Power Electronics Architecture R&D

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May 14, 2013

Project ID: APE056

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Overview

Timeline
• Start – FY13
• Finish – FY15
• 22% complete

Barriers
• Boost ratio/range and efficiency that can drive dc-dc converter architectural choices,
• Potential cost addition due to choice of dc-dc converter and hybrid energy storage systems

Targets Addressed
• Traction Drive Power Electronics DOE 2020 targets
  • Power density: >13.4 kW/l
  • Specific power: >14.1 kW/kg
  • Service life: >15 years or 13000 hours

Partners
• ORNL - Burak Ozpineci, Bradley Brown, Jianlin Li, Lixin Tang, Tim Burress, Madhu Chinthavali, Cliff White, Larry Seiber, Steven Campbell

Budget
• Total project funding
  - DOE share – 100%
• Funding for FY13: $ 375K
Project Objective

• Overall Objective
  – Develop a bi-directional buck/boost dc-dc converter between the regenerative energy storage systems (RESS) and the dc link (traction drive inverter),
    • Active energy management, inverter efficiency improvement, better RESS utilization.
  – Design a hybrid battery/ultra-capacitor energy storage system architecture,
    • Improved regenerative braking performance, improved overall fuel economy (all-electric range), improved power density, peak power capability, and improved battery lifetime.
  – Design a modular reconfigurable battery and dc-dc converter architecture,
    • Lower overall power electronics kVA rating and cost reduction on dc-dc converter.

• FY13 Objective
  – Model, simulate, and analyze a modular reconfigurable dc-dc converter architecture.
<table>
<thead>
<tr>
<th>Date</th>
<th>Milestones and Go/No-Go Decisions</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 2013</td>
<td><strong>Milestone</strong>: Model and simulate the modular reconfigurable dc-dc converter structures that are best utilized to meet the vehicle power demand.</td>
<td>On track</td>
</tr>
<tr>
<td>August 2013</td>
<td><strong>Milestone</strong>: Model and simulate various hybrid RESS architectures.</td>
<td>On track</td>
</tr>
<tr>
<td>August 2013</td>
<td><strong>Go/No-Go decision</strong>: CHANGE if simulation results show that hybrid RESS approach outperforms the reconfigurable and modular RESS battery approach.</td>
<td></td>
</tr>
<tr>
<td>September 2013</td>
<td><strong>Milestone</strong>: Prepare a summary report that documents the results, findings, performance comparisons, and recommendations to be incorporated into the annual VTO report.</td>
<td>On track</td>
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</table>
Approach/Strategy

• Current State-of-the-art Traction Drive System
  • Single battery pack utilized regardless of the power demand,
  • Single energy storage system (batteries) → Coupled power and energy requirement,
  • Regenerative Energy Storage System (RESS) - Motor drive inverter interface converter High inverter current → Lower efficiency

• Future traction drive system layout
Approach/Strategy

- Develop bidirectional dc-dc converter architectures:
  - Dual active bridge dc-dc converter,
  - Two-quadrant dc-dc buck-boost converter,
  - Resonant/improved dual active bridge converter,
  - Single stage dual active half-bridge dc-dc converter,
  - Current boosted active clamp forward dc-dc converter,
  - Bi-directional four switch buck-boost dc-dc converter,
  - Bi-directional dc-dc CUK converter,
  - Integrated buck/boost converter,
  - Multi-phase interleaved ZVS dc-dc converter.

*Dual active-bridge dc-dc converter*

*Interleaved 3-phase dc-dc converter*
Approach/Strategy (Cont’d)

- Develop control systems for active energy management that have potential for cost reduction and efficiency improvement.

- The RESS and modular dc-dc converters will be best utilized to meet the vehicle power demand.

- Utilize wide bandgap devices,

- Design for lower overall kVA rating and cost,

- Improved service life,

- Reduce the thermal management burden.

