Carl von Ossietzky Universität Oldenburg

Set-based identification of the open-circuit voltage characteristic of battery cells aiming at detecting aging effects

Marit Lahme, October 30, 2024

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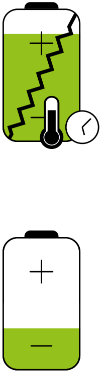
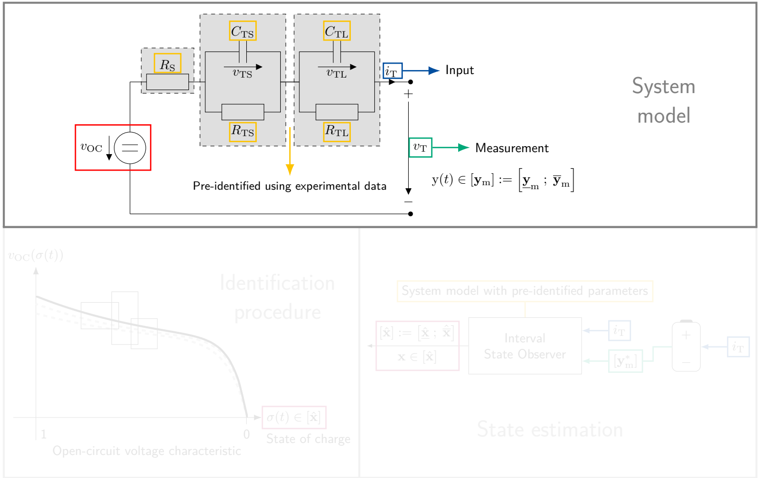
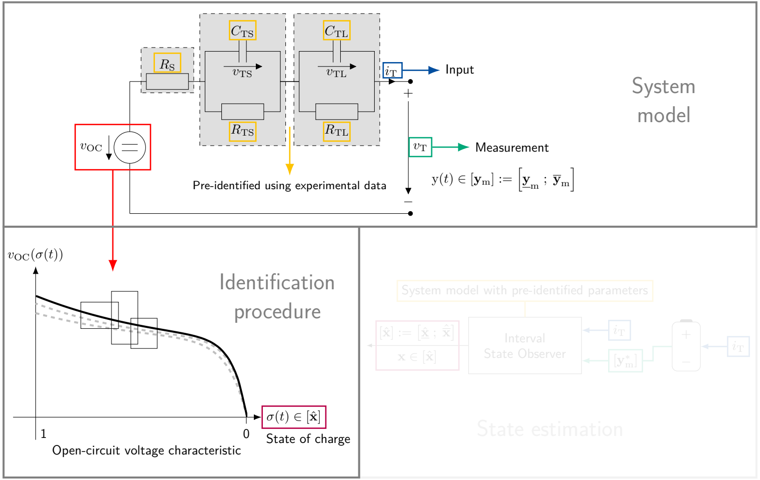
Motivation



