Enhanced battery model including temperature effects

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Outline

1. Introduction TNO
2. Goal
3. Motivation of work
4. Battery modelling
5. Results
6. Applications
7. Conclusions
Introduction TNO

- TNO is the Netherlands’ Organization for Applied Research
- Independent R&D organization
- Spin-off companies (e.g. tass)
- Over 75 years of experience
- 4,000 employees world-wide
- HQ in Delft, the Netherlands
- Annual turnover approx. 550 M€

TNO Powertrains – R & D
- Detailed Powertrain Modelling and Control
- Energy and Emission Management
- Battery modelling and state estimation
Develop a battery model which captures temperature influences on the battery electrical behaviour
Motivation of work - performance

Battery performance strongly influenced by temperature

Accurate battery models needed for numerous automotive applications:
- Battery State-of-Charge (SoC) Estimation
- Battery Management Systems
- Range Prediction Algorithms
- Supervisory Control Algorithms

Higher accuracy over various operating temperatures → Temperature effects must be accounted for in battery modelling
Motivation of work - ageing

Battery ageing influenced by temperature.

**ABattReLife European project**: battery ageing during vehicle usage and second life applications.

Vehicle simulator including coupled electro-thermal-ageing battery model used for sensitivity analysis of battery degradation phenomena in vehicular applications.

M. Ecker et al - Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data
TNO use cases

- SoC estimation, BMS, System level simulation, Total Cost of Ownership (TCO) tools

Approach

- Electric circuit equivalent, phenomenological dynamic battery model
- On-line implementable
- Temperature dependent components
- Automatic model identification procedure starting from measurements

\[
\begin{pmatrix}
\text{SoC}_k \\
V_{1,k} \\
V_{2,k}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 - \frac{\Delta t}{R_1 C_1} & 0 \\
0 & 0 & 1 - \frac{\Delta t}{R_2 C_2}
\end{pmatrix} \begin{pmatrix}
\text{SoC}_{k-1} \\
V_{1,k-1} \\
V_{2,k-1}
\end{pmatrix} + \begin{pmatrix}
\frac{\Delta t}{C_1} \\
\frac{\Delta t}{C_2}
\end{pmatrix} I_{\text{bat},k-1}
\]

\[
V_{\text{bat},k} = V_{oc}(\text{SoC}_k, T_k) + V_{1,k} + V_{2,k} + R_0(\text{SoC}_k, T_k) I_{\text{bat},k}
\]
**TNO use cases**

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\]
Experimental validation

- Battery cycling within a climatic chamber

<table>
<thead>
<tr>
<th>Test number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature [°C]</td>
<td>-18</td>
<td>-10</td>
<td>0</td>
<td>10</td>
<td>25</td>
<td>40</td>
</tr>
</tbody>
</table>

- Validation approach: tests 1, 2, 4, 5 and 6 used for model identification and test 3 for model validation
Battery modelling

Model identification

DISCHARGING

CHARGING

SoC [-]  

SoC [-]  

temperature [°C]  

temperature [°C]  

$V_{oc}$ [V]  

$R_0$ [Ω]  

$R_0$ [Ω]  

$C_1$  

$C_2$  

$I_{bat}$  

$V_{bat}$  

$V_{oc}$  

$R_0$  

$C_1$  

$C_2$  

$R_1$  

$R_2$  

Organized by
Hosted by
In collaboration with
Supported by
Experimental validation

Model validation - voltage prediction
ambient temperature: 0°C

Nominal voltage: 26.5 V
Discharge cut-off voltage

Nominal voltage: 26.5 V
Discharge cut-off voltage
Experimental validation

Model validation - voltage prediction
ambient temperature: 0°C

Nominal voltage : 26.5 V
Discharge cut-off voltage

- measurement
- model including thermal effects
- model without thermal effects
Experimental validation

Model validation - voltage prediction error
ambient temperature: 0°C

- green: model including thermal effects
- red: model without thermal effects

SoC [-]  Voltage error [%]
Battery state estimator - SoC

SoC estimation error [%]

-30 -20 -10 0 10 20 30

0.4 0.5 0.6 0.7 0.8 0.9 1

SoC [-]

Initial SoC estimation

SoC estimation error

- upper error bound for E-range prediction application
- lower error bound for E-range prediction application

Battery Model

Gain Factor

Battery SoC Estimator

I_{bat} \rightarrow U_{bat} \rightarrow \hat{U}_{bat} \rightarrow \hat{SOC} \rightarrow \hat{SOC}

\hat{SOC} = \hat{U}_{bat} + \varepsilon

\hat{SOC} = \text{SoC estimation}

SoC estimation

- estimated
- measured
Robust battery state estimation

Applications
Robust battery state estimation

Applications
• **Temperature** has a strong influence on battery performance and ageing behavior

• To correctly capture that influence, temperature effects have been included in the existing battery model, leading to increased model accuracy under different operating temperatures

• Enhanced battery model supports the development of embedded **SoC estimation** algorithms

• Enhanced battery model supports the development of battery lifetime assessment tools, essential for **Total Cost of Ownership** analysis for hybrid and electric vehicles
Thank you for your attention!

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You are welcome
at the booth G710
Top down vs. bottom up modelling

Top down – simple, fast, many simplifying assumptions

Bottom up – more complex, more effort needed, different layers of validation, can capture subsystem interactions

Choice: application dependent
Recommended current: 50A

Maximum current: 160A
Extra slide