U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

High Power Density Integrated Traction Machine Drive

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Oak Ridge National Laboratory
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Vehicle Technologies Program Annual Merit Review
and Peer Evaluation Meeting

Project ID: APE024

Overview

Timeline

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

Budget

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

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.
- 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

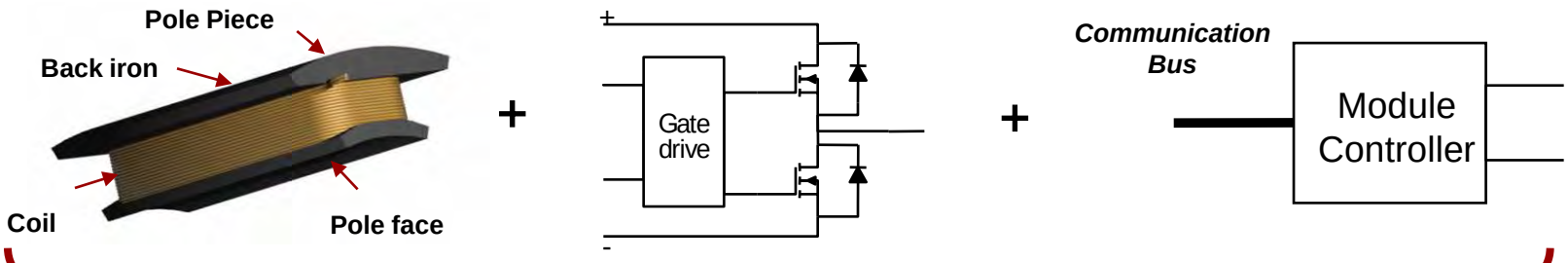
Milestones

Month/Year	Milestone or Go/No-Go Decision
June-2010	*Milestone:* Loss and thermal characterization of Si IGBT at 200˚C
Sept-2010	*Milestone*: Candidate packaging technologies selection
Dec-2010	*Milestone*: Complete design of prototype 10 kW machine
Jan-2011	*Go/No Go Decision:* Design reviews to evaluate performance and fault tolerance capability, and to determine if prototype machine are ready for construction
April-2011	*Milestone*: Complete characterization of the Si IGBT operation at 200˚C junction temperature
June-2011	*Milestone:* Fabricate a prototype 200˚C Si IGBT phase-leg module
August-2011	*Milestone*: Complete construction and testing of low-power (10 kW) version demonstrator IMMD motor
Sept-2011	*Go/No-Go Decision*: 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

Approach/Strategy

Integrated Modular Motor Drive (IMMD) Concept

Machine Pole ***Power Electronics*** ***Controller***



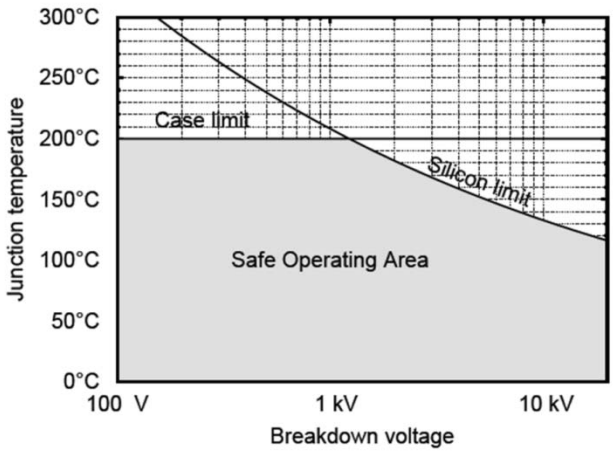
Modular Pole-Drive Unit

IMMD

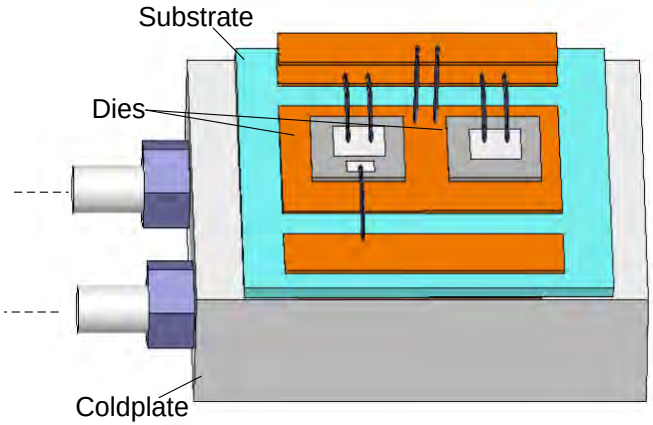
Integration of modular machine-power electronics units in a combined single structure for density and cost gains

