High Power Density Integrated Traction Machine Drive

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Oak Ridge National Laboratory
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Project ID: APE024

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Overview

Timeline
• Start Date: Jan. 2010
• End Date: Sept. 2013
• 30% Complete

Barriers
• Barriers:
  – Simultaneously achieve high performance and fault tolerance while meeting high power density targets.
  – Ability to use low cost devices (Si) with acceptable high-temperature performance and reliability.

Budget
• Total project funding
  – DOE Share 100%
• Funding received in FY10
  – $389K
• Funding for FY11
  – $670K

Targets: DOE FreedomCAR 2020 power density (>4 kW/L) and efficiency (> 94%), 2015 cost (<$12/kW)

Partners
• ORNL Team Members: Zhenxian Liang, Puqi Ning, and Laura Marlino
• University of Wisconsin – motor & control
• University of Tennessee – high-temperature packaging
Objectives

• Develop a 55 kW high-density, fault-tolerant, integrated modular motor drive (IMMD) that is capable of operating at 200°C junction and 105°C coolant temperatures with improved packaging

• FY11 Objectives
  – Design and build a 10 kW demonstrator version IMMD with fault-tolerant controller to verify key performance characteristics
  – Design and fabricate first version 200°C Si IGBT modules for IMMD implementation
## Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
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</thead>
<tbody>
<tr>
<td>June-2010</td>
<td><em>Milestone</em>: Loss and thermal characterization of Si IGBT at 200°C</td>
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<tr>
<td>Sept-2010</td>
<td><em>Milestone</em>: Candidate packaging technologies selection</td>
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<tr>
<td>Dec-2010</td>
<td><em>Milestone</em>: Complete design of prototype 10 kW machine</td>
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<td>Jan-2011</td>
<td><em>Go/No Go Decision</em>: Design reviews to evaluate performance and fault tolerance capability, and to determine if prototype machine are ready for construction</td>
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<td>April-2011</td>
<td><em>Milestone</em>: Complete characterization of the Si IGBT operation at 200°C junction temperature</td>
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<tr>
<td>June-2011</td>
<td><em>Milestone</em>: Fabricate a prototype 200°C Si IGBT phase-leg module</td>
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<td>August-2011</td>
<td><em>Milestone</em>: Complete construction and testing of low-power (10 kW) version demonstrator IMMD motor</td>
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<td>Sept-2011</td>
<td><em>Go/No-Go Decision</em>: Evaluate demonstrator IMMD test results to decide whether to proceed to full-scale 55 kW IMMD prototype in FY12; Determine whether the high-temperature phase-leg module can meet the full-power IMMD requirements</td>
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Approach/Strategy

Integrated Modular Motor Drive (IMMD) Concept

Integration of modular machine-power electronics units in a combined single structure for density and cost gains
Approach/Strategy (cont’d)

High-temperature Si Device and Packaging

Theoretical Limit for Si Devices (Ref. Buttay et al.)

- Design device package to extend Si power modules to 200°C junction to meet temperature requirement for 105°C coolant in IMMD
- Eliminate baseplate and thermal interface material to reduce the thermal resistance, increase power density and save cost
- Integrate inverter and motor structure and cooling design
- Make use of the packaging research capability at ORNL and in collaboration with Power Device Packaging Project
**FY11 Technical Accomplishments**

**IMMD Machine Evaluation and Selection**

**6-Phase Machine (6P-b): 12 Slots / 10 Poles**

- Thorough comparative evaluation led to choice of 6-phase configuration with 12 stator slots and 10 poles, constructed with 6 stator phase modules. The choice considers the impact to the inverter.
- Selected machine exhibits attractive metrics in categories of power density, excitation frequency, module number, and rotor radial forces.
- A 10 kW demonstrator IMMD motor is under construction.
FY11 Technical Accomplishments

IMMD Fault-Tolerant Controller Architecture Development

5-Phase IMMD Demonstrator
Unit Testbed

Heterarchical Control Implementation of
Field-Oriented Control for 6-Phase IMMD

• Preferred fault-tolerant control architecture has independent controller for each phase

• All phase controllers share same sensor information and make decisions in parallel

• Algorithms being tested using available 5-phase IMMD testbed combined with TMS320F28035 32-bit microcontroller
FY11 Technical Accomplishments

Si IGBT Characterization and Evaluation at 200°C

Losses in one phase leg

IGBT losses and thermal analysis

- Selected 1200V/40A/175°C Si IGBT from Infineon for high temperature evaluation.
- Tested IGBT static and switching characteristics. Leakage current is high but losses are acceptable for operation at 200°C.
- Built the nondestructive SOA test board for latching and second breakdown evaluation.
- The IGBT can be successfully turned off without latching at 300A/250°C.

