Ultracapacitor Applications and Evaluation for Hybrid Electric Vehicles

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Discussion Points

- Discussion of batteries vs. ultracapacitors for advanced vehicles
- Simulation results of HEV fuel economy impact from reducing the storage system’s energy window
- 15%-30% HEV fuel economy improvements with 50-100 Wh ultracapacitors
- Evaluation of lithium ion capacitors for HEV applications
- Thermal evaluation of a high-voltage ultracapacitor module for start-stop applications
## Strengths and Weaknesses of Ultracapacitors

<table>
<thead>
<tr>
<th>Strong Attributes of Ultracapacitors</th>
<th>Potential Specific Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>High specific power and efficiency</td>
<td>Engine assist</td>
</tr>
<tr>
<td>Efficient and fast charge acceptance</td>
<td>Regen capture</td>
</tr>
<tr>
<td>Low resistance</td>
<td>Lower cooling needs (less expensive)</td>
</tr>
<tr>
<td>Quick response (short time constant)</td>
<td>Supporting engine transients</td>
</tr>
<tr>
<td>Long anticipated calendar and cycle life</td>
<td>Fewer replacements (less expensive)</td>
</tr>
<tr>
<td>High specific power at low temperatures (cold starts)</td>
<td>Smaller size and less expensive</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak Attributes of Ultracapacitors</th>
<th>Specific Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low specific energy</td>
<td>Limited “durations” for power draw</td>
</tr>
<tr>
<td>High self-discharge</td>
<td>Loss of functionality and balance at start</td>
</tr>
<tr>
<td>Quick voltage variation</td>
<td>More difficult to control</td>
</tr>
<tr>
<td>Low energy density</td>
<td>Limited time for running auxiliaries at idle</td>
</tr>
<tr>
<td>High cost per unit energy</td>
<td>Too expensive currently</td>
</tr>
</tbody>
</table>

The best use for Ucaps are strategies that make engines operate more efficiently (idle off, load leveling), frequent use capturing regen energy, and start-stop.
A Couple of Thoughts

• Taking advantage of an ultracapacitor’s strengths while minimizing the impact of its weaknesses to make its “value” competitive with batteries
• It should be for a specific application to show “value” in terms of “life-cycle cost”
  — Fuel economy
  — Replacement cost
  — Life
  — Durability and reliability
  — Quality
  — Functionality
## Ucap Is Energy Limited!

### How Much Energy Is Needed for Various Events?

<table>
<thead>
<tr>
<th>Event</th>
<th>How Much Energy Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assist: 20/30 kW constant power for 15/10 s</td>
<td>83.3 Wh</td>
</tr>
<tr>
<td>Accessory: 3 kW constant draw for 1 minute</td>
<td>50</td>
</tr>
<tr>
<td>Accessory: 1 kW constant draw for 1 minute</td>
<td>16.7</td>
</tr>
<tr>
<td>2% Grade going 35 mph for 1 minute *</td>
<td>70 Wh</td>
</tr>
<tr>
<td>4% Grade going 35 mph for 1 minute *</td>
<td>170 Wh</td>
</tr>
<tr>
<td>US06 Driving Cycle *</td>
<td>155 Wh</td>
</tr>
<tr>
<td>UDDS Driving Cycle *</td>
<td>80 Wh</td>
</tr>
</tbody>
</table>

*T Note: Engine provides propulsion up a grade, the estimate is for capturing regen to hold a 1520 kg vehicle speed going down a grade.

- Total Energy (at wheels) calculated for 1520 kg vehicle (regen); 50% of energy in the cycle’s largest deceleration event

Cold-start capability is expected to dictate the size of batteries, but not the case for Ucap.

Prius has a 1.4 kWh NiMH battery but capacity is for life margin and warranty.

Vue mild hybrid has a 0.6 kWh NiMH battery.
## Potential Use of Ultracapacitors in Light-Duty Electric-Drive Vehicles

