Electric Drive Inverter R&D

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Overview

Timeline

- Start – FY15
- End – FY16
- 75% complete

Barriers

- Availability and the cost of the WBG devices for the inverter will be barriers for achieving the cost target.

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY15: $960K
- Funding for FY16: $1,100K

Partners

- WBG manufacturers: ROHM, CREE, USCi
- Inverter component suppliers: ROHM, SBE
- ORNL team members: Steven Campbell, Jack Wang, Curt Ayers, Cliff White

Project Objective and Relevance

- **Overall Objective**
  - Integrate wide bandgap (WBG) technology and novel circuit topologies with advanced packaging to reduce cost, improve efficiency and reliability, and increase power density.
- **FY16 Objective**
  - Evaluate latest 600V trench WBG devices and compare with planar DMOS technology
  - Design ORNL-module-based 30-kW liquid-cooled traction drive inverter
  - Complete the design of high frequency boost converter with low parasitics

Milestones

Date	Milestones and Go/No-Go Decisions	Status
Sep. 2015	Milestone: Build and evaluate a 10 kW WBG-based air-cooled three-phase inverter using advanced packages.	**Completed**
Sep. 2015	Go/No-Go decision: If prototype inverter meets 2022 efficiency and power density targets at 10 kW of operation, then design 30 kW liquid-cooled traction drive inverter prototype.	**Go**
Jun. 2016	Milestone: Design a 30 kW WBG-based liquid-cooled traction drive inverter and a high frequency boost converter using advanced packages.	**On track**
Sep. 2016	Go/No-Go decision: If the designed traction drive inverter meets 2022 efficiency and power density targets at 30 kW of operation, then build and test a 30 kW liquid-cooled prototype.	

Approach/Strategy

Reduce size and weight of the inverters to meet the 2022 targets of 13.4 kW/L and 14.1 kW/kg

WBG technology

- Increase the overall efficiency of the traction drive system
- Reduce the size of the passives with high frequency operation
- Reduced thermal requirements with high temperature operation

Integrated topologies and passives

- Reduce cost and volume of the passives
- Integrate more functionality and reduce cost through component count

Control algorithms and novel circuits

- Increase the safe operating area of the WBG devices using advanced gate driver circuits
- Increase the reliability of the system using protection circuits
- Design algorithms to optimize efficiency for light load conditions

Novel system packaging and advanced manufacturing techniques

- Minimize parasitics and increase heat transfer using advanced packaging
- Reduce cost through novel interconnects
- Reduce cost through process optimization

Approach/Strategy

WBG device evaluation

- Static and dynamic characterization: discrete devices
- Single phase test characterization: power modules
- Device models
- Evaluate electrical reliability of the devices

Commercial-module-based liquid-cooled inverter

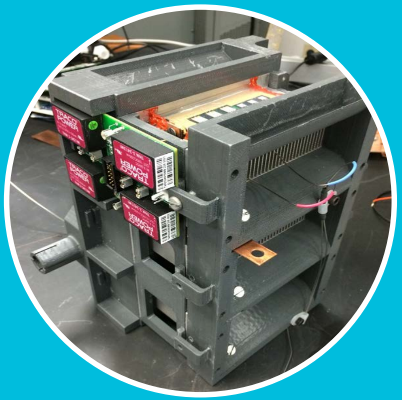
Build, test, and evaluate a 30 kW commercial-module-based WBG inverter

- Use the test results as benchmark
- Scale the inverter as the modules become available

ORNL-module-based liquid-cooled inverter

Build, test, and evaluate a 30 kW ORNL-module-based WBG inverter

- Compare the results with the commercial module based inverter
- Scale the inverter as the devices become available

