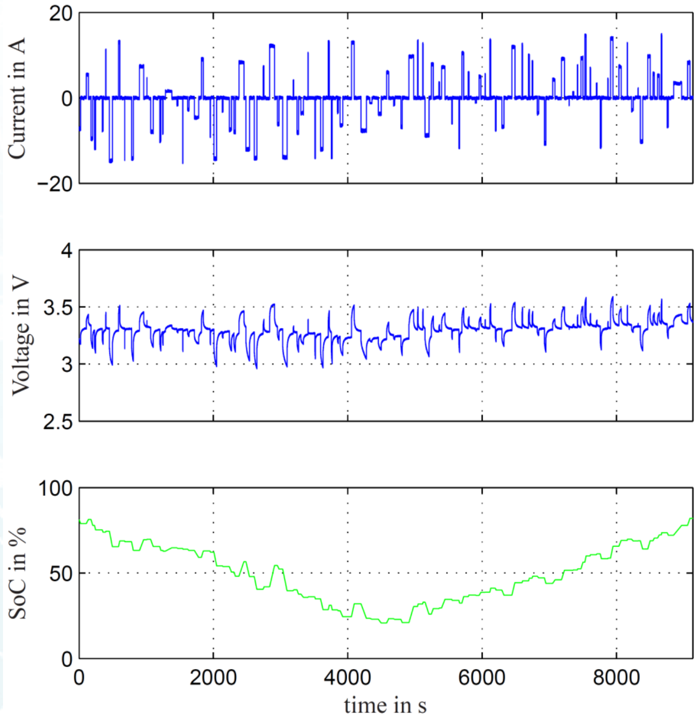
- Based on SOC SOH and lifetime estimates
- Optimization of operating strategy to e.g. reach lifetime target
  - Adaptation of SOF based on predicted lifetime and SOH estimates

References

1. '*State of charge estimation for Lithium Ion cells: Design of experiments, nonlinear identification and fuzzy observer design*', Christoph Hametner – Vienna University of Technology, Journal of Power Sources, 2013
2. '*Local Model Network based Dynamic Battery Cell Model Identification*', Christoph Hametner – Vienna University of Technology, ACM, 2012
3. '*Model based Lithium Ion cell ageing data analysis*', Christoph Hametner – Vienna University of Technology, IEEE, 2014

Calibration of Local Models
Optimum Design of Experiment - DOE

DoE



Modelling

Nonlinear battery model

- Inputs:
  - Current
  - State of Charge
  - Temperature
- Output: Terminal Voltage

Local model network

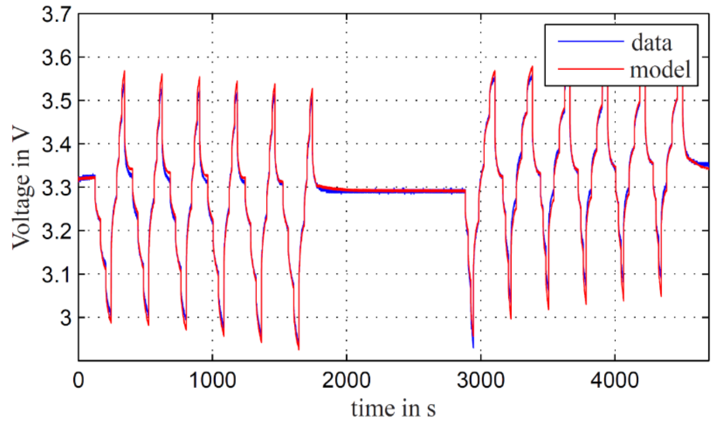
- Local linear models (diff. equ.):

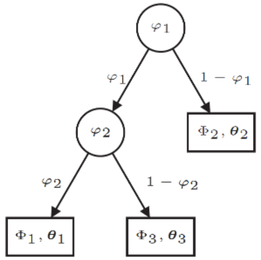
$$\hat{y}_i(k) = \boldsymbol{x}^T(k)\boldsymbol{\theta}_i$$