Modular reconfigurable RESS and dc-dc converters
Technical Accomplishments and Progress – Overall

• Reviewed and modeled bi-directional dc-dc converter architectures that interface the RESS to the traction drive inverter and created a summary report discussing on the operation principles, controls, advantages and drawbacks.

• Reviewed and modeled hybrid RESS architectures and created a summary report based on the advantages, drawbacks, control systems, performance, number of parts, etc.

• Selected and modeled four battery/UC hybridization strategies.
  – Built simulation models of the battery and UC.
  – Modeled hybridization architectures.
  – Due to simulation time constraints, a portion of the UDDS drive cycle, t=[690, 760] that includes acceleration, braking, and idling simulated for these hybridization architectures.
  – Collected and compared simulation results.
  – Created a comparison results table for these RESS hybridization architectures.
Technical Accomplishments and Progress

- Developed power electronic interfaces for hybrid RESS:
  - Decoupled energy and power: battery/ultra-capacitor (UC)
  - Active power and energy management based on the drive train power demand

**Passive Parallel Architecture (PPA)**

**Cascaded Converters Architecture (CCA)**

**UC – dc-dc Converter – Battery Architecture (UCDCBA)**

**Parallel with Multi-Converters Architecture (PMCA)**
Technical Accomplishments and Progress

- Implemented a cell pack model needed in dynamic system simulations

\[
\begin{aligned}
&\text{+ (charge)} \quad \frac{1}{s} \quad \text{Sel} \\
&\text{(discharge)} \quad Sgn \text{ fnc.} \\
&\begin{aligned}
\text{Exp}(s) &= \frac{A}{\text{Sel}(s)} \\
\text{Sel}(s) &= \frac{1}{B_i_i(t)} + 1
\end{aligned}
\end{aligned}
\]

- Utilized the governing charge and discharge equations of the model

- A controlled voltage source was used (current controlled voltage source to represent \( V=f(I) \) cell characteristics)

- Voltage was calculated with a non-linear equation based on the state-of-charge (SOC) of the cell; \( V=f(I,\text{SOC}) \)


- Example discharge curves
Technical Accomplishments and Progress

- Completed simulations for the passive parallel, cascaded, modified cascaded, and the multiple parallel converters architectures under same conditions.

- Due to simulation time constraints, a portion of the UDDS drive cycle, $t=[690, 760]$ that includes acceleration, braking, and idling simulated for these hybridization architectures.

**UDDS drive cycle power demand**
Technical Accomplishments and Progress

• Completed PPA (Passive Parallel Architecture) Simulations

PPA Control System

Voltage control loop

\[ V_{dc_{ref}} + \frac{s^2K_D + sK_P + K_i}{s} \]

PID Controller

Converter reference current

Current Control Loop

Switching Oscillator

\[ f_s = 10kHz \]

Comparator

S-R Latch

\[ G_{1,2} \]

Load current

Battery current

Battery SOC

UC SOC

DC link voltage
Technical Accomplishments and Progress

• Completed CCA (Cascaded Converters Architecture) Simulations

**Load current**

**Battery current**

**UC current**

**DC link voltage**

**Battery SOC**

**UC SOC**
Technical Accomplishments and Progress

- Completed CCA (Cascaded Converters Architecture) Simulations with modified controls

CCA Modified Control System

Battery reference current computation

\[ i_{batt}^* \left( \frac{V_{load}}{V_{batt}} \right) \]