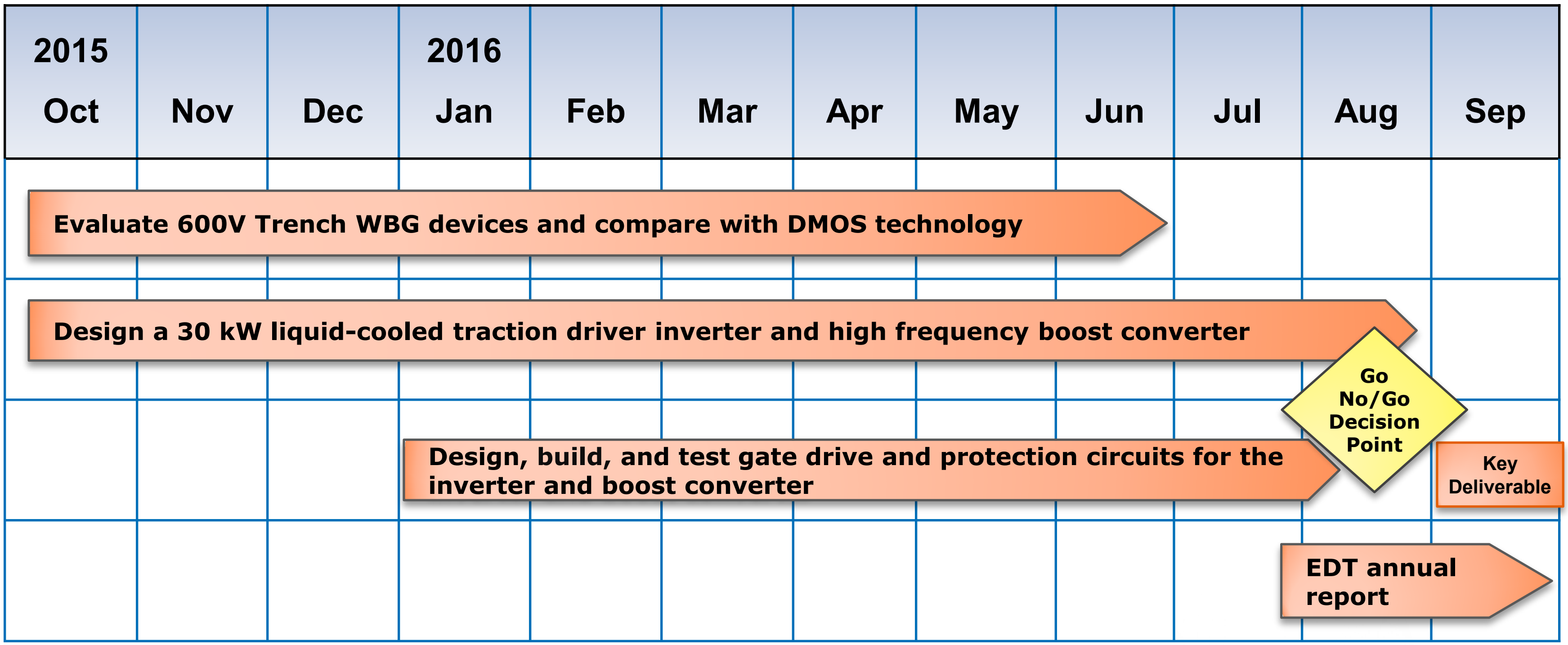


Air-cooled inverter designs

- Build and test a 10 kW air-cooled WBG inverter
- Compare the results with the liquid-cooled inverters
- Scale the inverter as the devices become available

2022 power electronics targets of 13.4 kW/L and 14.1 kW/kg

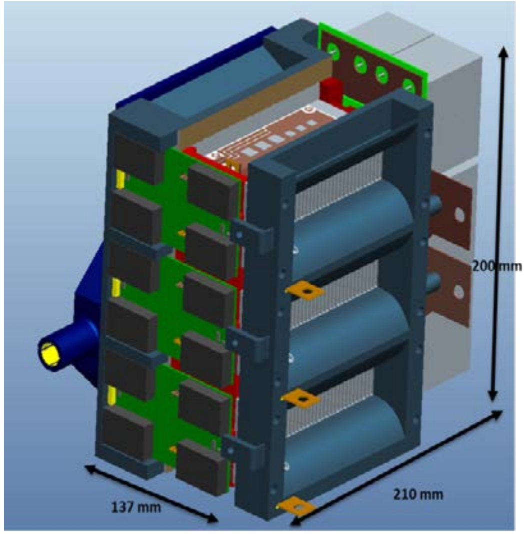
Approach FY16 Timeline

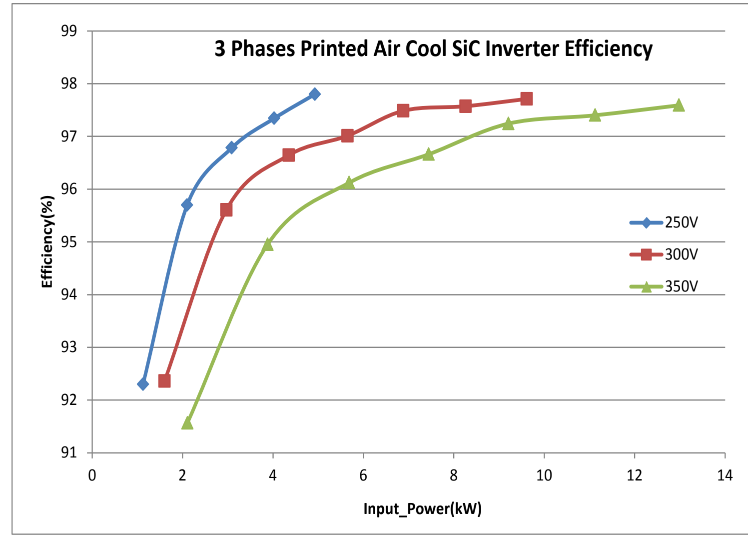


Go No/Go Decision Point: If the designed high frequency boost converter meets 2022 efficiency and power density targets, then build and test 30 kW liquid-cooled inverter prototype.

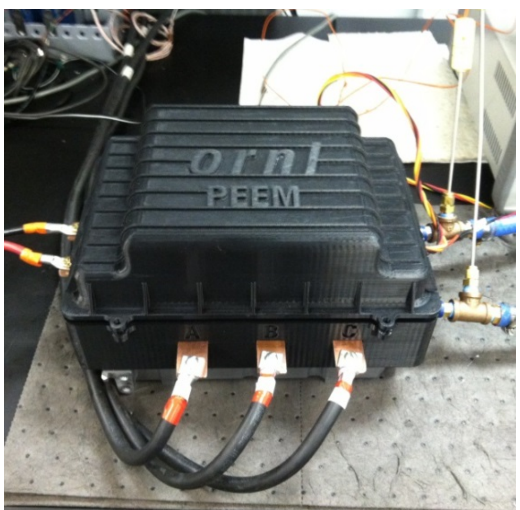
Key Deliverable: 1. Completed design of 30 kW WBG-based liquid-cooled inverter and high frequency boost converter. 2. Gate drive prototype with improved protection function for 30 kW converters

