Energy Storage Monitoring System and In-Situ Impedance Measurement Modeling

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Overview

**Timeline**
- Ongoing Project
- Start – October 2007

**Budget**
- Total project funding:
  - DOE – 660k (through FY11)
- Funding received in FY11:
  - $450k
- Funding for FY12:
  - $400k

**Barriers**
- Cost
- Performance
- Abuse Tolerance and Reliability
- Life Estimation

**Partners**
- Montana Tech of the University of Montana
- Qualtech Systems, Inc.
Relevance

• **Objective:**
  – Develop advanced in-situ diagnostic and prognostic tools for more accurate prediction of the state-of-health and remaining useful life of energy storage devices.

• **Benefits:**
  – **Safety and reliability:** Rapid identification of failure thresholds
  – **Cost:** Smarter replacement schedules
  – **Life Estimation:** Improved sensor technology for state estimation
  – **Performance:** Improved management systems based on battery condition using both energy and power.

• **Applications:**
  – Automotive (EV, HEV, PHEV)
  – Military (field radio operations, warehouses, vehicles, etc.)
  – Other applications include NASA, electric utilities, telecommunications, aeronautics, consumer electronics, etc.
Mission Areas:
- Rapid, in-situ impedance spectrum measurement techniques using hardware and control software – Impedance Measurement Box
- Modeling and prognostic tools that smartly combine impedance measurements with other observations to determine a more accurate definition of battery health.
- Hardware and software that directly interfaces with onboard battery technologies to smartly monitor and report health – Energy Storage Monitoring System.

FY-12 Objectives:
- Design and build a 50-V rapid impedance measurement system.
- Improve calibration system of rapid impedance measurement.
- Continue validation studies of rapid impedance measurement techniques using commercially available lithium-ion cells.
- Initiate incorporation of rapid impedance measurements into new and existing modeling and prognostic tools.
Approach

• Impedance Measurement Box:
  – Develop rapid impedance spectra measurement techniques
  – Design low-cost hardware and control software
  – Implement measurements under no-load and load conditions

• Modeling:
  – Equivalent circuit modeling of rapid impedance measurements
  – Feature extraction (e.g., effective charge transfer resistance, etc.)
  – Estimate pulse resistance and power capability from impedance measurements
  – Implement existing modeling capabilities (ES124) to develop prognostic tools for arbitrary aging conditions

• Energy Storage Monitoring System:
  – Passive measurements (voltage, current, temperature)
  – Active measurements (rapid impedance spectra)
  – Incorporate models to estimate overall state-of-health (SOH) and remaining useful life (RUL)
**Approach (cont.)**

- Flow diagram of the overall ESMS concept:

![Flow diagram of the overall ESMS concept](image-url)
Technical Accomplishments and Progress

- Novel techniques have been developed to acquire wideband impedance within seconds.
  - Harmonic Compensated Synchronous Detection (HCSD)
    - Low resolution, computationally intensive, short test duration

- Input signal is an octave harmonic sum-of-sines excitation current.
  - The excitation signal has a duration of one period of the lowest frequency.

- Synchronously detect the magnitude and phase of the captured voltage response time record.

- Long term validation testing was completed using Sanyo SA cells.
  - Cells aged at 40 and 50°C with periodic HCSD measurements under both no-load and load conditions.
Accomplishments and Progress (cont.)

- HCSDs under no-load conditions:
  - HCSD impedance spectra grow in both ohmic and effective charge transfer resistance.
  - The rate of impedance growth is higher at 50°C, as expected.
HCSDs under no-load conditions (cont.):

- The HCSD real impedance at the semicircle trough is highly correlated with both HPPC discharge resistance and available power.
- \( r^2 \geq 0.950 \) in all cases, most fits are \( r^2 \geq 0.980 \).
Accomplishments and Progress (cont.)

- HCSDs under no-load conditions (cont.):
  - HCSD results generally match standard EIS measurements in the key mid-frequency range.

NOTE: Data are shifted for emphasis, so x-axis is relative to each HCSD-EIS pair
Accomplishments and Progress (cont.)

- HCSDs under no-load conditions (cont.):
  - The calibration issue has been resolved and the EIS and HCSD measurements now match very well using test cell circuits.
Accomplishments and Progress (cont.)

- HCSDs under no-load conditions (cont.):
  - A new validation study is now underway with Sanyo SA cells to measure HCSD at multiple DODs.
  - At RPT0, the mid-frequency semicircle generally increases in both height and width with increasing DOD.
Accomplishments and Progress (cont.)

- **HCSDs under load conditions:**
  - Cells were cycled at elevated temperatures with HCSD measurements triggered every 50 cycles.
  - Under-load measurements were affected by a non-constant DC bias voltage.
Accomplishments and Progress (cont.)

- **HCSDs under load conditions:**
  - The Engine-Off impedance measurement under load still shows a mid-frequency arc, but the Warburg tail has flattened out.
  - The growth in effective charge transfer resistance is linearly correlated to the corresponding cycle-life pulse resistance.
• HCSDs under load conditions:
  – Despite the low-frequency effects, the height and width of the effective charge transfer resistance semicircle is similar under both no load and load conditions.
Accomplishments and Progress (cont.)