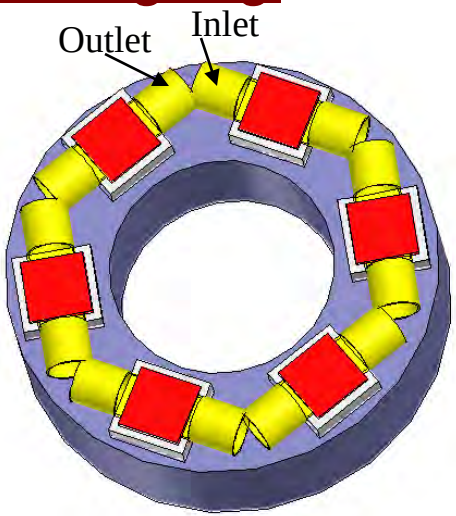
Approach/Strategy (cont'd)

High-temperature Si Device and Packaging



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





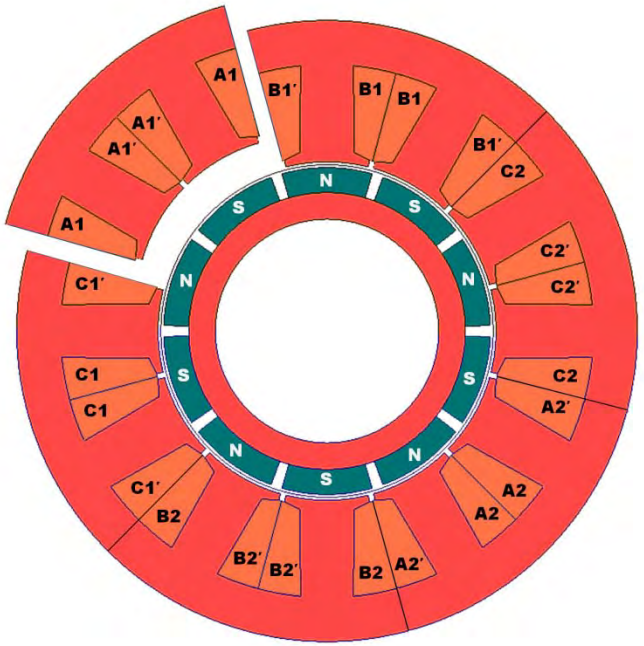
Device Packaging and Cooling

- ***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***

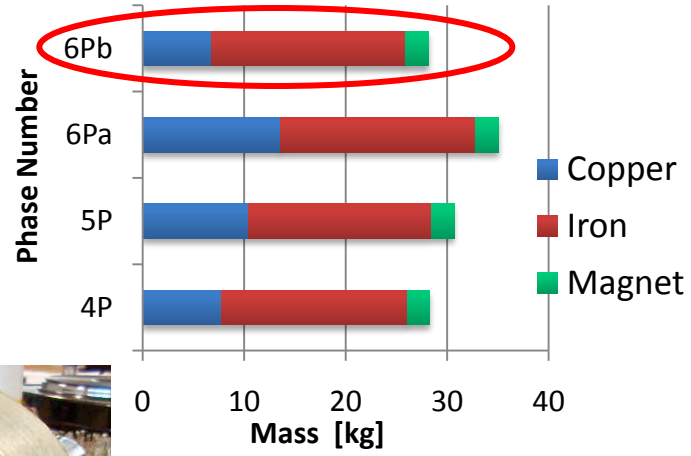