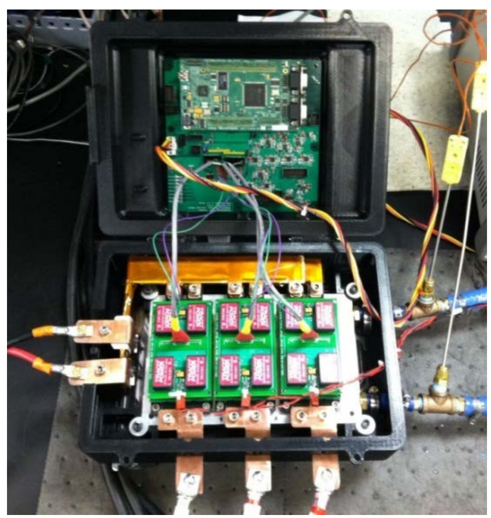
Technical Accomplishments - FY15

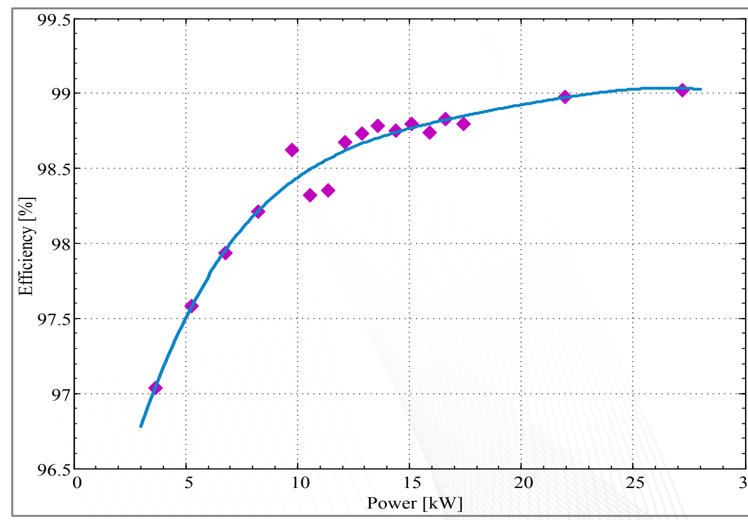




10kW Three Phase Air-Cooled Inverter – 3D Drawing, Prototype, and Efficiency*







30kW Three Phase Liquid-Cooled Inverter – 3D Drawing, Prototype, and Efficiency

****NREL collaboration: heat sink was optimized by NREL***

Technical Accomplishments – FY16

Acquired SiC Devices

Device Type	Rating
Packaged Devices	650V/70A SiC Trench MOSFET
	1200V/55A SiC Trench MOSFET
	1200V/40A SiC DMOSFET without / with body diode
Bare Dies	650V/70A SiC Trench MOSFET
	650V/70A SiC Trench MOSFET
	1200V/55A SiC Trench MOSFET
	1700V/34A SiC DMOSFET

- TO-247 650V/70A SiC Trench MOSFET is being tested and compared with SiC DMOSFET and Si CoolMOS™
- 1200V/55A SiC Trench MOSFET will be used for a EDT project to develop a high frequency high power density boost converter

Device testing data available online at: http://peemrc.ornl.gov/Testing.shtml

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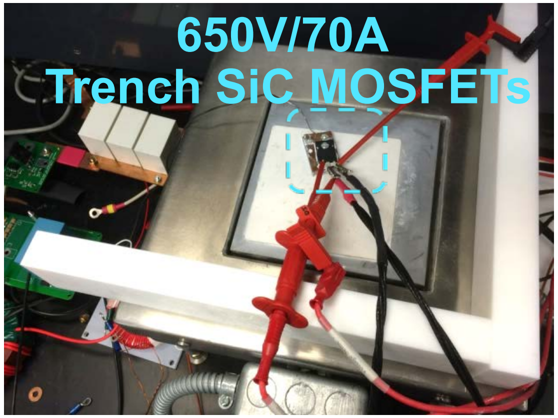
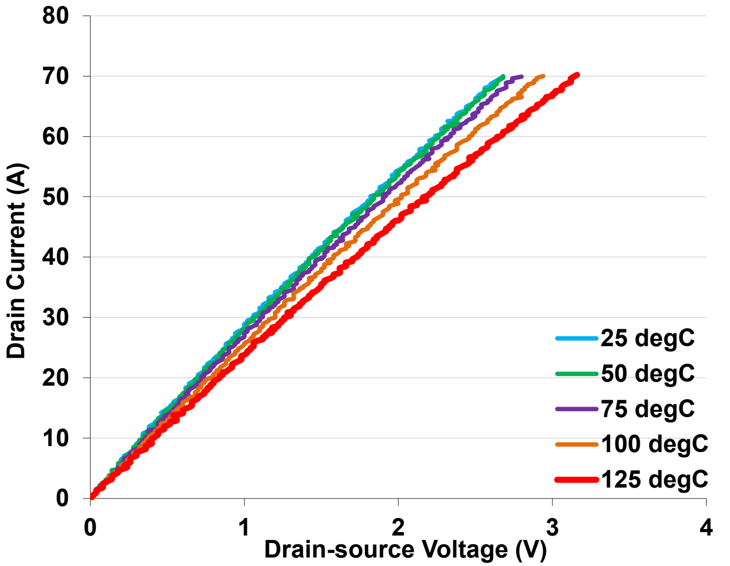
Technical Accomplishments – FY16