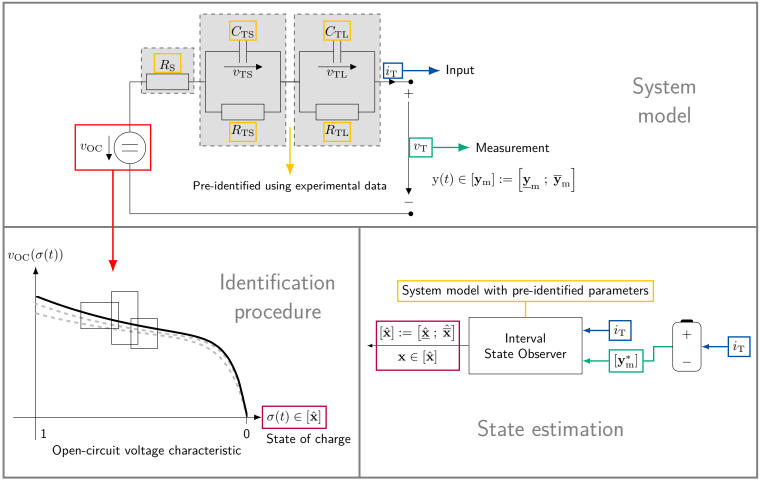
Objective


C_{TS}
C_{TL}
R_S
v_{TS}
v_{TL}
i_T
Input
System model
R_{TS}
R_{TL}
v_{OC}
v_T
Measurement
Pre-identified using experimental data
$y(t) \in [\mathbf{y}_m] := [\underline{\mathbf{y}}_m \; ; \; \overline{\mathbf{y}}_m]$
$v_{OC}(\sigma(t))$
Identification procedure
System model with pre-identified parameters
$[\hat{x}] := [\hat{\underline{x}} \; ; \; \hat{\overline{x}}]$
$x \in [\hat{x}]$
Interval State Observer
i_T
$[y^*_m]$
$\sigma(t) \in [\hat{x}]$
1
0
State of charge
Open-circuit voltage characteristic
State estimation

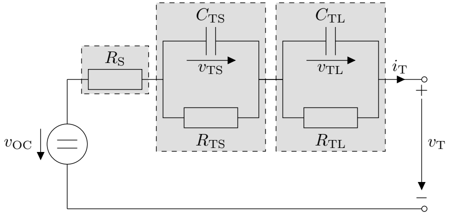
Objective


R_S
C_{TS}
v_{TS}
R_{TS}
C_{TL}
v_{TL}
R_{TL}
i_T
Input
System model
v_{OC}
Pre-identified using experimental data
v_T
Measurement
$y(t) \in [\mathbf{y}_m] := [\underline{\mathbf{y}}_m \, ; \, \overline{\mathbf{y}}_m]$
$v_{OC}(\sigma(t))$
Identification procedure
1
0
$\sigma(t) \in [\hat{\mathbf{x}}]$
State of charge
Open-circuit voltage characteristic
System model with pre-identified parameters
Interval State Observer
State estimation

Objective


R_S
C_{TS}
v_{TS}
R_{TS}
C_{TL}
v_{TL}
R_{TL}
i_T
Input
v_{OC}
+
v_T
Measurement
−
Pre-identified using experimental data
$y(t) \in [\mathbf{y}_m] := [\underline{\mathbf{y}}_m \, ; \, \overline{\mathbf{y}}_m]$
System model
$v_{OC}(\sigma(t))$
Identification procedure
1
0
$\sigma(t) \in [\hat{\mathbf{x}}]$
State of charge
Open-circuit voltage characteristic
System model with pre-identified parameters
$[\hat{\mathbf{x}}] := [\underline{\hat{\mathbf{x}}} \, ; \, \overline{\hat{\mathbf{x}}}]$
$\mathbf{x} \in [\hat{\mathbf{x}}]$
Interval
State Observer
i_T
$[\mathbf{y}_m^*]$
+
−
i_T
State estimation

Equivalent Circuit Model of a Lithium-Ion Battery Cell



SOC-dependent parameters

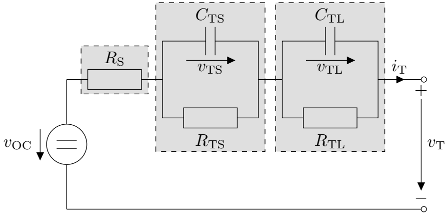
$$R_\iota(t) = R_{\iota\mathrm{a}} \cdot e^{R_{\iota\mathrm{b}} \cdot \sigma(t)} + R_{\iota\mathrm{c}}$$

$$C_\kappa(t) = C_{\kappa\mathrm{a}} \cdot e^{C_{\kappa\mathrm{b}} \cdot \sigma(t)} + C_{\kappa\mathrm{c}}$$

$$\iota \in \{\mathrm{S}, \mathrm{TS}, \mathrm{TL}\}\ ,\ \kappa \in \{\mathrm{TS}, \mathrm{TL}\}$$

$R_{\iota\mathrm{a}},\ R_{\iota\mathrm{b}},\ R_{\iota\mathrm{c}},\ C_{\kappa\mathrm{a}},\ C_{\kappa\mathrm{b}},\ C_{\kappa\mathrm{c}}$ are identified beforehand based on experimental data.