- Model output (weighted aggregation):

$$\hat{y}(k) = \sum_{i=1}^{M} \Phi_i(k)\hat{y}_i(k)$$

Calibration Result



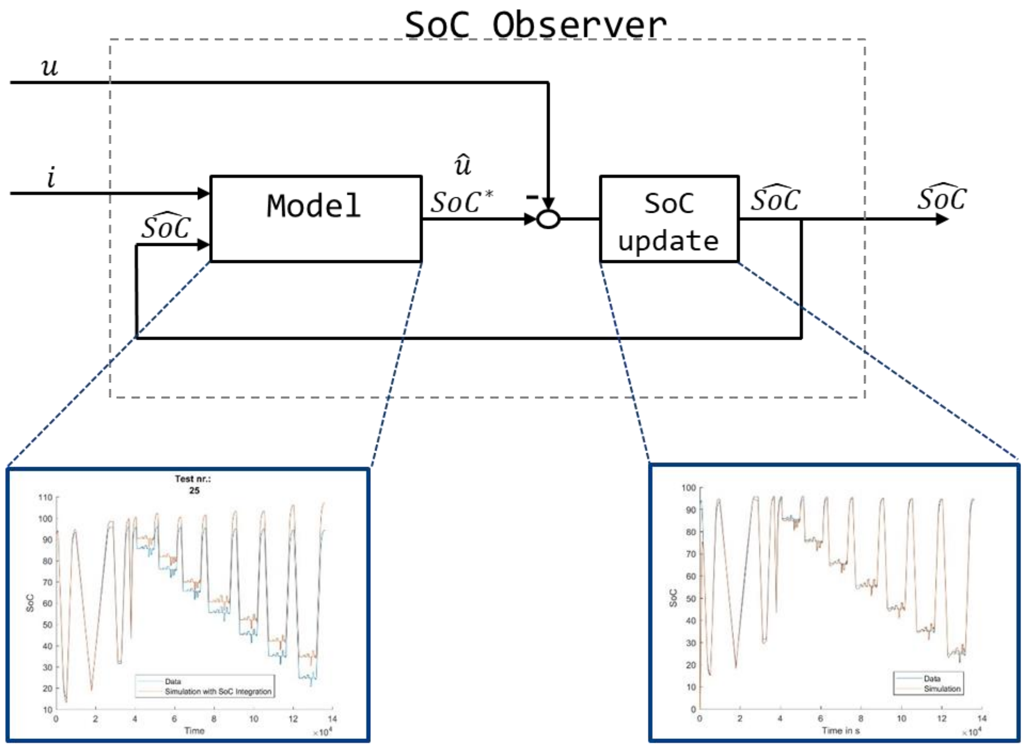


SoC Estimation
Model Structure and Observer Design

Based on model that can describe input to output dynamic characteristics of the battery => LMN

Local model network based observer design

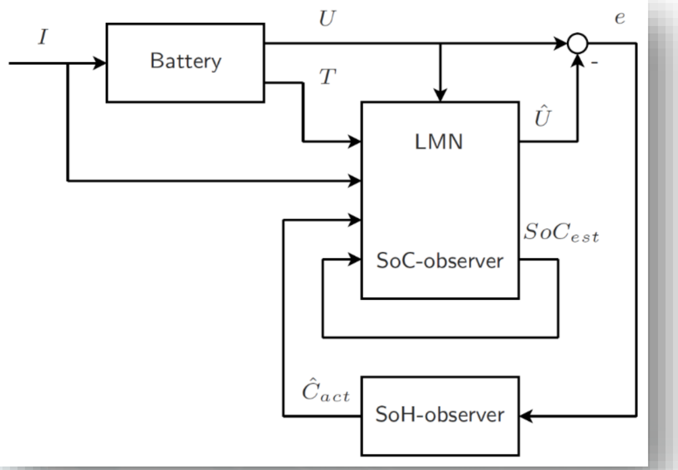
- **Extended Kalman filter**: The filter gain is computed using the local Jacobian of the nonlinear model
- **Fuzzy observer:** Linear combinations of the local filters are used to derive the global filter
- **Linear Observer**: Gain is predetermined and used for correction of internal states



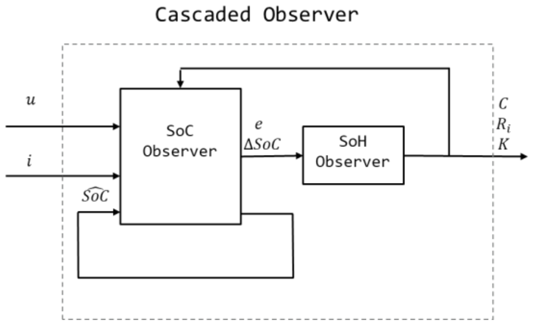
$$SoC^*(k) = \widehat{SoC}(k-1) + \frac{1}{c} i(k)$$