<table>
<thead>
<tr>
<th>Category</th>
<th>Powertrain Options</th>
<th>Ultracapacitor Options</th>
<th>Min Energy Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Micro Hybrids (12 V-42 V:</strong> Start-Stop, Launch Assist)</td>
<td>NiMH and Li-ion: Yes</td>
<td>Ucap: Likely</td>
<td>15-25 Wh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ucap + VRLA: Possible</td>
<td></td>
</tr>
<tr>
<td><strong>Mild Hybrids (42 V-150 V:</strong> Micro HEV Function + Regen)</td>
<td>NiMH and Li-ion: Yes</td>
<td>Ucaps: Likely if engine is not downsized</td>
<td>25-70 Wh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ucaps + VRLA: Possible</td>
<td></td>
</tr>
<tr>
<td><strong>Full Hybrids (150 V-350 V:</strong> Power Assist HEV)</td>
<td>NiMH and Li-ion: Yes</td>
<td>Ucaps: Possible</td>
<td>60-150 Wh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ucaps + (NiMH or Li-ion): Possible</td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Cell Hybrids</strong></td>
<td>NiMH and Li-ion: Yes</td>
<td>Ucaps: Likely if Fuel Cell is not downsized</td>
<td>60-150 Wh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ucaps + (NiMH or Li-ion): Possible</td>
<td></td>
</tr>
<tr>
<td><strong>Plug-in HEV (EV)</strong></td>
<td>Li-ion: Yes</td>
<td>Ucaps + high energy Li-ion: Possible</td>
<td>5-20 kWh (50-90 Wh*)</td>
</tr>
</tbody>
</table>

* Energy for a Ucap in combination with Li-Ion
Analyzing the Impact of Energy Window on Power-Assist HEVs

- **Motivation:** Investigate the relation between in-use energy window and fuel economy (a request from USABC/FreedomCAR)
- **Approach:** Simulate a midsize sedan with different component power levels and control settings for different drive cycles using PSAT

**Midsize Car Assumptions**

- Mass = 1675 kg
- Engine = 90 kW
- RESS/Motor = 30 kW
- Elec accessories = 500 W
- Mech accessories = 230 W

**Simulated different ES energy content cases with the otherwise constant platform values**

- Smallest ES energy
- Largest ES energy

**Constant 30 kW power → changing P/E ratio**

- Wh
  - Upper threshold
  - Target level
  - Lower threshold

**Constant SOC-based controls (charge sustaining)**

- Changing Wh control window tolerance

Source: J. Gonder, Presentation to USABC, July 19, 2007
Definition of ES Energy Window Use (for a drive cycle or event)

RESS use indicated by slope of energy line

Energy out for electric launch/assist

Energy return from charging/regen

“Energy window” defined by (max – min) for the particular cycle

Charge sustaining over cycle

(no net energy use)

Energy Window Used ≤ Available Energy

Source: J. Gonder, Presentation to USABC, July 19, 2007
Three Cycles Simulated to Observe Energy Window and Fuel Use

**Aggressive driving**
US06 Cycle
- Mean power during:
  - Propulsion = 21 kW
  - Deceleration = -17 kW
- No grade

**Mild urban driving**
UDDS Cycle
- Mean power during:
  - Propulsion = 7 kW
  - Deceleration = -5 kW
- No grade

**Up and down, foothills driving**
“NREL to Genesee Cycle”
- Mean power during:
  - Propulsion = 23 kW
  - Deceleration = -12 kW
- Considerable grade

Source: J. Gonder, Presentation to USABC, July 19, 2007
On City Cycle (UDDS), Large Fuel Savings Result from Hybridization

Conventional Vehicle

Smallest RESS case

Largest RESS case

21% decrease

18% decrease

Source: J. Gonder, Presentation to USABC, July 19, 2007
Summary Results of ES Energy Window and Fuel Economy Simulations

Source: J. Gonder, Presentation to USABC, July 19, 2007
All the charge sustaining (CS) tests use windows <200 Wh (for these vehicles and CS cycles)

Test data analysis seems to validate simulation finding of significant hybridization benefit in the 50-150 Wh range

Prius and Escape Test Data: Tony Markel, NREL
Camry and Accord Test Data: Mike Duoba, ANL
Test Data Analysis: Jaehun Rhee and Jeff Gonder, NREL

Source: J. Gonder, Presentation to USABC, July 19, 2007
2007 Mild Hybrid Dyno Data* Analysis Indicates <50 Wh Energy Use for Typical Driving—Already Reasonable Ucap Range

* Department of Energy-sponsored dynamometer testing
Mild and Power-Assist Hybrids with Ucaps

- It is possible to use ultracapacitors (with available energy of 50-150 Wh) in power-assist HEVs with modest fuel economy improvements
  - However, acceleration and passing on grade performance considerations could be limiting factors
- 15%-30% HEV fuel economy improvements with 50-100 Wh ultracapacitors
- A project is underway on a vehicle to demonstrate Ucaps in mild hybrids
  - To be discussed in future meetings
Previous NREL Tests Have Shown That Combining Ultracapacitors Filters High Current Transients In Batteries

Source: M. Zolot (NREL Reports and 2003 Florida Capacitor Seminar)

Parallel connection; no DC/DC converter May not be practical to implement in vehicles.