Characterization of 650V/70A SiC Trench MOSFETs

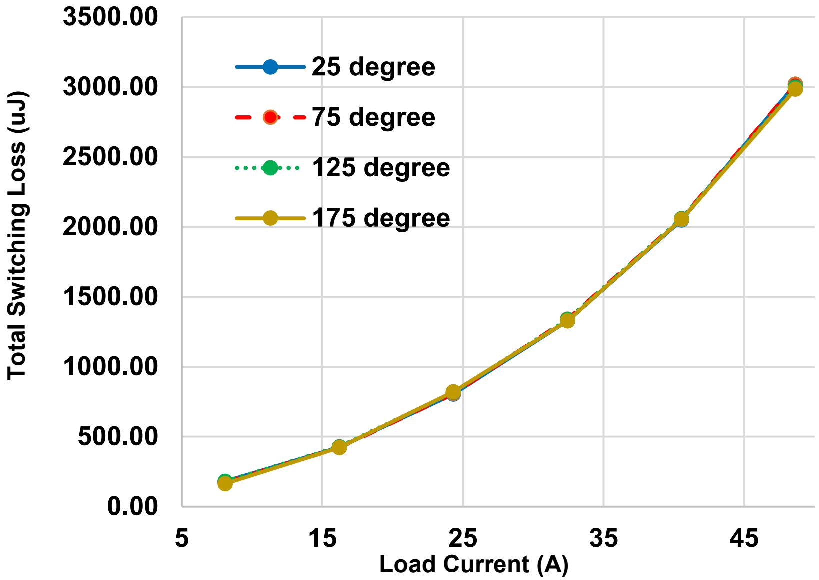
- Static and dynamic performance are characterized using ORNL WBG device evaluation facility
- SiC Trench MOSFET presents a positive temperature coefficient for on-state resistance
- The total switching energy loss of SiC Trench MOSFET is nearly temperature independent



Temperature dependent characterization test



Temperature dependent output characteristics



Total switching loss at 400 V

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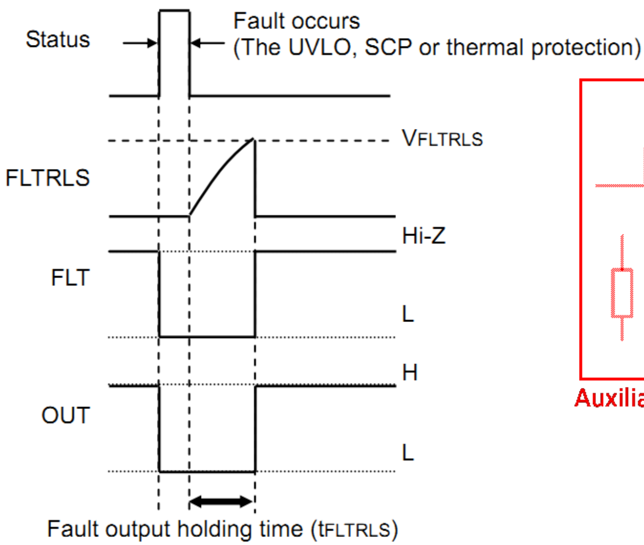
Technical Accomplishments – FY16

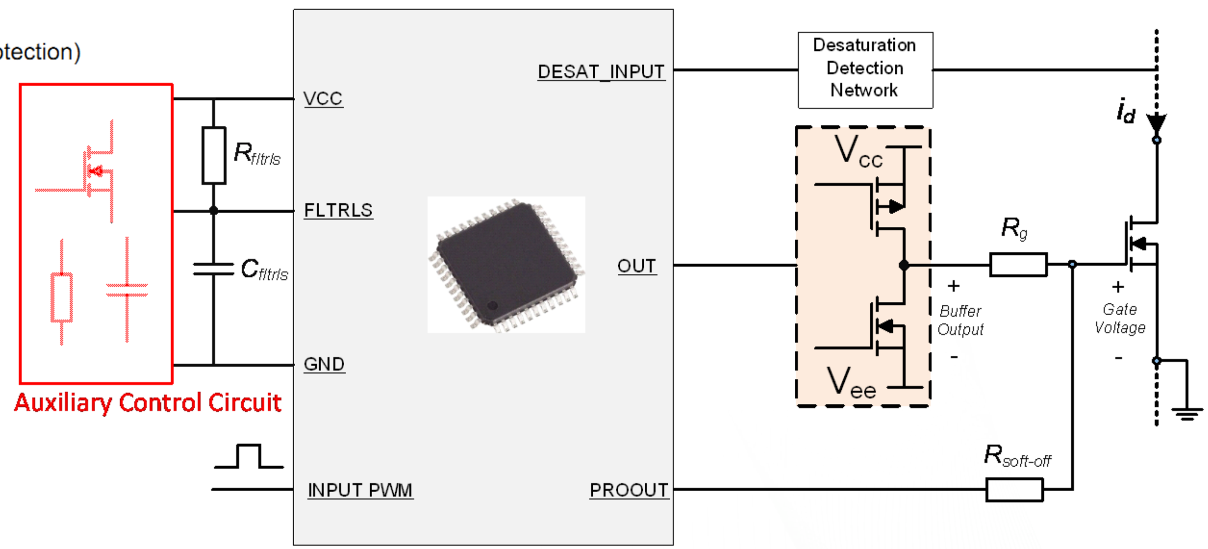
Gate Drive/Protection Improvement

Resolved critical issues: PWM noise, false triggering of short circuit protection, no protection with buffer stage, short fault holding time, no local shut down mode, etc.

