BRAMMO, INC.
SUSTAINABLE ENERGY SYSTEMS FOR POWER-SPORTS APPLICATIONS

Introduction

• **BRAMMO, Inc.**
  • Founded in 2002 as Brammo Motorsports, LLC
  • Privately held / CEO as majority shareholder
  • Located in Ashland, Oregon (280 miles south of Portland)
  • 20,000 square foot R&D facility
  • 3 manufacturing plants:
    • Enertia assembly at Flextronics Auto in Sarvar, Hungary.
    • Empulse assembly at Brammo-Ashland building-1
    • BPM battery module assembly at Brammo-Ashland building-2
Introduction

- **BRAMMO, Inc.**
- Focused on becoming the *market leader for BEV motorcycles*.
- Interested in exploring opportunities to supply Brammo powersports battery modules to other system developers.
BPM Background

- Development out of Brammo racing activities to maximize energy (specific energy) and power (specific power) density.
- 2009 Isle of Man TTXGP, FIM ePower Series.
BPM Background

• Using data recorded from real world testing and customer usage data of the Enertia Urban Commuter.
• Supplemented with learning from other R&D programs (racing, Empulse, etc...)

[Screen captures of data recordings and graphs related to motorcycle performance and battery status]
10Ah Cell Foundation

- Sourced from multiple high quality state-of-the-art suppliers.
- Fully automated manufacturing in clean-room environment.
- Very good cost/Wh
- High Specific Energy @ \( >200 \text{Wh/kg} \)
- Very high volumetric efficiency @ 400Wh/L
- “Right sized” for BEV motorcycle and powersports
  - Good Flexibility = Parallel and Series configuration options
  - Few connections (vs. 18650) = lower pack impedance
PRODUCT LINE Battery Systems

1kWh “Gold Box” Race Battery
- 11.1V / 90 Ah = 1.0 kWh
- 15 lbs / 7 kg
- Battery balancing, thermal management, RS485 communications
- Racing battery only, no production planned

Empulse RR Race Battery
- 155V / 40 Ah = 6.2 kWh
- 95 lbs / 43 kg
- Battery balancing, thermal management, RS485 communications
- Racing battery only, no production planned

BPM 44/70
- 44V / 70 Ah = 3.1 kWh
- 45 lbs / 22 kg
- Battery balancing, thermal management, RS485 communications
- Available now
- Standard equipment on Enertia-plus

BPM Flexible Module
- 14.8V / 90 Ah = 1.3 kWh
- 44.4V / 30Ah option
- 20 lbs / 9 kg
- Battery balancing, thermal management, RS485 communications
- Available now
- Standard equipment on Empulse (14.8V/90 Ah)
• Brammo Proprietary **44 VDC / 70 AH** Battery constructed from 10Ah Li-NCM pouch cells.

• Cell monitoring, SOC calculation, Active (current shuttling) intra-module and Passive (current shunting) inter-module cell balancing.

• Fully sealed (IP54 minimum) enclosure with recirculation fan.

• Specific Energy (pack) = >140 Wh/kg

BPM 44/70, BPM 15/90

- Developed fully in-house with dedicated Engineering staff for design and production support.
- Manufactured in Ashland Oregon.
Collaboration Project: Programmable Multi Channel Li-Ion Cell Battery Testing Platform

Brammo, Inc.
and
University of Toronto: ECE Dept.

Olivier Trescases, Assistant Professor
Andi Moshirvaziri, M.A.Sc Candidate
Introduction: Power Demand in EVs

- Power histogram for an electric bike as an example
  - The majority of the time is spent at low-power/idle
  - Higher power peaks occur less frequently

- Storage elements sized based on the load demand (energy, power)

- Single storage system with batteries as their only storage element
  - Very high Cost of high power batteries that have high specific energy
  - Reduced life-time with increasing charge/discharge current of batteries

IEEE Sustech Conf. 2013: Li-Ion Battery Pack Research and Development at Brammo Inc
Introduction: Hybrid Energy storage system (HESS)

- Reducing the size and cost of the storage system with increased life-span of the batteries
  - Battery
    - High specific energy (Wh/kg)
  - Ultra-capacitor (U-cap)
    - High specific power (kW/kg)

![Diagram of HESS system]

IEEE Sustech Conf. 2013: Li-Ion Battery Pack Research and Development at Brammo Inc
Introduction: Typical Drive Cycle Simulation Results

- Partial battery current during a 3-hour drive cycle

- Battery current histogram
  - Reduced peak discharge current by 47% utilizing the HESS
Objectives

- Effects of Current and Temperature Conditions on the Cell Aging
  - Regenerative Cycler
  - Six Programmable Channels
  - Capacity Measurement

- Effects of Internal Impedance on Deliverable Power From the Cell
  - Impedance Measurement
  - Battery Model
Using this cycler, we can analysis the effect of the following factors on life cycle of the Li-Ion cells
1. Average Current
2. Temperature
3. Current Dynamic

<table>
<thead>
<tr>
<th>Channel #</th>
<th>Mode</th>
<th>Ambient Temperature (°C)</th>
<th>Average C Rate (A)</th>
<th>Peak C Rate (A)</th>
<th>Duration (min)</th>
<th># Drive Cycles Per Cell Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Constant Discharge</td>
<td>25</td>
<td>1C</td>
<td>1C</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Constant Discharge</td>
<td>25</td>
<td>2C</td>
<td>2C</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Constant Discharge</td>
<td>15</td>
<td>2C</td>
<td>2C</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Constant Discharge</td>
<td>25</td>
<td>3.5C</td>
<td>3.5C</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Urban Drive</td>
<td>25</td>
<td>1C</td>
<td>3.5C</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Freeway Drive</td>
<td>25</td>
<td>2C</td>
<td>4C</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>
Drive Cycle Profile