$$\widehat{SoC}(k) = SoC^*(k) + (\hat{u} - u)K$$

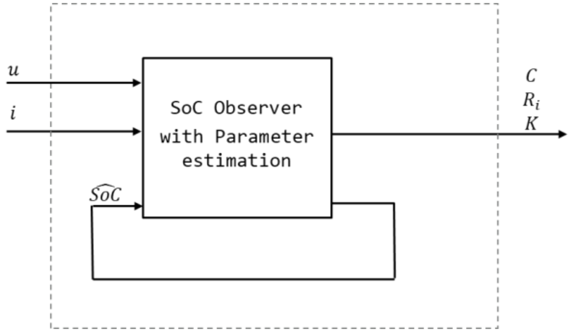
SoH Estimation
Model Structure and Observer Design



- SoH estimates the ageing parameters (capacity, internal resistance, stationary gain, time constants)
- SoH observer is coupled with the SoC observer
  - Cascaded Observer



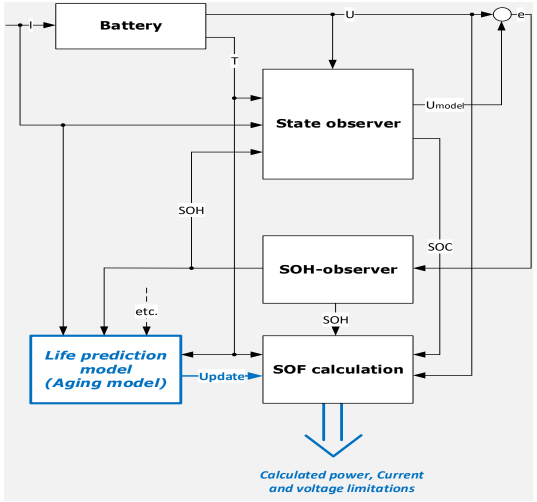
  - Extended Kalman Filter estimates the parameters of the system along with the states



Ageing Modelling

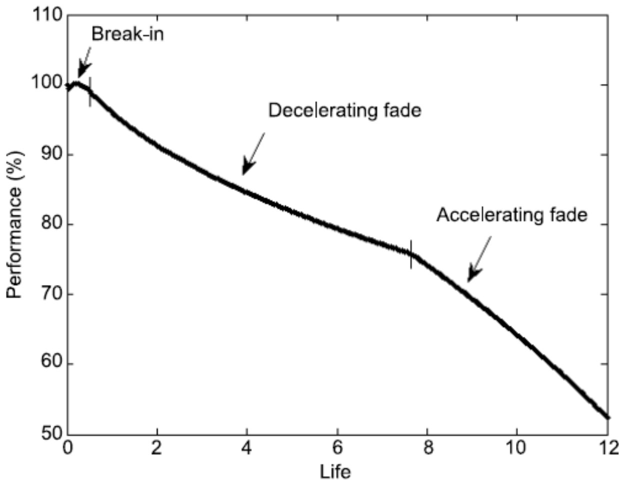
Ageing prediction model

- SoH prediction based on a future load signal
- Allows to modify and optimize the operating strategy in (hybrid) electrical vehicles in order to extend the battery life
- Combination with SoH observer to increase accuracy and robustness of aging model – online adaptation of model parameters



Question

- Which ageing factors are relevant for the ageing prediction model?
- How can the nonlinearities present in ageing cells be represented?



Ageing Modelling
Model Formulation

Data-driven live prediction model

- Delta model: damage contribution of one load cycle
- Parameter changes are summed up to obtain the overall change

Hazard Function

- Useful in modeling capacity loss as show in the figures before

Ageing Factors to be considered

N – Equivalent number of cycles	**t_cycle** – Sum of cycling times
T – Average temperature	**SoC** – Average state of charge
Crate – Average C-rate	**t_total** – Time between the start of 2 consecutive intervals.
Qch – Charging Ah	**Qdis** – Discharging Ah
Ich – Charging current	**Idis** – Discharging current
ddod – Delta depth of discharge ΔDoD	**wddod** – ΔDoD cycling frequency
V – Average terminal voltage	**dI** – Delta current (similar to ΔDoD)
wdI – Delta current cycling frequency	**I2avg** – Average of squared current
I2sum – Sum of squared current (~heating term)	