Low-pass Bessel Filter

Rate limiter

Saturation

Battery current

UC current

Battery SoC

UC SOC

DC link voltage
Technical Accomplishments and Progress

- Completed MPCA (Multiple Parallel Converters Architecture) Simulations

**Load current**

**Battery current**

**UC current**

**DC link voltage**

**Battery SoC**

**UC SoC**
Technical Accomplishments and Progress (Cont’d)

- Created Results Table

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Passive Parallel (PPA)</th>
<th>Cascaded Converters (CCA)</th>
<th>Cascaded (manipulated controls) (CCA)</th>
<th>Parallel Converters (MPCA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control simplicity</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Structure complexity</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of converters</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of inductors</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total inductor mass</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Number of transducers</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Cycle-end battery SoC</td>
<td>86.7194%</td>
<td>86.2462%</td>
<td>86.6598%</td>
<td>87.0305%</td>
</tr>
<tr>
<td>Cycle-end ultra-capacitor SoC</td>
<td>89.8995%</td>
<td>91.9084%</td>
<td>90.4502%</td>
<td>87.1022%</td>
</tr>
<tr>
<td>Maximum battery current ripple</td>
<td>~7 [A]</td>
<td>~9 [A]</td>
<td>~1.7 [A]</td>
<td>~1.8 [A]</td>
</tr>
<tr>
<td>Cycle based energy efficiency (RESS and dc-dc converters combined)</td>
<td>95.25%</td>
<td>90.34%</td>
<td>90.72%</td>
<td>95.25%</td>
</tr>
<tr>
<td>Maximum DC link voltage variation percentage</td>
<td>2.52%</td>
<td>2.42%</td>
<td>2.51%</td>
<td>0.77%</td>
</tr>
</tbody>
</table>
Conclusions

- According to the simulation results, PPA has the simplest structure and the least number of parts and components.

- The high efficiency of PPA is mainly due to the simple configuration and to the fact that there is no additional dc-dc converters used for hybrid RESS.

- Although PPA has high efficiency, it does not provide control flexibility and the battery current ripple and DC link voltage ripple values are not as good as MPC architecture.

- MPCA provides the highest efficiency (as high as the PPA) and the best DC link voltage and battery current ripples.

- Improving the controls with an additional current rate limiter for the CCA improved the efficiency and the overall performance.

- Efficiency is computed as the cycle based energy efficiency; i.e., the input and output power of the system is integrated over the time period of simulation.
## Collaboration and Coordination

<table>
<thead>
<tr>
<th>Organization</th>
<th>Type of Collaboration/Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell, IOXUS</td>
<td>Fast response electrochemical capacitor development</td>
</tr>
<tr>
<td>Chrysler</td>
<td>Power electronics dc-dc interface trends for RESS</td>
</tr>
<tr>
<td>ORNL Energy Storage Program</td>
<td>Design guidelines and research on modular battery pack configuration</td>
</tr>
<tr>
<td>ORNL Battery Manufacturing Facility</td>
<td>Manufacturing research on modular battery development</td>
</tr>
</tbody>
</table>
Proposed Future Work

• Remainder of FY13
  – Modeling, simulations, and analysis of modular reconfigurable dc-dc converter architectures. Share results with APEEM team members.

• FY14
  – Fabricate and test a candidate 10 kW reconfigurable dc-dc converter architecture for experimental validation of models and simulations. Share results with APEEM team members.

• FY15
  – Fabricate and test a full rated (55 kW) reconfigurable dc-dc converter architecture. Share results with APEEM team members.
Summary

- **Relevance:** This project is targeted toward active energy management and reduced size and cost of the power electronic converters that interface RESS and traction drive inverter.

- **Approach:**
  - Develop a bi-directional buck/boost dc-dc converter between the regenerative energy storage systems (RESS) and the dc link (traction drive inverter),
  - Design a hybrid battery/ultra-capacitor energy storage system architecture,
  - Design a modular reconfigurable dc-dc converter architecture,

- **Collaborations:** Collaborations with Chrysler, Maxwell, IOXUS, and ORNL’s Energy Storage Programs and Battery Manufacturing Facility are being used to maximize the impact of this work.

- **Technical Accomplishments:**
  - Reviewed and modeled bi-directional dc-dc converters.
  - Reviewed and modeled hybrid RESS architectures and created a summary report based on the advantages, drawbacks, control systems, performance, number of parts, etc.
  - Selected and modeled four battery/UC hybridization strategies. Run the simulations and compared the performance results.