Ultracapacitor Applications and Evaluation for Hybrid Electric Vehicles

Ahmad Pesaran
(ahmad.pesaran@nrel.gov)
Jeff Gonder, Matt Keyser
National Renewable Energy Laboratory
Presented at the 7th Annual Advanced Capacitor World Summit Conference
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• 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 Ṫ</td>
<td>70 Wh</td>
</tr>
<tr>
<td>4% Grade going 35 mph for 1 minute Ṫ</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>

(Pointer: 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>Type</th>
<th>Technology Options</th>
<th>Min energy needed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Micro Hybrids</strong> (12 V-42 V: Start-Stop, Launch Assist)</td>
<td>NiMH and Li-ion: Yes, Ucap: Likely, Ucap + VRLA: Possible</td>
<td>15-25 Wh</td>
</tr>
<tr>
<td><strong>Mild Hybrids</strong> (42 V-150 V: Micro HEV Function + Regen)</td>
<td>NiMH and Li-ion: Yes, Ucaps: Likely if engine is not downsized, Ucaps + VRLA: Possible</td>
<td>25-70 Wh</td>
</tr>
<tr>
<td><strong>Full Hybrids</strong> (150 V-350 V: Power Assist HEV)</td>
<td>NiMH and Li-ion: Yes, Ucaps: Possible, Ucaps + (NiMH or Li-Ion): Possible</td>
<td>60-150 Wh</td>
</tr>
<tr>
<td><strong>Fuel Cell Hybrids</strong></td>
<td>NiMH and Li-ion: Yes, Ucaps: Likely if Fuel Cell is not downsized, Ucaps + (NiMH or Li-Ion): Possible</td>
<td>60-150 Wh</td>
</tr>
<tr>
<td><strong>Plug-in HEV (EV)</strong></td>
<td>Li-ion: Yes, 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
- FA = 2.27 m²
- CD = 0.30
- Crr1 = 0.008
- Crr2 = 0.00012

### 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**

- 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)

Cumulative RESS Wh to vehicle

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

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

<table>
<thead>
<tr>
<th>RESS Energy Window (Wh)</th>
<th>Fuel Consumption (L/100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.8</td>
</tr>
<tr>
<td>50</td>
<td>20.5</td>
</tr>
<tr>
<td>100</td>
<td>22.4</td>
</tr>
<tr>
<td>150</td>
<td>24.8</td>
</tr>
<tr>
<td>200</td>
<td>27.7</td>
</tr>
<tr>
<td>250</td>
<td>31.4</td>
</tr>
<tr>
<td>300</td>
<td>36.2</td>
</tr>
<tr>
<td>350</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

**Source:** J. Gonder, Presentation to USABC, July 19, 2007
Vehicle Test Results: Battery Energy Use for Today’s HEVs under Various Drive Cycles

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.

Ultracapacitor module of 8 cells (up to 20V) and two 6.5Ah NiMH module of 14.4V (18V max). Ultracap module and battery pack were arranged in parallel to share the current load depending on internal impedance.

- 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

\[
\frac{1}{C_{\text{cell}}} = \frac{1}{C_-} + \frac{1}{C_+}
\]

- 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

Infrared Thermal Imaging

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

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