Example: short fault holding time & no local shut down mode



Fault Status Output Timing Chart [1]



Commercial gate drive with auxiliary control circuit

- Fault output holding time $t_{FLTRLS} = R_{fltrls} * C_{fltrls}$ (maximum holding time ≈ 200ms)
- Rely on central controller to permanently shut down the converter
- Not reliable under strong EMI noise environment and solid fault conditions

[1] Datasheet, BM6103FV-C – Rohm, available at: http://www.rohm.com

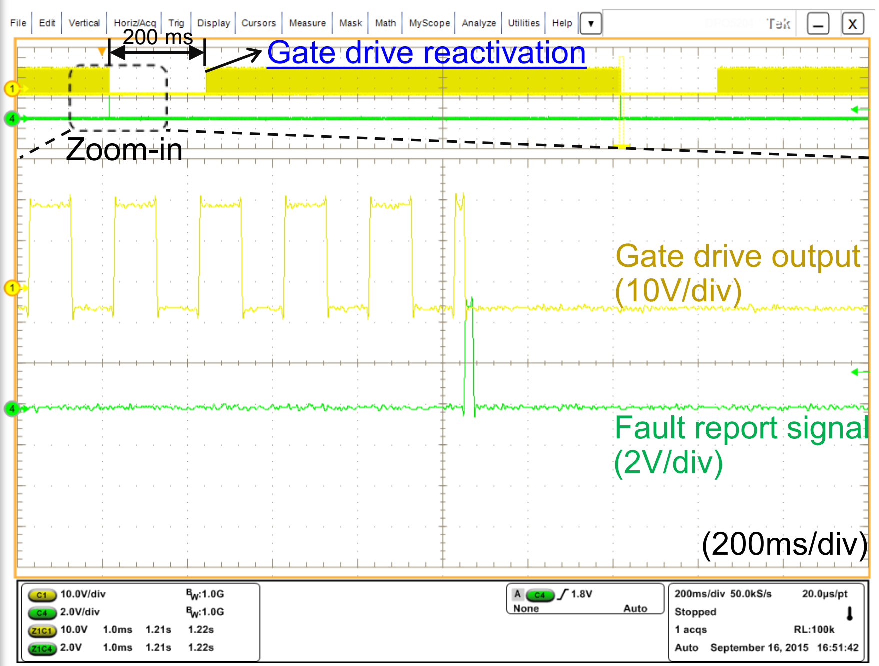
Technical Accomplishments – FY16

Gate Drive/Protection Improvement-*Experimental Verification*

Example: short fault holding time & no local shut down mode

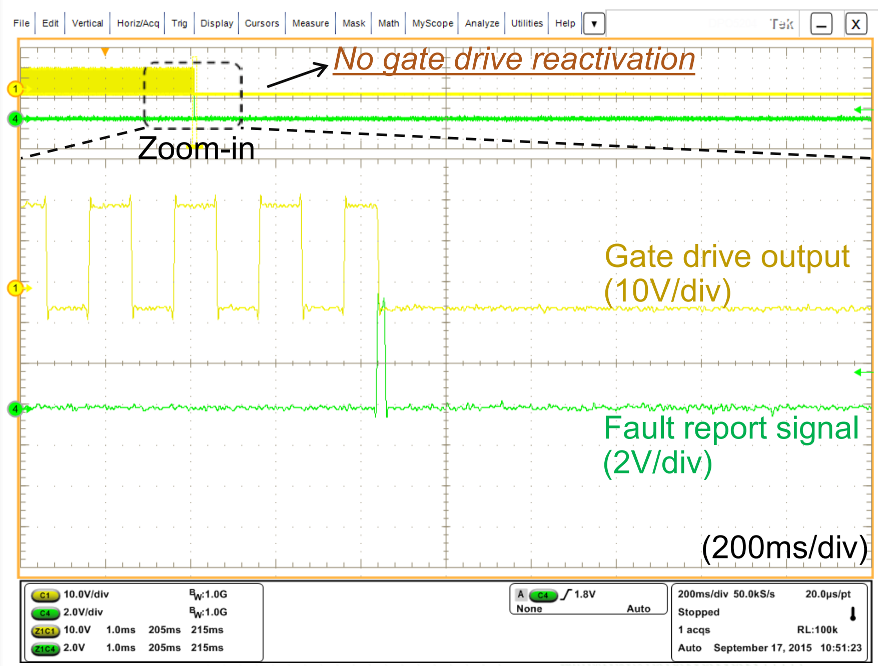
Without Auxiliary Control Circuit

Gate drive cannot shut down locally (maximum holding time: 200 ms)



With Auxiliary Control Circuit

Gate drive can shut down locally (holding fault status permanently)