Equivalent Circuit Model of a Lithium-Ion Battery Cell



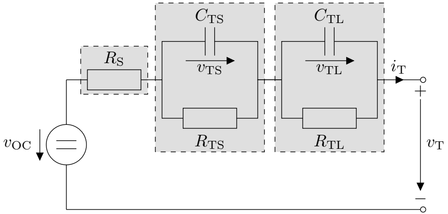
State equations

$$\dot{\sigma}(t) = -\frac{i_{\mathrm{T}}(t)}{C_{\mathrm{Bat}}}$$

$$\dot{v}_\iota(t) = \frac{-v_\iota(t)}{C_\iota(t)\cdot R_\iota(t)} + \frac{i_{\mathrm{T}}(t)}{C_\iota(t)}$$

$$\sigma(t) \in [0\;;\;1]\;,\quad \iota \in \{\mathrm{TS}, \mathrm{TL}\}$$

Equivalent Circuit Model of a Lithium-Ion Battery Cell



Open-circuit voltage

$$v_{\text{OC}}(\sigma(t)) = v_0 \cdot e^{v_1 \cdot \sigma(t)} + v_2 + v_3 \cdot \sigma(t) + v_4 \cdot \sigma(t)^2 + v_5 \cdot \sigma(t)^3$$

$v_0,\ v_1,\ v_2,\ v_3,\ v_4,\ v_5$ are identified beforehand based on experimental data.

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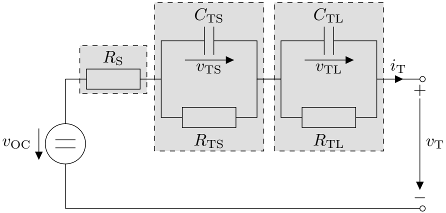
Equivalent Circuit Model of a Lithium-Ion Battery Cell



Output equation

$$v_T(t) = v_{OC}(\sigma(t)) - v_{TS}(t) - v_{TL}(t) - i_T(t) \cdot R_S\,(\sigma(t))$$

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Equivalent Circuit Model of a Lithium-Ion Battery Cell

Nonlinear expression for the open-circuit voltage

$$v_{\mathrm{OC}}(\sigma(t)) = v_0 \cdot e^{v_1 \cdot \sigma(t)} + v_2 + v_3 \cdot \sigma(t) + v_4 \cdot \sigma(t)^2 + v_5 \cdot \sigma(t)^3$$

Quasi-linear expression for the open-circuit voltage

$$\begin{aligned}\tilde{v}_{\mathrm{OC}}(\sigma(t)) &= \eta_{\mathrm{OC}}(\sigma(t)) \cdot \sigma(t) \\ &= v_{\mathrm{OC}}(\sigma(t)) - v_0 - v_2 \\ &= \left(v_0 \cdot \frac{e^{v_1 \cdot \sigma(t)} - 1}{\sigma(t)} + v_3 + v_4 \cdot \sigma(t) + v_5 \cdot \sigma^2(t) \right) \cdot \sigma(t)\end{aligned}$$

Equivalent Circuit Model of a Lithium-Ion Battery Cell

Quasi-linear output equation

$$\mathbf{y}(t) = v_{\mathrm{T}}(t) = \tilde{v}_{\mathrm{OC}}(t) - v_{\mathrm{TS}}(t) - v_{\mathrm{TL}}(t) - i_{\mathrm{T}}(t) \cdot R_{\mathrm{S}}(t)$$

Quasi-linear input-independent output equation

$$\begin{aligned} \mathbf{y}^*(t) &= \mathbf{y}(t) + i_{\mathrm{T}}(t) \cdot R_{\mathrm{S}}(t) \\ &= \tilde{v}_{\mathrm{OC}}(t) - v_{\mathrm{TS}}(t) - v_{\mathrm{TL}}(t) \end{aligned}$$

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State-Space Representation

State vector and measurement

$$\mathbf{x}(t) = \begin{bmatrix} \sigma(t) & v_{\mathrm{TS}}(t) & v_{\mathrm{TL}}(t) \end{bmatrix}^T$$

$$\mathbf{y}^*(t) = v_{\mathrm{T}}(t) + i_{\mathrm{T}}(t) \cdot R_{\mathrm{S}}(t)$$

Quasi-linear, continuous-time state-space model

$$\dot{\mathbf{x}}(t) = \mathbf{A}\left(\sigma(t)\right) \cdot \mathbf{x}(t) + \mathbf{b}\left(\sigma(t)\right) \cdot i_{\mathrm{T}}(t)$$

$$\mathbf{y}^*(t) = \mathbf{c}^T\left(\sigma(t)\right) \cdot \mathbf{x}(t)$$

Purpose of the quasi-linear representation: to make linear state observers applicable.

