Battery Management for Monitoring up to Six Lead-Acid Batteries at the Individual Battery and System Levels

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NDIA Joint Service Power Expo
May 3, 2011
Overview

• Why Do We Need a Battery Fuel Gauge?
• Capabilities and Benefits of HDM BFG Technology
• BFG Application Examples
• BFG Configurations
• HDM’s BFG Dual Tracking Methodology
• BFG Highlights Effects of Unhealthy Batteries on the Bank
• Re-Cap
You would not drive a car without a gas gauge…

Why would you execute a mission-critical operation, such as “silent watch”, without a Battery Fuel Gauge?
Capabilities of HDM BFG Technology

• Battery Power Usage Information: Diagnostics and Prognostics
  – State of Charge (SOC) at 95% Accuracy
  – State of Health (SOH) at 95% Accuracy
  – Hours Remaining (HR) at 90% Accuracy
  – Battery Voltage (V)
  – Battery Temperature (T)
  – Current (I)
  – State of Life (SOL)

• Functionality
  – System Interface: CANBUS, RS232, Control Panel-Mounted Display
  – Real-Time Data and Estimations
  – Self-Calibration
  – Lightweight Packaging
Benefits of HDM BFG Technology

• Operations
  – Alerts crew when re-charging is necessary
  – Provides Hours Remaining for silent watch
  – Ensures mission capacity and success

• Maintenance
  – Identifies unhealthy batteries for replacement
  – Facilitates Condition-Based Maintenance (CBM)

• Cost-Efficiency
  – Single BFG per system vs. multiple BFGs per system
  – Simple configuration reduces install, operation, and maintenance
  – Powerful tool for intelligent power management systems
BFG Implementation
Mobile Application

• Customer
  – Navistar Defense
    • UK MOD/NATO

• Vehicle
  – Husky Tactical Support Vehicle

• Application
  – Monitors Battery SOC and SOH

Over 1500 HDM BFGs have been installed in Husky TSVs in Afghanistan supporting the NATO troops
BFG Implementation
Stationary Application

- Customer
  - Raytheon Company
- System
  - R-Series Regenerator Hybrid Power System
- Application
  - USMC Experimental Forward Operating Base Phase IV Demonstration in 2010 at 29 Palms, CA

HDM BFG is critical component of intelligent Hybrid Power System
Battery Fuel Gauge Configurations
Configuration 1

System Level Monitoring Only

Advantage: SIMPLICITY
Configuration 2
Cell Level Monitoring Only

Advantage: PRECISION

<table>
<thead>
<tr>
<th>DATA</th>
<th>READINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOH</td>
<td>Cell</td>
</tr>
<tr>
<td>SOC</td>
<td>Cell</td>
</tr>
<tr>
<td>V (Voltage)</td>
<td>Cell</td>
</tr>
<tr>
<td>HR (Hr Remain)</td>
<td>Cell</td>
</tr>
<tr>
<td>I (Current)</td>
<td>Cell</td>
</tr>
<tr>
<td>Temp</td>
<td>Cell</td>
</tr>
</tbody>
</table>
Configuration 3
System/String/Cell Level Monitoring

Advantage: SIMPLE, PRECISE & COST-EFFECTIVE
HDM’s Battery Fuel Gauge Technology: Dual Tracking Methodology
SOC Measurement
Using Dual Tracking Method

SOC Accuracy at 95%
What is Dual Tracking Methodology?

Current-based SOC (I-SOC)

- Ah-Discharge and Ah-Regeneration
  \[ Ah(\Delta t) = \int_{t_1}^{t_2} I(t) \, dt \]

- Ah-Cumulative

- Ah-Adjusted

- Current Based I-SOC

Voltage-based SOC (V-SOC)

- Measure
  - Battery Internal Resistance \((R_i)\)
  - Voltage \((V_B)\)
  - Discharge Current \((I)\)

- Open Circuit Voltage \((V_{OC})\)
  \[ V_{OC} = V_B + I \cdot R_i \]

- Voltage-Based V-SOC (from \(V_{OC}\) vs. SOC Table)

Integration Combi-SOC
Lack of precise charge and discharge efficiency information results in accumulation of SOC estimation errors.
Error from Voltage-Based Tracking

Lack of voltage relaxation results in SOC errors

A (100%SOC)
B (78%SOC)

Voc (Open Circuit Voltage) Profiles of Battery with and without Resting

Voc 12Hrs Rest after Full Charge
Voc No Rest after Full Charge
Dual Tracking Methodology

Dual Tracking Method is optimal for all loading conditions

SOC (%)

Discharging Time (min)

Voltage-Based Tracking SOC

Combined SOC

Voltage-based SOC

Dual Tracking SOC

Dual Tracking Method is optimal for all loading conditions
Configuration 3
System/String/Cell Level Monitoring

Advantage: SIMPLE, PRECISE & COST-EFFECTIVE
BFG Detection of Unhealthy Battery: Cycle 1