Technical Accomplishments – FY16

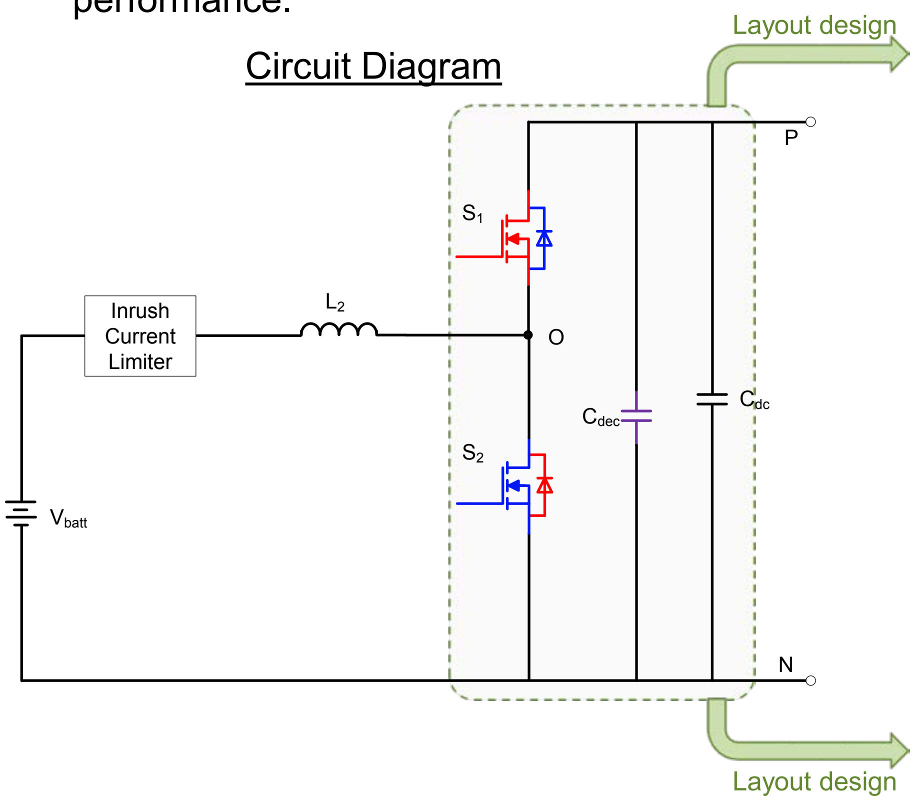
All SiC Power Module for Boost Converter

Module Substrate Layout Design

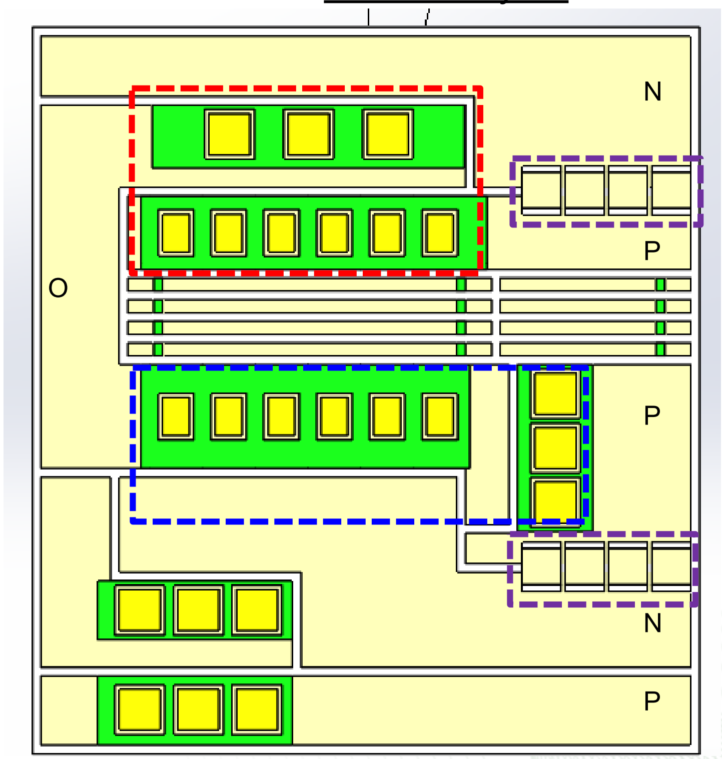
❑ **Mechanical Layout**

- All devices are integrated into one substrate, and decoupling caps are embedded as well.
- "P-cell/N-cell" concept is used to minimize the power loop parasitic inductance for high frequency operation.
- Lossy devices (lower MOSFETs) are located in the center of the module in order to improve thermal performance.

