Predictive Battery Management for Commercial HEVs

ARPA-E AMPED DE-AR0000279
Annual Review Meeting
Chicago, IL
04/01/15
Battery Sizing and Utilization

- Medium Duty HEV Application
  - Stop-go driving, 6 – 8 hours per day

- Battery Utilization – HEV functions
  - Engine Crank, EV Launch, Gear Shifts, Regenerative Braking

**Battery sized for power requirement, End-user pays for energy capacity**

- Can we reduce the battery size and manage utilization to maintain HEV performance and battery life?
Predictive Battery Management for Commercial Hybrid Electric Vehicles

Overview

**Partners:** Eaton, National Renewable Energy Lab  
**Funding and Duration:** $2.8M, 36 months  
- ARPA-E: $2M, Eaton Cost Share: $0.8M

Technology

- Battery life prognostics model based on electrochemical dynamics, capable of fast and accurate estimation of battery health and residual battery life  
- Predictive Powertrain Controls with Intelligent Electric Power Management System, capable of vehicle duty cycle prediction and real-time optimization of fuel economy and battery life

Advantage and Differentiation

- Combines model-based battery prognostics with vehicle duty cycle prediction  
- Integrates powertrain control with battery management  
- Enables dynamic battery utilization to achieve required system performance from a significantly downsized battery pack with minimum impact on battery life:
  
1. **Lower cost and higher ROI for HEVs**  
2. **Accurate residual battery life estimation for improved estimation of secondary market**

Performance Targets

<table>
<thead>
<tr>
<th>Metric</th>
<th>State of the Art</th>
<th>Proposed</th>
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<tbody>
<tr>
<td>Battery pack cost, weight and capacity</td>
<td>Oversized by factor of 4</td>
<td>Battery downsizing by 50% while maintaining life and performance</td>
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<tr>
<td>Battery residual life prediction</td>
<td>Prediction uncertainty of nearly 30%</td>
<td>Electrochemical model capable of error of less than 10%</td>
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1. iEPM – Battery model-based Electric Power Management
   • Combined empirical and first-principles models for battery health and life
   • Reduced order modeling for fast real-time implementation

2. PPM – Predictive Power Management
   • Co-optimizes HEV fuel economy (FE) and battery life, enabling dynamic battery utilization
   • Real-time search-based global optimization algorithm
Health/Life Model Development

1) Cell life test data
   - Constant temperature & duty cycle

2) Regress life model parameters

3) Pack life test data
   - Variable temperature & duty cycle

4) Validated pack life model
   - Forward looking prognosis based on observed I,V,T,SOC,…

5) Control strategy prototyping

6) Closed-loop HIL testing
Battery Health Model Status

Current Status
- Secondary verification (EOL tests) underway
- Verification of iEPM algorithm based on battery health model

Next Steps
- Validation testing to evaluate closed-loop performance

Cell Aging Model Estimation Error

Battery Pack Aging Model Estimation Error
Predictive Power Management

Objective function:

\[ J(X,U) = \sum_{t=k}^{k+N_P} w_1 \cdot fuel + w_2 \cdot drivability + w_3 \cdot battery \]

- Constrained nonlinear multi-objective optimization problem
- Compute global optimal solution using Two-Stage Real-time Dynamic Programming
Optimal Battery Utilization

- Battery health model in iEPM predicts aging for different PPM control set points

- Dynamic battery utilization to maximize fuel economy while meeting target battery life requirements

- Currently implementing closed loop iEPM + PPM on HIL test stand
• Typical MD HEV Customer
  • City bus, Shuttle bus, Package delivery truck, Utility truck
• Voice of Customer
  • Under 3 year payback period for hybrid powertrain
Value Proposition – Battery Leasing

Battery Leasing Alternative to Ownership

Powertrain Integrator
Vehicle OEM
End Customer
Battery Manuf.
Battery Lessor

HEV Payback Analysis (Leased Battery)

- AMPED PBMS technology enables leasing model – confidence in controlled battery aging
Validation Test Plan

- Battery-in-loop testing
  - Two full size packs, virtual downsizing
  - Real-world hybrid vehicle duty cycles

- Test 1 – 50% downsizing
  - AMPED target
  - RUL at end of 12 months within target
  - *Dynamically utilize the significantly downsized battery to maximize MPG within target RUL constraints*

- Test 2 – 30% downsizing
  - RUL at end of 12 months within target
  - Start from previous lease term (previously cycled battery)
  - *Lease model battery management*
  - *Robustness of battery algorithms to history*
Summary and Next Steps

• Hypothesis – significantly downsize battery, maintain life and performance

• Model-based battery health and HEV performance co-optimization

• Simulation results promising, validation testing underway

• Stationary domain applications – energy storage management for smart grid, renewable integration