Urban Drive Cycle
Frequency of 1Hz
Duration of 302s

Freeway Drive Cycle
Frequency of 1Hz
Duration of 122s

\[ I_{\text{Max}} = 35A \]

\[ I_{\text{Avg}} = 10A \]

\[ I_{\text{Max}} = 40A \]

\[ I_{\text{Avg}} = 20A \]
## Cycler Diagram

![Diagram Image]

### Table: Component Specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Part Number</th>
<th>Manufacture</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Power Supply</td>
<td>ZWS150BAF-5</td>
<td>TDK</td>
<td>Output Voltage: 5-6V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power: 150 Watt</td>
</tr>
<tr>
<td>Inverter</td>
<td>GTI-250W</td>
<td>SWEA</td>
<td>Programmable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Input Voltage: 25-55V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power Max: 250 Watt</td>
</tr>
<tr>
<td>Li-Ion Capacitor</td>
<td>Prismatic</td>
<td>JSR Micro</td>
<td>Rated Voltage: 2.2-3.8V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Capacity: 3300F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ESR: 1mΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Energy Density: 12Wh/kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power Density: 7 kW/kg</td>
</tr>
<tr>
<td>Schottky Diode</td>
<td>VS-STPS20</td>
<td></td>
<td>Reverse Max: 15V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average Current Max: 20A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Voltage Forward: 410mV@ 19A</td>
</tr>
</tbody>
</table>

### Inverter Power-Voltage Profile

![Graph Image]
The Cycler Board Consists of
1. Two Phase DC/DC Buck Converter
2. Two Phase DC/DC Boost Converter

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Max. P_{in}$</td>
<td>400</td>
<td>W</td>
</tr>
<tr>
<td>$Max. V_{in}$</td>
<td>4.5</td>
<td>V</td>
</tr>
<tr>
<td>$Max. V_{out}$</td>
<td>35</td>
<td>V</td>
</tr>
<tr>
<td>$Max. I_{in}$</td>
<td>80</td>
<td>A</td>
</tr>
<tr>
<td>$f_s$</td>
<td>250</td>
<td>KHz</td>
</tr>
<tr>
<td>#Phase Buck</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>#Phases Boost</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>
Discharging Scenario

Buck converter operates in current control mode
Boost converter operates in voltage control mode

Mode 1: $V_{Buss} \geq 7 \quad V_{Buss} \geq 7 \text{ v}$
Mode 2: $V_{Buss} < 7 \quad V_{Inv} = 25 \text{ v}$
Charging Scenario

Buck converter operates in current control mode
Boost converter operates in voltage control mode

Mode 1: $V_{Buss} \geq 7 \ V_{Buss} \geq 7 \ \text{v}$
Mode 2: $V_{Buss} < 7 \ V_{Inv} = 25 \ \text{v}$
IEEE Sustech Conf. 2013: Li-Ion Battery Pack Research and Development at Brammo Inc
Battery Modeling

Why do we need a battery model?
1. Predicts battery’s behavior under various conditions
2. Improves Battery Management Systems (BMS)

Modeling Method:
1. Measure internal impedance at different temperatures.
2. Extract model parameters using MATLAB.
3. Measure ambient and cell temperature during the tests.
4. Extract thermal parameters using MATLAB.
Impedance Measurement

1. LabVIEW VI sends the desired sinusoidal current
2. Current-voltage data will be processed using MATLAB
3. Real and imaginary part of the impedance are plotted versus frequency (Nyquist Plot)

\[ I = A \sin(\omega t) \]
\[ V = B \sin(\omega t + \phi) \]
\[ Z = \frac{V}{I} = a + i b \]
Impedance Measurement

Frequency Range: 0.5 Hz – 6 KHz
Temperature Range: 39°F - 69°F

Nyquist Curve for Cell Impedance Construction 1

Nyquist Curve for Cell Impedance Construction 2
A battery model consists of two parts
1. Open Circuit Voltage (OCV)
2. Over Potential

How many RC circuits are enough? In our application we are using 3 RC filters, based on the load’s dynamic
Thermal Model

Heat Generated Because of Current Flow

\[ Q_{elec} = Z I^2 \]

Heat Exchange with Ambient

\[ q_n = h_{conv} S_{cell} (T_{cell} - T_{Ambient}) \]

Energy Balance Inside the Cell

\[ m C_p \frac{dT}{dt} = Q_{elec} - q_n \]

Cell Temperature Plot \( I_{cell} = 20A \)

Thermal Picture of the Cell
The model can predict
1. Cell Performance at Different SOCs and Temperatures
2. Cell Temperature
Simulation Results

Temperature 39°F

Cell with construction 1 can deliver 4 drive cycles
Cell with construction 2 can deliver 10 drive cycles

Battery Terminal Voltage Plot
Construction 1

Battery Terminal Voltage Plot
Construction 2
Conclusion

• Programmable multi-channel Li-Ion battery testing platform was designed.

• Capacity measurement and Impedance measurement will be conducted for each channel after a certain number of cycles.

• Six individual channels were implemented to run the battery cells in different conditions.

• A battery model was derived from the impedance measurement.

• Utilizing the battery model, the performance of the cell can be evaluated in different SOC and temperature conditions.
THANK YOU!