Inverter Using Current Source Topology

Gui-Jia Su
Oak Ridge National Laboratory
May 10, 2011

Project ID: APE002


This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline

• Start – FY10
• Finish – FY12
• 50% complete

Budget

• Total project funding
  – DOE share – 100%
• Funding for FY10
  – $816K
• Funding for FY11
  – $640K

Barriers

• Cost, weight, volume of the bus capacitor
  – Cost and weight, up to 23% of an inverter
  – Volume, up to 30% of an inverter
• Capacitor high temperature capability
• Undesirable characteristics of the VSI
• High system cost resulted from use of single-function modules

• Inverter targets (2015): $5/kW, 12 kW/kg, 12 kW/l

Partners

• ORNL team members: Lixin Tang, Cliff White, Mike Jenkins, John Hsu
• Michigan State University
• Fuji Electric Semiconductors
• Powerex
Objectives

• Develop novel ZCSI topologies that combine the benefits of ORNL’s Current Source Inverter (CSI) efforts and MSU’s work on Z Source Inverters (ZSI) to significantly reduce cost and volume through the integration of voltage boost, inverter, regen and PEV charging functions

• FY11 Objectives
  – Perform a simulation study on ways to reduce passive component requirements for ZCSIs
    • New voltage boost control methods
    • Impact of increasing switching frequency with wide bandgap switches
  – Assemble and test a 10 kW ZCSI setup using RB-IGBT to validate the simulation study
## Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
</tr>
</thead>
</table>
| Sept-2010  | **Milestone**: Completion of simulation study on selected new ZCSI topologies.  
**Go/No-Go Decision**: Determine from simulation results whether the ZCSIs can meet these goals: 1) a voltage boost capability of 3X, 2) a capability to charge the battery in both buck and boost mode during dynamic breaking, and 3) a reduction of motor voltage harmonic distortion of 90%. |
| Sept-2011  | **Milestone**: Completion of building and testing a 10 kW ZCSI  
**Go/No-Go Decision**: Determine from test results whether the ZCSI can meet these goals: 1) an inherent voltage boost capability of 3X, 2) a capability to charge the battery in both buck and boost mode during dynamic breaking, and 3) a reduction of motor voltage harmonic distortion of 90%. |
Approach (1)

- The VSI
  - Require a bulky & expensive bus capacitor
  - Produce undesired output voltage waveforms that cause
    - High EMI noises
    - High stress on motor insulation
    - High-frequency losses
    - Bearing-leakage currents
  - Present a shoot-through failure mode that is a cause for long-term reliability concerns
  - Output voltage limited by battery voltage; a separate dc-dc converter is needed for voltage boosting

- ZCSI with a quasi-Z network:
  - Use a passive quasi-Z network of inductor, capacitor, and diode in the CSI to enable
    - Single stage buck & boost conversion
    - Battery charging
    - Safe operation in open circuit events
  - Eliminate antiparallel diodes with reverse-blocking IGBTs and GaN switches
  - Reduce total capacitance
  - Produce sinusoidal voltages & currents to the motor
  - Tolerant of phase-leg shoot-through and open circuit
  - Extend constant-power speed range without a separate boost converter
Approach (2)

- Eliminate antiparallel diodes with reverse-blocking IGBTs could shrink the footprint of power modules by 50 – 60%
CSI can be configured to operate as a charger in PEVs

- Charge battery from a single-phase source of 120V or 240V
- Charge battery from a three-phase source
- Charge batteries over a wide range of voltage levels due to CSI’s capability to buck and boost the output voltage
FY10 Technical Accomplishments (1)

- Confirmed by simulation the feasibility of using the ORNL CSI topology in series and power-split series/parallel HEV configurations
- The CSI dual-motor-drive (DMD) PE using RB-IGBTs provides significant performance improvements over the Camry PE
- Developed two new ZCSIs with a reduced component count and a higher voltage boost ratio (3 vs. 2 for the previous ZCSIs)
  - Current-fed Trans-ZSI (CF-trans-ZSI)
  - Current-fed Trans-quasi-ZSI (CF-trans-qZSI)
- Completed a design for a 55 kW ZCSI based on the CF-trans-qZSI
  - Using the first generation RB-IGBT technology
  - Power density: 16.6 kW/L
  - Specific power: 4.89 kW/kg
FY10 Technical Accomplishments (2)

- ORNL CSI dual-motor-drive (DMD) for HEVs/PHEVs using two motors
  - Share a single dc link inductor and battery interface circuit
  - Enable 3 operation modes: 1) both M/Gs in motoring, 2) both in regen, and 3) one in motoring and one in regen
  - Can produce even higher output voltages for the motor compared to a single CSI drive
FY10 Technical Accomplishments (3)