- Overall, batteries in the hybrid pack experienced no currents larger than ±40 A, while the batteries in traditional pack saw currents up to ±110 A.
- Up to 33% narrower battery SOC cycling range was observed in hybrid pack; this has the potential to increase battery life.
Advantages/Disadvantages of Hybridizing Energy Storage (Ucap + Battery)

Advantages
• Reduced battery currents
• Reduced battery cycling range
• Increased battery cycle/calendar life (to what extent?)
• Increased combined power and energy capabilities
• Lower cooling requirements
• Better low-temperature performance

Disadvantages
• Complex control strategy
• Larger volume & mass
• Need for electronics for each system
• Increased energy storage cost
• Unknown side effects if directly coupled
• Any need for DC/DC converters adds even more cost and complexity

Thermal/Electrical Characterization of JSR Micro Lithium Ion Capacitor (LIC)

- JSR Micro contacted us to express interest in thermal characterization of their asymmetric capacitor

- JSR Micro claimed higher energy than C-C Ucaps with the same power capability

- We received 3 cells for characterization per USABC protocols

Source: www.jmenergy.co.jp/en/product.html
## JSR Micro LIC Cell Characteristics

<table>
<thead>
<tr>
<th>Cell Number (#)</th>
<th>Mass (kg)</th>
<th>Voltage (Volts)</th>
<th>Dimensions (inches)</th>
<th>Impedance (mOhms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>0.205</td>
<td>2.669</td>
<td>5.5&quot; x 4&quot; x 0.330&quot;</td>
<td>1.58</td>
</tr>
<tr>
<td>Cell 2</td>
<td>0.205</td>
<td>2.669</td>
<td>5.5&quot; x 4&quot; x 0.330&quot;</td>
<td>1.62</td>
</tr>
<tr>
<td>Cell 3</td>
<td>0.205</td>
<td>2.672</td>
<td>5.5&quot; x 4&quot; x 0.330&quot;</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Nominal 2200 F  
14 Wh/kg  
3.8 V – 2.2 V

Source: www.jmenergy.co.jp/en/product.html
Infrared Thermal Imaging

Temperatures: Ambient
Profiles: 50°C, 100°C, and Geometric Cycle

Cell #1  Cell #2  Cell #3

Cell #1

Cell #2

Cell #3
Thermal Image and Thermal Lines of 3 LIC Cells – 100 A Discharge
Thermal Characterization in NREL Calorimeter
Lithium Ion Capacitor 2200 F Cells

- Temperatures: +30°C
- Profiles: CC discharge cycles

Discharge - Exothermic

Charge - Endothermic

Increasing Discharge Current

Increasing Charge Current

Calorimeter Response to Constant Current Charge/Discharge
Electrical Characterization:
Lithium Ion Capacitor Cells

• C/1, 10 C, 100 C, and HPPC Testing

Energy: 14 Wh/kg

Power: 1500 W/kg

This asymmetric capacitor had high resistance; the next generation is claimed to be better.
Expected Calendar Life of Typical Current EDLC Technology
Much Better Than Batteries if Stored at Low Voltages

Source: Anderman, 2004 Advanced Automotive Battery Conference
Thermal Evaluation: High-Voltage Ultracap Module

- Tested as part of USABC deliverable
- Eighteen (18) symmetric carbon-carbon ultracapacitors
- Tested under realistic conditions and operation
- Used different power profiles and chamber temperatures

Heat from cells is conducted through the ends to the case and rejected through the top metal heat sink/fins.
Thermal Evaluation: High-Voltage Ultracap Module

- Continuous US06 cycling for two hours
- Balancing board did a good job equalizing cells
- Energy drain for balancing could be a concern

Temperature difference less than 1.5°C except for Cell #1 which heated due to balancing board.
Concluding Remarks

• Ultracapacitors provide opportunity for modest fuel savings in hybrid cars
  — Idle-off: 5%-10% FE improvement and most likely to be implemented
  — Mild and full hybrid: 15%-25% FE improvement, possible
  — Plug-in hybrids: possible Ucap combined with batteries; cost??

• Competition from Li-ion is strong; ultracapacitors should provide “added value” to compete
  — Low-temp performance
  — Longer cycle and calendar life

• Asymmetric capacitors such as lithium ion capacitors have potential if power and cost are improved

• Thermal issues are important and must be taken into account to achieve the desired performance and life

• Lower cost is the key for increased market growth in automotive

• Micro and mild hybrids provide biggest opportunity for Ucaps in the short term; will be accelerated by new CAFÉ mandates
Acknowledgements

• Support provided by FreedomCAR and Fuel Partnership in the Vehicle Technologies Program of the U.S. Department of Energy
  — David Howell, Energy Storage Technology Manager

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  — Harshad Tataria, USABC/GM
  — Jim Banas, JSR Micro Inc.

nrel.gov/vehiclesandfuels/energystorage/publications.html