- **Hardware Development:**
  - The 50-V Impedance Measurement Box, including prototype hardware and upgraded control software, has now been completed.
  - Upgraded features for this hardware system include:
    - Applied dynamic voltage range between 0 and 50 V (i.e., system can test 5-V cells and 50-V modules)
    - Significantly reduced noise crosstalk in voltage feedback loop when removing the DC bias (up to 50 V)
    - Modular design for easier debugging and future upgrades
    - Voltage and current probe protection
    - Improved calibration technique
Accomplishments and Progress (cont.)

- **Modeling and State-of-Health Estimation:**
  - Preliminary SOH assessment tool under development using results from the HCSD validation studies.

![Diagram]

\[ \text{Training Data} \rightarrow \text{Feature Extraction / Training Regression} \rightarrow \text{Battery Models} 
- ABR (ES096)
- DADT(ES124)
- TLVT/BLE
- Lumped-Parameter Models

\[ \text{Online Measurements} \rightarrow \text{Feature Extraction / Online Regression} \rightarrow \text{Dynamic Parameter Estimation} \rightarrow \text{Dynamic Parameter Prediction} \rightarrow \text{Online Parameter Interpretation} \rightarrow \text{Online Health Estimation/Prediction} \rightarrow \text{SOH / RUL} \]
Collaborations

• Montana Tech of the University of Montana:
  – Expertise in signal processing, hardware design
  – A professor and several graduate students have been involved in this effort.

• Qualtech Systems, Inc.:
  – Expertise in software development

• Other (future) collaborators:
  – Agreement for a developmental collaboration between INL and the Army (CERDEC) is being drafted.
  – Various discussions with private industry about IMB/ESMS applications are also underway.
Proposed Future Work

• Impedance Measurement Box:
  – Investigate possibility of lower frequency measurements while still retaining fast measurement speeds.
  – Mitigate observed transient effects and bias voltage error for under-load measurements.

• Modeling:
  – Develop dynamic parameter estimation and prediction tools for online prognostics at arbitrary aging conditions.
    • Feature extraction from impedance spectra
    • New and existing modeling tools (e.g., ES124)
  – Continue validation testing for enhanced modeling capability.

• Energy Storage Monitoring System:
  – Explore low-cost hardware solutions for embedded system applications.
  – Seek collaborative opportunities with other groups involved in battery prognostics and control.
Summary

• The Impedance Measurement Box (IMB) enables low-cost, rapid, in-situ impedance spectra measurements.
  – The IMB addresses cost, safety, performance, and life estimation barriers for energy storage devices.

• Significant IMB accomplishments:
  – The 50-V Gen 3 IMB hardware design has been completed.
  – Improved calibration techniques have been implemented for more accurate impedance measurements.
  – Initial validation study is complete and a new study is underway with rapid impedance measurements at multiple DODs.

• A preliminary state-of-health assessment architecture design has been developed.
  – Dynamic parameter estimation and prediction rely extensively on battery modeling capability and training regression tools
• Novel techniques have been developed to acquire wideband impedance within seconds:
  – Impedance Noise Identification (INI)
    • Very high resolution, computationally very intensive, very long test duration
  – Compensated Synchronous Detection (CSD)
    • Lower resolution, computationally intensive, long test duration
  – Harmonic Compensated Synchronous Detection (HCSD)
    • Low resolution, computationally intensive, short test duration
  – Fast Summation Transformation (FST)
    • Low resolution, computationally simple, short test duration
  – Cross-Talk Compensation (CTC)
    • High resolution, computationally intensive, short test duration

• INL, Montana Tech, and Qualtech Systems Inc. collaborated on the development of these techniques.
HCSD Validation Testing

• Purpose of the initial HCSD validation tests:
  – Demonstrate the effectiveness of the rapid impedance spectra measurement technique under both no-load and load conditions using Sanyo SA cells.

• Cells aged at 40 and 50°C for 150,000 cycles with periodic reference performance tests (RPTs) to gauge degradation.

• HCSD measurements under no-load conditions conducted on all cells at each RPT.

• HCSD measurements under load conditions conducted on some cells during cycling.
  – Designated cells were subjected to a total of 10,000 HCSD measurements under load with no obvious signs of additional degradation.
Sanyo SA Cells

- **Chemistry:**
  - Li(Mn, Co, Ni)O$_2$ + Li-Mn-O spinel / Graphite

- **Rated Capacity:**
  - 1.2 Ah (C/1 Rate)

- **Battery Size Factor:**
  - 1400

- **HPPC Voltage Range:**
  - $V_{\text{max}} = 4.1$ V
  - $V_{\text{min}} = 3.0$ V

- **USABC Application:**
  - Minimum PHEV
**Voltage Bias (Under Load)**

- The voltage bias profile for HCSD measurements under load can be observed with simulations.
- A bias voltage remains once the DC term is removed and it affects the measured spectra, especially at low frequencies.