FY11 Technical Accomplishments

IMMD Machine Evaluation and Selection

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



Machine Mass Comparison



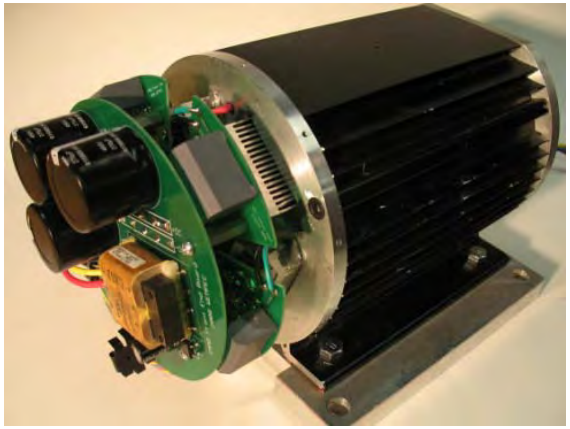
Assembled 10-Pole Rotor

- **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

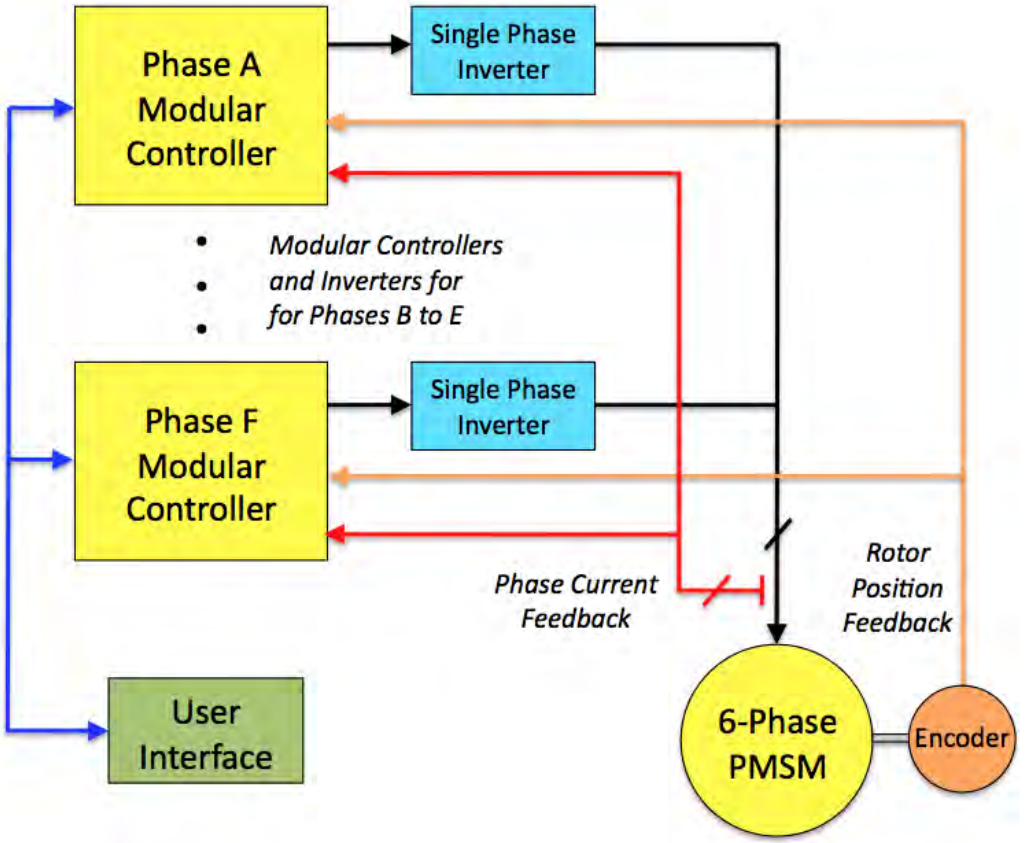
IMMD Fault-Tolerant Controller Architecture Development

