Control Enabling Solutions with Ultrathin Strain and Temperature Sensor System for Reduced Battery Life Cycle Cost

2015 Annual Meeting – Open Session
April 1, 2015
Program Overview

Develop Sensors

Characterize Cells

Multi-Physics Models

Data & Model Fusion

Pack Integration & Validation

Ultra-thin Temp & Expansion Sensor Development

Swelling due Li-Intercalation (top) & Thermal Expansion (bottom)

Thermal Electrochemical Mechanical

Observability Integration & Controls Development

Estimation / Limits
- State of Power
- State of Charge
- State of Health

Multi-parameter in-situ cell monitoring to increase operating window and improve SOH

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Team

Aaron Knobloch - Principal Investigator
Jason Karp
Chris Kapusta
Yuri Plotnikov
David Lin

Brian Engle – Automotive Vertical Ldr
Rob Twiney – GM Advanced Sensors
Dave Geer – Principal Engineer
Dave Villella – Test Engineer
Ron Martonik – Product Manager

Anna Stefanopoulou – Michigan Lead
Jason Siegel
Bogdan Epureanu
Charles Monroe
Krishna Garikipati
Nassim Samad
Ki Yong Oh
Howie Chu
Zhenlin Wang

Dyche Anderson – Ford Lead
Arnold Mensah-Brown
Ramzi Chraim
Tommy Coupar
Xinfan Lin
Bruce Blakemore
Program Summary & value Proposition
Expected System Benefit

Estimation

Temp & Expansion Sensor

Real-time Dynamic Model-based Power Limits

20% Reduction in pack size while maintaining life at higher throughput

Test Case – 5 Amp-hr Panasonic Cell for HEV Applications
Enabling Sensor Technologies

Benefits

**Temperature**
- Thin film RTD
  - Thin (<100μm) – locate anywhere on surface
  - Develop arrays
  - Accuracy
  - Time response
  - Enables lower cost battery packaging

**Eddy Current**
- Not able to measure expansion today
- Small / cost effective
- Can measure between cells
- Potential correlation to battery health, SOC, …

**Leverages high volume, low cost Flex manufacturing**

Competitive Technologies

**Thermistors**
- Thick (>1mm)
- Limited locations
- Slower
- Lower accuracy
- Higher installation costs

**Strain Gages:**
- Drift, low signal level
- Temp effects

**Load Cells:**
- Thick (>1/4”)
- Not cell specific

36 point Temperature Array

Integrated Expansion & Temperature Sensor
Fusion of Sensor Data and Models

Thermal
- Thermal and Intercalation swelling, sensor response, and porosity change.

Mechanical

Electrochemical (ECM or DFN)

Modeled Pack Temp

Free and Constrained Swelling

Measured Temp

Enhanced SOC Estimation with Measured Expansion

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Model Based Power Limit

Prediction

- Improved battery core temperature estimation using thin film temperature sensor -> 2 minute faster convergence rate.
- Model based power limiting strategy enables faster warmup to full power, and wider SOC operation.
- Dynamic power limits can be more conservative when necessary for health and safety.
- At low temperatures (-5°C), battery utilization (Whr throughput per cell) can be increased up to 26%.

Estimation
Key Learnings & Results
Electro-Thermal Model Validation

- Performed observability analysis for optimal sensor placement.
- Thin film sensor enables faster core temp estimation over existing measurement location (side vs top of cell).
- Less than 2°C modeling error in pack cell temperature predictions over a 35°C operating range.

Charge sustaining pulses
- 20, 39, 50A
- Fan on, fan off

Experiment

Comsol

Reduced TEM

Surface temperatures [°C]

Finite element and reduced order pack models validated against vehicle drive cycle data.

Sensor Index

20A excitation
39A excitation
50A excitation

Swelling (Free)

Li Intercalation Swelling
(-)  (+)  Thermal Swelling

Swelling (Constrained)

Intercalation ($\Delta$SOC=100%)
Thermal ($\Delta$T=10°C)

Response at GE Sensor location
$\Delta$T 6°C $\leftrightarrow$ $\Delta$SOC 100%

SOC Estimation

The relation among temperature, SOC, current and force enables the use of measured for in SOC estimation.


The relation among temperature, SOC, current and force enables the use of measured force in SOC estimation.

Estimation quality improved by adding force measurement - more prominent in SOC range between 30~50%.


3-Cell Degradation Testing

• Established baseline degradation
  – 25°C cell temperature (-10°C ambient air)
• Open loop US06 power profile, no controls (yet).

Using 3-fixtures to assess capacity loss

56k equivalent miles driven

• Conclusion: Lower capacity loss at lower SOC.
• Next steps: compare degradation effects for closed loop power limiting and wider SOC window on downsized pack.
Power Limits, Downsizing, and Degradation

- Shift to lower SOC operation for reduced degradation and more charge acceptance (regen braking) at -5°C.

Projected capacity fade at 150k miles using model based power limit

\[
S_{loss}(Ah) = \alpha_c + \gamma_c (0.66 - SOC_0)^c \cdot Ah^z
\]

# of times algorithm would limit power deliver/acceptance, i.e. Energy left on the table \(\leftrightarrow\) FE.

Unavailable Total Whr at T=-5°C, range=60%
Validation Plan & Performance Targets
Status of Proof of Concept – Demonstration Pack

Baseline U-M 3 Cell Rig
56k miles
Complete Q1 2015

Sensor-Pack Integration
Gen 1 Open Loop UM Model
Complete Q1 2015

Developmental Pack Operation
Validate UM Testing & Simulation
Start Q2 2015

Verify model & control
• Hardware in the loop simulation
• Impact on degradation on validation conditions

Confirm functionality
• Verify sensor fit
• Test software / find bugs
• Confirm accuracy of model estimates

Operation
• Integration
• Examine target SOC window
• Sensor accuracy & perf
• Confirm accuracy of model estimates
Benefit Demonstration & Validation

Ford Controls
Wider Operating Window

- Use existing test profiles, adjusting SOC ranges
  - Two cycles “high”, two cycles “low”
  - Adjust between cycles if significant drift in center point
- Run for c. 30,000 mi equivalent minimum
- Capacity & power tests every month – examine degradation
Expected Performance Benefits

- Improved state of charge and power capability estimation
- Improved power availability at low temperatures
- Pack may be downsized (fewer cells or smaller cells)

Full Pack (76 cells) – 2014MY

Reduced Pack (60 cells) same total power

Cell Count Reduction
-21%

Increased Utilization (Wh throughput per cell)

Cold (-5C) +23%
+25C +27%

Faster Warmup 105s *

*Results for scaled US06 battery power profile at 25°C.
Summary
Summary

• Proven
  – Temperature sensor + physics based model enables more accurate and faster (2x) prediction of core temperature
  – Developed SOC estimation based on force / expansion – more sensitive (in 30-50% SOC range) than typical voltage based measurements
  – Demonstrated integration of sensors & open loop control with Ford pack
  – Simulated validation performance based on improved state estimation

• Ongoing
  – Verify validation windows on 3 cell rig and developmental pack
  – Development of closed loop control with expansion/force input
  – Instrument and run validation pack to demonstrate benefit

• Challenges Addressed
  – Cell SOC estimation
  – SOH measurements / battery lifetime
  – Model to extract maximum power capability and throughput with long life
Program Next Steps

• Examining sensor performance on other cell types (soft pouch, larger size)
• Commercialization of sensors & model-based algorithms