Online Estimation of Lithium-Ion Battery SOC and Capacity with Multiscale Filtering Technique for EVs/HEVs

Battery Management Systems Workshop

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1. Module Sensing System 
(V, I, T measurements)

2. **Battery Monitoring Module**

3. Battery Control Module

4. Thermal Management System 
(cooling pumps/fans)

5. Battery Warning Device and Safety Module

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**Battery Management System (BMS)**

1. Sensing System

2. Battery Monitoring Module
   - SOC, SOH, SOL Module
   - Sensory Data
   - Decision Logic

3. Battery Control Module
   - Charging & Equalization
   - Control Signals

4. Thermal Management System

5. Safety Module

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External Charger or Alternator

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Battery Health Management (BHM) for BMS

Benefit 1. Cell balancing in multi-cell battery chains

Passive capacity

Adaptive capacity (BHM)

Maximizing charging & discharging pack capacity

Benefit 2. Cell health management

Case 1: Enabling use of full cell capacities

Case 2: Anticipating & preventing future failures
It is not clear how short-term and long-term benefits can be distinguished.

The titles have been revised to be more specific.
Overview of Battery Health Management

Task I: Battery Health Diagnostics
- Battery Cycle Testing
  - Battery Cells
  - Cycle Tester
- SOC & Capacity Estimation
  - SOC: Micro EKF/UKF
  - Capacity: Macro EKF/UKF

Task II: Battery Health Prognostics
- Remaining Useful Time
  - Voltage Projection
    - Voltage: 4.2V
    - Prediction
    - Current time: UDDS
    - End time: 3.0V
- Remaining Useful Life
  - Battery Health Database (Offline)
    - Temperature
    - Discharge rate
    - Chemistry
    - Cycle
    - End life
  - Particle Filter Projection (Online)
    - Background health knowledge
    - Predicted RUL

Task III: Battery Health Management
- Cell Balancing
  - Unbalance: $C_{dis} = 20\%$, $C_{char} = 10\%$
  - Boosting/shuffling
  - Balance: $C_{dis} = 60\%$, $C_{char} = 40\%$
- Cell Replacement
  - Cell 1 life
  - Designed life
  - Cell N life
  - Cell to replace
Overview of Battery Health Management

**Task I**

**Battery Health Diagnostics**
- **Battery Cycle Testing**
  - Battery Cells
  - Cycle Tester
  - Test condition

**SOC & Capacity Estimation**
- SOC: Micro EKF/UKF
- Voltage
- Current
- SOC
- Capacity: Macro EKF/UKF

**Task II**

**Battery Health Prognostics**
- **Remaining Useful Time**
  - Voltage Projection
  - Operation History
  - Capacity
  - RUT Estimate
  - UDDS
  - 3.0V
  - Current time
  - End time

- **Remaining Useful Life**
  - Battery Health Database (Offline)
  - Temperature
  - Discharge rate
  - Chemistry
  - Capacity
  - Cycle
  - End life

**Task III**

**Battery Health Management**
- **Cell Balancing**
  - Unbalance: $C_{dis} = 20\%$, $C_{char} = 10\%$
  - Balance: $C_{dis} = 60\%$, $C_{char} = 40\%$

- **Cell Replacement**
  - Designed life
  - Cell $N$ life
  - Cell to replace

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Concluding Remarks

Multiscale Extended Kalman Filter (EKF) Proposed

Two Unique Strategies in Capacity Estimation
- Multiscale estimation of SOC and capacity with time-scale separation
- State projection scheme for accurate and stable capacity estimation

Improved Performance
- Enhanced accuracy (less noise and more stable) in capacity estimation
- Higher efficiency by reduced frequency ($1/L$) in capacity estimation

Future Research
- Extension of the proposed algorithm from a cell level to a pack level
- Validation of the proposed algorithm with more extensive accelerated life test
Highlight the unique features of our proposed method: multiscale, stochastic, etc.