5-Phase IMMD Demonstrator Unit Testbed



- **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**

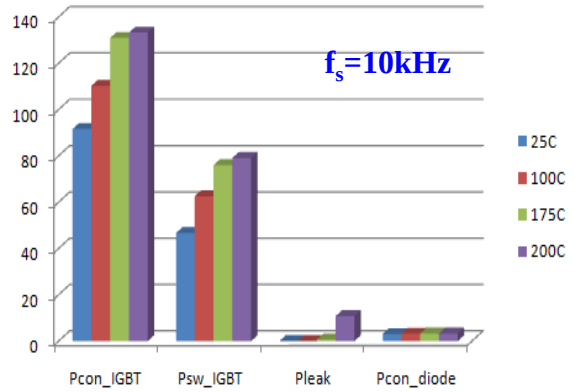
Heterarchical Control Implementation of Field-Oriented Control for 6-Phase IMMD



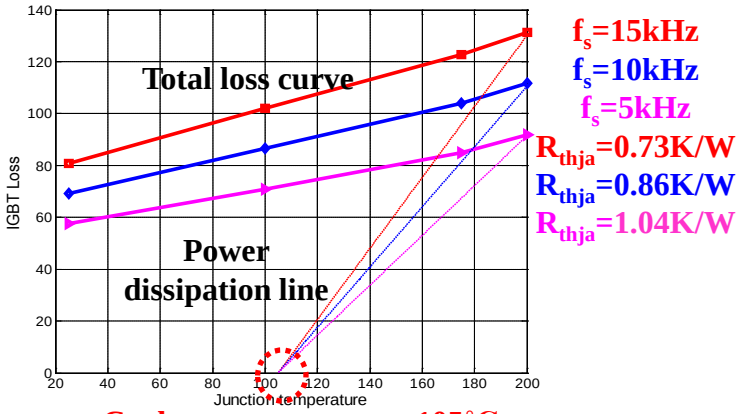
FY11 Technical Accomplishments

Si IGBT Characterization and Evaluation at 200˚C

Losses in one phase leg

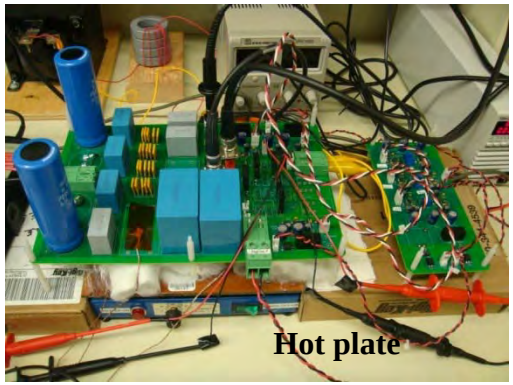


IGBT losses and thermal analysis



Coolant temperature: 105˚C

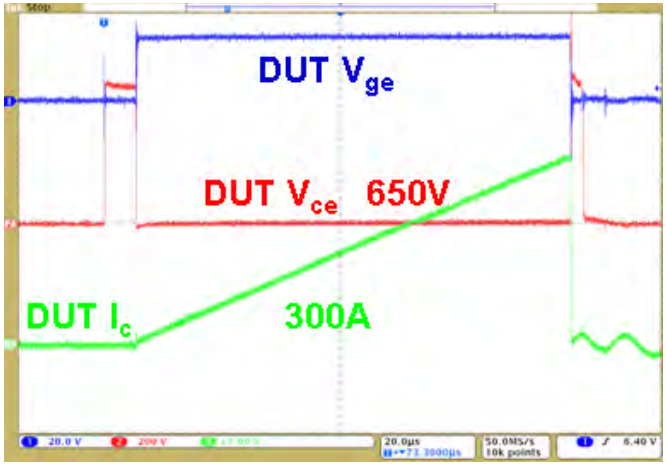
Nondestructive SOA verification board



Nondestructive latch-up current test board

Gate signal generation board

Latch-up current test at 250˚C

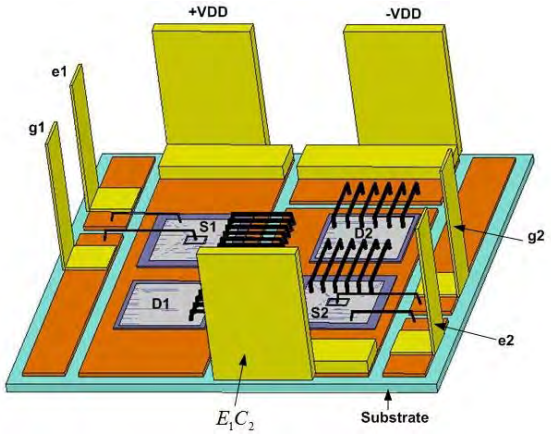


- Selected 1200V/40A/175˚C Si IGBT from Infineon for high temperature evaluation.
- Tested IGBT static and switching characteristics. Leakage current is high but losses are acceptable for operation at 200˚C.
- Built the nondestructive SOA test board for latching and second breakdown evaluation.