Nondestructive SOA verification board
Hot plate

Nondestructive latch-up current test board
Gate signal generation board

Latch-up current test at 250°C

DUT $V_{ge}$
DUT $V_{ce}$ 650V
DUT $I_c$ 300A

Coolant temperature: 105°C

Physics

Power dissipation line

Total loss curve

f$_s$=15kHz
f$_s$=10kHz
f$_s$=5kHz
R$_{thja}$=0.73K/W
R$_{thja}$=0.86K/W
R$_{thja}$=1.04K/W

Junction temperature

20 40 60 80 100 120 140 160 180 200
IGBT Loss

25C 100C 175C 200C

Pcon,IGBT  Psw,IGBT  Ploss  Pcon,diode
• Designed a Si device based 10 kW phase-leg power module package including materials selection, layout design, parasitics extraction and thermal performance characterization.

• With a two-pass tube liquid cold plate, the analysis shows the package can meet the IMMD power and thermal performance requirement, considering different coolants and 150°C ambient.

• Designed a modular cooling structure for 6-phase inverter.

<table>
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<tr>
<th>Component</th>
<th>Dimension (mm)</th>
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<tbody>
<tr>
<td>IGC50T120T6RL</td>
<td>7.25×6.84×0.115</td>
</tr>
<tr>
<td>Emitter Pad</td>
<td>5.36×5.74×0.004</td>
</tr>
<tr>
<td>Gate Pad</td>
<td>1.31×0.81×0.004</td>
</tr>
<tr>
<td>SIDC42D120F6</td>
<td>6.5×6.5×0.12</td>
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<tr>
<td>Anode Pad</td>
<td>5.78×5.78×0.004</td>
</tr>
<tr>
<td>Substrate</td>
<td>30.6×30×(Cu: 0.3, Al₂O₃: 0.635)</td>
</tr>
<tr>
<td>Die Attachment</td>
<td>Solder Au80Sn20, thickness: 0.2</td>
</tr>
<tr>
<td>Aluminum Wires</td>
<td>Gate pad 5 mils, others 10 mils ×6</td>
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</tbody>
</table>

(a) Simulated cooling performance of the packaging design

(a) 105°C water ethylene glycol

(b) 90°C transmission oil
FY11 Technical Accomplishments

Fabricated First Version Custom Module

- ABB dies (1200V/75A/150°C)
- DBC: alumina
- Die attachment: Sn63Pb37, thickness 100 μm
- Copper bus and lead frame: thickness 10 mils
- Encapsulant: Nu-2188
- Module fabricated with support from Power Device Packaging Project

IGBT Output Characteristics

DC Blocking Characteristics
FY11 Technical Accomplishments

System-level Electrical Design

Modular multiphase motor drive architecture

- Controller board and carrier board hardware designed and built
- Version 1 converter using phase-leg modules based on commercial IGBT modules built and tested
- Power board designed and built

Version 1 phase-leg modules (with driver boards)
Collaboration

• Partners
  – University of Wisconsin: Subcontractor, design and develop integrated modular motor drive system
  – University of Tennessee: Subcontractor, assist in design and testing power modules based on Si devices operating with 105°C coolant and 200°C junction temperatures
Future Work – FY11

• Complete fabrication and test the 10 kW 6-phase demonstrator IMMD motor to verify the machine design
• Implement and test fault-tolerant controller in the demonstrator IMMD
• Complete experimental evaluation of Si IGBT short-circuit and second breakdown characteristics at high temperatures
• Fabricate and test 10 kW high-temperature phase-leg power modules using Si devices appropriate for full power 55 kW IMMD
• Conduct system-level electrical and thermal design considering machine, device modules as well as passives and controllers under 105°C cooling conditions
Future Work – FY12 and beyond

- Scale up the power level of the IMMD technology to design, build, and demonstrate a prototype 55 kW IMMD system meeting the performance targets.
- Develop the power electronics needed for implementing the full power IMMD with 105°C coolant and junction temperatures up to 200°C.
- Combine the machine with high-temperature power converter and test the complete drive.
- Evaluate prototype drive test results against performance predictions to determine success of project.
Summary

• The project is developing a high-density integrated modular motor drive that will meet DOE 2020 power density and efficiency targets and the 2015 cost target

• The design will utilize low cost Si devices and high-temperature packaging and will be capable of operating at 200°C junction temperature with 105°C coolant

• The key FY10-FY11 accomplishments include:
  – A 6-phase 10-pole machine configuration has been selected and a 10 kW prototype is under construction
  – A fault-tolerant controller is being implemented and tested
  – Selected commercial Si IGBTs have been characterized at 200°C with acceptable loss characteristics and safe-operating-area
  – A prototype high-temperature custom Si IGBT phase-leg module has been designed and fabricated