M. Lahme — Carl von Ossietzky Universität Oldenburg, Department of Computing Science (Group: Distributed Control in Interconnected Systems)

State-Space Representation

$\mathbf{A}\left(\sigma(t)\right)$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{-1}{C_{\mathrm{TS}}(\sigma(t))\cdot R_{\mathrm{TS}}(\sigma(t))} & 0 \\ 0 & 0 & \frac{-1}{C_{\mathrm{TL}}(\sigma(t))\cdot R_{\mathrm{TL}}(\sigma(t))} \end{bmatrix}$$

$\mathbf{b}\left(\sigma(t)\right)$

$$\begin{bmatrix} \frac{-1}{C_{\mathrm{Bat}}} \\ \frac{1}{C_{\mathrm{TS}}(\sigma(t))} \\ \frac{1}{C_{\mathrm{TL}}(\sigma(t))} \end{bmatrix}$$

$\mathbf{c}^T\left(\sigma(t)\right)$

$$\begin{bmatrix} \eta_{\mathrm{OC}}\left(\sigma(t)\right) & -1 & -1 \end{bmatrix}$$

Interval Observer

Goal	Bound the true value, so that $\underline{\hat{\mathbf{x}}} \leq \mathbf{x} \leq \overline{\hat{\mathbf{x}}}$
Prerequisite	choose initial condition so that $\underline{\hat{\mathbf{x}}}_0 \leq \mathbf{x}_0 \leq \overline{\hat{\mathbf{x}}}_0$
	observer system matrix has a Metzler structure (monotonicity condition)

Metzler matrix

All off-diagonal elements are non-negative.

Interval Observer

This interval observer is based on two Luenberger observers.

- one observer to estimate the upper bound
- one observer to estimate the lower bound

Example of a Luenberger observer

$$\begin{aligned}\dot{\hat{\mathbf{x}}} &= \mathbf{A}\cdot\hat{\mathbf{x}} + \mathbf{b}\cdot i_{\mathrm{T}} + \mathbf{H}\cdot(\mathrm{y_m} - \hat{\mathrm{y}}) \\ &= \mathbf{A}\cdot\hat{\mathbf{x}} + \mathbf{b}\cdot i_{\mathrm{T}} + \mathbf{H}\cdot(\mathrm{y_m} - \mathbf{c}^T\cdot\hat{\mathbf{x}}) \\ &= (\mathbf{A} - \mathbf{H}\cdot\mathbf{c}^T)\cdot\hat{\mathbf{x}} + \mathbf{b}\cdot i_{\mathrm{T}} + \mathbf{H}\cdot \mathrm{y_m}\end{aligned}$$

Interval Observer

$$\mathbf{A}(\sigma(t)) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -|a_{22}| & 0 \\ 0 & 0 & -|a_{33}| \end{bmatrix}, \; \mathbf{c}^T(\sigma(t)) = \begin{bmatrix} +|c_{11}| & -1 & -1 \end{bmatrix}, \; \mathbf{H} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix}$$

$$\mathbf{A} - \mathbf{H} \cdot \mathbf{c}^T = \begin{bmatrix} -h_1 \cdot |c_{11}| & h_1 & h_1 \\ -h_2 \cdot |c_{11}| & -|a_{22}| + h_2 & h_2 \\ -h_3 \cdot |c_{11}| & h_3 & -|a_{33}| + h_3 \end{bmatrix} \mathrel{\widehat{=}} \begin{bmatrix} * & \geq 0 & \geq 0 \\ \geq 0 & * & \geq 0 \\ \geq 0 & \geq 0 & * \end{bmatrix}$$