- The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

FY11 Technical Accomplishments

High Temperature Device Packaging Development

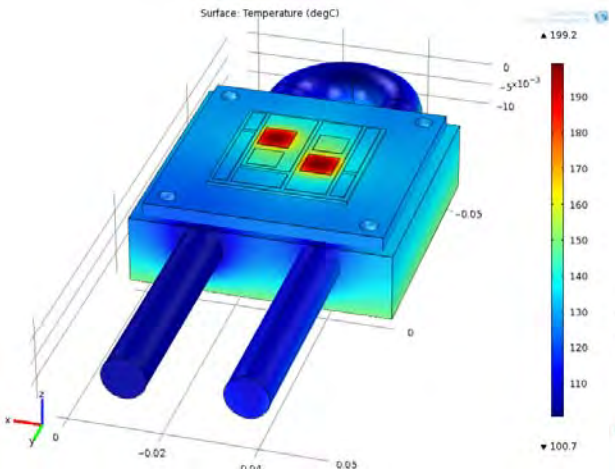
- **Designed a Si device based 10 kW phase-leg power module package including materials selection, layout design, parasitics extraction and thermal performance characterization.**
- **With a two-pass tube liquid cold plate, the analysis shows the package can meet the IMMD power and thermal performance requirement, considering different coolants and 150˚C ambient.**
- **Designed a modular cooling structure for 6-phase inverter.**



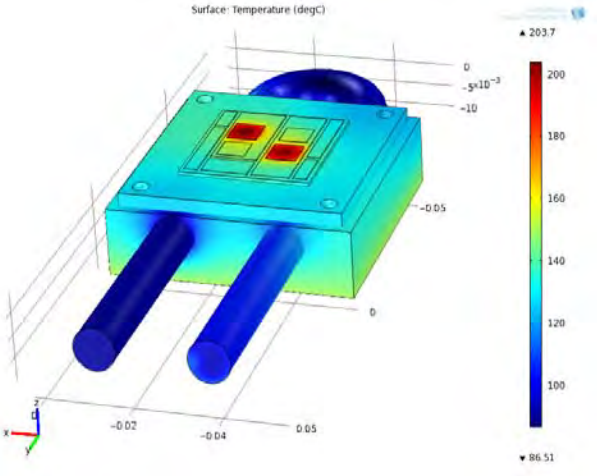
Layout design of 10 kW phase-leg module

Materials Selection

Component	Dimension (mm)
IGC50T120T6RL	7.25×6.84×0.115
Emitter Pad	5.36×5.74×0.004
Gate Pad	1.31×0.81×0.004
SIDC42D120F6	6.5×6.5×0.12
Anode Pad	5.78×5.78×0.004
Substrate	30.6×30× (Cu: 0.3, Al_2O_3: 0.635)
Die Attachment	Solder Au80Sn20, thickness: 0.2
Aluminum Wires	Gate pad 5 mils, others 10mils×6