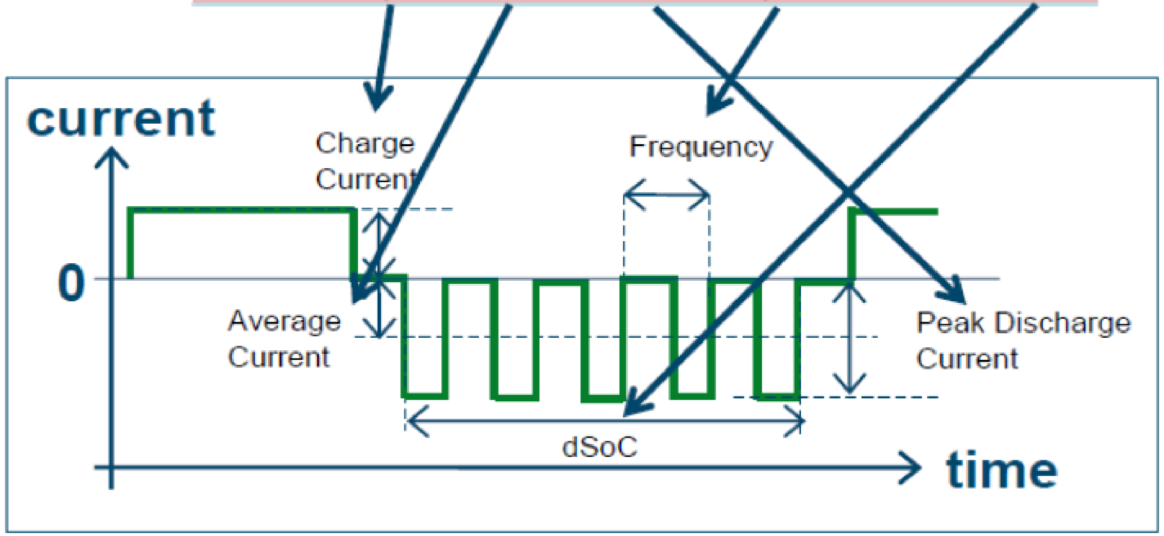
Aging Models which are investigated

- 2 Linear Models with low/high number of parameters
- 2 Hazard Function Models with low/high number of parameters
- 2 Decision Trees with low/high number of parameters (modeled on the rate)
- 1 Arrhenius-based Model

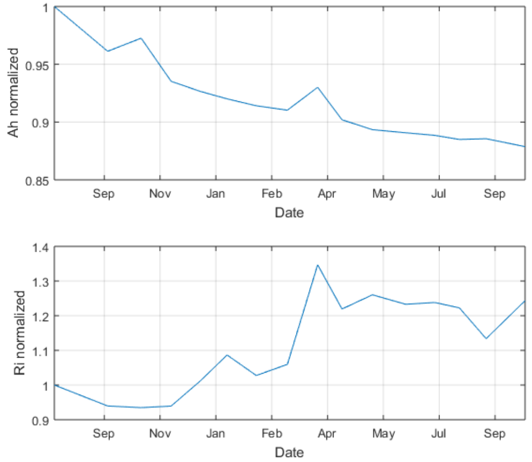
Ageing of LiIon Cells
Correlation between resistance & capacity change

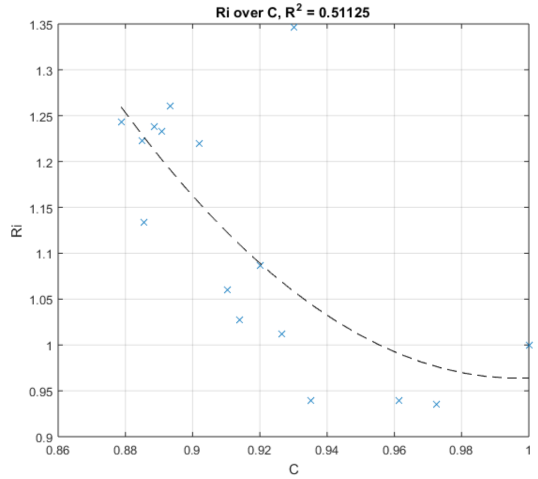
- Cells of the same type are cycled with different load until EOL
- Load profile is defined as following:

T	CC	ADC	PDC	F	SoC	dSoC
40	2,4	8	10	0,03	55	80

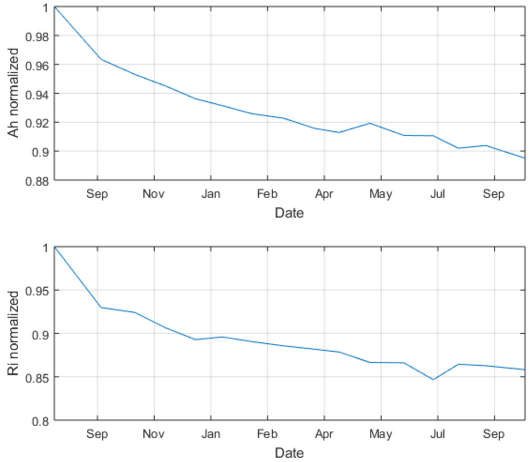


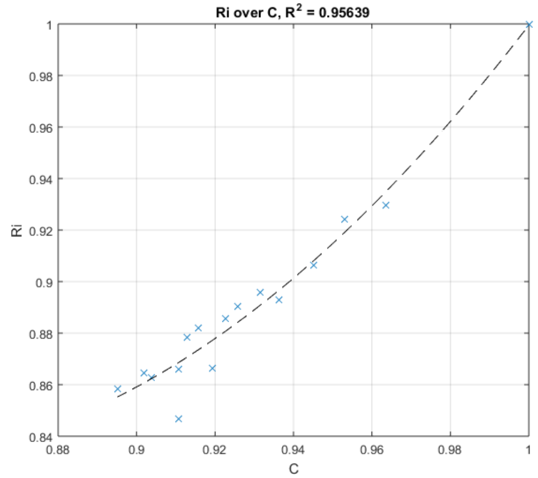
Testing Results 25°C, 50%SoC





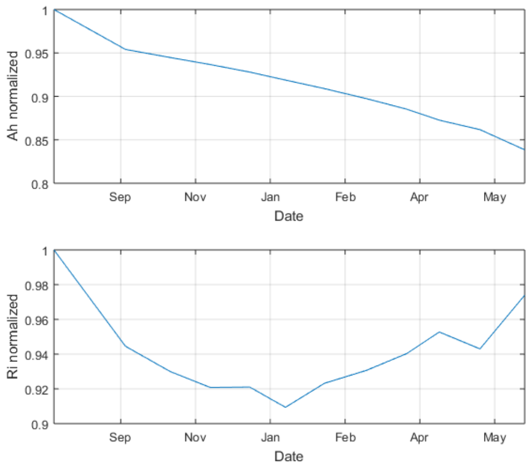
T	CC	ADC	PDC	F	SoC	dSoC
20	0,2	1	12	0,1	55	80

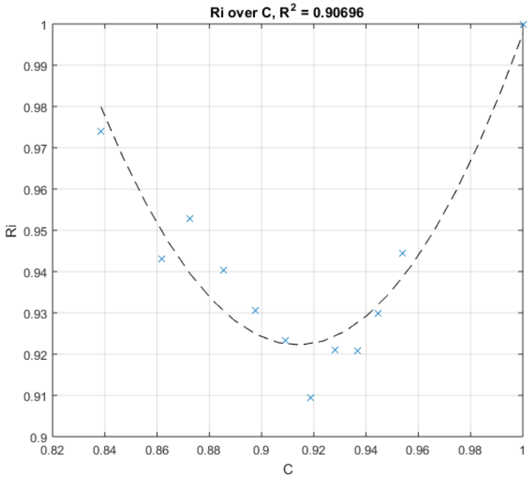




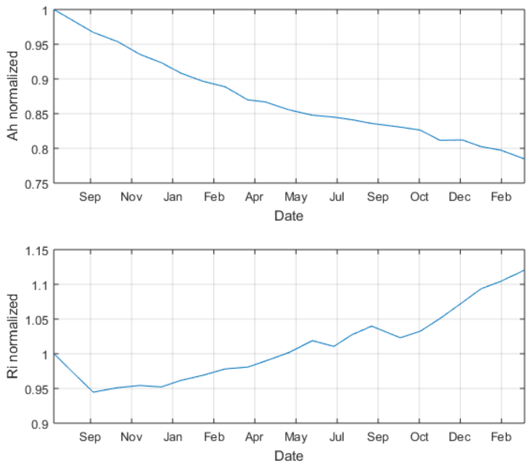
T	CC	ADC	PDC	F	SoC	dSoC
-10	0,2	0,2	6	0,03	55	15