HDM BFG identifies weak battery during discharge cycle 1
BFG Accuracy Established: Cycle 3

HDM BFG achieves 95% accuracy by discharge cycle 3 (i.e. no adjustments needed)
Effects of Unhealthy Battery on Bank 1*

- String 3: Divergence of voltage and reduction in discharge current cause over-current stress on Strings 1 and 2
- Premature termination of discharge cycle, resulting in 19% loss in usable capacity

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<table>
<thead>
<tr>
<th>String #</th>
<th>Battery #</th>
<th>Individual Battery Voltage @ End Point</th>
<th>Discharge Current From</th>
<th>To</th>
<th>SOC %</th>
<th>SOH %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>11.3V</td>
<td>12A</td>
<td>19A</td>
<td>10</td>
<td>73</td>
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<tr>
<td></td>
<td>2</td>
<td>11.5V</td>
<td></td>
<td></td>
<td>16</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>11.4V</td>
<td>10A</td>
<td>18A</td>
<td>12</td>
<td>71</td>
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<tr>
<td></td>
<td>4</td>
<td>11.4V</td>
<td></td>
<td></td>
<td>12</td>
<td>73</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>10.8V</td>
<td>18A</td>
<td>4A</td>
<td>0</td>
<td>50</td>
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<tr>
<td></td>
<td>6</td>
<td>12.0V</td>
<td></td>
<td></td>
<td>36</td>
<td>78</td>
</tr>
<tr>
<td>Sum 1 - 3</td>
<td>Sum 1 - 6</td>
<td>System Battery End Voltage: 22.8V</td>
<td>System Discharge Current: ~41A</td>
<td>~41A</td>
<td>0%</td>
<td>68%</td>
</tr>
</tbody>
</table>

* Battery Bank 1: Optima Batteries
## Effects of Unhealthy Battery on Bank 2*

<table>
<thead>
<tr>
<th>String #</th>
<th>Battery #</th>
<th>Individual Battery Voltage @ End Point</th>
<th>Discharge Current From To</th>
<th>SOC %</th>
<th>SOH %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>11.3V</td>
<td>33A, 49A</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11.4V</td>
<td></td>
<td>19</td>
<td>80</td>
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<tr>
<td>2</td>
<td>3</td>
<td>10.6V</td>
<td>33A, 6A</td>
<td>0</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12.1V</td>
<td></td>
<td>51</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>11.2V</td>
<td>34A, 45A</td>
<td>12</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>11.5V</td>
<td></td>
<td>22</td>
<td>87</td>
</tr>
<tr>
<td>Sum 1 - 3</td>
<td>Sum 1 - 6</td>
<td>System Battery End Voltage: 22.7V</td>
<td>System Discharge Current: 100A</td>
<td>0%</td>
<td>62%</td>
</tr>
</tbody>
</table>

* Battery Bank 2: Hawker Batteries

- **String 2**: Divergence of voltage and reduction in discharge current cause **over-current stress on Strings 1 and 3**
- **Premature termination of discharge cycle**, resulting in **17% loss in usable capacity**
By extending the system run-time (e.g. by 30 minutes), would be at the expense of the weakest battery
Single BFG at 95% Accuracy for up to 6 Individual Batteries

- Provides breadth and depth necessary for Cost-Effective Battery Management Systems and CBM
- User Level
  - Ensures power system reliability and performance
- Maintenance Level
  - Enables precision pinpoint of unhealthy batteries for CBM
- Incorporates theoretically scalable algorithm, for banks greater than 6 batteries (i.e. important for larger, stationary energy storage systems)
Thank You!

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Appendix
In a battery pack, HDM’s BFG provides accurate SOC & SOH information within 2-3 cycles in a battery pack.
SOC Measured by Dual-Tracking Method

Scenario 2: Partial Discharge – Cycle 1 to Cycle 4

SOC error is within 5% at cycle 4
Partial Charge/Discharge Cycles of Battery Bank 2 – Battery #2/System

- SOC accuracy is 95% after four partial charge and discharge cycles
Whole Battery Bank (6 Batteries) Monitoring

- SOC accuracy is 20% in first cycle, it quickly improves to 5% within a few cycles
- Total AH discharge is measured around 200 AH
- System discharge termination point: is set when any battery in the system reaches a low voltage of 10.5V
• Battery #3 is the weakest. SOH ~ 50%, other batteries are 75% to 80%
• At 1st cycle, SOC of battery #3 is 40%. After a few cycles, SOC is within 5% error
• Battery #3 capacity is only 50Ah and is fully utilized when the system reaches the termination point
• Battery #4 in the same string only used up 50% capacity when system reaches the termination point
Bad battery causes battery voltage divergence in a battery pack
Current vs. Discharge Time of Battery Pack 1, 2, 3, 5
Cycle 1

Bad battery causes discharging currents unbalanced between battery strings (1&2) vs. (3&5)
BFG: Water Submersion Test

BFG was submersed in water at 25°C for three hours, and was tested for operational performance.