Express the unique features, contributions, advantages of the proposed method.

The conclusion has been revised to reflect the unique features, contributions and benefits of the proposed multiscale filtering method.
Acknowledgements

• PCTEST Laboratory (Battety Certification Firm, Columbia, MD)

• National Research Foundation (NRF), Korea (2011-2014)

• Hyundai Motors R&D, Electric Vehicle Department, Korea (2011-2012)
Highlight the uniquenesses of our proposed method: multiscale, stochastic, etc.

Express the uniquenesses, contributions, advantages of the proposed method.

The conclusion has been revised to reflect the uniquenesses, contributions and benefits of the proposed multiscale filtering method.
Thank You!

Q/A
Task 1: Battery Health Diagnostics

Time-Scale Separation in State of Charge (SOC) and Capacity Evolutions

Capacity: *slowly* time-varying health condition (*macro time-scale*);
SOC: *fast* time-varying system state (*micro time-scale*)

→ Multiscale EKF – Hybrid of Coulomb counting and adaptive filtering technique
Task 1: Battery Health Diagnostics

Contribution 1 – Multiscale EKF for SOC & Capacity Estimation

Time update
\[ x_{k,l} = x_{k,l-1}^\text{^} + \eta_i \cdot T \cdot i_{k,l-1} / C_{k-1} \]

Capacity transition
\[ C_k = C_{k-1}^\text{^} \]

SOC projection
\[ x_{k,l}^\text{^} = x_{k,0} + \eta \cdot T \cdot i_{k,0,l-1} / C_k \]

Measurement update (cell dynamic model)

Measurement update
\[ x_{k,l}^\text{^} = C_k - x_{k,l}^\text{^} \]

SOC estimation

Capacity estimation

Zoom of first minutes

Macro EKF (Capacity)

Yes

No

Macro EKF achieved (go to Macro EKF)?

Micro EKF

Cell terminal voltage (V)

Cell terminal voltage

SOC estimation

Capacity estimation

Zoom of first minutes

SOC estimation

Capacity estimation

Zoom of first minutes

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Contribution 2 – State Projection for Accurate Capacity Estimation

1. Capacity transition

\[ C_k^- = C_{k-1}^+ \]

2. SOC projection (coulomb counting)

\[ \hat{x}_{k,L} = \hat{x}_{k,0} + \frac{\eta \cdot T}{C_k^-} \sum_{j=0}^{L-1} i_{k,j} \]

3. Measurement update

\[ C_k^+ = C_k^- + K_k^C \left[ \hat{x}_{k,L} - \hat{x}_{k,L} \right] \]

Estimated SOC

Task 1: Battery Health Diagnostics
Task 1: Battery Health Diagnostics

**Test Steup – Urban Dynamometer Drive Schedule (UDDS) Test**

- Testing cells: Li-ion prismatic cells (around 1.50Ah)
- Testing facilities: Arbin BT2000 cell tester with Espec SH-241 temperature chamber at 25°C
  - **Test step 1:** Setup UDDS test System
  - **Test step 2:** Program and load UDDS test profile into cell tester
  - **Test step 3:** Start test and acquire test data (duration: around 20hrs)

**Experiment Setup – UDDS Test System**
Task 1: Battery Health Diagnostics

Test Result – Urban Dynamometer Drive Schedule (UDDS) Test

1. Comparison of accuracy (small initial)

<table>
<thead>
<tr>
<th>Method</th>
<th>RMS Error (mAh)</th>
<th>Error Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEKF</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>MEKF</td>
<td>63</td>
<td>41.7%</td>
</tr>
</tbody>
</table>

2. Comparison of efficiency (overall)

<table>
<thead>
<tr>
<th>Method</th>
<th>Computational Time (s)</th>
<th>Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEKF</td>
<td>5.813</td>
<td></td>
</tr>
<tr>
<td>MEKF</td>
<td>3.711</td>
<td>36.2%</td>
</tr>
</tbody>
</table>

Average RMS errors after convergence (at t = 200min)

MATLAB Version 7.11.0.584 on Intel Core i5 760 CPU 2.8 GHz and 4 Gbyte RAM.
We need to highlight the benefits and advantages of our approach far more clearly.