Circuit Diagram



Module Layout

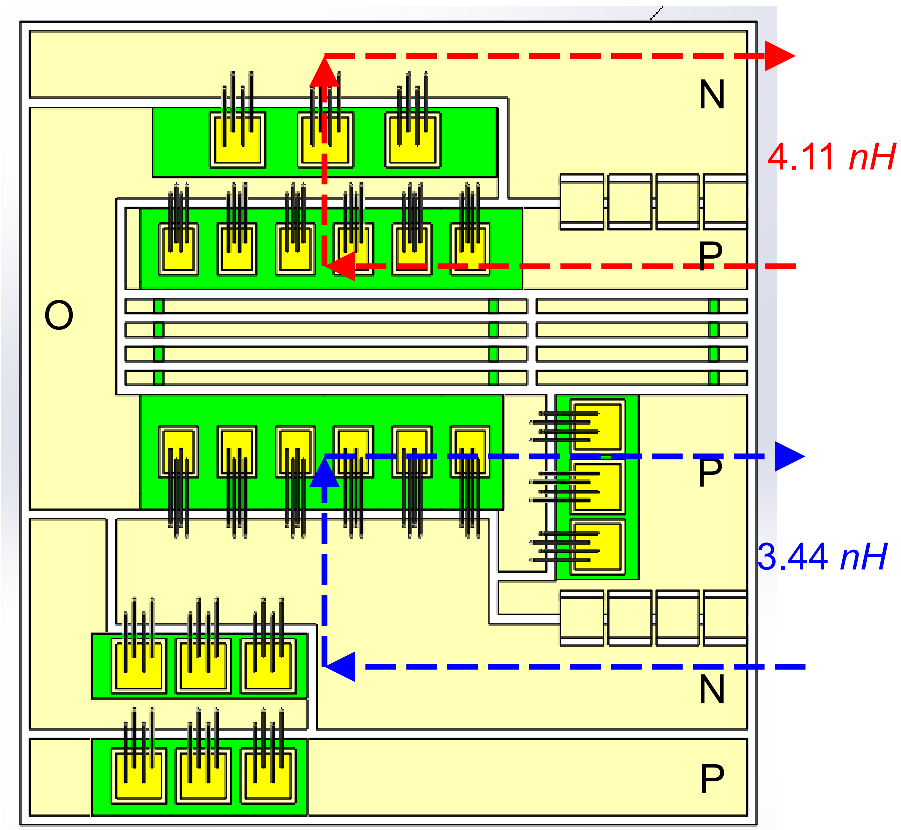


Technical Accomplishments – FY16

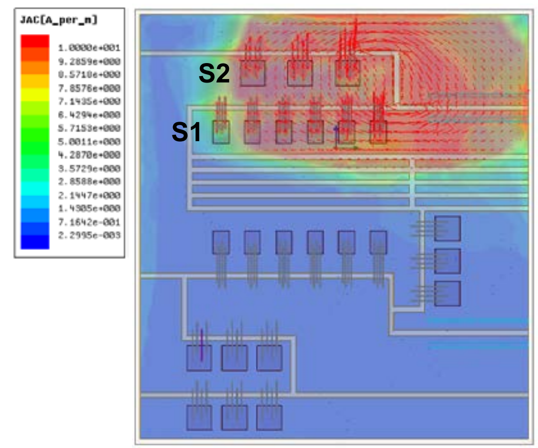
All SiC Power Module for Boost Converter

Module Substrate Simulation

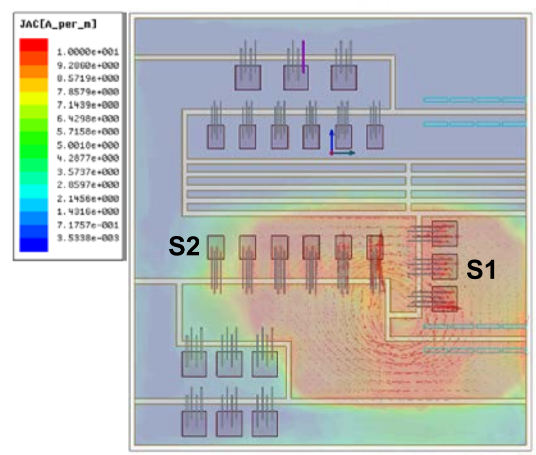
- **Parasitic Inductance Simulation Results**
  - The lumped parasitic inductance is below 5 nH for each switching commutation loop.
  - Current is evenly distributed within both switching loop areas.



Power loop parasitic inductance



Current distribution (S1 MOSFET& S2 Diode)



Current distribution (S1 Diode& S2 MOSFET)

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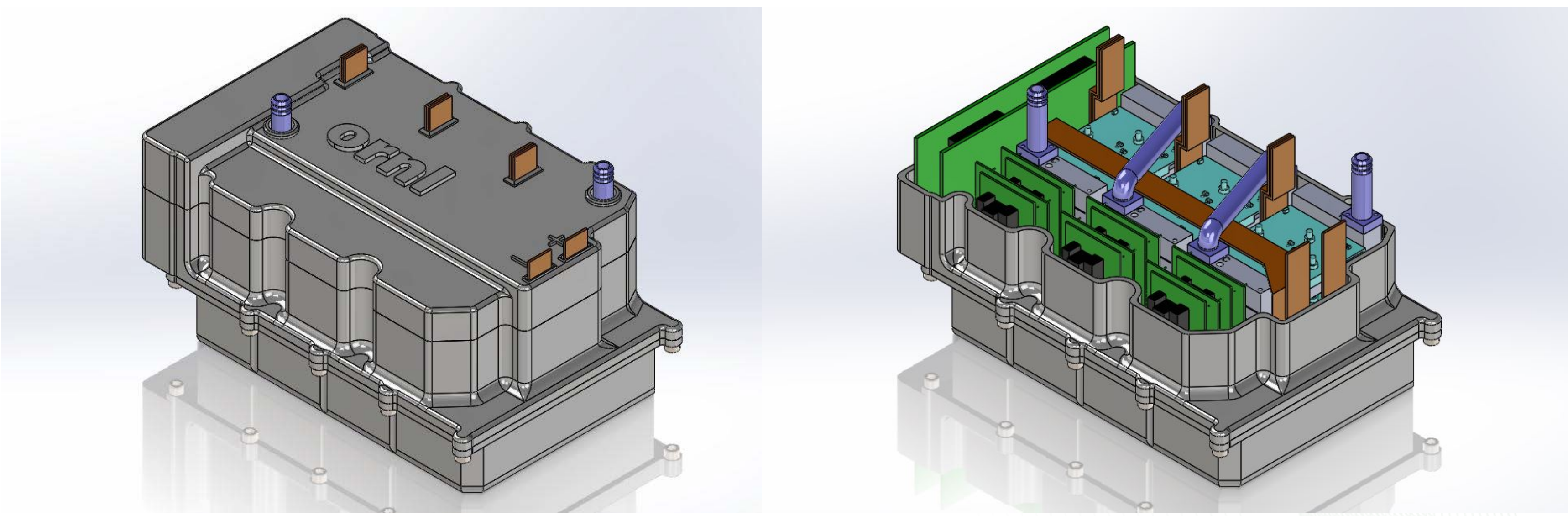
Technical Accomplishments – FY16