(a)105˚C water ethylene glycol

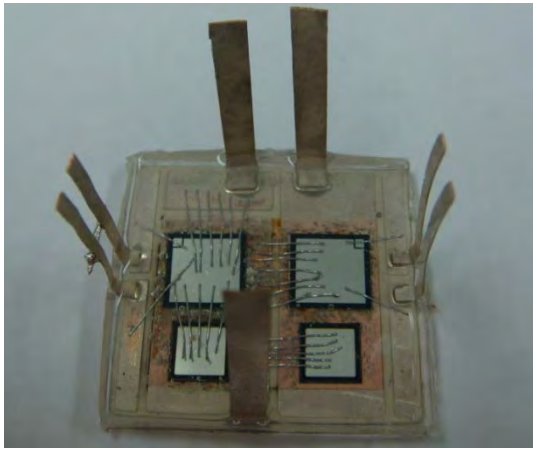


(b) 90˚C transmission oil

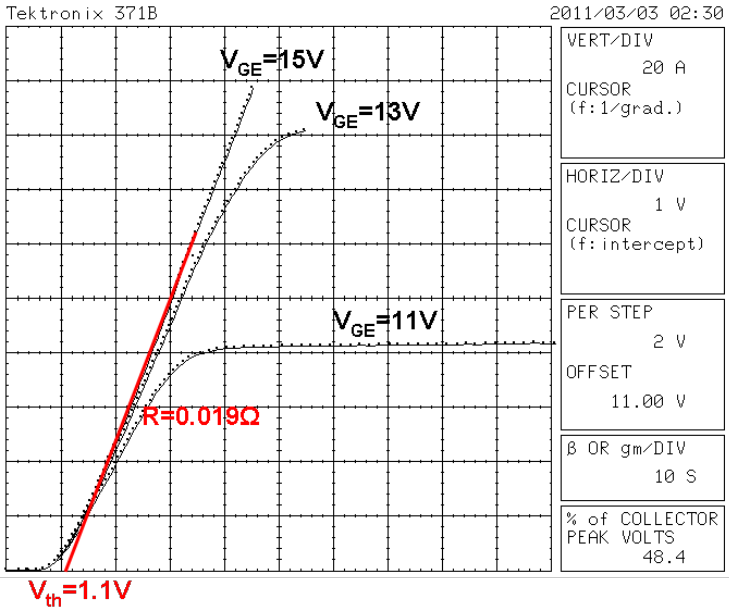
Simulated cooling performance of the packaging design