1. Capacity estimation results of MEKF and DEKF are plotted in the same figure to deliver a more clear comparison.

2. Quantitative comparison results have been added to clearly show the superior performance of MEKF.
Task 2: Battery Health Prognostics

Preliminary Results – Accelerated Cycle Life Test (Ongoing)

<table>
<thead>
<tr>
<th>Charging Rate</th>
<th>Discharging Rate</th>
<th>Number of Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0C</td>
<td>1.0C</td>
<td>4</td>
</tr>
<tr>
<td>1.5C</td>
<td>1.0C</td>
<td>4</td>
</tr>
<tr>
<td>1.0C</td>
<td>2.0C</td>
<td>4</td>
</tr>
<tr>
<td>1.5C</td>
<td>2.0C</td>
<td>4</td>
</tr>
</tbody>
</table>

C = 1.5A; Temperature = 25°C
One cell to check 1.5C charge and 2.0C discharge

Capacity and impedance check

10 charging & discharging cycles

1.0C Charging, 1.0C Discharging

1.5C Charging, 1.0C Discharging

1.0C Charging, 2.0C Discharging

1.5C Charging, 2.0C Discharging
It is not clear what we can observe out of the results. Also not clear correlation between C-rate and degradation. Please analyze these results to get more insightful understanding.

user, 9/21/2011

Can we update the results with recent cycle data? This could be critical in order to make some conclusions.

user, 9/21/2011

The results have been updated with recent cycle data. At this stage, it is still very difficult to see a clear correlation between the C-rate and capacity degradation, since cells (9-16) with higher C-rates exhibit similar degradation behavior compared to cells (1-8) with lower C-rates. This slide can be used for the purpose of demonstrating our ongoing cycle life testing with preliminary results.

huchaiostu, 9/22/2011
Task 2: Battery Health Prognostics

Preliminary Results – Hybrid Algorithm for SOL Prediction (Ongoing)

Offline Process
- Cell Dynamic Model Training
- Degradation Model Training

Online Process
- Health Filtering (Mutiscale EKF)
- Health Projection (Particle Filter)

SOC& Capacity
Remaining Life

Life Prediction
- Capacity (Ah)
- Prediction at 300 cycles
- True RUL
- RUL PDF

Performance Plot
- RUL prediction (mean)
- 10% error bounds

Test data
1.5C Charging, 1.0C Discharging

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Not clear how this result comes from.
Is it based on someone else's results or ours?
The workshop has many participants in this research. It is not a good idea to present others' results.

user, 9/21/2011

The life prediction approach with Particle Filter has been developed by researchers from NASA. But this integrated framework combining health diagnostics (with MEKF) and health prognostics has not been attempted. Thus, we may present this integrated framework and show some preliminary results (shown in the bottom figures) to support it.

huchaostu, 9/23/2011
Task 3: Battery Health Management

Cell-Module-Pack Health Information Panel (Conceptually Created)

**Module 1 (5 Cells)**
- Remaining life (yr)
- State of charge (%)
- Cell ID

**Module 2 (5 Cells)**
- Remaining life (yr)
- State of charge (%)
- Cell ID

**Pack (2 Modules)**
- Remaining useful time: 4 hours 30 min.
- Cells requesting replacement: 5, 7

Real-time & user-friendly health information feedback for effective cell balancing/replacement
Is it based on the result or just conceptual slide? Please clarify this.
user, 9/21/2011

This table is conceptually created to show the ultimate objective (the creation of a cell-module-pack health information panel).
huchao, 9/22/2011