All SiC Three Phase Inverter

Preliminary Inverter Layout

- **Key Advanced Features:**
  - Lower convection thermal resistance by utilizing a new optimized 3D-printed cold plate
  - Higher power density compared to the previous 30 kW liquid-cooled inverter (estimated power density ~8.5 kW/L)
  - Modular design (wire-bond module, cold plate, busbars, etc.) for easy fabrication



30 kW Three Phase Liquid-Cooled Inverter – Conceptual 3D Drawing

Responses to Previous Year Reviewers' Comments

Reviewer comment 1: Selecting a commercial power module and building an inverter around it is a good approach to establish a baseline. It would be helpful to quantify results by creating a table, to show the comparison points to the baseline.

Response/Action: A similar power rating traction drive inverter based on commercial power modules will be built to compared with ORNL developed prototypes in terms of power density, die areas, thermal resistance, cost, etc.

Reviewer comment 2: The reviewer would like to see more on bulk capacitor plans in this project, and also adequately addressed plans for switches, as the project also includes "reduce cost through novel interconnects."

Response/Action: We are collaborating with DC link capacitor manufacturers to develop a new 3D-printed capacitor packaging concepts to improve its thermal performance and thus power density.

Reviewer comment 3: This reviewer suggested in the future to include a summary for the power transistor by manufacturer, voltage, generation number, specific RDSON, EON, and EOFF."

Response/Action: The summary and comparison of all tested WBG devices are available online at an ORNL webpage (http://peemrc.ornl.gov/Testing.shtml). The webpage will keep updating the information for the new devices.

Collaboration and Coordination with Other Institutions

Organization	Type of Collaboration/Coordination
WBG manufacturers: International Rectifier, GeneSiC, ROHM, CREE, USiC, General Electric, Infineon	Device prototype suppliers
Capacitor manufacturers: SBE, KEMET, AVX	Custom capacitor suppliers

Remaining Challenges and Barriers

- The power density for the current liquid-cooled boost converter designs need to be further optimized to meet the targets.
- Parasitic inductance of the DBC substrate for the boost converter needs to be minimized to support high frequency operation
- Not having a fast local shut down mode for the short circuit protection of multiple-device module will be a challenge; Reliable operation of the boost converter will be achieved through advanced protection circuits.
- The dc link capacitor volume is a barrier to achieve the overall volume target.

Proposed Future Work

- **Remainder of FY16**
  - Complete the evaluation of 600V trench SiC MOSFETs and compare with planar DMOS Si/SiC MOSFETs
  - Complete design of ORNL-module-based 30 kW liquid-cooled traction drive inverter and high frequency boost converter
  - Simulate, build, and test of the gate drive circuits with improved protection function for the high frequency boost converter

- **FY17**
  - Develop, and test a 55 kW three-phase traction drive inverter
  - Develop, and test a 30 kW liquid-cooled WBG high frequency boost converter
  - Evaluate embedded novel soft startup scheme for boost converter
  - Integrate the novel protection function for the developed boost converter and test different protection modes for improved reliability

Summary

- **Relevance:** Project is targeted toward reducing volume, weight, and cost of the traction drive inverter with improved reliability
- **WBG inverter development approach:**
  - WBG inverter prototypes: 10 kW ORNL air cooled inverter and 30 kW commercial-module-based liquid-cooled inverter.
  - 30 kW WBG converter design: ORNL optimized phase-leg power module for traction drive inverter and high frequency boost converter.
- **Collaborations:** Interactions with WBG device manufacturers, inverter component suppliers to maximize the impact of the inverter R&D.
- **Technical Accomplishments:**
  - Completed evaluation of 600 V trench SiC MOSFET.
  - Completed design of a 30 kW WBG-based liquid-cooled traction drive inverter and boost converter using ORNL's WBG modules.
  - Completed design, build, and test a ORNL-optimized gate drive circuits with advanced protection.
- **Future Work:**
  - Build and test a 30 kW WBG-based liquid-cooled boost converter with embedded soft startup capability and improved short circuit protection function.
  - Collaborate with OEMs and Tier 1 suppliers to license the technology.