FY11 Technical Accomplishments

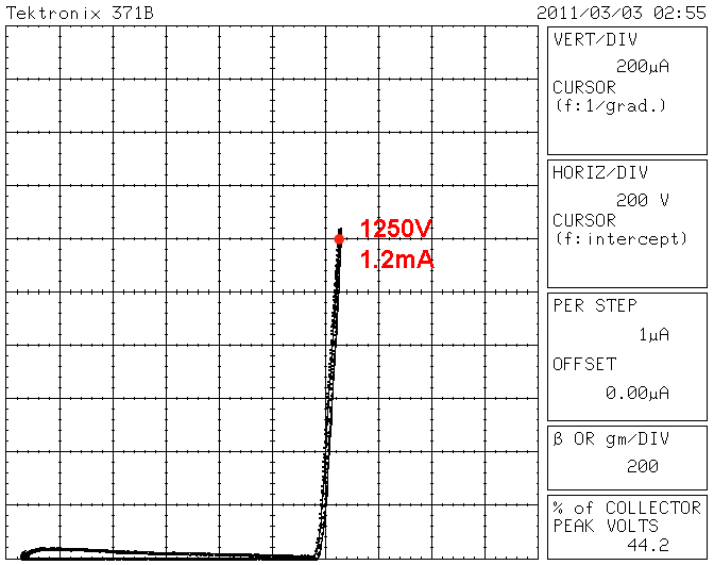
Fabricated First Version Custom Module



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



IGBT Output Characteristics

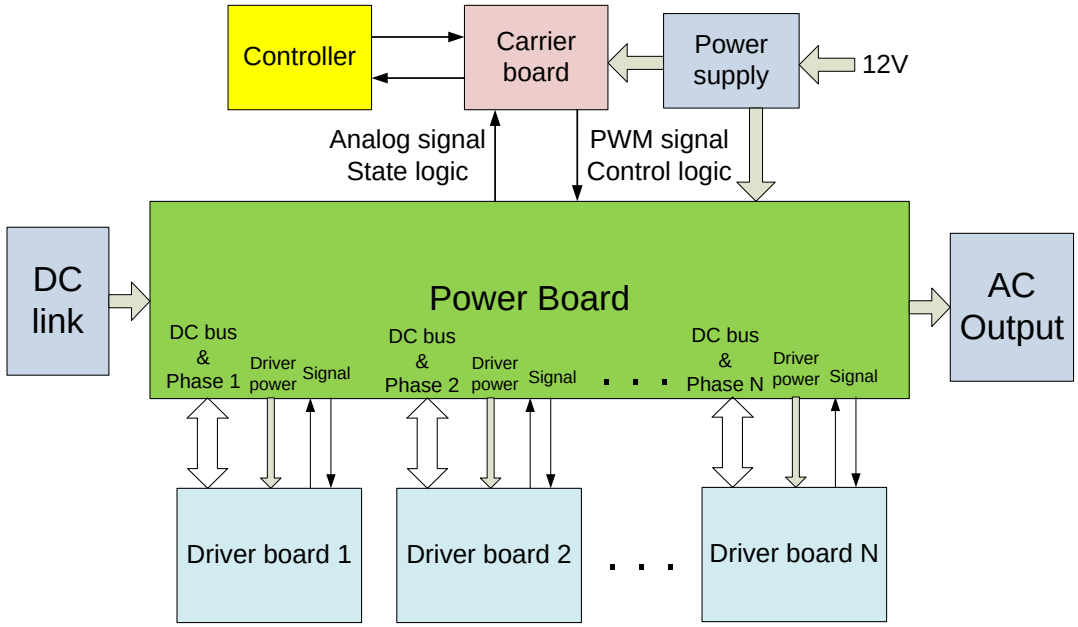


DC Blocking Characteristics

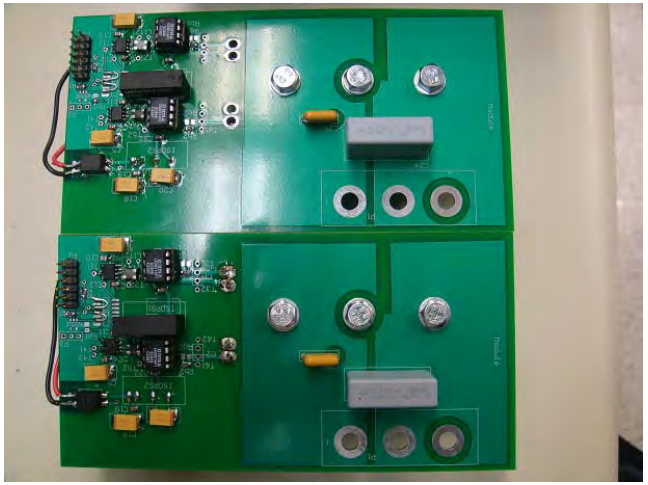
FY11 Technical Accomplishments

System-level Electrical Design

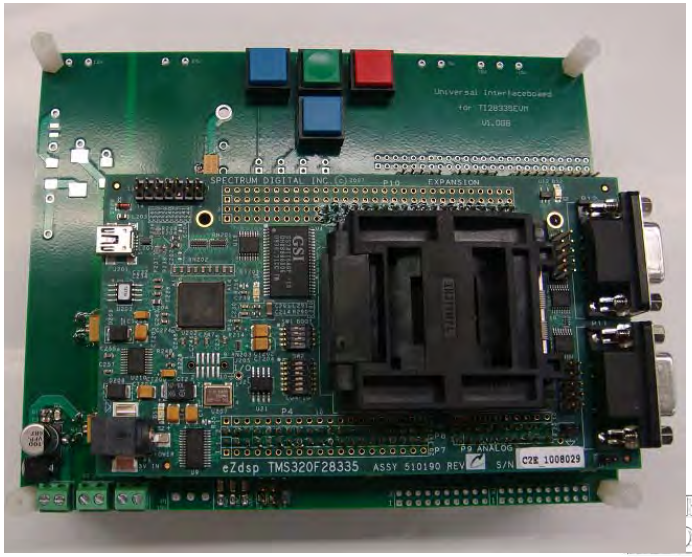
Modular multiphase motor drive architecture



Version 1 phase-leg modules (with driver boards)



Controller with carrier board



- **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**

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**