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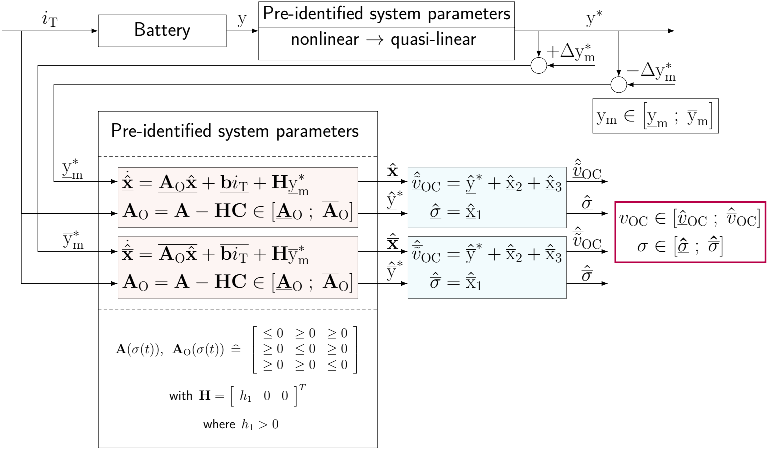
Interval Observer

$$\mathbf{A}(\sigma(t)) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -|a_{22}| & 0 \\ 0 & 0 & -|a_{33}| \end{bmatrix}, \ \mathbf{c}^T(\sigma(t)) = \begin{bmatrix} +|c_{11}| & -1 & -1 \end{bmatrix}, \ \mathbf{H} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix}$$

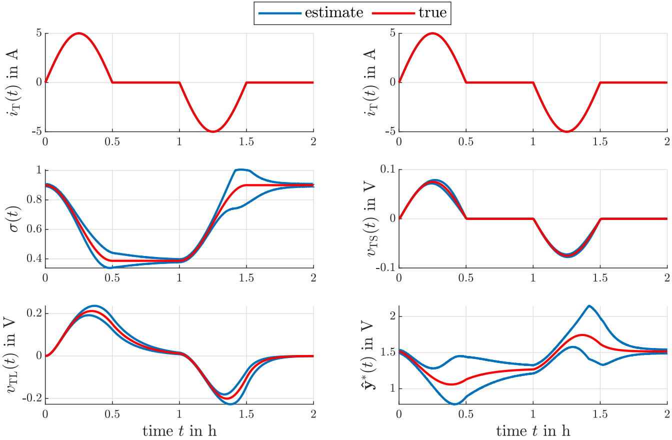
$$\mathbf{A} - \mathbf{H} \cdot \mathbf{c}^T = \begin{bmatrix} -h_1 \cdot |c_{11}| & h_1 & h_1 \\ -h_2 \cdot |c_{11}| & -|a_{22}| + h_2 & h_2 \\ -h_3 \cdot |c_{11}| & h_3 & -|a_{33}| + h_3 \end{bmatrix} \widehat{=} \begin{bmatrix} * & \geq 0 & \geq 0 \\ \geq 0 & * & \geq 0 \\ \geq 0 & \geq 0 & * \end{bmatrix}$$

$\mathbf{H} = \begin{bmatrix} h_1 & 0 & 0 \end{bmatrix}^T$ with $h_1 > 0$

Interval Observer-Based State Estimation



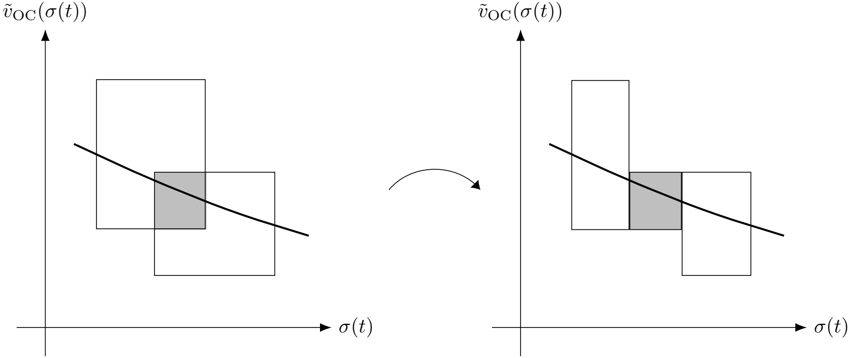
Interval Observer-Based State Estimation



Identification procedure

Estimation result based on the interval observer

$\forall\ \sigma_j \in [\sigma_j]\ , \exists\ \tilde{v}_{\mathrm{OC},j} \in [\tilde{v}_{\mathrm{OC},j}]\ \ s.t.\ \tilde{v}_{\mathrm{OC},j} = \tilde{v}_{\mathrm{OC}}(\sigma_j)\ ,\ j = 1, ...,$



Simulation result