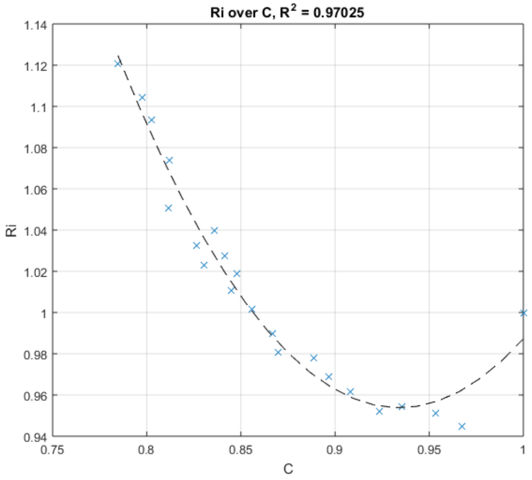
Testing Results 25°C, 50%SoC





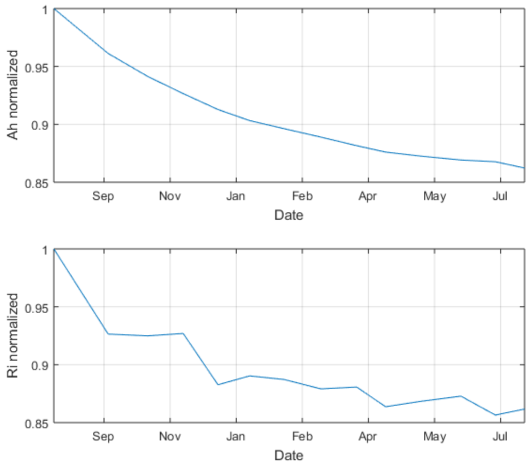
T	CC	ADC	PDC	F	SoC	dSoC
20	2,4	0,2	0,2	0,5	50	60

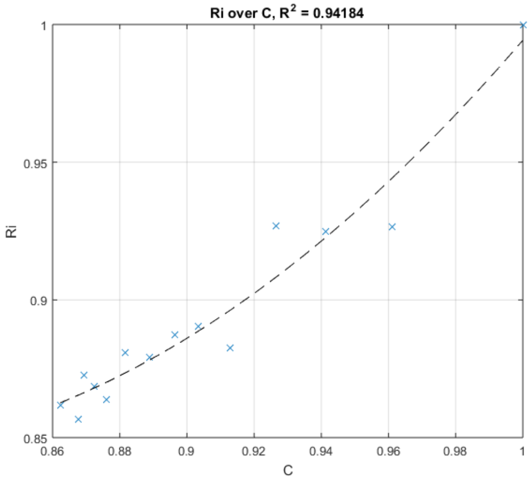




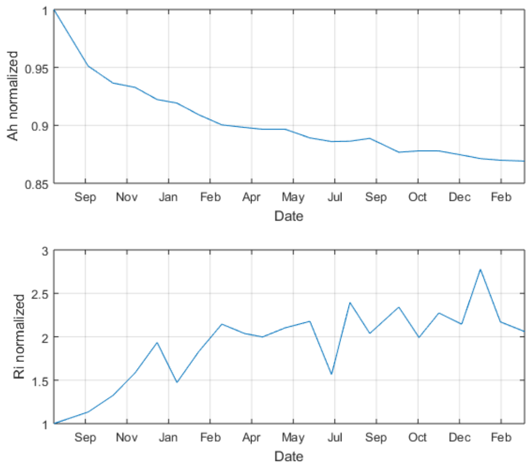
T	CC	ADC	PDC	F	SoC	dSoC
40	2,4	2	3	0,03	25	15

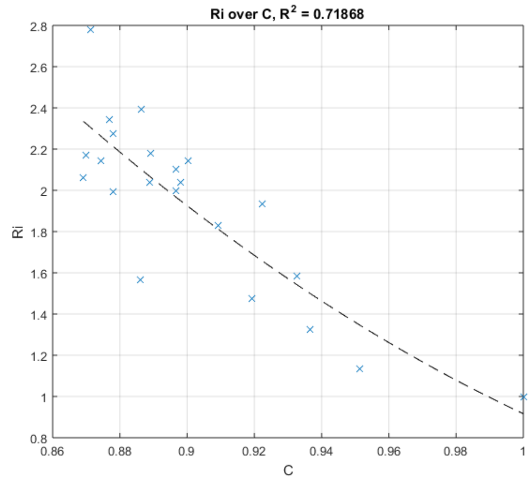
Testing Results 25°C, 50%SoC





T	CC	ADC	PDC	F	SoC	dSoC
-10	0,2	1,3	2	0,5	55	50





T	CC	ADC	PDC	F	SoC	dSoC
5	0,2	0,2	12	0,03	60	70