- Predicated performance improvements of the CSI DMD PE over the Camry PE

<table>
<thead>
<tr>
<th></th>
<th>Camry PE</th>
<th>CSI DMD PE with regular IGBT&lt;sup&gt;a,b&lt;/sup&gt;</th>
<th>CSI DMD PE with RB-IGBT&lt;sup&gt;a,b,c,d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>3.57</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Volume (L)</strong></td>
<td>2.6</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Cost ($)</strong></td>
<td>$260</td>
<td>$26</td>
<td>$26</td>
</tr>
<tr>
<td><strong>Side housing</strong></td>
<td>1.2</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td><strong>Volume (L)</strong></td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>Cost ($)</strong></td>
<td>$1,040</td>
<td>$1,040</td>
<td>$728</td>
</tr>
<tr>
<td><strong>Power module</strong></td>
<td>5</td>
<td>5.00</td>
<td>2.75</td>
</tr>
<tr>
<td><strong>Volume (L)</strong></td>
<td>4.3</td>
<td>4.30</td>
<td>2.37</td>
</tr>
<tr>
<td><strong>Cost ($)</strong></td>
<td>$1,040</td>
<td>$1,040</td>
<td>$325</td>
</tr>
<tr>
<td><strong>Boost/V-I converter</strong></td>
<td>6.6</td>
<td>6.60</td>
<td>6.60</td>
</tr>
<tr>
<td><strong>Volume (L)</strong></td>
<td>3.5</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td><strong>Cost ($)</strong></td>
<td>$325</td>
<td>$325</td>
<td>$325</td>
</tr>
<tr>
<td><strong>subtotal</strong></td>
<td>16.37</td>
<td>13.16</td>
<td>10.91</td>
</tr>
<tr>
<td><strong>Weight (kg)</strong></td>
<td>1.20</td>
<td>2.75</td>
<td>2.75</td>
</tr>
<tr>
<td><strong>Volume (L)</strong></td>
<td>0.98</td>
<td>2.37</td>
<td>2.37</td>
</tr>
<tr>
<td><strong>Cost ($)</strong></td>
<td>$728</td>
<td>$325</td>
<td>$325</td>
</tr>
<tr>
<td><strong>Reduction in kg, L &amp; $</strong></td>
<td><strong>20%</strong></td>
<td><strong>21%</strong></td>
<td><strong>14%</strong></td>
</tr>
<tr>
<td><strong>Metrics</strong></td>
<td>4.3</td>
<td>5.3</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>kW/kg</strong></td>
<td>6.2</td>
<td>7.7</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>kW/L</strong></td>
<td>23.2</td>
<td>19.9</td>
<td>15.4</td>
</tr>
<tr>
<td><strong>$/kW</strong></td>
<td>$260</td>
<td>$1,040</td>
<td>$728</td>
</tr>
<tr>
<td><strong>Increase in kW/kg &amp; kW/L</strong></td>
<td>24%</td>
<td>26%</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Reduction in $/kW</strong></td>
<td>14%</td>
<td>14%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Assumptions:  
a) 90% reduction of capacitance,  
b) 20% of inverter cost from capacitor,  
c) 30% reduction in diode cost of the inverter switch module,  
d) 45% reduction in diode volume and weight of the inverter switch module,  
e) no changes between the boost converter in the Camry PE and V-I converter in the CSI.
FY10 Technical Accomplishments (4)

- Original current-fed ZSIs topologies
  - The original current-fed ZSI
  - Current-fed qZSI

- New ZCSIs developed under this project
  - The newly developed current-fed Trans-ZSI and Trans-quasi-ZSI feature wider motoring operation range and reduced component count.
FY10 Technical Accomplishments (5)

- Comparison of voltage boost ratio vs. duty ratio $D_A$ (simulation results)

Current-fed qZSI

New current-fed Trans-ZSI
FY10 Technical Accomplishments (7)

- Completed a design for a 55 kW CF-trans-qZSI for the following conditions:
  - Peak power rating: 55 kW
  - Battery voltage, $V_{in}$: 260 V
  - Output line-to-line voltage: 0~500 V
  - Switching frequency: 10 kHz
  - Coupled inductor turns ratio: 2

Power density: 16.6 kW/L
Specific power: 4.89 kW/kg

Camry: 7.4 kW/L, 4.6 kW/kg
2015 targets: 12 kW/L, 12 kW/kg
FY11 Technical Accomplishments (6)

- Simulation results of the CF Trans-qZSI with wider motoring operation range

Simulated waveforms in boost mode

Simulated waveforms in buck mode
FY11 Technical Accomplishments (8)

- Hardware design and fabrication for a 10 kW ZCSI setup
  - Use Fuji RB-IGBTs
  - Optimize design of coupled inductor with amorphous core

Water cooled heat sink: 12”x7”

- Z-network coupled inductor
- Output Capacitors
- Fuji RB-IGBT module: has 18 600V/200A switches; only six are needed
Collaborations

• Michigan State University – current-fed Z-source inverter (ZCSI) topologies

• Powerex – design and fabrication of custom IGBT modules for prototype development

• Fuji Electric Semiconductor – reverse blocking (RB) IGBT modules and RB-IGBTs developments

• ORNL, John Hsu - collaborating to eliminate the inductors
Future Work

• Remainder of FY11
  – Finalize hardware design for a 10 kW ZCSI
  – Complete DSP code development that implements the new boost control algorithm
  – Complete fabrication and test of the 10 kW ZCSI

• FY12
  – Design, fabricate, and test a 55 kW ZCSI prototype
Summary

- The ZCSIs offer opportunities to meet the 2015 inverter targets while providing additional capabilities of voltage boost and PEV charging function.

- ZCSIs using RB-IGBTs can substantially reduce power module cost, weight and volume by eliminating anti-parallel diodes.

- The ZCSIs possess desirable characteristics:
  - Sinusoidal voltages and currents to the motor.
  - Elimination of failure modes caused by open or short-circuit dc link.
  - Elimination of the uncontrolled PM regeneration failure mode.
  - Ripple-free battery currents.